DAYLIGHTING OF BUILDINGS

Nancy Ruck

This note, DES 6, originally published in August 2000, was revised and rewritten by Nancy Ruck in August 2001. The information herein is considered contemporary and relevant.

SUMMARY OF

ACTIONS TOWARDS SUSTAINABLE OUTCOMES

Environmental Issues/Principal Impacts

- The intensity, spectrum and availability of daylight together with its inherent energy efficiency is part and parcel of providing healthy lighting for interiors during the daytime, ensuring substantial energy savings and contributing to sustainability in buildings. Working long-term in electric lighting is believed to be deleterious to health, therefore it is necessary to provide opportunities for increasing daylight exposure by the good use of daylight.
- Good daylighting quality can be obtained by controlling daylight to prevent glare and heat gain.
- Innovative daylighting systems to redirect daylight where it is needed, control glare, and provide solar shading, have a high aggregate electricity savings potential when applied in schools, commercial and institutional buildings.
- Controlled daylighting reducing the heating and cooling of buildings can have a considerable impact on the size of air-conditioning equipment.
- Taking into account human response to daylighting control technologies is a critical element in the determination of energy savings from daylit buildings.

Basic Strategies

In many design situations, boundaries and constraints limit the application of cutting EDGe actions. In these circumstances, designers should at least consider the following:

- In the conceptual stage of building design, study obstructions at the site with respect to daylight availability and the daylight potential of building facades to determine building shape and siting (Littlefair 1991).
- Consider tradeoffs and optimisation between competing elements in the facade and electric lighting systems, e.g. finding the optimum between a transmittance value of a window/daylighting system and the control of heat input and unwanted glare (O'Connor et al 1997).
- Design for glare control by the separation of light and view windows. Use higher transmission clear glazing and/or a simple daylighting system such as a light shelf with clerestory windows above the eye line and lower transmission glazing in the view windows below (Ruck et al 2001).
- Consider using innovative daylighting systems in new and existing buildings such as reflective light shelves, lamellas, laser cut panels and anidolic systems to increase usable daylight at greater depths from the window for either climates with predominantly overcast skies, or where control of sunlight is required, or for windows that have a restricted view of the sky (Ruck et al 2001, Edmonds et al 1996, Courret et al 1996, Littlefair 1996, Aizlewood 1993).
- Develop daylighting strategies for different parts of the building in the design of the facades, and selection and integration of systems and services including electric lighting. These should all be related to the building's daylighting plan.
- Use the IEA SHC's book *Daylight in Buildings – A Source Book of Daylighting Systems and Components* to assist in an appropriate application of a daylighting system according to the predominant sky type at the location, the building orientation and performance capabilities (Ruck et al, 2001).
- Integrate these daylighting strategies with daylight responsive control systems for the electric lighting and shading systems. There is no efficiency in energy saving when daylighting technologies are not integrated with daylight responsive control systems (Ruck et al 2001).
- Use controls that are capable of adapting to users' preferences – a necessary condition to lead to a wider acceptance of automatic control systems in buildings (Morel et al 2001).
- Use appropriate daylighting design tools at the various stages of building design, to predict the impact of the daylighting technologies on a building's energy consumption (de Boer and Erhorn,1999 [a]).

Cutting EDGe Strategies

- Consider using innovative and self-adaptive integrated daylighting and shading systems for building energy and comfort management, including controllers for heating, cooling, ventilation, blinds, electric lighting and a shading device controller (Morel et al, 2001).
- Consider using electrochromic glazing (now currently being tested in laboratories) with a light transmission that varies depending on the amount of incident daylight or temperature.
- Consider using a daylighting design road map to simplify the process of daylighting design for buildings (refer IEA SHC Task 31 work programme).

