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UE Project IMAGE

IMPLEMENTATION OF ADVANCED GLAZING IN EUROPE

Synthesis Report

Energy Systems
Research Unit

Laboratoire d'Energie Solaire
et de Physique du Bâtiment

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Synthesis Report

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Foreword

This report describes the outcome of the ESRU/ EPFL contribution to the EC's IMAGE (IMplementation of Advanced Glazing in Europe) project. This work entailed the application of combined thermal/daylight simulations to existing and proposed building designs incorporating advanced glazing systems. It also entailed the development of an Glazing Design Support Tool (GDST) to assist the European glazing industry in its marketing and research activities.

The work could not have progressed so far without the support of the project partners, to whom we are grateful:

Belgian Building Research Institute (Belgium)
Building Research Establishment (Scotland)
Fraunhofer Institut fur Solar Energy Systems (Germany)
Glaverbel (Belgium)
Halcrow Gilbert Associates (England)
Pilkington Glass Products Ltd (England)
Saint-Roch (Belgium).

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Abstract

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, daylighting and view.

The IMAGE project set out 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 behavior of these glazing systems when applied to different building types operating under different climates. This report relates to the latter activity.

The report describes the simulation method used and summarises the results obtained when the method was applied to several existing and proposed buildings. For each case studied, performance has been assessed in terms of HVAC and electrical system capacities, fuel consumptions, environmental emissions, thermal and visual comfort and glare sources. The report also describes the form and content of a new software product - the GDST (for Glazing Design Support Tool) - which has been established to allow the project's industrial partners to subject their products to a multi-variate performance appraisal.

Résumé

Les parties vitrées d'un bâtiment possèdent, du point de vue de l'énergie et de l'environnement, à la fois des avantages et des inconvénients. Elles contribuent de façon positive aux gains solaires passifs et à l'éclairage naturel du bâtiment, mais sont associées aussi malheureusement à des pertes de chaleur et à des situations d'inconfort thermique et visuel.

Le projet UE IMAGE a pour but de favoriser une application appropriée des techniques avancées de vitrage, de réaliser un transfert efficace de connaissances vers la pratique en ce qui concerne de nouveaux produits et de créer ainsi des impulsions favorables à leur pénétration dans le marché. Le projet comprend deux volets:

- l'évaluation des performances de systèmes de vitrages avancés en laboratoire (Platzer et Kuhn, 1997) et à l'aide des modules d'expérimentation PASLINK (Martin et al, 1996),
- l'utilisation de programmes numériques afin de déterminer le comportement de ces systèmes de vitrages dans différents climats et conditions d'utilisation.

Ce rapport concerne ce deuxième volet du projet. Il décrit les méthodes de simulation numérique utilisées, ainsi que les résultats de leur application à certains bâtiments. Pour chacun d'entre eux, différents critères de performance ont été considérés incluant les puissances de pointe des installations techniques et électriques du bâtiment, sa consommation énergétique, les émissions environnementales, ainsi que les prestations de confort thermique et visuel.

Le document présente, par ailleurs, le programme informatique GDST (Glazing Design Support Tool), développé à l'intention des partenaires industriels du projet, et permettant d'évaluer les performances de nouveaux produits de vitrage sur la base de plusieurs critères.

1 INTRODUCTION

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, as Table 1 shows:

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

Table 1: Approaches to advanced glazing system design

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

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 W/m^2K 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 $W/m^2.K$, $T_s = 0.37$, $T_{vis} = 0.67$.

Mild: Combination of the above, with variable solar/visual control achieved by encapsulated blind (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 to facilitate further performance improvements. Table 2, for example, lists some of the many possible targets for optimisation.

Insulating Glazings	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 obstruction to view, i.e. glazings that have minimum effect on visible light but are opaque at other wavelengths, particularly within the infra-red portion of the solar spectrum (e.g. a typical advanced glazing product will have a visible transmissivity of 67% for a total solar transmissivity of only 37%).

