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ASSESSING THE OVERALL PERFORMANCE OF ADVANCED GLAZING SYSTEMS

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Abstract—This paper describes the approach taken within the European Community's IMAGE (IMplementation of Advanced Glazing in Europe) 97 project to apply combined thermal/daylight simulations to existing and proposed building designs incorporating advanced glazing systems. The application of the approach to a live design project is described to exemplify the process and the outcome. © 1998 Elsevier Science Ltd. All rights reserved.

1. INTRODUCTION

From an energy and environment viewpoint, it is well understood that the glazed component of a building is, at the same time, the weakest and strongest element. Its disadvantages are associated with heat loss, thermal discomfort (radiant asymmetry and down-draughts) and visual discomfort (disability and discomfort glare); its benefits include passive solar heat gain, electric lighting power reduction and view. Previous research has therefore sought to assist the industry in accentuating the benefits while eliminating the disadvantages. By focusing on specific technologies, such research has brought about significant developments in advanced glazing systems in the form of new glazing types and window system encapsulations: electrochromic, aerogel and low emissivity products are examples of the former and evacuated glazing of the latter. While the overall potential of advanced window systems is high, the actual benefits that will accrue in any specific case will depend critically on the technical capabilities of the glazing and the nature of the interactions with the other building sub-systems.

The IMAGE project (IMAGE, 1997) aims to encourage appropriate applications of advanced glazing, to raise awareness of products amongst designers, and to give impetus to market penetration. The project comprises two complementary activities: the testing of representative advanced glazing systems using laboratory facilities (Platzer and Kuhn, 1997) and the PASLINK outdoor test cells (Martin *et al.*, 1996); and the use of computer simulations to determine the overall behaviour of these glazing systems when applied to different building types operating under different climates. This paper describes the latter activity.

2. ADVANCED GLAZING STATE-OF-THE-ART

Just as there are a number of approaches to energy conscious building design—natural ventilation, daylight utilisation, photovoltaic technology integration, and the like—there are many approaches to advanced glazing system design: monolithic and granular aerogels, transparent insulation materials, encapsulated shading devices, low-emittance coatings, evacuated systems, angular selective transmittance coatings, holographic and prismatic materials, variable transmittance electrochromic, thermochromic and liquid crystal devices.

Indeed, commercial systems now exist or are emerging which are well matched to the range of typical climate conditions:

Cool: Low thermal transmittance (U) with a high total solar transmittance (T_s), e.g. triple glazed, argon filled with 2 low-ϵ coatings giving $U=0.95\ \mathrm{W\ m^{-2}\ K^{-1}}$ and $T_s=0.5$.

Hot: Solar control with low thermal transmittance and high visible transmittance (T_{vis}), e.g. double glazed, argon filled with 1 low-ϵ spectral selective coating giving $U=1.35\ \mathrm{W\ m^{-2}\ K^{-1}}$, $T_s=0.37$, $T_{vis}=0.67$.

Mild: Combination of the above, with variable solar/visual control achieved by encapsulated blinds (commercially available) or electrochromic/thermochromic glass (not yet commercially available).

Recent research, e.g. the work of IEA Task

18 on advanced glazing materials (Hutchins, 1996), has been concerned with facilitating further performance improvements. Table 1, for example, lists some of the many possible targets for optimisation.

When the qualitative issues—of cost, colour, visual amenity, glare, etc. (Moeck *et al.*, 1996)—are added to these quantitative parameters, it is clear that there is a high potential for conflict. Some means is required to handle the dynamic interactions within the advanced glazing system, and between this system and the building. Simulation provides such a mechanism.

3. INTEGRATION: THE KEY ISSUE

The striking of a balance between energy efficiency and occupant comfort can only be achieved at the room level where occupant needs and behaviour, daylight and solar utilisation/exclusion, system response and orientation effects give rise to contradictory requirements. The success of an advanced glazing system depends crucially on the designer's ability to obtain an integrated performance view (IPV; Clarke *et al.*, 1996) at this level of resolution. An IPV is a collection of representative performance metrics which quantify building fuel use, equivalent environmental impact, and room level comfort in a way which supports comparisons between alternative designs.

Unfortunately, the performance of advanced glazing products are characterised by basic parameters such as *U*-value, solar and visible transmittance, etc. which do not readily translate to an IPV. Within the IMAGE project, the ESP-r (Clarke, 1985) and RADIANCE (Ward, 1994) programs for thermal and lighting simulation, respectively, have been placed within an application framework whereby the results from standardised simulations are collated to provide a succinct summary of overall performance, the IPV.

Stated briefly, and for the case of an existing building, which does not incorporate advanced glazing, the approach is as follows.

