Daylight performance: daylight quality and control of energy consumption
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Introduction

The European Commission's Daylight-Europe (DL-E) project set out to produce design guidelines for practitioners wishing to incorporate daylight utilisation principles within buildings as a means to displace the electrical power consumption associated with artificial lighting. The intention was to produce these guidelines in a designer-friendly format, where notable examples are used to illustrate the operational and integration aspects of the different possible approaches.

Within the project simulation was applied to several existing buildings incorporating different daylight utilisation technologies. For each case studied, performance has been assessed in terms of HVAC and electrical system capacities, fuel consumption, environmental emissions, thermal and visual comfort and glare sources.

The DL-E project

The overall aim of the Daylight-Europe (DL-E) project [6] is the generation of daylighting design guidelines for architects and engineers. The project's method was to evaluate and exemplify the daylighting behaviour of 60 European buildings, which typify the range of design types and climatic contexts. To this end, the techniques of monitoring, simulation and post occupancy evaluation were employed. The role of simulation was to ensure, firstly, that daylight utilisation was not being achieved at the expense of other performance parameters (such as thermal comfort or heating energy consumption) and, secondly, to determine the effects of design and climate parameter variations in order to generalise the results from the case studies.

Simulated case study buildings Combined thermal/ lighting simulation was used in the project to critically examine the performance of 7 case study buildings as identified in the following table.

Table 1: Buildings selected for simulation.

Case Study Building	Daylighting Technology
College La Vanoise, Modane, France	External, sloped, low level light shelves, borrowed light from atrium and lighting system control.
Victoria Quay, Edinburgh, Scotland	Mix of open plan and cellular offices with configurable lighting control and borrowed light from atria.
Queens Building, Leicester, England	Electronics laboratory with bilateral lighting and internal light shelves.
Brundtland Centre, Toftlund, Denmark	Light directing blinds, reflective ceiling, linked control of blinds and luminaires, borrowed light from atrium, atrium light diffused by PV modules.
Town Hall, Trundholm, Denmark	Lighting control and fixed external solar shading.
Architect's Office, Athens, Greece	First floor offices use borrowed light from upper zones. Ground floor lighting via a light well in north facade. Indirect lighting and high efficiency fixtures.
EOS Office, Lausanne, Switzerland	Light shelves and special optical coatings.

The simulation approach

Each of these 7 buildings have been extensively monitored [4] so that data is available to facilitate model calibration before the integrated appraisal exercise commences. The premise underlying the DL-E performance assessment method (PAM) is that the impact of daylight utilisation can best be determined by systematically removing relevant technologies and comparing the performance to result with some base case representation of the existing design. The method comprises several steps as listed in Table 2. The intention is that such a PAM may be attributed with alternative knowledge instances depending on the user's viewpoint and simulation program capabilities.

Table 2: DL-E PAM: actions <u>underlined</u>, knowledge entities in *italics*.

Step	Description
1	<u>Establish computer representation</u> corresponding to a *base case design*.
2	<u>Calibrate</u> model using *reliable techniques*.
3	<u>Locate representative boundary conditions</u> of *appropriate severity*.
4	<u>Undertake integrated simulations</u> using *suitable applications*.
5	<u>Express multi-variate performance</u> in terms of suitable *criteria*.
6	<u>Identify problem areas</u> as a function of *criteria acceptability*.
7	<u>Analyse simulation results</u> to identify *cause of problems*.
8	<u>Postulate remedies</u> by associating problem causes with *appropriate design options*.
9	For each postulate, <u>establish a reference model</u> to a *justifiable level of resolution*.
10	<u>Iterate from step 4</u> until overall performance is *satisfactory*.
11	Repeat from step 3 to <u>establish replicability</u> for other *climate zones*.
12	<u>Archive models</u> for possible future use in other *contexts*.

Some of the essential steps within the PAM are now elaborated.

Step 1: A base case computer model is formed for the target building to a level of resolution which is sympathetic to the particular technical system. For example, a light shelf would require a detailed representation of sky and sun reflections, an illuminance-based switching system would require that the characteristics of the photocell be included, while an atrium used for `borrowed light' would require a rigorous treatment of geometry and inter-reflections. Clearly, for a daylighting focus, some aspects of the model can be abstracted: e.g. the operational characteristics of the heating system or the control applied to the ventilation system.