Synergies and References

- Aizlewood, M.E., 1993. *Innovative daylighting systems: an experimental evaluation*, Lighting Research and Technology 14 (4).
- *BDP Environment Design Guide*: GEN 24, GEN 61, DES 1, DES 6, DES 7, DES 35, DES 36, DES 37, DES 60, DES 61, TEC 3, TEC 9, TEC 16, PRO 3, PRO 32, CAS 22, CAS 35
- de Boer, J., and Erhorn, H., (Ed) 1999 (a). *Results of Subtask C: Daylighting Design Tools*, IEA SHC Task 21/ECBCS Annex 29 Report, Fraunhofer Institute for Building Physics, Stuttgart, Germany.
- de Boer, J., and Erhorn, H., (ed) 1999 (b). *Survey Simple Design Tools*, IEA SHC Task 21/ECBCS Annex 29 Report, Fraunhofer Institute for Building Physics, Stuttgart, Germany.
- Courret, G., Paule, B., Scartezzini, J.L., 1996. *Anidolic zenithal openings: Daylighting and Shading*, Lighting Research and Technology 28(1): 11-17.
- Edmonds, I.R., Jardine, P.A., Rutledge, G., 1996. *Daylighting with angular selective skylights: predicted performance*, Lighting Research and Technology 28(3):22-28.
- Guillemin, A., Morel, N., Scartezzini, J.L., 2004. *Energy Efficiency and User Adaptation in Automatic Building Control*, to be published in Energy & Buildings 2005.
- IEA SHC Task 31 work programme. See www.iea-shc.org/task31
- Littlefair, P.J., 1995. *Computer assessment of the daylighting performance of light shelves*, Lighting Research and Technology 27 (2).
- Littlefair, P.J., 1991. *Site layout planning for daylight and sunlight: a guide to good practice*, British Research Establishment (BRE) Report, Garston, UK. LUMEN 1995.
- Morel, N., Guillemin, A., and Molteni., S, 2001. *An innovative and self-adaptive lighting controller using fuzzy logic*. International Daylighting R, D & A, Issue No 1 September 2001.
- Morel N., Bauer, M., El-Khoury, M., Krauss, J., 2001. *NEUROBAT, A Predictive and Adaptive Heating Control System Using Artificial Neural Networks*, International Journal of Solar Energy, 21 (2001).
- Scartezzini, J.L., Courret, G., 2002. *Anidolic Daylighting Systems*, International Journal of Solar Energy, 21 (2) 2002.
- O'Connor, J., Lee, E.S., Rubinstein, F.M., Selkowitz, S.E., 1997. *Tips for daylighting with windows: the integrated approach*, PUB 790, Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley.
- Ruck, N., et al, 2001. *Daylight in Buildings: A Source Book on Daylighting Systems and Components*, IEA SHC Task 21/ ECBCS Annex 29 Report Lawrence Berkeley National Laboratory, Berkeley, CA 94720. See www.iea-shc.org

DAYLIGHTING OF BUILDINGS

Nancy Ruck

Daylighting and the impact of daylighting strategies on the lighting, heating and cooling of buildings, is a vital issue to building owners, design professionals and building occupants with respect to energy use and associated carbon emissions. This paper introduces the concept of daylight-conscious building design and outlines strategies to realise and predict energy savings, which take into account the occupants' visual and thermal comfort.

1.0 INTRODUCTION

There are a number of ways in which natural lighting can play an important role in sustainable design. In a world becoming increasingly concerned with reducing CO_2 carbon emissions, the planned use of natural light in residential and non-residential buildings is an important strategy in improving energy efficiency and sustainability by minimising lighting, heating and cooling loads. An innovative approach is the introduction of advanced daylighting strategies and systems, which can considerably reduce a building's electricity consumption and also significantly improve the quality of light in an indoor environment. Current electrical energy use, particularly in non-residential buildings is a matter of concern, and while photovoltaic electricity production could partly cover the demand, incorporating these systems requires a high capital investment. Daylighting systems serving multiple functions with a mix of strategies (e.g. the redirection of direct sunlight and the use of controlled shading devices), may be much more economical than using photovoltaic electricity. This paper addresses the use of daylighting strategies and their integration with electric lighting and shading controls.

2.0 THE IMPORTANCE OF DAYLIGHT

Apart from providing a view and contact with the outside world, windows and roof lights have other psychological and physiological advantages (Tabert and Shelley, 1993). Occupant preference for natural rather than electric light lies also in the quality of light, its colour rendering ability, as well as its changeability and variability (Boyce, 1998). Daylight falls off rapidly with distance from the window wall. Vertical planes and luminance/brightness contrasts in the interior space are important, as large contrasts have definite negative effects on the physical wellbeing of occupants.

3.0 DAYLIGHT AVAILABILITY

Daylighting techniques use both diffuse light from the sky or skylight (i.e. excluding sunlight and direct beam radiation from the sun), including sunlight reflected from the ground and other surfaces. The sky is a very dynamic light source. The large differences in the spatial distribution of natural light are due, not only to the sky type and the influence of the sun's movement, but also to the changing, moving clouds and reflectances from surrounding external surfaces. Universal sky models of reference daylight conditions, based on new sky standards have been adopted by the Commission Internationale de L'Eclairage (CIE) (Kittler, Darula and Perez, 1998). This universal exterior daylight standard enables the comparison and characterisation of the daylight climate in any location either by analyzing measured data or simulating illuminance conditions by the fifteen sky standards.