(1) A *base case* computer model of the as-built scheme is formed to some required level of resolution (and using measured thermo-optical data within the context of the IMAGE project). Where measured data exists, this model is subjected to a calibration study whereby the predictive accuracy is examined and judicial adjustments made to the inputs as necessary. (Note that the purpose is to improve confidence in the model, not to validate the simulation program.)
(2) One or more *reference* models are developed to represent possible advanced glazing options or to facilitate study of a proposed optimisation measure. The as-built case can then be compared with these references in

Table 1. Areas for performance optimisation

Insulating glazing	The insulating properties of a window can be improved by including multiple glass layers, by applying low-ϵ coatings to layers surfaces, or by using a low-conductivity gas such as argon or krypton instead of air (Arasteh *et al.*, 1987).
Spectrally selective coatings	Spectrally selective coatings can be applied to the glass to reduce transmission at specific wavelengths. Of foremost interest are those coatings which give solar control with little adulteration of view, i.e. glazings that have minimum effect on visible light but are opaque at other wavelengths, particularly within the infrared portion of the solar spectrum (e.g. a typical advanced glazing product will have a visible transmittance of 67% for a total solar transmittance of only 37%).
Edge spacers	These provide the seal for multiple glazing and are invariably made of aluminium or steel to provide mechanical strength under thermal stress. Because such materials give rise to a high conductivity thermal bridge, low-conductivity spacers are being developed (Aschehoug and Baker, 1995; Svendsen and Fritzel, 1995).
Insulating frames	Typical double glazing frames have higher *U*-values than the corresponding centre pane *U*-values for low-ϵ double glazing. With frames comprising some 20–25% of the aperture area, or 10% in the case of a curtain walling system, improved frame systems are required to achieve a low, overall component *U*-value (Beck and Arasteh, 1992).
Variable transmittance	Adjustable glazing systems offers the best prospect for providing an optimum solution as occupant and system needs vary throughout the year and daily. Blinds or louvers operated under automatic or manual control offer one option. An elegant alternative, which is currently under development, is electrochromic glazing whereby the transmittance can be varied by the application of a small voltage, which changes the oxidation state of the electrochromic coating. Both visible and total solar transmittance can be varied from their normal value (say 60%) down to some lower value (say 10%). The time taken to change (from the maximum to minimum values) is typically about 5 min. Because the voltage is only required to effect the change, and need not be sustained thereafter, the power consumption is small. The effective integration of this technology will require the development of appropriate control algorithms (Sullivan *et al.*, 1994).

order to quantify the benefits (or otherwise) of the proposed scheme.
(3) Simulations are then carried out and the results collated as an IPV which highlights the as-built to reference performance differences across relevant criteria.

Within IMAGE, the approach is being applied in two different situations:
(1) In *Case Studies* of existing buildings to determine the thermal and visual performance benefits that would accrue from the adoption of advanced glazing; and
(2) in *Design Studies* of proposed designs in order to expose the method to practitioners and identify situations where advanced systems may be realised in practice.

In each case the focus is on the advanced glazing systems as listed in Table 2, selected because they typify the spectrum of future opportunity.

To elaborate the approach, the following section describes a design study where, because the budget was fixed, any extra capital cost would have to be balanced by other cost savings (e.g. the avoidance of air conditioning) and/or by lower fuel costs.

4. DESIGN STUDY, 4 BRINDLEY PLACE, BIRMINGHAM

The building is a 13,000 m^2 speculative development for single or multiple tenancy. The main features are fully glazed facades facing south-east and north-west; deep plan, air-conditioned offices; external horizontal overhangs on the south-east facade and a central atrium with a horizontal glazed roof. Figure 1 shows the proposed design and the ESP-r model as established for the study.

4.1. Glazing options

Four glazing systems were considered for the office facades:
(1) In the *base case* simulation, a double-glazed unit with a low-ϵ coating ($\epsilon = 0.176$) applied to surface 3, with an air filling.
(2) In the *reference 1* simulation, a solar control double-glazed unit with a low-ϵ coating ($\epsilon = 0.04$) applied to surface 2 (inward-facing side of the external pane), with argon filling.
(3) In the *reference 2* simulation, a solar control double-glazed unit with a low-ϵ coating ($\epsilon = 0.04$) applied to surface 2, with an air filling.
(4) In the *reference 3* simulation, a system similar to reference 2 but with a less efficient coating.

Table 3 lists the thermal and optical characteristics for these glazing systems. Three system types were applied to the atrium roof:
(1) In the *base case* simulation, a double-glazed unit with low-ϵ coating ($\epsilon = 0.176$) applied to surface 3 (laminated glass) with air filling.
(2) In the *reference 1 and reference 2* simulation, a solar control double-glazed laminated unit with low-ϵ coating ($\epsilon = 0.04$) applied to surface 2 with air filling.
(3) In the *reference 3* simulation, a solar control double-glazed laminated unit with low-ϵ coating ($\epsilon = 0.04$) applied to surface 2 with air filling.

Table 4 lists the thermal and optical characteristics for these glazing systems.