Step 2: The results from simulations using this model are compared with experimental data and, if required, judicious adjustments made to the model until its performance is satisfactory.

Step 4: Simulations are then carried out using detailed thermal/lighting simulation programs and the outputs collated in the form of an integrated performance view or IPV (see Figures 2 and 3) which quantifies overall performance in terms of a range of relevant criteria.

Step 9: A corresponding reference model is then developed by removing the particular daylight capture/control device(s) and adjusting the design as required. Results from the base case model can then be compared with this reference in order to quantify the benefits (or otherwise) of the daylighting features. Where a building incorporates several features, these may be systematically removed by the creation of several reference models.

Step 10: As required, new models can be established in order to 'optimise' the performance of specific design features which have merit on the basis of IPV comparison.

Step 11: Replication studies can be undertaken to establish the sensitivity of a design to

location.

Step 12: Finally, the base case and reference models, along with their IPVs, are contained within an electronic `model manager' which allows 3D browsing, model exporting to CAD, and further exploratory thermal/lighting analysis.

The tools used

Within the DL-E project, the ESP-r system [3] was used to create and manipulate the models and map these to the thermal and lighting simulation programs. ESP-r provides access to databases of material properties, climate, plant components, etc. and supports the attachment of constructional and operational attributes to geometrical models created internally or imported from CAD packages. The simulation tools used within the project include RADIANCE [14] for room luminance/illuminance distribution computation, JINDEX [1] for visual comfort assessment, and ESP-r [9] and TSBI3 [5] for building/plant energy simulation.

The approach to combined thermal/ lighting simulation

The modelling of daylight-responsive luminaires requires the prediction of the time varying internal illuminance distribution to accommodate the various *climate-building-systems-occupant* interactions (e.g. blind actuation). The approach used offers:

• High frequency variation of the sky luminance.

• Fully 3D, variable building geometry to accommodate movable and light redirecting systems.

• Comprehensive treatment of light transfer by multiple reflections and transmissions.

• Accurate representation of artificial lighting control.

• Full integration of the approach within the overall building/ HVAC energy simulation.

The approach is based on the conflation of the ESP-r [3] and RADIANCE [14] systems, within a *UNIX™* platform, and with the former system providing the overall supervisory control at simulation time as shown in Figure 1.
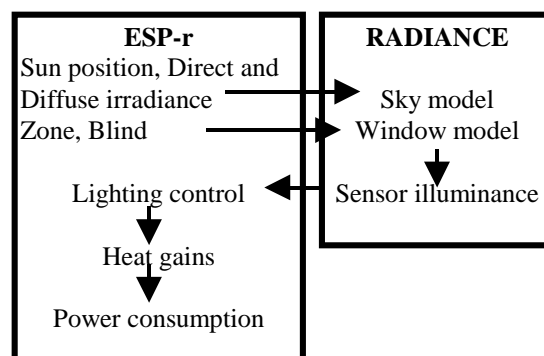

Figure 1: ESP-r/ RADIANCE Interactions at the time-step level.

At each simulation time-step, ESP-r's luminaire control algorithm initiates the daylight simulation. RADIANCE is then driven by ESP-r to carry out several tasks as follows: (1) transfer of data defining current solar position, solar irradiance and building state; (2) generation of sky model; (3) re-building of scene model; (4) calculation of internal illuminance for defined sensor locations; (5) transfer back of illuminance data to luminaire controller. The returned data are then used to determine, as a function of the active control

algorithm, the luminaire status and hence the casual gain associated with lights at the current time-step.

In essence, ESP-r supports luminaire and shading device control on the basis of the value of any model parameter (although some combinations may not be available because they are unrealistic or too esoteric). For example, window blind control may be achieved on the basis of the internal zone air temperature, the ambient air temperature or the prevailing irradiance level on a specified facade, while luminaire control may be based on the illuminance at a given point or averaged across several points. Likewise, control parameters may be imposed in terms of aspects such as photocell position, vision angle, controller set-point, switch-off lux level, switch-off delay time and minimum stop.