There are several sources of information on daylight availability. Data from the CIE International Daylight Measurement Program (IDMP) can provide accurate climatic information for more than 50 sites around the world including Australia (Dumortier, Avouac and Fontoynont, 1994). In addition, results can be obtained for all Europe by computing meteosat satellite data, which can be downloaded from the web using the Satel-light Server. European maps are provided by www.satel-light.com, showing the frequency at which a certain level of global horizontal illuminance is exceeded, and by computing the percentage of glazed area required to reach a given objective (Dumortier, 2000). An indication of how to use these data sources in daylighting calculations and design in daylighting industrial buildings using square roof apertures is given by Yannick Sutter (Sutter, Fontynont and Dumortier, 2001).

Daylight availability strongly depends on building and window orientation; therefore each orientation is characterised by distinct operating conditions, e.g. the presence or not of sunlight. The requirements of these different conditions may be contradictory; nonetheless a good daylight strategy should perform well under all typical conditions. Design studies of vernacular architecture and other well performing constructions are an appropriate way to understand the relationship between daylight climate and building design.

4.0 DAYLIGHT AND ENERGY

Practical experience and calculation have shown that daylight can replace up to 50% of the electric lighting energy used in buildings with daytime occupancies. Studies in actual offices have indicated that lighting accounts for about 30% of total lighting, heating and cooling costs over a year (Goulding et al, 1992). However, lighting, heating and cooling are interdependent and, unless carefully planned, increasing daylight input into buildings in Australia may bring with it unwanted heat gains. Energy savings in non-residential buildings will be influenced by:

- the daylighting strategies adopted
- the method of electric lighting control
- the impact of shading control devices
- the electric lighting power density and type of heating/ventilation/air conditioning (HVAC) system; and
- occupant acceptance of controls.

Daylight optical systems, daylighting and shading control elements, and electric lighting control systems must be considered concurrently. Energy savings cannot be realised in daylit buildings unless the electric lights are dimmed or switched to correspond with the amount of available daylight. An evaluation of currently available responsive control systems has shown that energy savings of up to 40%, compared to a non-controlled system, have been found in daylit zones. Cooling load reductions have also been noted which could result in additional savings in electrical energy consumption. It has also been found that savings can be larger in toplighted spaces or hot climates.

5.0 DAYLIGHTING STRATEGIES

There are three major functions of daylighting systems for buildings:

- to provide solar shading
- to provide protection from glare; and
- to redirect daylight.

Daylight strategies not only depend on the availability of natural light, they respond to climate as a whole. The latitude, ambient temperatures and sunshine probability are among the most significant descriptors of climate. The sunshine probability has to be considered when deciding whether strategies for direct sunlight are applicable. While high latitudes have distinct summer and winter conditions, the seasonal variation of the daylight level at low latitudes is less apparent. Due to the low levels of daylight in winter at high latitudes, the designer can usually aim to maximise the penetration in winter months. In this case, the redirection of daylight from the brightest regions of the sky into buildings is a suitable strategy. In the tropics, with high levels of daylight throughout the year, the predominant design problem is to prevent overheating and consequently to restrict the amount of daylight entering the building. The obstruction of large parts of the sky, especially of areas near the zenith and the admission of daylight only from lower parts of the sky, or the admission of ground reflected sunlight alone, are among the strategies applied in tropical regions.

5.1 Strategies for skylight

The most significant characteristic of strategies for skylight is the way direct sunlight is managed. Solar-shading and protection from glare are different functions, and require individual design considerations. While solar shading is a thermal function that primarily protects from direct sunlight, glare protection is a visual function that moderates high luminances in the visual field. Apart from south oriented spaces in the southern hemisphere and north oriented spaces in the northern hemisphere, where solar-shading may not be necessary, solar shading needs to be considered in the daylighting of buildings.

5.2 Strategies for cloudy skies

Daylight strategies using skylight in predominantly cloudy conditions require that the windows be located in high positions, and that both windows and roof lights are of relatively large size. Some innovative daylighting systems, such as the anidolic ceiling, are designed to enhance daylight penetration in cloudy sky conditions and are able to control sunlight by the addition of an external blind device if needed (refer to Table 1: Non shading systems using diffuse light). The application of simple architectural measures, such as a reflective sill, is another design opportunity to enhance the daylight penetration.

5.3 Strategies for clear skies

In contrast to daylighting strategies for cloudy skies, strategies using diffuse skylight from clear skies have to deal with direct sunlight. Openings for clear sky strategies need not be sized with respect to the low daylight levels of overcast skies. Shading systems primarily using diffuse skylight are applicable in this case, such as the anidolic zenithal opening or louvres and venetian blinds (refer to Table 1).