4.2. Boundary conditions

Table 5 gives the average and extreme monthly climate parameters for the standard

Table 2. Advanced glazing systems within the IMAGE project

Multi-glazed systems	Low heat loss, high solar gain, triple glazed, argon filled, with 2 low-ϵ coatings, giving $U = 0.75$ to $1.0\ \mathrm{W\,m^{-2}\,K^{-1}}$, $T_s = 0.5$ and $T_{vis} = 0.61$. Solar control, high light transmittance, double glazed, argon filled, with 1 low-ϵ coating, giving $U = 1.35\ \mathrm{W\,m^{-2}\,K^{-1}}$, $T_s = 0.35$ and $T_{vis} = 0.65$. Light diffusing, double glazed, argon filled, with 1 low-ϵ coating, giving $U = 1.1$ to $1.3\ \mathrm{W\,m^{-2}\,K^{-1}}$, $T_s = 0.28$ and $T_{vis} = 0.54$.
Improved frame systems	Curtain wall system (DIN 4108 Group 1). Silicon-bonded curtain wall. Advanced "hole in wall" frame.
Variable transmittance systems	Triple-glazed unit with mid-pane blind in inner cavity allowing ventilation air pre-heat. Triple-glazed unit with mid-pane blind in ventilated outer cavity. Double-glazed unit with un-ventilated mid-pane blind. Electrochromic system.
Super windows	A combination of the above depending on the results of the testing and modelling programmes.

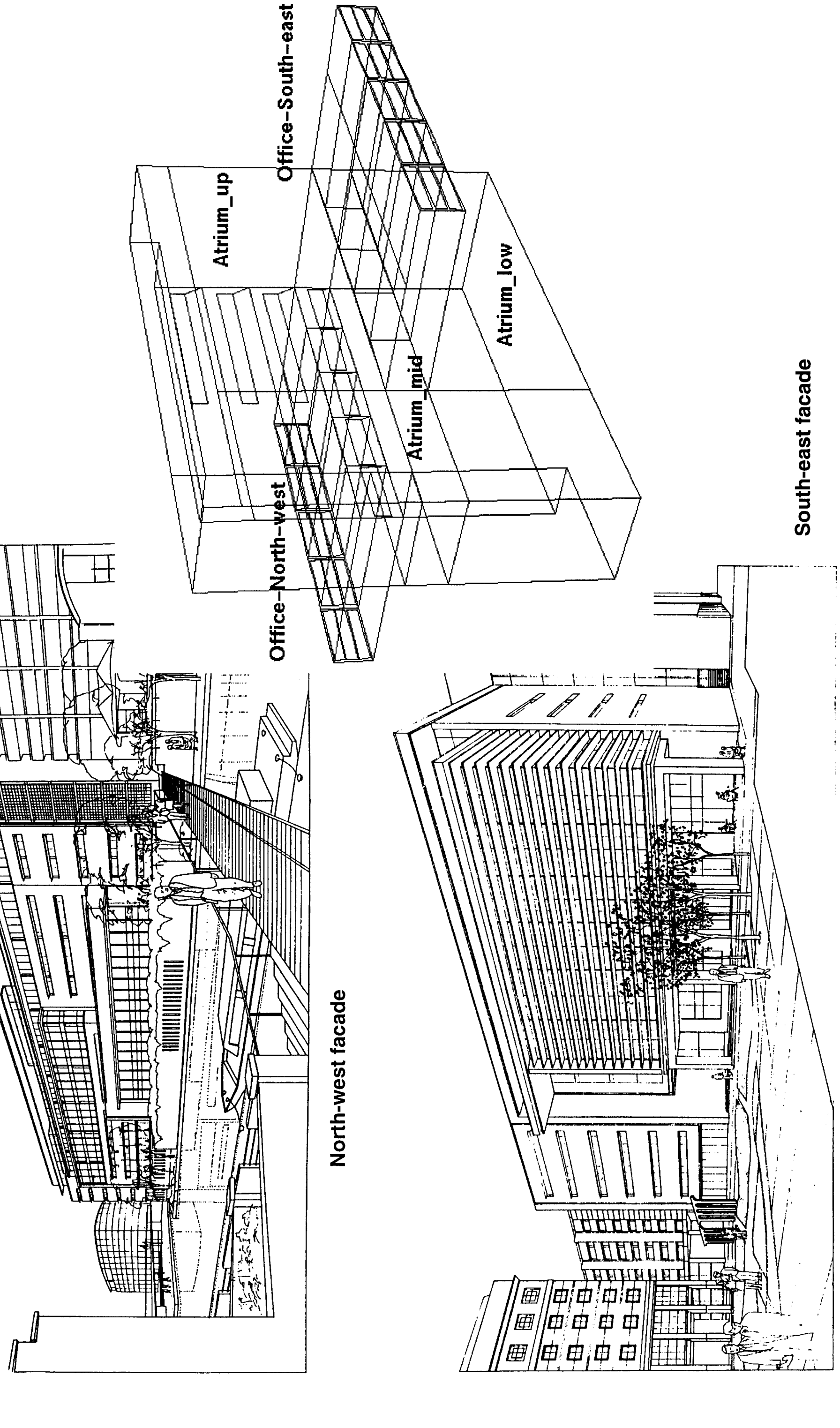

Fig. 1. The 4 Brindley Place proposed design and the related ESP-r model.

Table 3. Optical and thermal properties of perimeter facade glazing

Glazing	LT	GF	LEP	CE	GE	OVT	OST	U
Base case	6/12/6	Air	3	0.17	0.84	0.67	0.49	1.93
Reference 1	6/12/6	Argon	2	0.04	0.84	0.65	0.33	1.28
Reference 2	6/12/6	Air	2	0.04	0.84	0.65	0.33	1.68
Reference 3	6/12/6	Air	2	0.04	0.84	0.61	0.36	1.78

LT: layer thickness (mm); GF: gas filling; LEP: low-emissivity coating position (2 means innermost surface of the external pane); CE: coating emissivity; GE: glass emissivity; OVT: overall, normal incidence visible transmittance; OST: overall, normal incidence solar transmittance; U: centre of glass thermal transmittance ($W\,m^{-2}\,K^{-1}$).