Edge Spacers	These provide the seal for multiple glazing are usually 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 Frame	Typical double glazing frames have a 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 Transmission	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 louvres operated under automatic or manual control offer one option. An elegant alternative, which is currently under development, is electrochromic glazing whereby the transmissivity can be varied by the application of a small voltage which changes the oxidation state of the electrochromic coating. Both visible and total solar transmissivity 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 to 10 minutes. 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) and investment in relation to product durability.

Table 2: Areas for performance 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.

2 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) at this level of resolution. An IPV (Figure 1) 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 1993) 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.

The IMAGE performance assessment method (PAM)[#], which essentially defines a best practice simulation procedure, has the following elements (actions underlined, knowledge in *italics*).

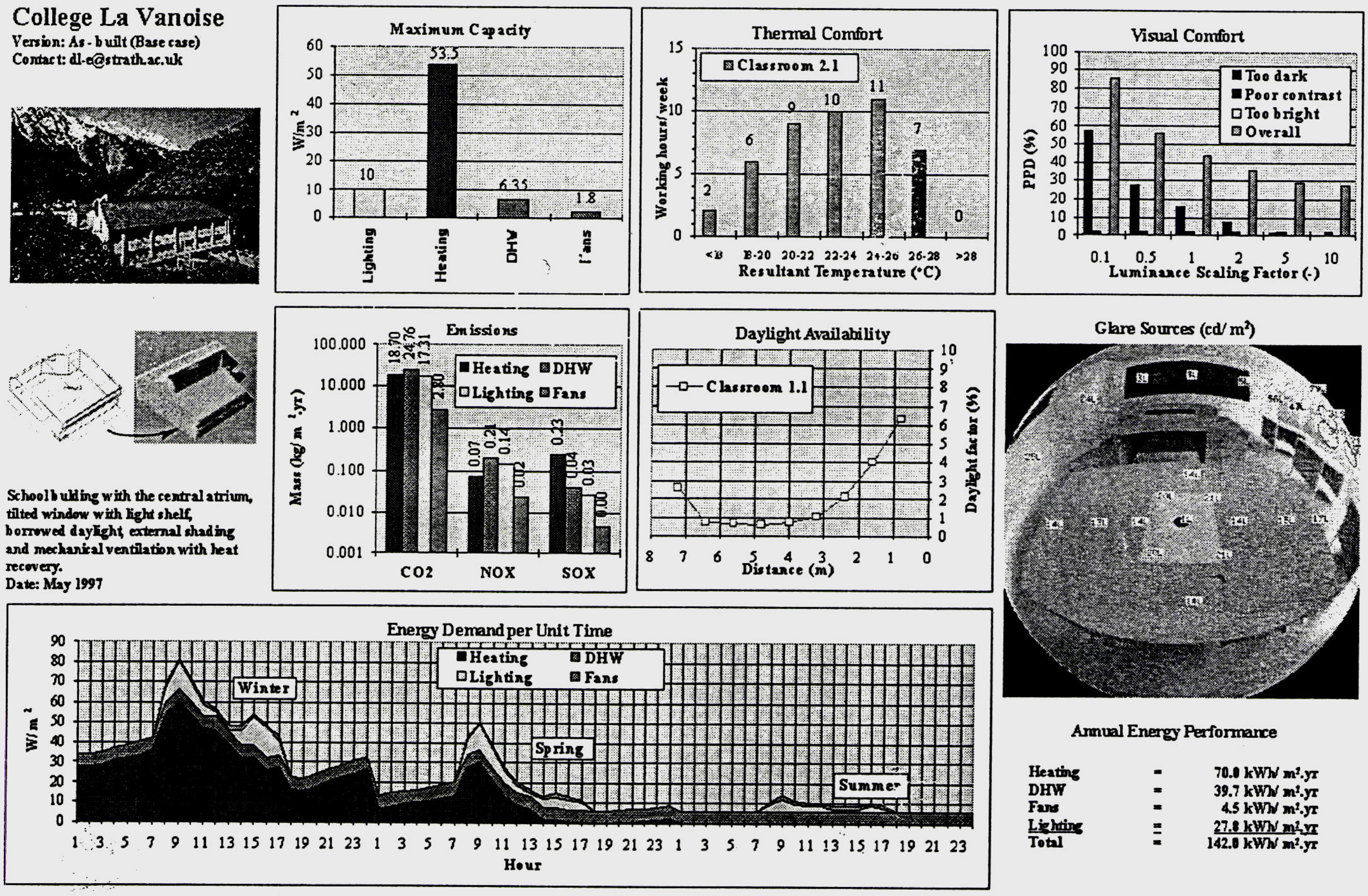
1. Establish computer representation corresponding to a *base case design* (here as-built within a case study and as-intended within a live design study).
2. Calibrate model using *reliable techniques* (here by comparison with empirical data).
3. Locate representative boundary conditions of *appropriate severity* (here corresponding to the selected building location).
4. Undertake integrated simulations using *suitable applications* (here ESP-r and RADIANCE).
5. Express multi-variate performance in terms of suitable *criteria* (here the entities of an IPV).
6. Identify problem areas as a function of *criteria acceptability.*
7. Analyse simulation results to identify *cause of problems.*
8. Postulate remedies by associating problem causes with *appropriate design options.*
9. For each postulate, establish a reference model to a *justifiable level of resolution.*
10. Iterate from step 4 until overall performance is *satisfactory.*
11. Repeat from step 3 to establish replicability for other *climate zones.*

