University of Strathclyde

Energy Systems Research Unit

Daylight-Europe Project

Simulation Case Study:
Victoria Quay, Leith, Scotland

Clarke J A, Hand J W, Janak M, Johnstone C

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University of Strathclyde
Energy Systems Research Unit
James Weir Building
Glasgow G1 1XJ, UK

Email esru@strath.ac.uk
Phone +44 141 548 3986
Fax +44 141 552 8513

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1. Introduction

The overall aim of the DL-E project (Kristensen 1996) is the generation of daylighting design guidelines for architects and engineers. There are two main research activities in support of guideline production: the monitoring of around 70 existing buildings throughout Europe and the in-depth simulation of a sub-set of 6 of these.

The simulation work adheres to a standard performance assessment method (Clarke et al 1996a) whereby simulation programs are used to determine the thermal and visual performance of the building and a corresponding reference case arrived at by removing any special daylight features. In this way, the contributions of these features are quantified and a check is made to ensure that good daylight practice is not being achieved at the expense of other performance aspects, such as thermal comfort or heating fuel consumption. Once established, the computer model can also be used for parametric studies in support of daylight component optimisation. Finally, these models are contained within an electronic Project Manager which allows 3D browsing, model exporting to CAD, and further exploratory thermal/lighting simulations.

This report relates to a study of the new Scottish Office, located at Victoria Quay, Edinburgh, Scotland. It summarises the computer model of the building and its related reference design, and presents the simulation results from the ESP-r and RADIANCE systems in the form of an *Integrated Performance View* (IPV) for both models. It also reports on the impact of some possible design changes. Complete details of the computer model and performance results are available on-line within the ESP-r system (Clarke et al 1996b).

2. Computer Representation

The case studied is the new Scottish Office situated 1km north of Edinburgh, latitude 55°50’N, 3°W, altitude 5m. The base case computer model was developed on the basis of information extracted from architectural drawings (RMJM 1995), measured on-site or supplied by the accommodations department of the Scottish Office.

Figure 1 depicts the building and its principal features: note the shading on the south facade, the borrowed light from the atrium, the different plan depths between the 2nd and 3rd floors and the perimeter lighting control. The spaces are predominantly open plan with cellular offices adjacent to the atrium. Significantly, the colour, density and height of the partitions obstruct daylight from a portion of the workspace.

2.1 Model Geometry and Construction

The building is composed of two linear blocks of offices punctuated by a series of courtyards and atria. The base case model is focused on the 2nd and 3rd floors adjacent to the central atrium as shown in Figure 2. To account for the displacement ventilation system and the structural mass of the building, the office spaces have been subdivided into a floor and ceiling plenum and an occupied space. And because the office furniture critically influences the daylight distribution, an explicit representation has been included in the model. The areas and volumes of the principal modelled zones are as listed in Table 1.

Constructional information was extracted from architectural drawings and, where possible, assessed by on-site inspections, e.g. internal surface reflectance properties were measured. Construction thermo-physical properties were taken from appropriate engineering handbooks.

To reflect the daylighting focus of the project, the glazing layers are represented explicitly so that the intra-pane temperature and radiation processes are modelled in detail. Table 2 lists the describing thermal and optical characteristics for the window system in terms of the total visible transmittance (TVT), direct solar transmittance (DST) and the solar heat gain coefficient (SHG),