5.4 Strategies for direct sunlight

Strategies for sunlight and strategies for diffuse skylight are quite different. Direct sunlight is so bright, that the amount of incident sunlight on a small aperture is sufficient to provide adequate daylight levels in large interior spaces. Beam daylighting strategies are applicable if sunshine probability is more than 60%. The parallelism of sunlight allows direct sunlight to be guided and to be piped relatively easily. Optical systems for direct light guiding and systems for light-transport are applicable in this case. Apertures designed for the redirection of sunlight do not usually provide interior spaces with a view to the outside and should therefore be combined with other openings providing an external view.

6.0 SHADING CONTROLS

With daylighting, there is the need to distinguish between the control of glare caused by the sun and/or high sky luminances, and shading to control heat gain. Some shading systems can operate independently of a daylighting system, others can be an intrinsic part of the system, such as in the transparent sun excluding system or the light directing skylight (refer to Table 1). The potential of an integrated system with automatic control of daylight and electric lighting using a dynamic envelope/lighting control system has been demonstrated in experimental studies (Lee et al, 1997). In this preliminary experimental work, carried out at Lawrence Berkeley National Laboratory, daylight responsive dimming of fluorescent lamps was coupled with automatically controlled venetian blind slats, which exclude sunlight by automatically varying the slat angle. This system was designed to balance cooling loads and daylight admission by preventing direct sun penetration, and actively manage daylight and electric light to provide 500 lux on the work plane.

7.0 DAYLIGHTING SYSTEMS

To select an appropriate daylighting system, the design professional needs to identify the major objectives of incorporating such a system. These might include:

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

There are two major groups of daylighting systems - those with and without shading. The two types of daylighting systems with shading are:

- systems that rely primarily on diffuse daylight and reject direct sunlight; and
- systems that use primarily direct sunlight, sending it onto the ceiling or locations above eye height.

Daylighting systems without shading are designed primarily to redirect daylight to areas away from a window or skylight opening. These may or may not block direct sunlight and include:

- diffuse light guiding systems; and
- direct light guiding systems using direct sunlight.

Some examples of these daylighting systems are in Table 1.

7.1 Daylighting systems summary

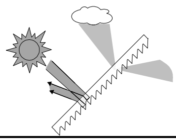
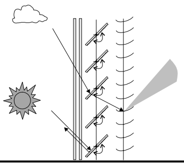
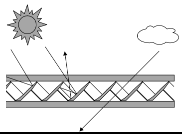
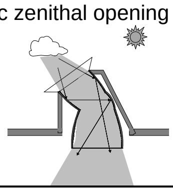
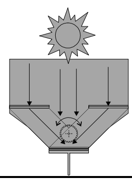
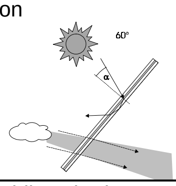
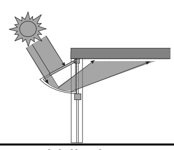
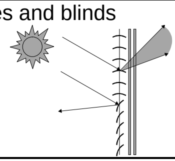
With conventional shading systems, daylight for seeing and working is blocked, requiring the use of electric light. To prevent this, shading systems that redirect diffuse skylight or sunlight can be employed (see Table 1). The overcast or cloudy sky is much brighter in the zenithal area of the sky. Using light guiding elements that redirect light from these areas into the depth of a room, such as the anidolic ceiling, increases the utilisation of daylight.

A light shelf combines solar shading and the redirection of sunlight, improves the distribution of daylight and allows a view through the lower part of the window. Light shelves are applicable in sunny climates, in medium latitudes on orientations pointing to the equator. They are most successful if external and tilted upwards.

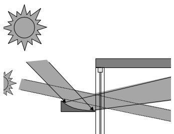
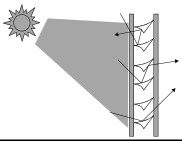
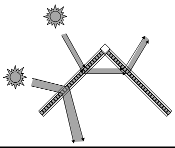
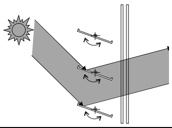
Other daylighting systems are designed for only one function. Light guiding glass for example, redirects sunlight but does not include solar shading or protection from glare. Interior roller blinds primarily protect from glare, but they only have a limited effect on solar shading and usually do not redirect daylight.

Table 1. Daylighting systems (Ruck et al, 2001).