The premise underlying the above PAM is that the impact of advanced glazing systems can best be determined by systematically removing (or adding in the case of new designs) relevant technologies and comparing the overall performance to result with some base case representation of the existing (or proposed) design.

In general use, the PAM can be attributed with alternative knowledge instances depending on the user's viewpoint and program capability. Within the IMAGE project, these knowledge instances were chosen to reflect state-of-the-art advanced glazing appraisal procedures. For example, the base case and reference computer models were highly resolved in relation to the thermo-optical processes associated with the glazings. Base case model calibration was then carried out using experimental data obtained from laboratory testing and the PASLINK outdoor test cells. Finally, combined thermal (ESP-r) and daylighting (RADIANCE) simulations were carried out and the results collated into IPVs to highlight the performance differences between the base and reference cases across relevant criteria. It is stressed that within the IMAGE project, this intercomparison was applied in two different situations:

- * In Case Studies of existing buildings to determine the thermal and visual performance benefits that would accrue from the adoption of advanced glazings;
- * and in Design Studies of proposed buildings in order to expose the method to practitioners and identify situations where advanced systems may be realised in practice.

The focus throughout the project was on the advanced glazing systems as listed in Table 3, selected because they typify the spectrum of future opportunity.



College La Vanoise
Version: As - built (Base case)
Contact: dl-e@strath.ac.uk

School building with the central atrium, tilted window with light shelf, borrowed daylight, external shading and mechanical ventilation with heat recovery.
Date: May 1997

Annual Energy Performance

Heating	=	70.0 kWh/ m².yr
DHW	=	39.7 kWh/ m².yr
Fans	=	4.5 kWh/ m².yr
Lighting	=	27.8 kWh/ m².yr
Total	=	142.0 kWh/ m².yr

Figure 1: Example Integrated Performance View.

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 $W/m^2.K$, $T_s = 0.5$ and $T_{vis} = 0.61$. * Solar control, high light transmission, double glazed, argon filled, with 1 low-ε coating, giving U = 1.35 $W/m^2.K$, $T_s = 0.35$ and $T_{vis} = 0.65$. * Light diffusing, double glazed, argon filled, with 1 low-ε coating, giving U = 1.1 to 1.3 $W/m^2.K$, $T_s = 0.28$ and $T_{vis} = 0.54$.
Improved Frame Systems	Curtain wall system (DIN 4108 Group 1). Silicon bonded curtain wall. Advanced 'hole in wall' frame.
VariableTransmission 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

Table 3: Advanced glazing systems within the IMAGE project.

3 CASE AND DESIGN STUDY BUILDINGS

Table 4 summarises the targeted buildings, 4 existing and 5 proposed, and lists the glazing options studied within the base and reference case computer representations.