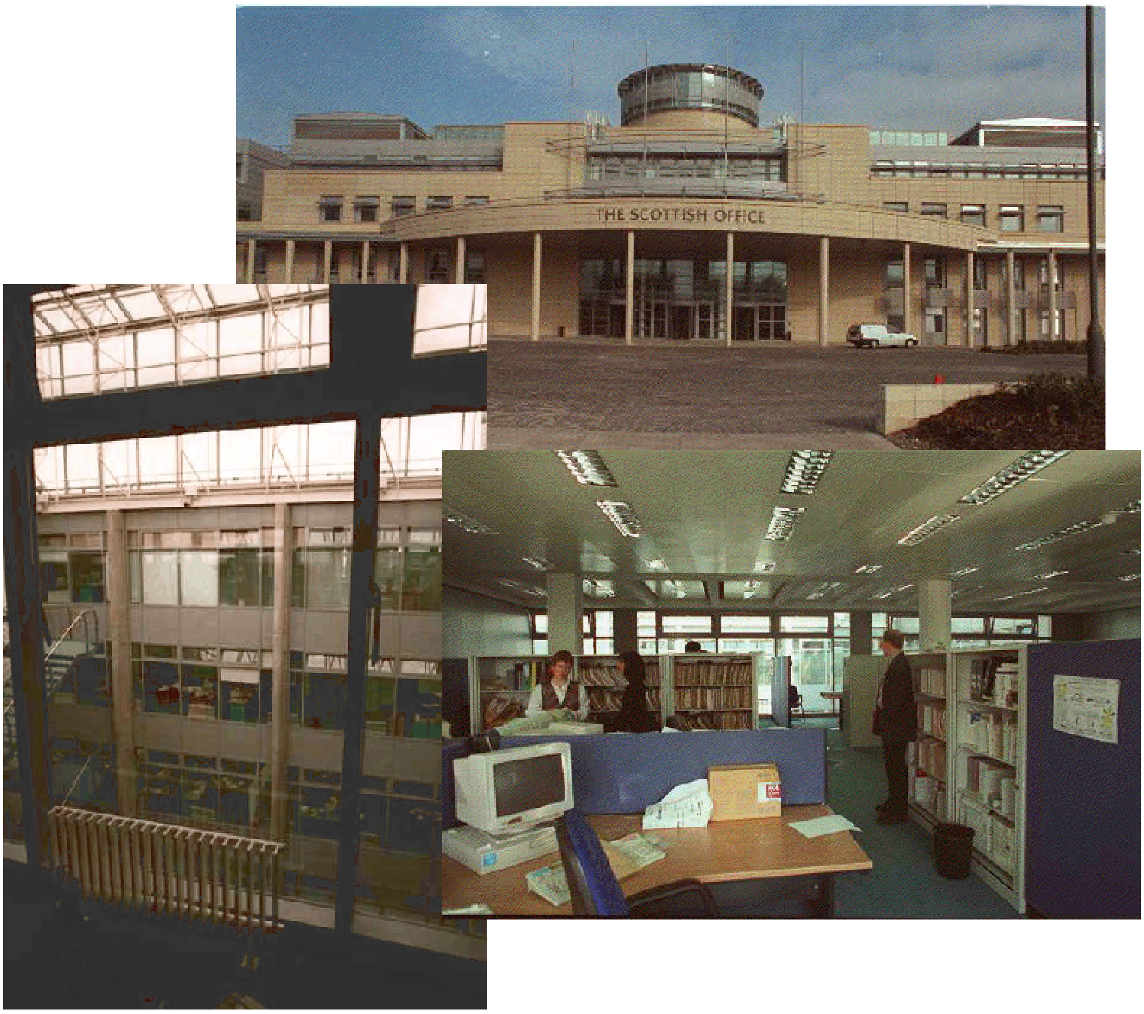

Figure 1: Victoria Quay, principal features.

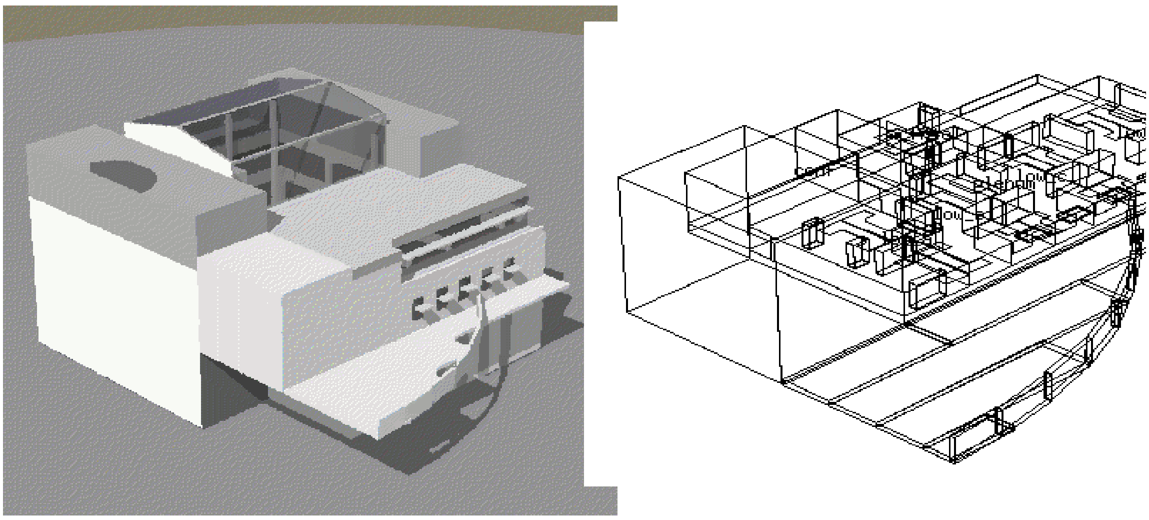

Figure 2: Victoria Quay, computer representation.

Table 1: Description of modelled zones.

Zone	Volume (m^3)	Floor Area (m^2)	Description
plenum	230	0.0	raised floor, 2nd level
low_a	101	63.0	occupied space (west part), 2nd level
low_b	76	47.3	occupied space (2nd part), 2nd level
low_c	101	63.0	occupied space (middle), 2nd level
low_d	151	94.5	occupied space (east), 2nd level
conf	163	47.2	conference room, 2nd level
friel	43	27.1	supervisor's office, lower part
u_friel	50	27.1	supervisor's office, upper part
upper	495	267.7	ceiling portion, 2nd level
plenum3	230	0.0	raised floor, 3rd level
floor_3	499	311.6	office, 3rd level
floor_3up	452	311.6	office ceiling, 3rd level
Subtotal	2589	653.6	
atrium	4446	292.5	atrium, lower portion
atrium_up	2121	292.5	atrium, upper portion
Total	6566	292.5	

all at normal incidence angle, and the overall thermal transmittance (U). The table also lists the opaque surface total diffuse reflectance values.

Table 2: Optical and thermal properties of glazing.