A demonstration of the appraisal method

To demonstrate the application of the above method, consider the problem shown in Figure 2: an office of dimensions 4.5m x 4.5m x 3.2m with a combination window comprising an upper portion with integral light shelf and a lower portion with a movable blind. The office is to be lit by wall mounted, asymmetric luminaries designed to provide an average workplace illuminance of $E_{electric\text{-}workplace} = 320\ lux$. The lamp luminous output can be regulated between 10% and 100% of the full light output. Daylight responsive control is implemented via a ceiling mounted photocell located at *2/3* of the room depth.
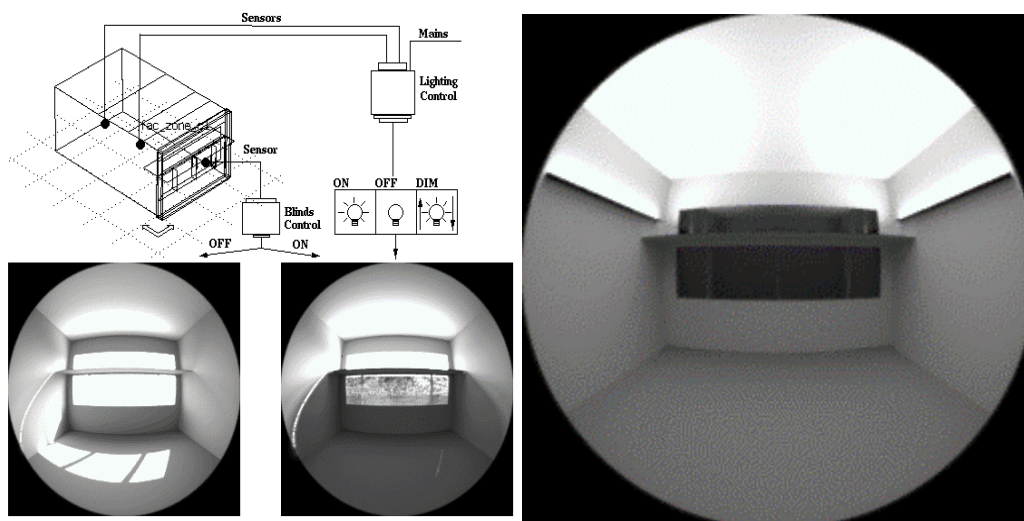

Figure 2: Thermal and lighting model configuration (left); Office with wall mounted, asymmetric luminaires during night-time calibration (right).

Within the study, the following control parameters were applied:
- daylight sensor set-point - 320 lux;
- switch-off light reference level - 150% of set-point;
- minimum light dimming - 10% of full light output;
- minimum power dimming - 10% of full circuit power;
- switch-off delay time - zero for 60 minutes time-step simulations; 15 minutes for 5 minute time-step simulations;
- blind control sensor location - vision window plane measuring vertical global irradiance;
- set-point for blind rotation to the shading position (45°) - 300 W/m^2 (corresponding to a window luminance of approximately 6000 cd/m^2).

Two objectives were set for the study. The first was to investigate the influence of explicit controller type and explicit photocell geometry under the influence of short-term (5 minute) variations in direct normal and diffuse horizontal irradiance. The second was to compare explicit, daylight-linked control modelling with the traditional approach of using 60 minute average irradiance values and the assumption of ideal control behaviour. A sample of the 5 minute irradiance values from *IDMP* station in Bratislava, Slovakia [21] was used in the study with the simulations carried out over a day in December during which the solar irradiance was highly variable, i.e. a period during which the dimming control was within its dynamic range.

Figure 3 shows a comparison between two photocell geometries - a partially shaded case ($E_{electric-sensor} = 44.5\ lux$) and fully shaded case ($E_{electric-sensor} = 14.1\ lux$). For the closed loop, proportional control action considered here, the linear control slope m_{slope} was set at -0.023 for the partially shaded case and -0.056 for the fully shaded case.
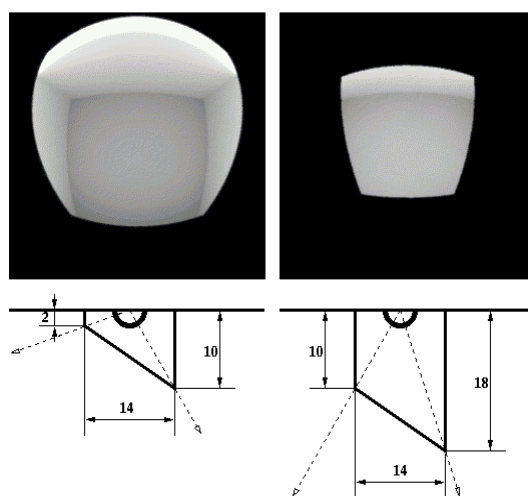

Figure 3: Partially and fully shading photocell geometry
(top figure shows sensor's view from ceiling towards floor and walls.