Table 4. Optical and thermal properties of atrium roof glazing

Glazing	LT	GF	LEP	CE	GE	OVT	OST	U
Base case	6/12/8.7	Air	3	0.17	0.84	0.64	0.42	1.91
Reference 1	6/12/8.7	Air	2	0.04	0.84	0.63	0.30	1.68
Reference 2	6/12/8.7	Air	2	0.04	0.84	0.63	0.30	1.68
Reference 3	6/12/8.7	Air	2	0.04	0.84	0.59	0.36	1.78

LT: layer thickness (mm); GF: gas filling; LEP: low-emissivity coating position (2 means innermost surface of the external pane); CE: coating emissivity; GE: glass emissivity; OVT: overall, normal incidence visible transmittance; OST: overall, normal incidence solar transmittance; U: centre of glass thermal transmittance ($W\,m^{-2}\,K^{-1}$).

Table 5. Weather data, Kew 1967

	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Air temperature (°C)												
Average	5.4	6.5	8.1	8.7	11.9	15.4	18.7	16.9	14.6	12.0	6.6	5.2
Minimum	−2.2	−0.2	0.9	0.0	0.0	6.5	9.7	9.6	5.6	2.8	−0.5	−4.4
Maximum	13.2	13.3	16.7	20.1	25.1	24.4	28.7	24.7	22.0	20.1	15.0	13.2
Global horizontal irradiance ($kWh\,m^{-2}$)												
Total	18.5	30.9	71.0	85.7	117.5	134.2	150.2	114.4	65.9	40.5	20.7	14.8
Relative humidity (%)												
Average	82.2	77.3	69.5	72.1	75.9	70.3	70.9	76.6	81.8	82.3	85.7	83.1

U.K. reference year as used in the study. All simulations were annual.

4.3. *Simulation results*

This section summarises the overall performance results as obtained from the annual simulations. The results are given in the form of an integrated performance view (IPV), which presents several performance criteria across a range of performance types. These criteria are described in this section in relation to a south-east office with a fan coil system. Note that most of the parameters are normalised by floor area.

Figures 2 and 3 give the IPVs for base case and reference 3 (which resulted in the best overall cost–performance). An inter-comparison of the performance entities contained within the IPVs gives rise to the following conclusions.

4.3.1. Maximum capacity. The diversified total of peak capacities ($W\,m^{-2}$) represents critical plant sizes and hence capital costs. Table 6 summaries the results from IPVs and shows the relative reduction in plant peak capacities relative to the base case scenario. As can be seen, the reference 1 case delivers the greatest reduction in heating capacity—4.5% when compared to the base case. Reference 2 delivers the greatest reduction in cooling capacity—10.9% when compared to the base case.

4.3.2. Annual energy performance indicators. The annual energy consumption for the base case is 139.7 $kWh\,m^{-2}\,yr^{-1}$, while the reference cases are 133.9, 132.0 and 132.6 $kWh\,m^{-2}\,yr^{-1}$, respectively.

The reference 2 case delivers the largest energy consumption reduction (6%) relative to the base case, closely followed by the reference 3 case. Table 7 summarises the reduction in energy consumption relative to the base case.

Based on these data it can be concluded that reference 3 provides the highest cooling energy savings (14%) but there are almost no heating energy savings with any glazing scenario. This