Glazing	TVT	DST	SHG	U
	-	-	-	(W/m^2K)
Triple	0.650			
Double	0.740	0.610	0.710	2.75
Single	0.910	0.820	0.860	5.4

Surface	Reflectance (%)	Surface	Reflectance (%)
Carpet	8.2	Concrete Ceiling	80
White Wall	82	Concrete Column	57
Grey Wall	48	Suspended Ceiling	80
Cabinet	55	Window frame	39
Low Partition	16	External wall	52
Desk	33		

2.2 Usage and Environmental Systems

The offices are predominantly open plan with below average occupancy levels and above average computer use.

Occupants and small power

Office spaces have an occupant density of one person per $15m^2$ or $6W/m^2$ during the period 8h00 to 17h00 on weekdays. It is assumed that the building is unoccupied during weekends.

Office equipment comprises personal computers and group copying facilities: the loading is $21W/m^2$ from 8h00 to 17h00.

Lighting and Control

On each level, the lighting is arranged in four banks with those adjacent to the atrium and facade proportionally dimmable (within the range of 20% to 100%) based on ceiling mounted photocells. The core lighting (two banks) is controlled by timed functions in the BEMS: off before 6h00, 25% on between 6h00 and 7h45, and nominally full on from 7h45 to 17h45. The overall lighting density is $9.5W/m^2$.

The south facing facade has fixed solar shading associated with each window above mid-height. The window reveals are significant in terms of daylighting and solar insolation.

The base case model corresponds to a well managed regime of peripheral lighting control with the photocells set to provide 500 lux on the working plane. As the control of lighting is based on conditions at the ceiling rather than the working plane, one task was to correlate the former to the latter in order to devise the optimum set-point value. Simulations show that a photocell positioned at the south facade ceiling will detect approximately 42% of the working plane illuminance while one mounted at the atrium facade will detect approximately 20%. Table 3 lists the measured daylight factors used for lighting control simulation. Distances are measured from the south facade.

Table 3: Measured daylight factors as used for lighting control.

Point(m)	Daylight factors (%) Base case
0.39	8.23
1.89	3.25
3.39	1.04
4.89	0.52
6.39	0.46
7.89	0.60
9.39	0.99
10.89	2.79
12.39	8.98

Heating and Ventilation

Gas-fired boilers supply radiators in the offices with a set point of 18.5°C from 8am to 6pm with a night set-back to 15°C. Radiators are mounted adjacent to the exterior and atrium facades. The site visit indicated that the latter are rarely used.

A mixture of fresh and recirculated air is supplied from the floor plenums at either 2 or 4.5 ac/h and tempered to 17°C during occupied periods and 14°C otherwise. This displacement ventilation is used for night purge cooling and to augment natural ventilation. The building is designed to allow natural ventilation by operable windows in the occupied spaces. Atrium ventilation is controlled centrally. There is no cooling provision in the building (except for dining and computer rooms, which are excluded from this study).

In the spring and winter, 1 ac/h of fresh air is injected into each floor plenum along with 1 ac/h of recirculation air from the upper portion of each floor. The air flows from the floor plenum into the occupied space and then to the upper space before being exhausted to the atrium and exterior. In the summer, a similar regime is in operation except that the fresh air input is increased to that of the higher fan capacity, i.e. 4.5 ac/h.

Because of the difficulty in obtaining reliable data to model natural infiltration explicitly, design values (CIBSE 1994; Table B2.2) have been assumed.

2.3 Boundary Conditions

The standard year of UK climate, corresponding to 1967 at Kew, has been used in the simulations. Average monthly temperatures are summarised in Table 4.

Table 4: Monthly maximum and minimum temperatures (°C), Kew.

	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
minimum	-6.4	-1.9	-0.8	-1.9	0.0	5.0	9.4	7.7	5.0	2.2	-0.8	-4.2
maximum	12.7	12.2	16.1	19.4	22.7	21.1	27.7	24.4	22.2	19.4	14.4	12.7

In addition to annual simulations, periods were selected to characterise seasonal performance:

- 9-15 January, which also contains a design cold condition;
- 6-12 March, with average values for spring/autumn;
- 11-17 July, which also contains a design warm condition.

2.4 Reference Model

The Reference model was constructed by removing the daylight enhancing devices - the borrowed light and the peripheral lighting control. The glazing ratio at the atrium facade was set equal to the external facade. The daylight factors used for artificial lighting control were altered accordingly.

3. Model Calibration

Before using the computer model, it is important to ensure that its predictions are acceptable when compared to measurements. Within the DL-E project, this process of *model calibration* is centred on the acceptability of the daylight factor calculations. Calibration has been carried out by applying judicious adjustments to the RADIANCE input model until reasonable agreement was obtained. The calibration process was assisted by a second set of measurements taken at the level of the filing cabinets so that the local affects of furniture placement could be incorporated within the model.

Figure 4 lists the final daylight factors as used in the study for the base case model.

To achieve this level of agreement it was necessary to make several iterative model refinements: the addition of office furniture (demountable partitions, filing cabinets, desks), the incorporation of the framing of the atrium glazing and window reveals on the south facade as well as structural features in the upper atrium which cause shading. The probable cause of the residual disagreement is the contribution of the directional blinds on the south facade which have not been explicitly modelled.

Figure 5 shows the daylight factor contours as predicted for the Base case after calibration (the top portion is the atrium facade). Note the low daylight factors in the core. Having calibrated the model for the Base case, RADIANCE predicted daylight factors were computed for use in the Reference design.