Table 3 shows the predicted power consumption for the different controller, photocell and simulation approaches studied while Figure 4 shows the predicted illuminance variation at selected locations.

Table 3: Comparison of predicted lighting power consumption for studied cases.

Case	Time-step (minutes)	Lighting power consumption (Wh/day)	Relative difference (%)
Integral reset partially shaded sensor	5	1168.2	-32.5
Integral reset fully shaded sensor	5	997.0	-42.4
Closed loop proportional partially shaded sensor	5	1670.4	-3.4
Closed loop proportional fully shaded sensor	5	1636.0	-5.4
Closed loop proportional partially shaded sensor	60	1792.2	+3.6
Ideal control	60	1730.0	0.0

These results give rise to some interesting observations. It is clear that to achieve realistic lighting control behaviour, short-term daylight availability should be considered. It is also clear that the different controllers result in large differences in estimated power consumption (c.f. integral reset vs. closed loop action). On the other hand, a properly calibrated closed loop proportional controller will give rise to the same power consumption as a more traditional simulation approach (i.e. ideal control with 60 minutes time step). With an integral reset controller application, the ideal control approach will fail to reproduce the dynamic behaviour and predict the correct power consumption. It is clear

therefore that the method of direct run-time coupling allows explicit modelling of the many important interactions that occur between the thermal and visual domains.

However, there remains a number of outstanding issues which require further research:

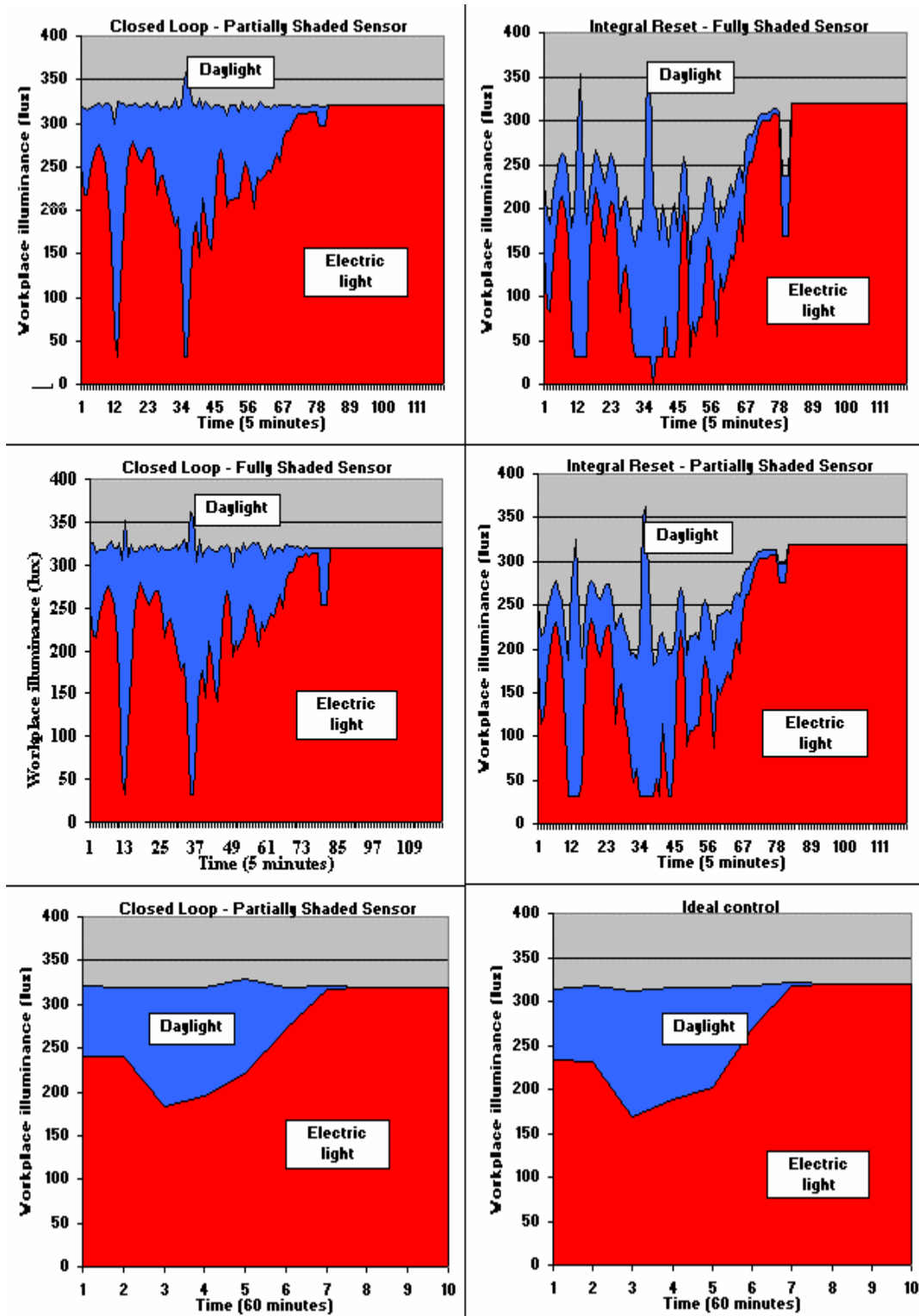- The use of solar irradiance data and sky angular luminance distribution;