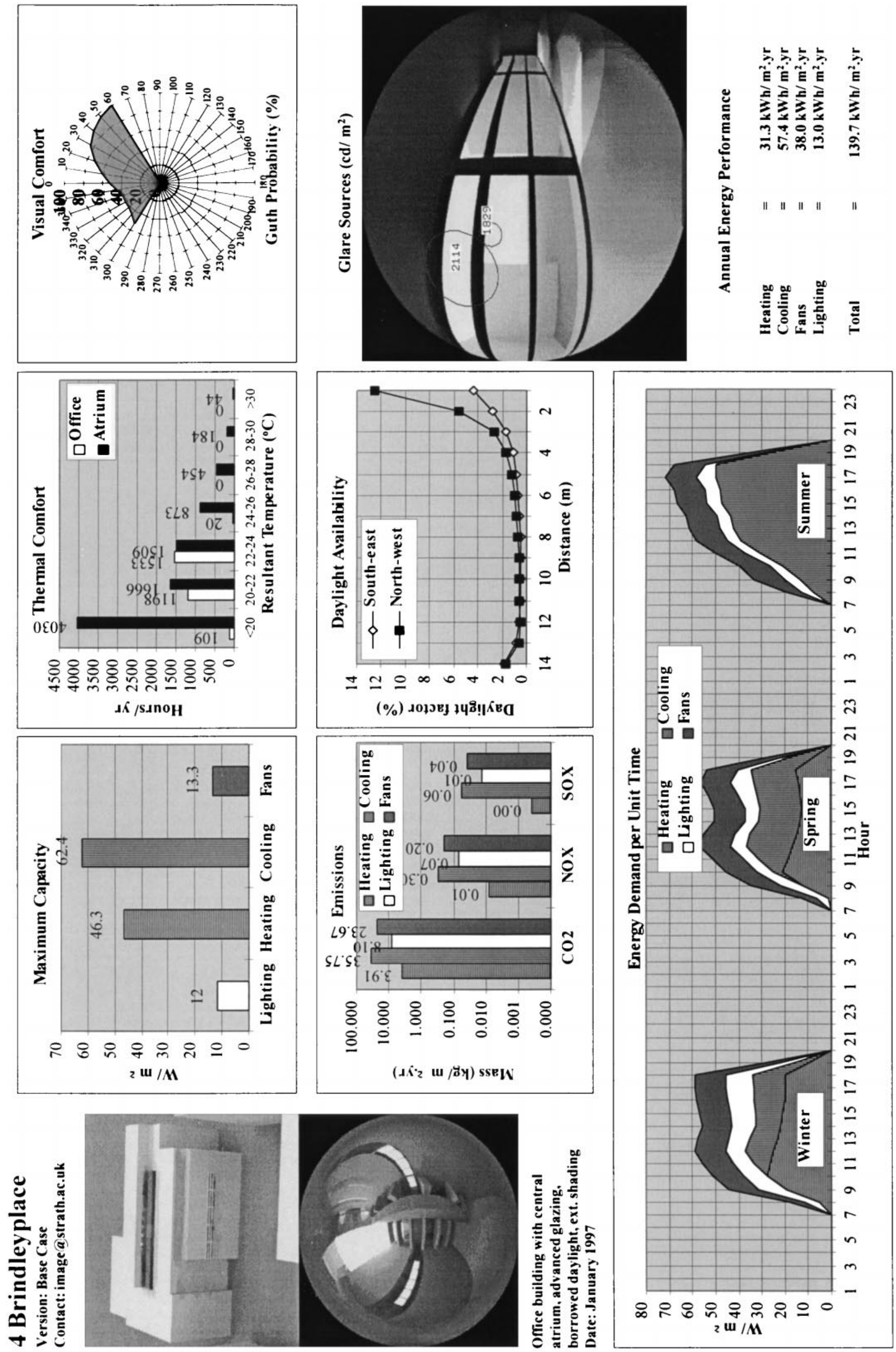

Fig. 2. Integrated performance view, base case.