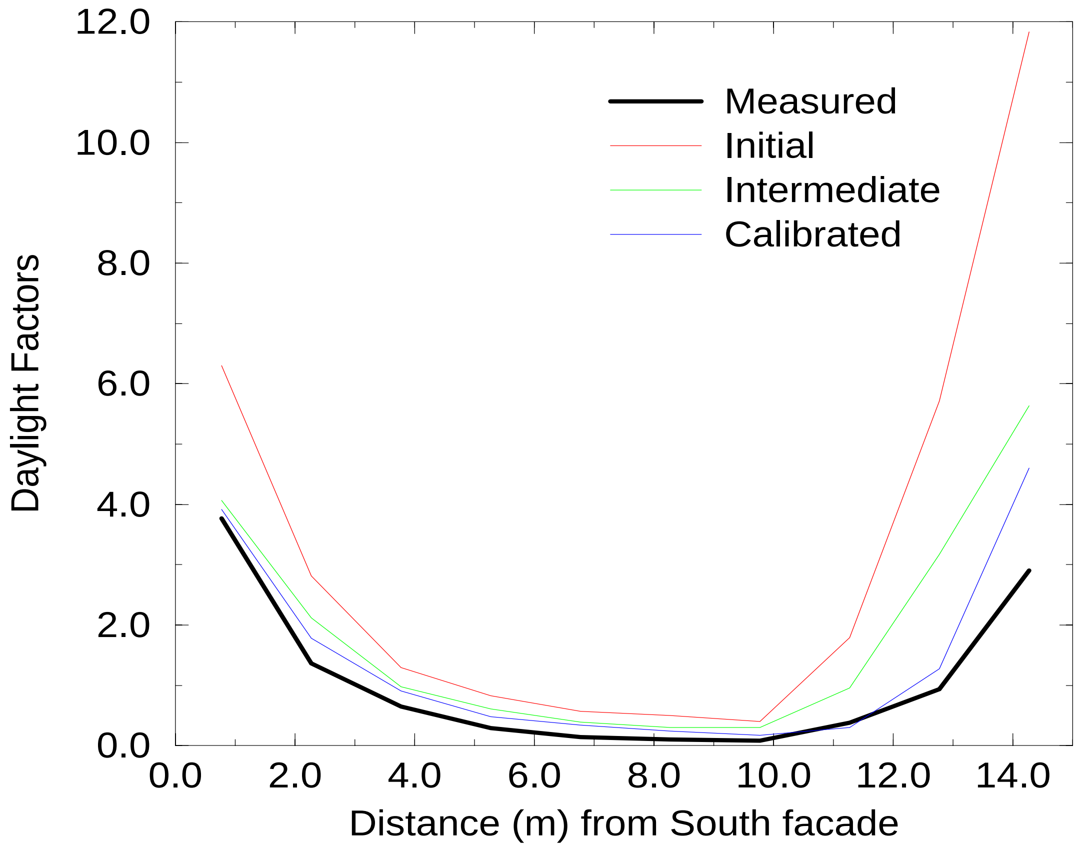

Figure 4: Daylight factors, base case model.

4. Simulation Results

This section summarises the predictions obtained from ESP-r and RADIANCE when presented in the form of an *Integrated Performance View* (IPV) which presents several performance criteria across a range of performance types.

4.1 Integrated Performance View

The IPVs correspond to the overall building model but with the results normalised by heated floor area. The Appendix gives the IPVs for all cases. An inter-comparison of the performance entities contained within the IPVs gives rise to the following conclusions.

Maximum Capacity

The diversified total heating peak capacity (W/m^2) represents critical plant sizes and hence capital costs. Table 5 summarises the results in terms of the relative change in peak capacities.

Table 5: Change in peak capacities.

Case	Capacity change (%)				
	Heating	Lighting	DHW	Fans	Small power
Base	+0.6	0.0	0.0	0.0	0.0
Reference	0.0	0.0	0.0	0.0	0.0