Figure 4: Average predicted light level at selected locations.

- For long term simulations it is necessary to optimise the lighting simulation run time. Two approaches are being considered: daylight coefficients [18] and the grouping of Perez model parameters [15] into classes.
- Techniques for the representation of light control device movement.

Project findings

By applying this simulation method, in conjunction with the previously described PAM, to the case study buildings listed in Table 1, it proved possible to explore several issues as summarised in the following table.

Table 4: The DL-E parametric simulation set.

Case Study Building	Issue Studied
College La Vanoise, Modane, France	Light shelf removal; borrowed light removal; proportional dimming control; comparison of as-built with conventional light shelf.
Victoria Quay, Edinburgh, Scotland	Effect of interior design (finish colour and partition heights); use of atrium light shelf to control glare; luminaire control strategy.
Queens Building, Leicester, England	Use of local light shelf to control glare; geometry and finish of courtyard.
Brundtland Centre, Toftlund, Denmark	Impact of redirecting blind and control; impact of PV shading on discomfort glare and illuminance in offices adjacent to an atrium.
Town Hall, Trundholm, Denmark	Effect of fixed external shades and lighting control
Architect's Office, Athens, Greece	Effect of borrowed daylight
EOS Office, Lausanne, Switzerland	Effect of light shelf removal.

From the outcome, the following conclusions were drawn in relation to several daylight utilisation technologies.

On light shelves (Figure 5):
- Modify daylight distribution by reducing the sky component and increasing reflection from the ceiling resulting in a more uniform daylight distribution.
- Compared to a standard window:
    ⇒ with an overcast sky, daylight decreases at perimeter but sustained at core;
    ⇒ with a clear sky and low sun (winter) there is an enhancement of the internal illuminance over the entire room depth;
    ⇒ with a clear sky and high sun (summer) there is an enhancement of the internal illuminance, but only close to the perimeter for the case of a conventional light shelf;
    ⇒ the low level light shelf in College la Vanoise provides a global reduction of the internal illuminance;
    ⇒ specular light shelves generally provide a higher internal illuminance than diffusing light shelves (this is especially noticeable with clear, low sun, winter skies).
- The College La Vanoise light shelves are not effective in increasing core illuminance under overcast skies. They increase glare under clear skies (because of reflections) and make no significant contribution to energy saving.

- Light shelves could be used within the Victoria Quay building to prevent glare from the atrium, maintain core daylight penetration and diminish the perimeter daylight levels. They are significantly more effective than blinds.