Building	*Advanced Glazing Technology*
1. College La Vanoise (School), Modane, France.	base case: double glazed unit with an air filling and translucent plastic atrium roof. reference 1: low-ε coated (surfaces 3 and 5) triple glazed unit with argon filling.
2. Victoria Quay (Office Complex), Edinburgh, Scotland.	base case: double glazed unit with an air filling. reference 1: as base case but with a low-ε coating (surface 2). reference 2: as reference 1 but with an argon filling. reference 3: as reference 2 but with reduced low-ε coating. reference 4: low-ε coated (surfaces 3 and 5) triple glazed unit with Krypton filling.
3. Brundtland Centre (Exhibition and Conference Facility), Toftlund, Denmark.	base case: low-ε double glazed facade with light directing blinds, linked control of blinds and luminaires, central atrium with low-ε double glazed roof with integral PV modules. reference 1: as base case but with the advanced glazing/ blinds removed and luminaire control deactivated.

4. Passive Solar Housing, Linford England.	base case: clear float double glazed unit with an air filling. reference 1: low-ε coated (surface 3) double glazed unit with an air filling. reference 2: low-ε coated (surfaces 3 and 5) triple glazed unit with an argon filling. reference 3: solar control low-ε coated (surface 2) double glazed unit with an argon filling.
5. 4 Brindleyplace (Office Complex), Birmingham, England.	base case: low-ε coated (surface 3) double glazed unit with an air filling. reference 1: low-ε coated (surface 2) double glazed unit with an argon filling. reference 2: low-ε coated (surface 2) double glazed unit with an air filling. reference 3: low-ε coated (surface 2) double glazed unit with an air filling.
6. Britannia House (Office Complex), London, England.	base case: hard low-ε coated (surface 3) double glazed unit with an air filling and an internal venetian blind. reference 1: hard low-ε coated (surface 3) double glazed unit with an air filling and a mid-pane venetian blind. T{ T{ reference 2: soft low-ε selective coated (surface 2) double glazed unit with an air filling and an internal venetian blind. reference 3: soft low-ε selective coated (surface 2) double glazed unit with an air filling, mid-pane venetian blind and single pane float glass. reference 4: soft low-ε selective coated (surface 2) double glazed unit with an air filling and a mid-pane venetian blinds.
7. Glenview Hospital Inverness, Scotland.	base case: clear float double glazed unit with an air filling. reference 1: double glazed unit with a tint-coated external pane (surface 2), laminated clear float internal pane and an air filling. reference 2: double glazed unit with a tint-coated external pane (surface 2), a hard low-ε coated (surface), laminated internal pane and an air filling. reference 3: double glazed unit with a tint-coated external pane (surface 2), a hard low-ε coated (surface 3), laminated internal pane and an air filling.
8. Hyndburn (Office Complex), London, England.	Base Case: vertical facade, fully glazed, with atrium north light. Reference 1: as base case but without atrium north light. Reference 2: as base case but with light shelf and opaque window sill to 800*mm*. Reference 3: as reference 2 but with a stepped floor plate. Reference 4: as base case but with opaque window sill, reduced glazed area and prismatic glazing. Reference 5: as base case but with modified atrium north light.
9. Lighthouse (Retail and RE Demonstration), Glasgow, Scotland.	base case: doubled glazed unit with air filling. reference 1: low-ε coated (surfaces 3 and 5) triple glazed unit with argon filling. reference 2: as reference 1 but with daylight-related luminaire control.

Table 4: Buildings simulated within the IMAGE project.

Some of the above glazing components were experimentally evaluated within the project so that data was available to support computer model calibration prior to undertaking the integrated performance appraisals. This calibration procedure is detailed in the next section.

4 ESP-R/ RADIANCE MODEL CALIBRATION

Within the project, the following simulation tools were used to characterise overall building performance.