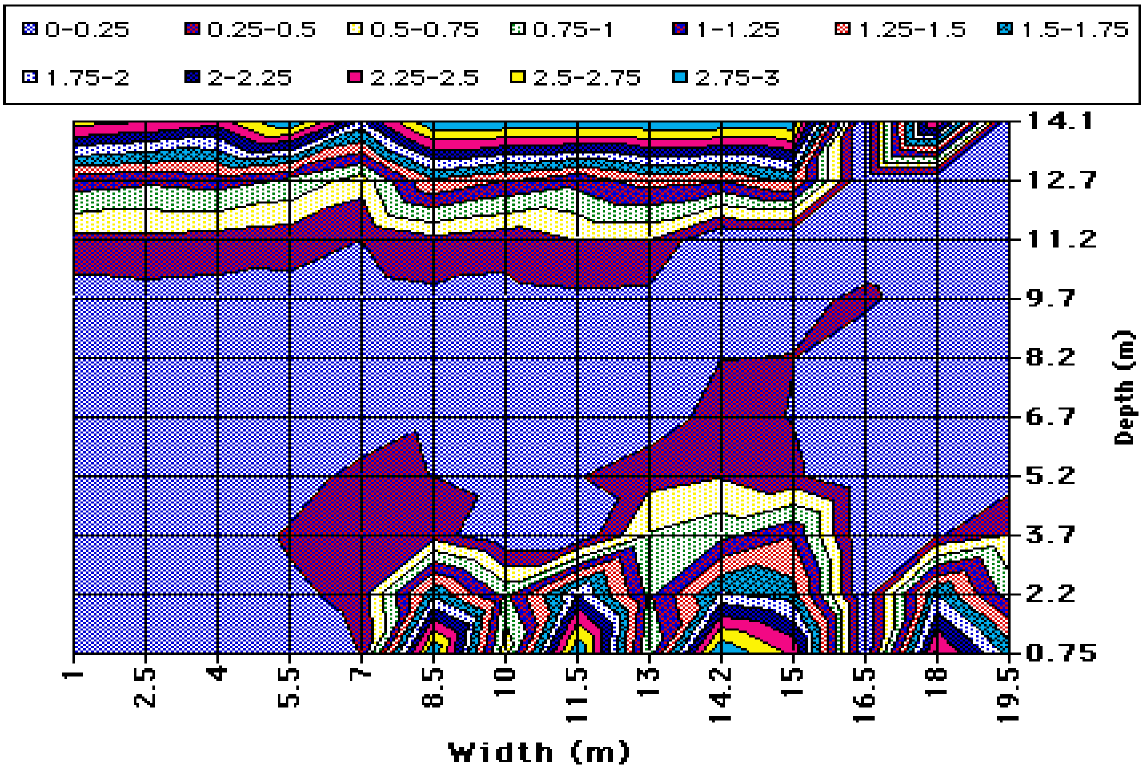

Figure 5: Daylight factors, Base case.

In terms of peak heating capacity, there is little difference between the two cases. Likewise, there is no difference in the maximum electrical load for lighting, fans, DHW and small power loads.

Annual Energy Performance Indicators

The normalised annual energy requirement for the Base is 143.3 kWh/m^2yr, while the Reference is 158.2 kWh/m^2yr. In the absence of European figures, these values could be compared with the characteristic British NPI ranges for offices as listed in Table 6. As can be seen the Base is in the good category, while the Reference is in the average category.

Table 6: British NPI ranges for offices.

Category	NPI Range (kWh/m^2yr)
Good	< 190
Average	190-260
Poor	> 260

The Base delivers an overall energy consumption reduction of 9.4% relative to the Reference. This energy consumption reduction of the Base over its Reference is mainly due to a positive effect of the daylight linked dimming control of the perimeter artificial lighting as well as the effect of the borrowed light from the atrium.

Typical Seasonal Energy Demand Profiles

The delivered energy data are expressed as cumulative daily profiles for each season. In both cases, the building heating energy consumption is dominated by ventilation losses (note the consumption peaks after mechanical ventilation start up in the early morning). On the other hand, small power (computers, printing, copying) energy consumption is rather high in the both cases and could be reduced by selection of low powered devices. This would also have a positive effect on summer thermal comfort in offices.

Environmental Emissions

The annual energy performance data have been converted to primary energy units determined on the basis of the Table 7 generating inefficiency factors which are averages for the EU.

Table 7: EU averaged generating factors.

Fuel	Use	Delivered-to-Primary Energy Modulus
Gas	Heating	1.25
Electricity	All	1.73
Oil	Heating	1.67

The primary energy data is converted to equivalent gaseous emissions on the basis of EU averaged conversion factors as given in Table 8.

Table 8: Gaseous emission conversion factors.

Fuel	Emissions (g/kWh)		
	CO_2	NO_x	SO_x
Gas	190.	0.3	0.02
Electricity	360.	3.0	5.7

Table 9 summarises the results in terms of the relative changes in environmental emissions.

Table 9: Change in the environmental emissions.

Case	Emissions changes (%)		
	CO_2	NO_2	SO_2
Base	-10.7	-9.8	-16.6
Reference	0.0	0.0	0.0

Thermal Comfort

It is possible that optimising the daylighting performance of a design may affect thermal comfort. To test this, resultant temperatures in several offices have been frequency binned during the occupied period in a typical week in each season.

As can be seen, the Base and Reference perform similarly with 9 hours of the resultant temperature in the range of 26°C - 28°C what represents effectively about 17% of the working time. Considering the fact that the occupants will adapt (clothing, blinds, natural ventilation) the predicted level of the thermal comfort is conservative.

Daylight Availability

The daylight factor is a common metric which is well understood by the design community; the level and distribution of daylight factors being a reasonable indicator of daylight availability and consequently artificial lighting requirements.

As can be seen, the Base case daylight factors adjacent to the atrium are higher than the Reference case. This has the potential to reduce artificial lighting consumption.

On the other hand, interior design (high cabinets and dark colours) unfavourably influences daylight distribution in both cases (see, for example, the low daylight factors in office core in Figure 5). Clearly, changes in interior design, such as lower cabinets and light colours could be tested as optimisation options.

Glare Sources

Daylight factors are not always indicative of daylight quality. This performance output highlights potential glare sources within a 3D colour picture, with luminance values given in cd/m^2. As can be seen in Figure 6 (or in the Appendix), the relatively bright atrium introduces glare sources in the both cases.