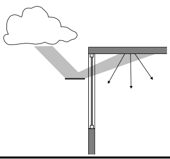
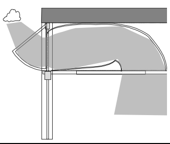
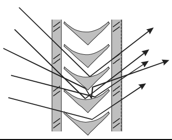
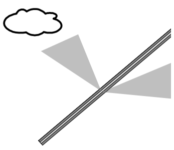
Shading systems using diffuse light

Type	Climate	Attachment
Prismatic panels 	All climates	Vertical windows, skylights
Prisms and Venetian blinds 	Temperate climates	Vertical windows
Sun protecting mirror elements 	Temperate climates	Skylights, glazed roofs
Anidolic zenithal opening 	Temperate climates	Skylights
Directional selective shading system with concentrating Holographic Optical Elements (HOE) 	All climates	Vertical windows, skylights, glazed roofs
Transparent shading system with HOE based on total reflection 	Temperate climates	Vertical windows, skylights, glazed roofs
Light guiding shade 	Hot climates, sunny skies	Vertical windows above eye height
Louvres and blinds 	All climates	Vertical windows

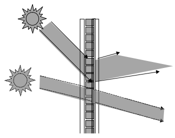
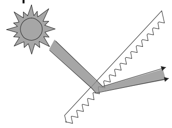
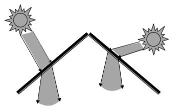
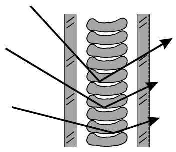
Shading systems using sunlight

Type	Climate	Attachment
Light shelf for redirection of sunlight 	All climates	Vertical windows
Glazing with reflecting profiles (Okasolar) 	Temperate climates	Vertical windows, skylights
Skylight with Laser Cut Panels 	Hot climates, sunny skies, low latitudes	Skylights
Turntable lamellas 	Temperate climates	Vertical windows, skylights

No shading systems using diffuse light

Type	Climate	Attachment
Light shelf 	Temperate climates, cloudy skies	Vertical windows
Anidolic ceiling 	Temperate climates, cloudy skies	Vertical facade above viewing window
Fish system 	Temperate climates	Vertical windows
Zenith light guiding elements with Holographic Optical Elements 	Temperate climates, cloudy skies	Vertical windows (especially in courtyards), skylights

Non shading systems using sunlight

Type	Climate	Attachment
Laser Cut Panel (LCP) 	All climates	Vertical windows, skylights
Prismatic panels 	All climates	Vertical windows, skylights
Holographic Optical Elements in the sky light 	All climates	Skylights
Sun directing glass 	All climates	Vertical windows, skylights

8.0 ELECTRIC LIGHTING CONTROLS

Electric lighting is a major energy end use in buildings and can affect cooling and heating loads. The internal generation of heat from lighting, other equipment, occupants etc, will often result in a cooling demand most of the year during daytime occupancy hours. It is possible to conserve this electrical energy by a greater use of daylight, together with the use of daylight responsive lighting controls (Lee et al, 1997). Fluorescent lighting is the type of light source generally used with electric lighting controls but consideration should be given to the colour rendering ability and colour appearance of the source type. To achieve optimum results, a room or interior space needs to be zoned for optimal placement of the luminaires and sensors with the luminaires parallel to the windows. The colour temperature of the lamp (in most cases fluorescent lamps of 3000 - 4000K) should be in agreement with the colour temperature of the daylight.

In the past ten years, the use of electric lighting controls has highlighted the opportunities for significantly reduced lighting energy use and moderating peak demand in commercial buildings, compared to conventional systems without controls. The lighting control strategies used have included automatically dimming the lights in response to daylight, dimming and switching luminaires on or off according to occupancy, and lumen maintenance i.e. automatic