ESP-r:	A building/plant performance simulation environment originating from the University of Strathclyde in Glasgow (Clarke 1985). The system is based on a numerical approach in which the building and its systems are discretised and conservation equations for each resulting finite volume are solved simultaneously. A central "Project Manager" co-ordinates the model construction and simulation tasks, giving access to CAD, database management, report generation and image manipulation tools as required.
RADIANCE:	A simulation package, developed by Lawrence Berkeley Laboratory, for the prediction of the distribution of visible radiation in spaces illuminated by natural and/or artificial means (Ward 1993). System outputs include 3D representations with illuminance contours superimposed.

Significantly, all models are created by, and contained within ESP-r's Project Manager (ESRU 1997) to enable future model browsing, further exploratory performance appraisals and model mapping to other simulation applications.

As shown in Figure 2, 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 such as AutoCad.

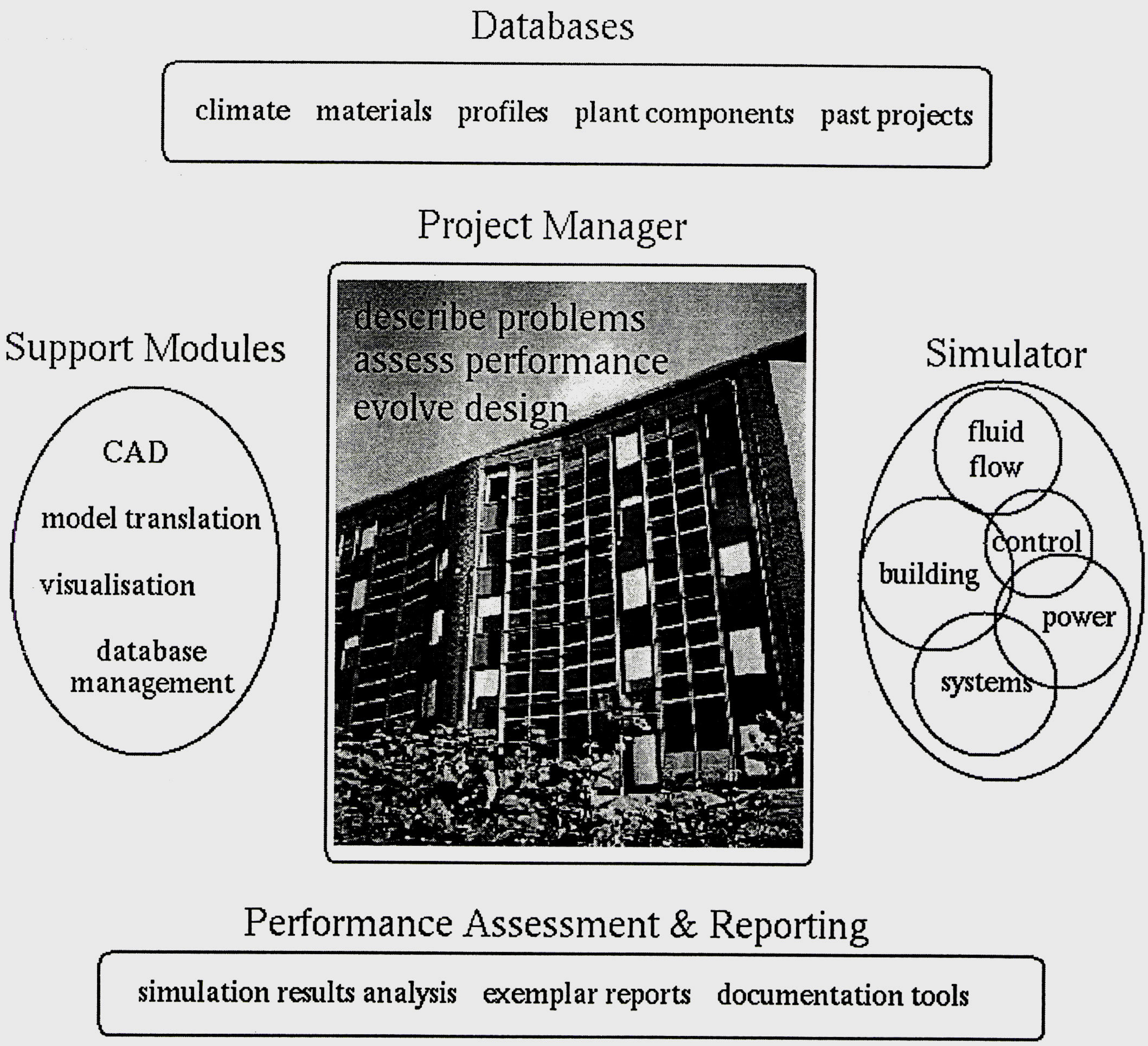


Figure 2: The ESP-r System.