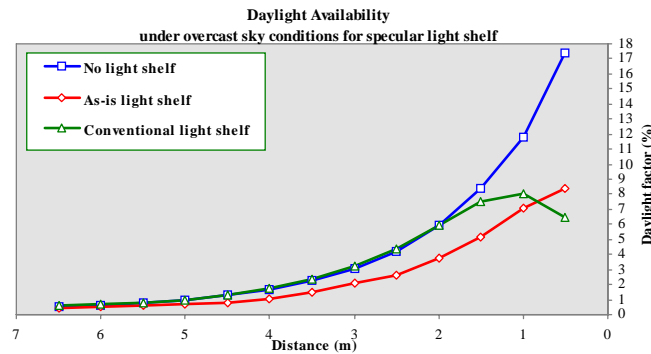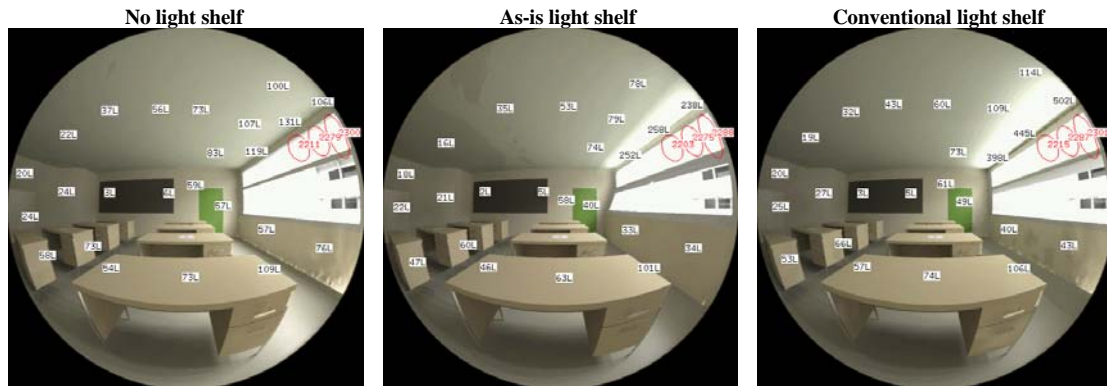**Overcast sky and specular light shelf**

Figure 5: Light shelf issues.

- Within the Queens building light shelves are effective in providing a glare free environment for VDU users but they give rise to no energy saving. Blinds would be even less effective.

- Conventional notions of required lighting levels might underestimate the viability of daylighting. For example, a detailed study within the Queens building showed that the natural lighting levels with light shelves can be compatible with VDU work, where daylight factor contours did not indicate this to be the case.

- Light directing systems can often be used in place of light shelves.

On light redirecting blinds:

- Light redirecting (towards ceiling) blinds showed higher levels of daylight availability in the perimeter (up to 2m from the facade, see Figure 6) and maintenance of light levels further from the facade, when compared to open conventional blinds.

- Redirecting blinds which allowed no direct transmittance ('fish' blinds) result in a higher level of daylight availability in the perimeter with little degradation of daylight levels further from the facade, when compared to conventional blinds.

- Special 'fish' redirecting blinds improve visual comfort when evaluated by state-of-the-art discomfort glare indices. They produce relatively low directional luminance (towards the occupant), while maintaining background luminance.

- In the Brundtland Centre, daylight factor indices were found to under-predict the