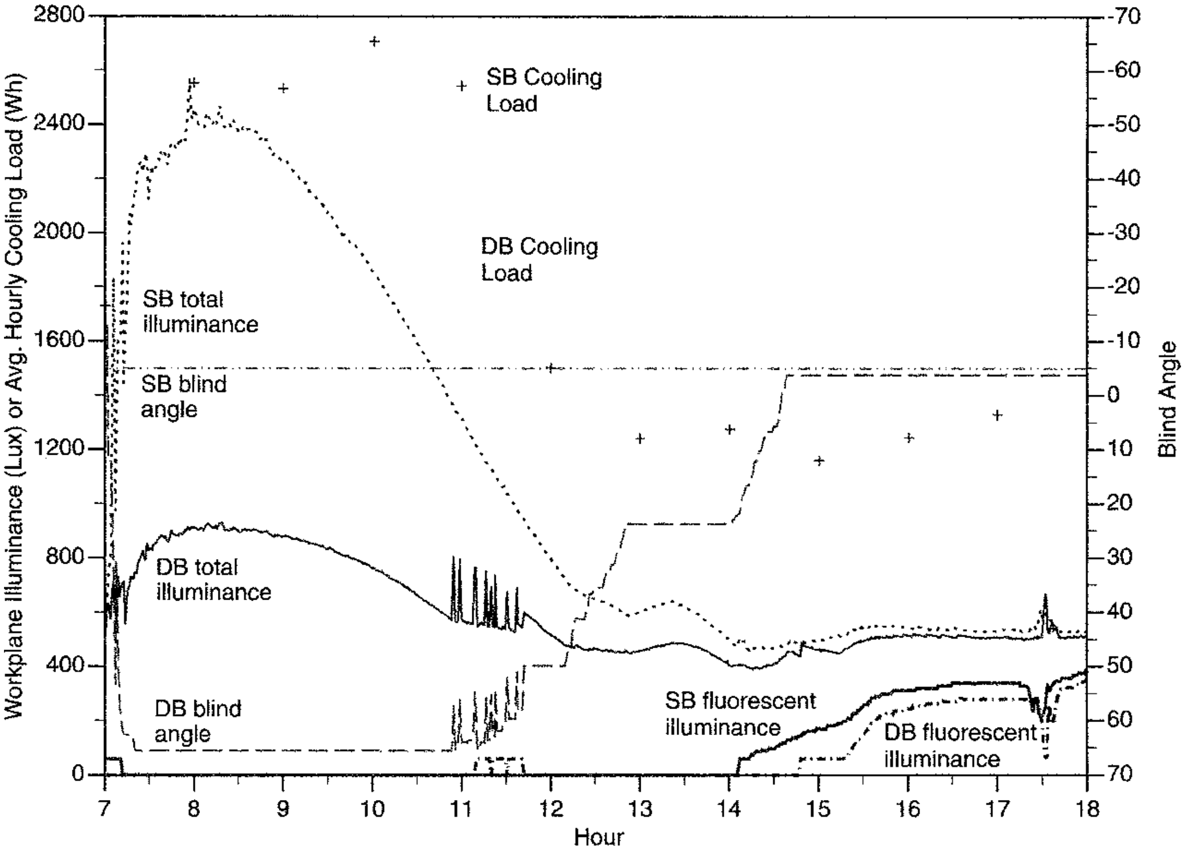


Figure 1. Monitored total work plane illuminance, electric lighting illuminance, angle of blinds of the static horizontal blind (SB) and the dynamic venetian blind (DB) on a clear day in California, USA.

compensation for long-term lumen losses. Lighting controls that are now becoming available have more accessible dimming capabilities and the ability to respond to real-time utility pricing methods. Research using these advanced electric lighting control systems has found that daylight linked control systems can bring about sustainable reductions in electrical energy (30-40% for an outermost row of lights in a perimeter zone, [Figure. 2]); and slightly less for the second row of lights. However, it should be noted that if the cost of dimming is based on the system's ability to produce a cost effective reduction in lighting energy, the installed cost of the lighting controls should not exceed about \$10 per m^2 if a payback period of 3-4 years is required. With the advent of inexpensive handheld remote controls, occupant controlled dimming is becoming an affordable option and has shown to have a high occupant satisfaction rating.

It is now possible to program the response of ballasts through a remote system using computer software. Setting up a programmable system is more costly in wiring and commissioning, but has the ability to adjust lighting levels from a remote location in response to an occupant's request. This is a new area of control technology, which is now being researched. Other computer techniques used in the LESO-PB/EPFL experiments also take the user into account. For example, a blind controller using fuzzy logic has been developed, simulated and measured (Guillemin and Morel, 1999).

9.0 DESIGN TOOLS

Design tools must fit the most significant phases of an architectural project, where important decisions regarding daylighting strategies are taken. The large number of tools existing today gives the building designers the possibility of selecting the one most appropriate for their needs. Daylighting design tools include:

- simplified tools, which are probably more applicable in the early design phases and are best suited for basic design problems (simple openings)
- computer based tools, which can handle advanced daylighting systems and provide a vast variety of different deliverables (image rendering, visual comfort calculation, etc); and
- physical models, which are well mastered and shared by building design professionals.