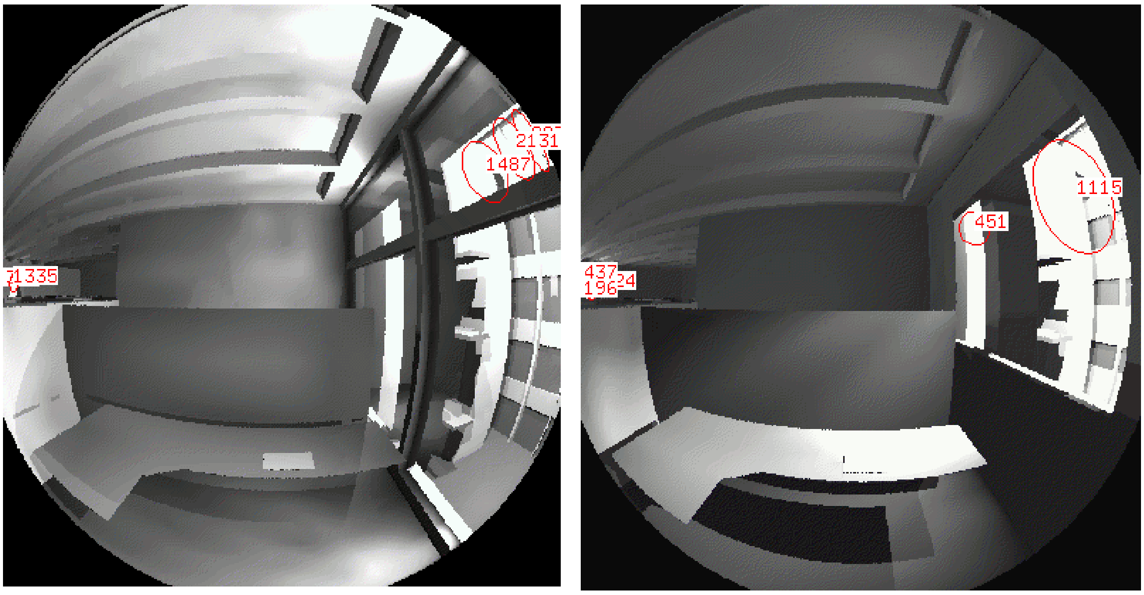

Figure 6: Comparison of glare sources in Base and Reference cases.

The Base tends to have more glare sources with higher luminances and smaller size (a combination which causes considerable discomfort) when compared to the Reference.

The smaller window restricts views towards bright portions of the atrium in the Reference and improves the distribution, luminance levels and size of glare sources. However, this reduces daylight penetration into the offices adjacent to the atrium.

One technique for limiting glare at the same time as improving daylight distribution is by the application of light redirecting devices. This is addressed in the System Optimisation section.

Visual Comfort

The JPPD (J index of Previsible Percentage of Dissatisfied) visual discomfort index relates discomfort to any excess/lack of light or inadequate contrasts in the field of view of a person performing a reading task.

As can be seen from IPVs the Reference case performs better then the Base case in the "lack of light" and overall visual comfort categories.

4.2 System Optimisation

It is now possible to use the Base case computer model to explore the impact of specific design parameters or opportunities for daylight component optimisation. The intention is that such analyses can serve to complement the knowledge base from which the design guidelines are produced and specific principles elaborated.

Three design variants have been explored as follows.

- Reference 1 - the control of the perimeter banks of luminaires is optimised by reducing the working plane illuminance to 300 lux from the 500 lux assumed in the Base case.
- Reference 2 - the interior surface reflectances are less than optimum from a daylighting viewpoint and the height of filing cabinets and partitions prevents daylight reaching some of the working surfaces. These two issues have been combined within Reference 2.
- Reference 3 - the glare problem at the atrium facade is mitigated by the addition of a high level light shelf. This design reduces visual access to the sky vault via the atrium roof and reflects light to the office core.

The results of these assessments are given in the IPVs which are included in the Appendix.

Table 8 summarises the results for the three cases. As can be seen, the energy savings are greatest for the Reference 1 case (lowered light switching set-point), with the Reference 2 case (modified interior design option) coming second in the energy terms.

Table 8: Design optimisation summary.

Category	Base Case	Reference	Lower Set-Point	Modified Interior Design	Light Shelf
NPI (kWh/m^2yr)	143.3	158.2	140.6	141.9	142.8
Heating (kWh/m^2yr)	41.0	39.0	41.6	40.5	41.1
Lighting (kWh/m^2yr)	29.7	46.6	26.4	28.8	29.1
Heating capacity (W/m^2)	53.7	53.1	53.7	53.0	53.7
CO_2 (kg/m^2yr)	68.4	77.1	66.9	68.2	68.5
NO_x (kg/m^2yr)	0.5	0.5	0.5	0.5	0.5
SO_x (kg/m^2yr)	0.1	0.1	0.1	0.1	0.1

Figure 7 shows that the modified interior design case (Reference 2) results in improved daylight levels in the office core. By comparing Figures 9 and 5, it can be seen that the reduced furniture height in combination with higher surface reflectivities extends the daylight penetration from both facades towards office core.

However, reductions in luminaire use is constrained because the sensors are located near the facades and activate only the peripheral luminaires. Assessments showed that the improved daylight distribution could allow some core zone luminaires to be dimmed, thus reducing the luminaires which must remain on for safety reasons.

Figure 8 shows that the addition of the light shelf in Reference 3 improves the light distribution in the core of the office (beginning at a point 4.0m from the atrium facade). It also moderates the light levels adjacent to the atrium facade.