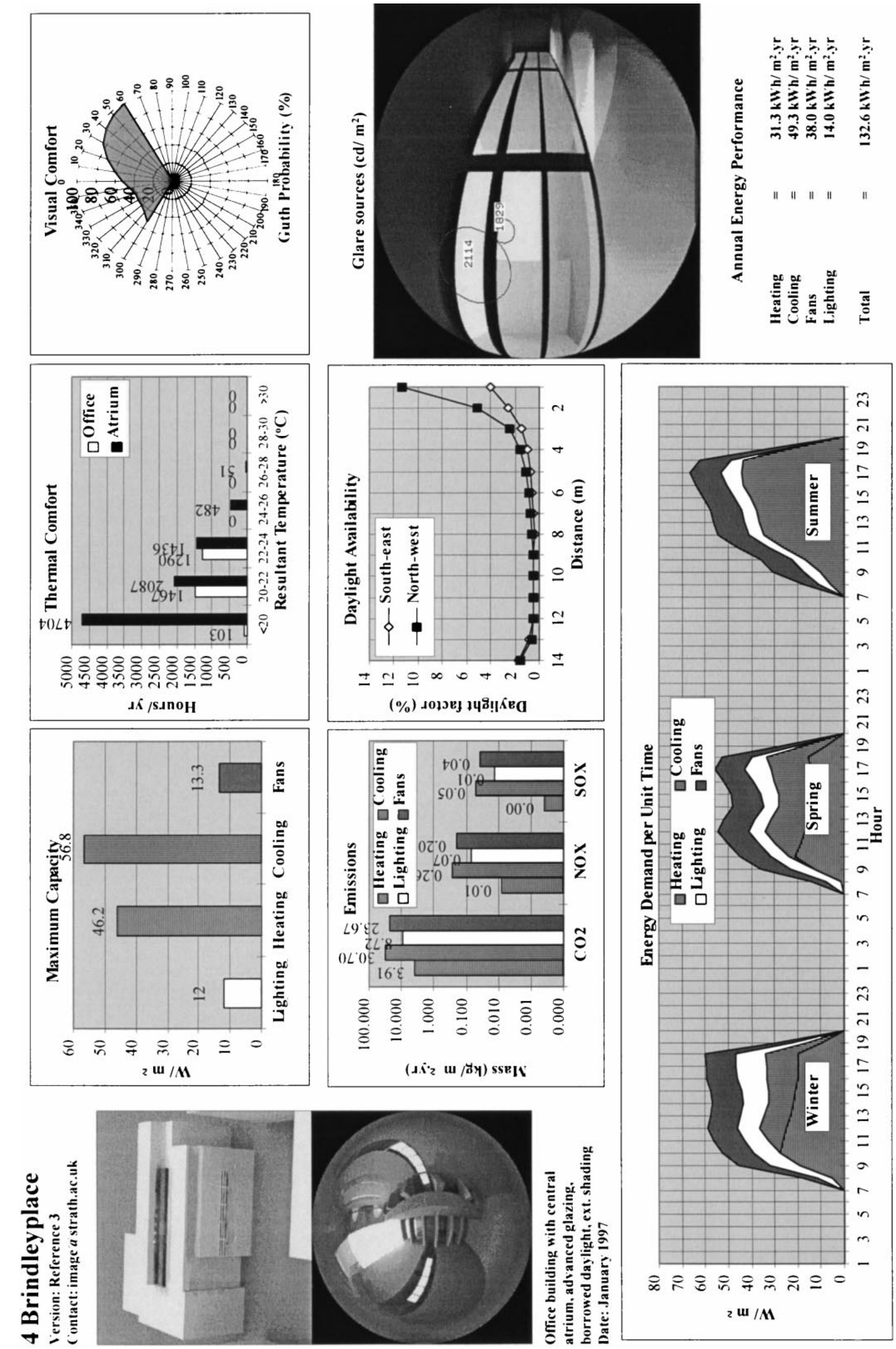

Fig. 3. Integrated performance view, reference 3 simulation.

Table 6. Reduction in peak capacities for a south-east office with fan coil system

Case	Capacity reduction (%)			
	Heating	Cooling	Lighting	Fans
Base case	0.0	0.0	0.0	0.0
Reference 1	4.5	10.7	0.0	0.0
Reference 2	2.6	10.9	0.0	0.0
Reference 3	0.4	8.9	0.0	0.0

Table 7. Reduction in energy consumption for a south-east office with fan coil system

Case	Consumption reduction (%)			
	Heating	Cooling	Lighting	Fans
Base case	0.0	0.0	0.0	0.0
Reference 1	0.9	10.4	−3.0	0.0
Reference 2	0.6	13.9	−3.0	0.0
Reference 3	0.0	14.1	−9.0	0.0

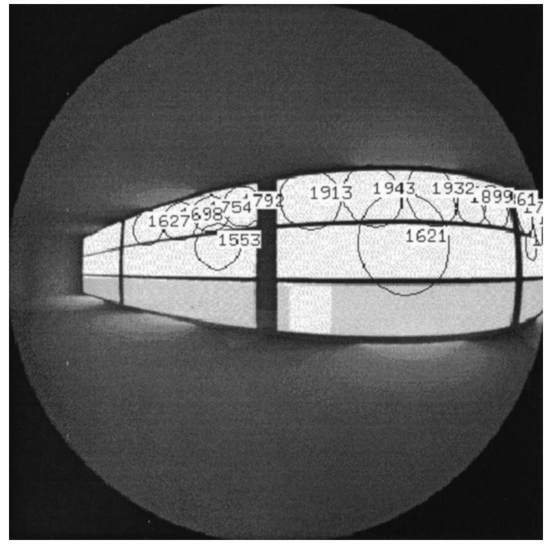

Fig. 4. Glare sources (cd m^{-2})—north-west facade.

latter finding may be attributed to the fact that it is fresh air heating which represents the majority of the energy consumption and so any change to the building facade will have minor effect on the heating energy consumption.

There is also a small absolute penalty from application of the advanced glazing scenarios in terms of increased artificial lighting consumption.

4.3.3. Typical seasonal energy demand profiles. The delivered energy data are expressed as cumulative daily profiles for each season. Regardless of the glazing scenario applied, the building will require cooling, even during winter, and will require artificial lighting, even during sunny spring and summer days. This is typical for fully air conditioned, deep plan office buildings.

4.3.4. Environmental emissions. The annual energy performance indicators have been converted to equivalent gaseous emissions.

The electricity consuming items—cooling systems, fans and artificial lights—are responsible for the largest portion of the gaseous emissions in all categories. The reduction in emissions for the reference models follows the energy consumption trends, i.e. reference 3 will result in a 4.4 kg m^{-2} yr^{-1} reduction in CO_2 emission.

4.3.5. Thermal comfort. The IPVs give the annual frequency of occurrence of the resultant temperatures within the south-east office space and the upper part of the atrium. As can be seen, the office overall thermal comfort is not significantly affected by the different glazing scenarios. A closer inspection of the simulation results indicated that the local thermal comfort is improved by the use of advanced glazing with a lower *U*-value. This is due to the mitigation of radiant asymmetry and cold down-draughts.

The central atrium is conditioned by the displacement ventilation system located at the ground floor level. Simulations show that temperature stratification will be established and the upper three atrium floors will experience resultant temperatures in excess of 26°C.

The application of solar control advanced glazing to the atrium roof reduces significantly the number of hours of thermal discomfort in the upper atrium. The rank ordering of the glazing scenarios is: reference 1 and 2 with 37 h above 26°C, followed by reference 3 with 51 h above 26°C. The base case glazing scenario results in 682 h when an average resultant temperature of 26°C is exceeded.

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

As shown on the IPVs, there is a slight reduction in the daylight factors: 3% for reference 1 and reference 2 and 9% for reference 3 attributed to the decrease of the glazing visual transmittance.