Currently available daylighting design tools can provide:

- visualisation of a luminous environment of a given daylighting design
- prediction of daylighting factors in a space lit by diffuse daylight
- identification of potential glare sources and evaluation of visual comfort indexes
- prediction of potential energy savings achievable through daylighting; and

Table 2. Summary of lighting simulation tools

Name of package	Operating system	Information source/comments
Adeline	MS Windows	http://www.IBP.FhG.de/wt/adeline Fraunhofer-Institut fur Bauphisik, Stuttgart, Germany http://radsite.lbl.gov/adeline/HOME.html Lawrence Berkeley National Laboratory, Berkeley, California, USA uses a PC version of Radiance
Microstation	MS Windows	http://www.bentley.com Bentley Systems Inc, Exton, Pennsylvania, USA
Lightscape	MS Windows Unix	http://www.lightscape.com Autodesk Inc, San Jose, California, USA
Specter		http://www.integra.co.jp/eng/products/specter/index.htm Integra Inc, Japan
Radiance	Unix	http://radsite.lbl.gov/radiance/HOME.html Lawrence Berkeley National Laboratory, Berkeley, California, USA This is the most commonly used simulation package and is integrated into a number of others (e.g. Adeline). It is also freely available (Unix only)
Genelux	Web-based and Unix	http://genelux.entpe.fr/ Light and Radiation Group, Departement Genie Civil et Batiment, URA CNRS Ecole Nationale des Travaux Publics de l'Etat Vaulx-en-Velin, Lyon, Cedex, France This is a fully fledged simulation package, a version of which can be accessed via the web where the user uploads a data file, the simulation is done at the server, and the results downloaded to the user.
Leso-DIAL	MS Windows	http://lesowww.epfl.ch/anglais/Leso_a_software_lesodial-e.html Laboratoire d'energie solaire et de physique du batiment EPFL - LESO-PB / ITB, CH - 1015 Lausanne, Switzerland
Rayfront	MS Windows	Schorsch Inc http://www.schorsch.com A converter for AutoCAD files to Radiance input
Radout	MS Windows	Space & Light, 2164 Jefferson Ave, Berkeley, California, USA http://www.schorsch.com/download/radout/ A converter for AutoCAD files to Radiance input
Desktop Radiance	MS Windows	http://radsite.lbl.gov/radiance/HOME.html Lawrence Berkeley National Laboratory, Berkeley, California, USA This is a new plug-in for AutoCAD to prepare data files for Radiance
RADTOOL	MS Windows	School of Architecture http://fridge.arch.uwa.edu.au/software/index.html This tool assists in the preparation of input files for Radiance

- control of the penetration of sunrays and visualisation of the dynamic behaviour of sunlight.

9.1 Simplified tools

The simplified design tools available use a large variety of calculation techniques and performance evaluation methods, ranging from rules of thumb and mathematical formulas to simple experimental equipment based on easy-made scale models. Most of the available simplified design tools reflect the days where daylighting design had to be approached without the support of any computer technology: this is the case for empirical equations, tables, nomograms, diagrams and protractors. With the advent of computers at almost every workspace, a certain number of simplified methods benefited from the advantage offered by this technology and have been adapted to that purpose.

Most of the simplified tools however, have significant drawbacks for practitioners, in that:

- they are limited in the complexity they can handle and can cope only with simple rectangular spaces
- they consider only simple openings, like rectangular windows and skylights, and no advanced daylighting systems; and
- they usually use daylight factor calculations, which supposes a standard overcast sky.

Consequently, computer based design tools have gained more importance in the last few years and have lead to new developments and improved deliverables for their users.

9.2 Computer based tools

Computer based tools offer fewer limitations regarding the geometry and the photometry of the modelled architectural spaces, and allow larger and richer graphic outputs (illuminance contours and mapping). Image based daylighting computer tools have even improved these output features by providing synthetic imaging of the modelled spaces: they belong today to the common architectural design practice. Most of these tools have now been transferred to the PC world, and some of them have been linked to common CAD programmes of the architectural domain, which lead to easier input and handling of geometric data.

Three simulation packages have been compared using a realistic situation, Lightscape, Specter and Radiance. The resulting luminances demonstrated similar results although on average, Radiance was the better performer (Khodulev and Kopylov, 1996).

Table 2 shows a list of lighting simulation packages, which have been compared for their accuracy and/or usability (Roy, 2000). Most of the packages give useful results. The Radiance package produces a consistent level of accuracy. There are now several plug-in packages for AutoCAD, which provide the connection between the CAD drawing and the data requirements for Radiance.