As the both modifications tend to alter distribution of daylight availability, they will effect the level of visual comfort and the distribution of glare sources. Figure 9 shows the glare reduction potential of modifying the interior design (left figure) and introducing the light shelf (right figure).

While no obvious glare reduction potential is observed for Reference 2 (modify interior design), for Reference 3 (atrium light shelf) the light shelf obscures the occupants view toward the most pronounced glare sources at the upper part of the atrium window.

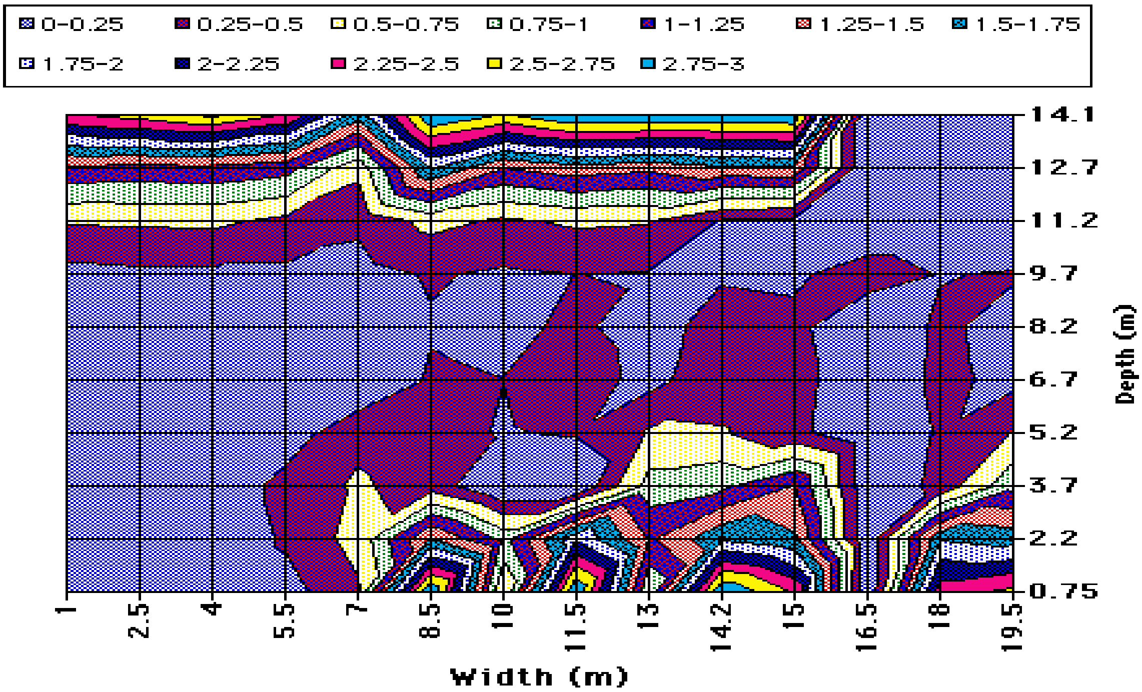

Figure 7: Daylight factors, modified interior design case.

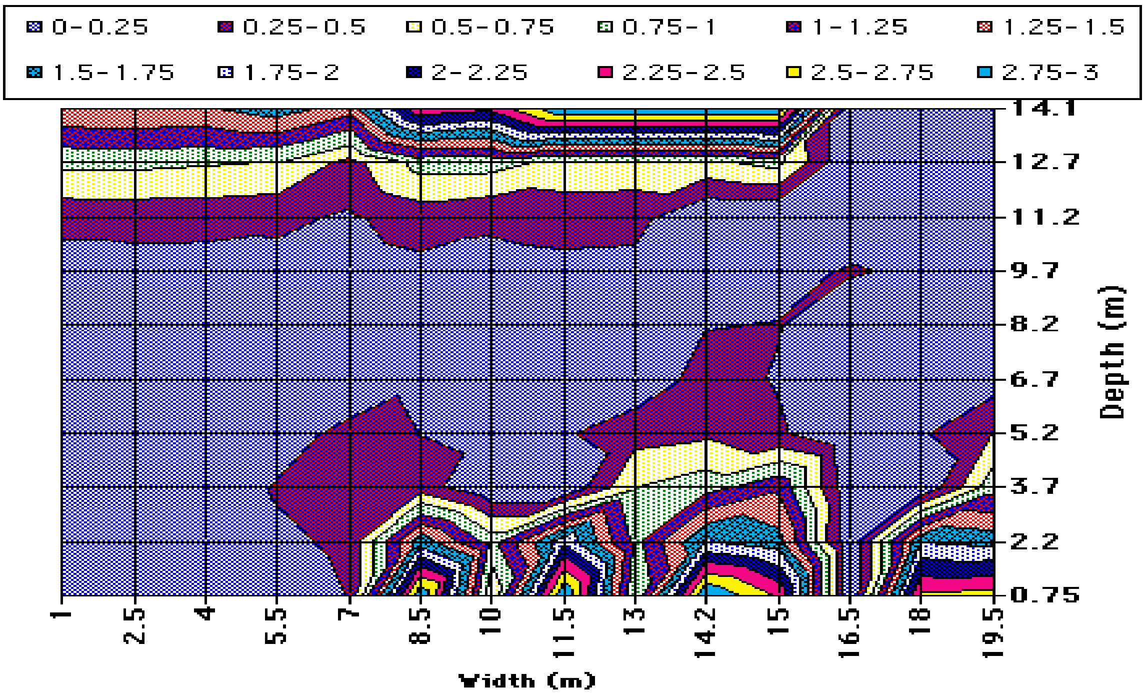

Figure 8: Daylight factors with atrium light shelf.