benefits of light directing systems. It was also found that, where incident radiation is predominantly diffuse (as in a PV shaded atrium), light directing systems provide little benefit.
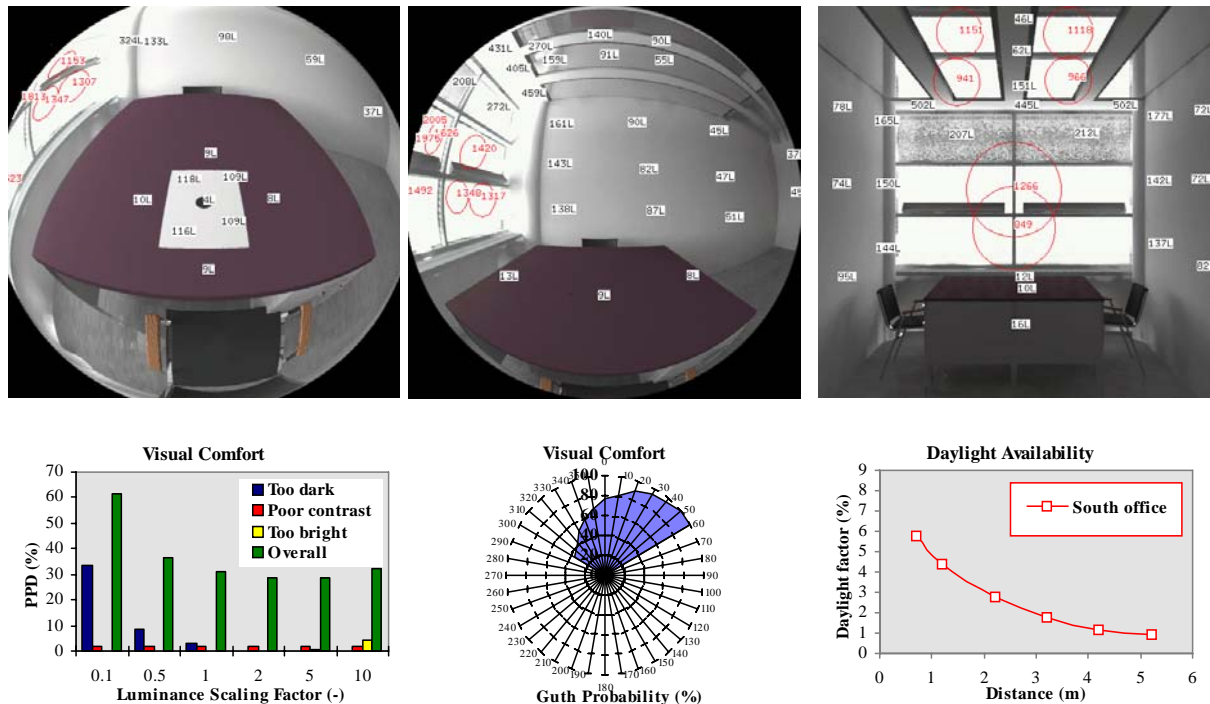
BRUNDTLAND CENTRE

Redirecting blind system

Figure 6: Light redirecting blind issues.

On luminaire control:

• The simple control strategy used in College la Vanoise is effective (i.e. hourly switch off).

• The proportional dimming system within Victoria Quay produces significant energy savings but requires careful photocell zoning and set-point/ field of view setting.

• The best energy performance is achieved from closed-loop proportional control with appropriate sensor field of view and shielding from direct light.

• Within the Queens building there is an enhanced level of core daylight but reliance on manual switching results in no energy saving.

• Local luminaire/task lighting control offers the best solution for deep plan buildings.

• Algorithms are required for managed blind systems.

On atria (Figure 7):

• Within Victoria Quay and College la Vanoise atria provide the principal contribution to enhanced daylight factors and energy savings.

• Within the Victoria Quay building, the atrium is a source of excessive glare because of direct sky access and intra-reflections.

• Within the Brundtland Centre, the application of PV glazing panels on the south atrium roof improves the visual comfort and helps to achieve an adequate internal illuminance.

- Diffusing/redirecting roof glazing is required to reduce glare and maintain daylight penetration. Non-specular, highly reflective finishes will help to ensure daylight penetration to the atrium base.

Figure 7: Atria design issues – visual comfort under advanced

diffusing (left) vs. normal (right) roof glazing system.

On plan depth & interior design:

- In Victoria Quay the deep plan causes glare problems due to limited daylight penetration causing maximum contrast. An inappropriate solution is to use artificial lighting to balance contrasts and therefore reduced energy savings.

- Victoria Quay has non-optimum finishes and partitioning heights, which cause poor daylight factor distribution.

- Within the Queens building, the VDUs/trunking obstruct daylight penetration. The importance of task orientation in the relation to light source is also highlighted.

Conclusions

Within the project, it has been observed that enhanced daylight performance has often resulted in reduced thermal performance. Effective design solutions will require supervisory level control algorithms by which designers can balance the visual and thermal aspects. Also, the use of daylight factors has been shown to have limitations, especially in the case of light directing components and advanced control systems. The direct, real-time coupling of thermal and lighting simulation offers a new level of information to the design process [20].

A methodology has been developed for the combined thermal and lighting appraisal of buildings and applied to existing buildings in support of design guideline production within the EC's Daylight-Europe project. The method includes the notion of an Integrated

Performance View by which the benefits associated with a particular set of daylighting features can be ascertained across a range of criteria. The method has been applied to six existing buildings in order to determine the performance of specific daylight utilisation approaches and the impact of selected design changes on this performance.

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