9.3 Physical models

Physical models are used extensively for daylighting design. The main advantages of this approach compared to other design methods are that:

- Building design professionals can use scale models as design tools to study various aspects of the building; and
- When properly constructed, scale models portray the distribution of daylight within the model room almost exactly as in a full size room, due to the extremely small size of light wavelengths. The scale chosen will depend on the function of the daylighting purpose.

Sky simulators offer reliable and reproducible conditions that simulate daylight under real skies. Some new sky simulator configurations, such as those used in the International Energy Agency's research, are based on a scanning process (Tregenza, 1989, Michel et al, 1995). These types of simulators have numerous advantages as compared with other sky simulators, including a close match to the sky measuring format of the International Daylighting Measuring Program (IDMP), reproductions of all existing standards or statistical sky models and contributing to lower construction, maintenance and operation costs.

10.0 CONCLUSIONS

In many design situations, boundaries and constraints limit the application of advanced daylighting systems and controls. Designers should therefore consider the:

- integration of advanced daylighting systems, electric lighting and shading controls
- use of daylighting design tools at various stages of a building design, by the selection of appropriate software to predict the impact of the various daylighting technologies and control strategies
- use of the IEA SHC's *Source Book on Daylighting Systems and Components* to determine the correct application of advanced daylighting technologies (Ruck et al, 2001); and
- cost implications of installing a particular advanced daylighting strategy. It may require specific design of the building structure.

REFERENCES

Boyce, P, 1998, 'Why Daylight?' *Proceedings Daylight 98,* International Conference on Daylighting Technologies for Energy Efficiency in Buildings, Ottawa, Ontario, Canada, pp 359-365.

Dumortier, D, 2000, 'Deriving daylight and solar radiation from satellite images: the Satel-Light web server', *International Daylighting, R D & A*, Issue No 1, September.

Dumortier, D, Avouac, P, and Fontoynont, M, 1994, *World network of daylight measuring stations*, Report IEA-SHCP-17E-2 No 1.

Goulding, JR, Lewis, JO, and Steemers, TC, 1992, *Energy conscious design: A primer for architects*, London, Batsford for the European Commission.

Guillemin, A, and Morel, N, 1999, 'A self-adoptive and smart system for blind control', *Proceedings CISBAT '99*, Conference Internationale Energie Solaire et Batiment, pp 143-148.

Khodulev, AB, and Kopylov, EA, 1996, 'Physically accurate lighting simulation in computer graphics software', *Proceedings GraphiCon '96*, 6th International Conference on Computer Graphics and Visualisation, St. Petersburg, Russia, July 1-5, Vol 2, pp 111-119.

Kittler, R, Darula, S, and Perez, R, 1998, *A set of standard skies*, Report, Institute of Construction and Architecture, Slovak Academy of Sciences, Bratislava.

Lee, ES, DiBartolomeo, DL, and Selkowitz, SE, 1997, *Thermal and daylighting performance of an automated venetian blind and lighting system in a full-scale office*, Ernest Orlando Lawrence Berkeley National Laboratory Report LBNL-40509, Berkeley, CA, USA.

Michel, L, Roecker, C, and Scartezzini JL, 1995, 'Performance of a new scanning sky simulator', *Lighting Research and Technology* 27 (4), pp 197-207.

Roy, GG, 2000, *A comparative study of lighting simulation packages suitable for use in architectural design*, School of Engineering, Murdoch University, WA, Australia.

Rubinstein, F, 1999, Advanced lighting controls testbed at the Phillip Burton Federal Building, LBNL Report.

Ruck, NC, Aschehoug, O, Christoffersen, J, Jakobiak, R, Johnsen, K, Lee, ES, and Selkowitz, SE, (ed) 2001, *Daylight in Buildings: A Source Book on Daylighting Systems and Components*, Report of IEA SHC Task 21/ ECBCS Annex 29. To be published by Lawrence Berkeley National Laboratory, Berkeley, CA, USA in 2001.

Sutter, Y, Fontoynont, M, and Dumortier, D, 2001, 'Daylighting industrial buildings using square roof apertures', *International Daylighting R D & A*, Issue No 2, April 2001.

Tabert, K, and Shelley, G, 1993, 'An investigation on the effect of access to windows on visual comfort, motivation and productivity in an office building', *Proceedings*, 3rd European Conference on Architecture, Florence, May.

Tregenza, PR, 1989, 'Daylight measurement in models: new type of equipment', *Lighting Research and Technology* (21) 4, pp 193-194.

BIOGRAPHY

Dr Nancy Ruck, PhD, MBdgsSc, BArch is an architect and a research associate in Architectural and Design Science at the University of Sydney. Her research areas include modelling daylight availability and advanced daylighting technologies in buildings.