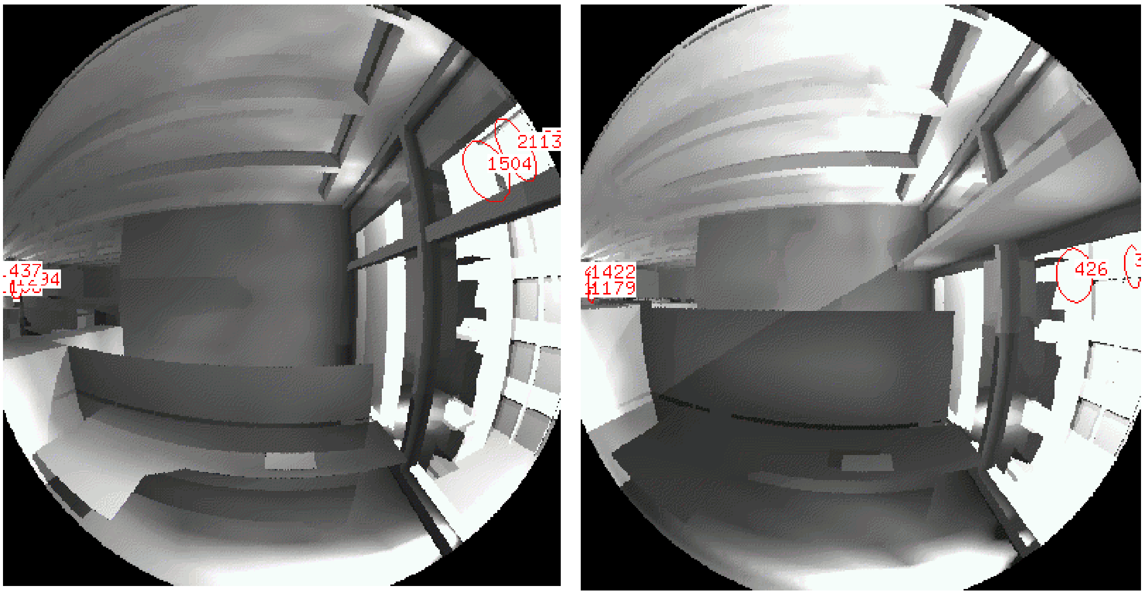

Figure 9: Glare reduction potential.

5. Conclusions

Based on the IPV performance indicators for the various cases, it can be concluded that the Base case offers:

- a significant energy consumption reduction (9.2%), particularly in relation to the artificial lighting electrical power consumption;
- significantly higher daylight levels, particularly at the atrium side of the office space;
- no significant reduction in maximum heating capacity and therefore plant capital cost;
- no improvements with respect to thermal comfort;
- no improvement in the term of visual comfort and the discomfort glare.

This integrated performance picture indicates that the Base case provides significant performance improvements when compared to a design without the special daylighting features. On the other hand, there is still a room for improvement, which has been analysed via number of the design modifications.

From the design modification analysis it can be concluded that:

- a modified interior design (lower filing cabinets and higher interior surface reflectance) will enhance daylighting and improve visual comfort throughout the office;
- a high level light shelf applied to the atrium facade will alleviate glare problems;
- a lower photocell set-point will give rise to significant additional energy savings (especially if automatic control is extended to the luminaires situated in the office core).

6. References

Berrutto V, M Fontoynont (1995) ‘Monitoring of the College de La Vanoise in Modane - France’ *Report presented at Daylight-Europe meeting*, Modane, 2-4 May.

BS (1996) Article in *Building Services Journal*, February.

CIBSE 1994. *Code for Interior Lighting* Chartered Institution of Building Services Engineers, London.

Clarke J A, Hand J W, Hensen J L H, Johnsen K, Wittchen K, Madsen C and Compagnon R (1996a) ‘Integrated Performance Appraisal of Daylight-Europe Case Study Buildings’ *Proc. 4th European Conference on Solar Energy in Architecture and Urban Planning* Berlin, March.

Clarke J A, Hand J W, Hensen J L H, Strachan P A (1996b) ‘ESP-r Users’ Manual’ *ESRU Publication U96/2* University of Strathclyde.

Kristensen P E (1996) ‘Daylight Europe’ *Proc. 4th European Conference on Solar Energy in Architecture and Urban Planning* Berlin, March.

RMJM (1995) Architectural Drawings for the Scottish Office at Victoria Quay, available from RMJM, 10 Bells Brae Edinburgh EH4 3BJ.

Appendix - Integrated Performance Views

Integrated Performance View, Base case (as built)

Integrated Performance View, Reference case (without atrium borrowed light, and lighting control)

Integrated Performance View, Reference 1 (as built with lower lighting lux set-point)

Integrated Performance View, Reference 2 (as built with alternative interior design)

Integrated Performance View, Reference 3 (as built with a light shelf on the atrium side)