4.3.7. Visual comfort and glare. These performance outputs give the visual comfort probability for different viewing directions and highlight potential glare sources within a 3D picture (circled). The results show insignificant variations in these parameters from application of the advanced glazing. This is because of the

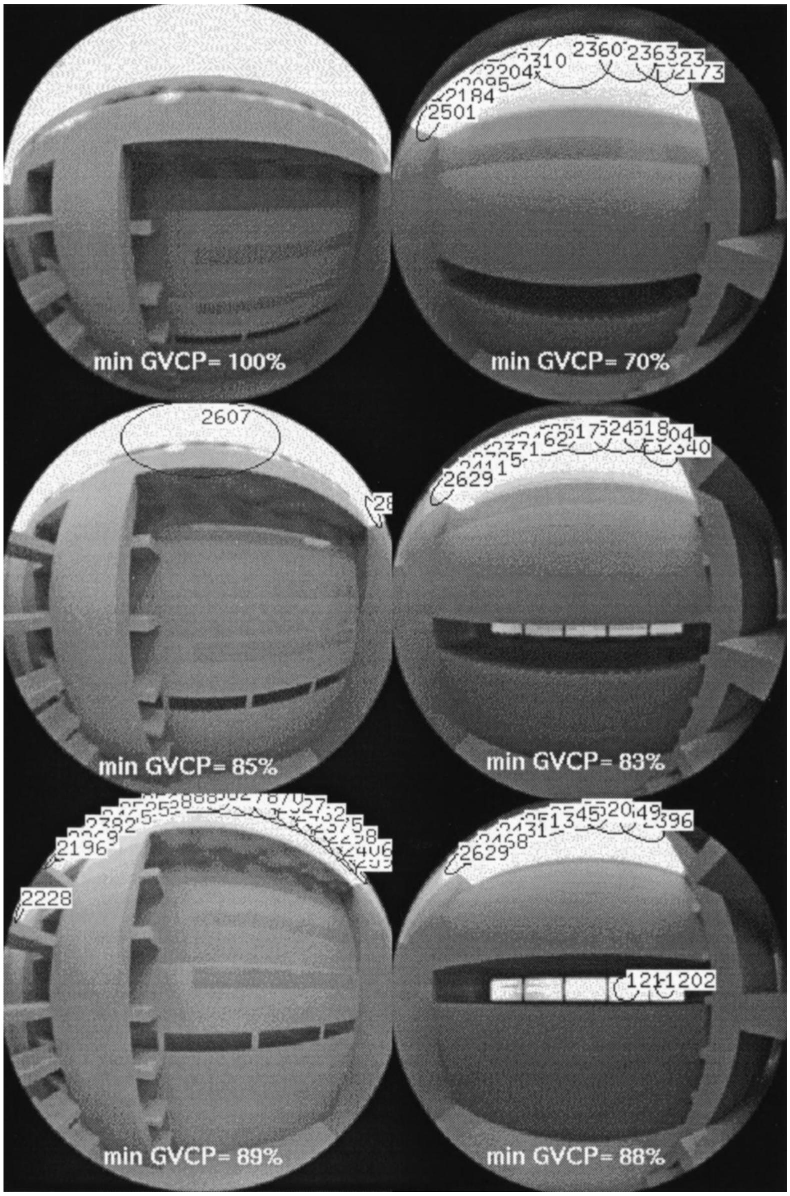

Fig. 5. Atrium glare assessment under CIE overcast sky conditions. (Min GVCP – minimum predicted value of Guth visual comfort probability %.)

relatively small decrease, 3% and 9% for the reference 1 to 3 cases, in visible transmittance relative to the base case.

It is likely that the vertical facades will give rise to glare problems—as can be seen on the IPVs for the south-east office and in Fig. 4 for the north-west office. The simulations indicate a 40% visual comfort probability for the given viewing directions. This situation is not uncommon in deep plan offices where daylight can contribute to the internal illuminances only up to about 5 m from the facade. The resulting low ratio of core to perimeter brightness then gives rise to visual discomfort. This usually results in the continuous usage of artificial lighting in order to counteract the brightness contrasts.

A possible improvement would be to install light redirecting glazing to the upper facade window (aimed towards the ceiling), with a high visible transmittance and good solar control. As can be seen from the IPVs and Fig. 4, this is the facade portion which gives rise to the glare problem. The natural light penetration to the office spaces from the central atrium roof could be enhanced by recessing individual floors towards the perimeter facade.

Figure 5 shows the results of the visual comfort assessment for an occupant looking into

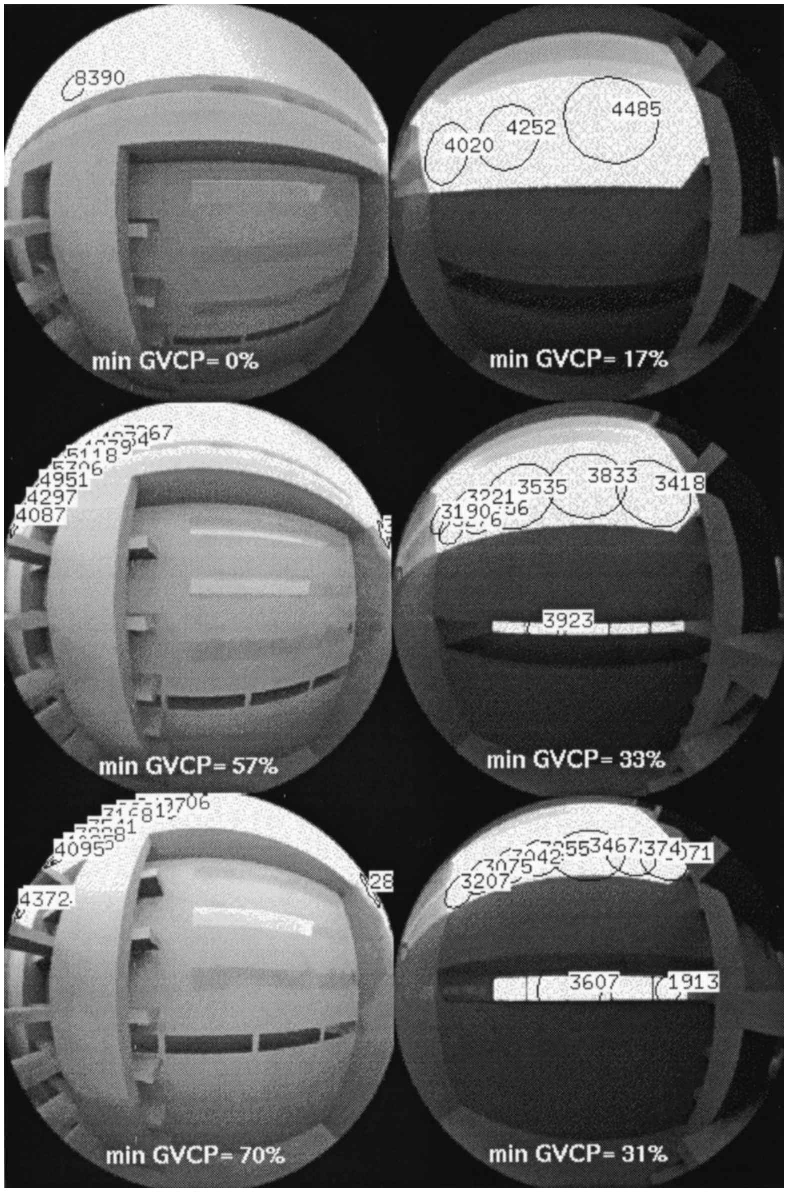

Fig. 6. Atrium glare assessment under CIE clear sky conditions on 21 June at 3 P.M. (Min GVCP – minimum predicted value of Guth visual comfort probability %.)

the atrium from two different atrium sides, as well as for different floor levels. The results are presented for the CIE overcast sky. The view into the atrium is visually comfortable, as indicated by high Guth visual comfort probability (GVCP) values. As explained elsewhere (Kaufman, 1984), the GVCP index rates visual comfort in terms of the percentage of people who will consider a given lighting system to be acceptable. The method, which takes into account the luminance of the glare source, the viewing solid angle and the background luminance, is applicable to all types of interior lighting systems. Direct glare will not be a problem if the GVCP is 70% or more and if certain maximum luminances are not exceeded.

A dramatic change in the visual comfort is predicted for a clear sky condition. As shown in Fig. 6, the view into the atrium is now visually uncomfortable, as indicated by low GVCP values. This is due to the direct disability glare caused either by direct solar insolation (south-east offices) or by secondary direct solar insolation via reflections from the atrium internal glass facades (north-west offices). The simulation results indicate that the problem will be both severe and widespread.

As with facade glazing, a possible solution would be to install diffusing glazing or a light redirecting system with a high visible transmittance and good solar control. Diffusing glazing under clear skies would give similar results to that for CIE overcast sky conditions.

5. CONCLUSIONS

The approach to integrated performance appraisal being used within the IMAGE project has been described. The contention is that by allowing designers to determine the multivariate, contextual performance of advanced glazing systems, robust applications will result. For example, for the case of the Brindleyplace design study, the following conclusions can be drawn.

(1) Advanced glazing offers a 4.5% reduction in the maximum heating capacity and a 10.9% reduction in maximum cooling capacity.

(2) Advanced glazing offers a 6% reduction in total energy consumption, a 14% reduction in cooling energy consumption and a marginal reduction/increase in heating/lighting energy consumption. (It is interesting to note that if the performance assessment had been based on standard product-centred data, combined with a non-simulation calculation approach, then the 33.6% reduction in *U*-value between the base case and reference 3 would have resulted in a significant heating energy savings prediction.)

(3) The application of advanced glazing to the atrium roof offers a significant improvement in thermal comfort and reduces summer overheating to acceptable levels. The local comfort conditions close to the perimeter facade will also improve.

(4) Advanced glazing will insignificantly decrease the daylight availability but will not change its characteristic distribution.

(5) The advanced glazing systems examined do not influence visual comfort and glare source distribution.

(6) The IPV approach is particularly adept at highlighting complex interactions. For example, as can be seen from Figs. 2 and 3, cooling energy is required even in winter. The low *U*-value of the advanced glazing, by acting to reduce heat loss, effectively increases the required cooling. On the other hand, the lower *U*-value significantly improves the thermal comfort in areas near to the facade.

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