Also significantly, the models, climates and glazings evaluated within IMAGE have been encapsulated within a new glazing industry decision support tool as described Section 7 and Annex 10.

ESP-r offers the following functionality.
- Interactive definition of building models.
- Cooperative working.
- Full 3D representation and complex constructional and operational attributions.
- Automatic exchange of building models between work groups.
- On-line images of the case study buildings.

- Storage of documents and performance details on the case study buildings to support outcome dissemination.
- Automatic generation of models for Radiance, tsbi3, AutoCad and ESP-r.

To ensure that the ESP-r glazing models were well configured prior to use, it was first necessary to calibrate these models using empirical data as described in the following sub-sections.

4.1 ESP-r/Radiance integration

In general, integrated simulation programs use the split-flux method (BRE 1996) to compute internal illuminance, which is not suitable for complex glazing systems. To improve the calculation, the Radiance (Ward 1994) program has been linked to allow a time step calculation of the illuminance.

Using Radiance, ESP-r's Project Manager can perform an illuminance calculation at each time step of the thermal calculation as shown in figure 3.

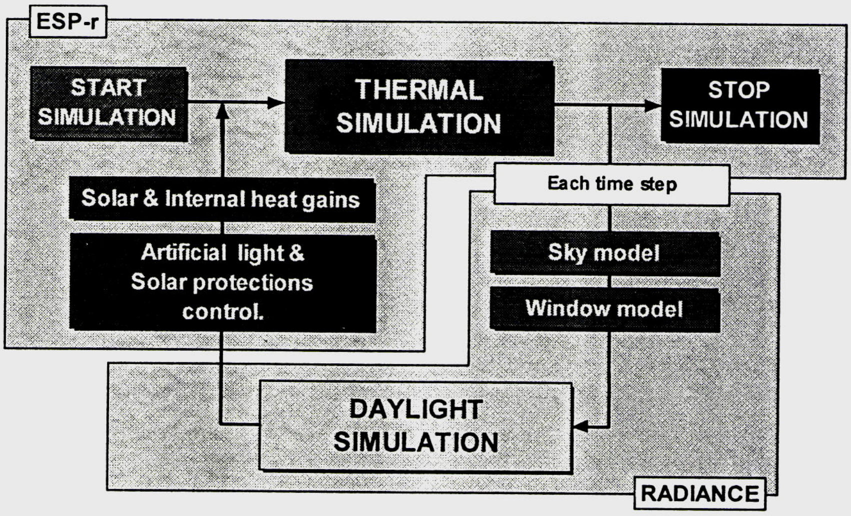


Figure 3 ESP-r/RADIANCE coupling.

For each time step of the RADIANCE/ESP-r coupling, a luminance distribution of the sky is generated. Using the sky, windows and room characteristics, RADIANCE compute the illuminance at a certain point as for instance at a movable shading sensor location. Then, ESP-r uses the results of RADIANCE's calculation to adapt the scene parameters such as electric light power or light and energy transmission through windows (due to a movable shading device). Finally, ESP-r starts the thermal simulation. The loop is then completed and a new daylighting calculation can take place at the next time step.

To avoid the calculation to be time consuming, the illuminance is calculated for specific location. There is no rendering of a whole Radiance scene, which can take an hour; its a question of few seconds for each time step. To avoid that these few seconds become few minutes for a long simulation run, only representative location, such as a work plane, an electric lighting or movable shading device sensor location, are simulated. Thus illuminance values can be used for instance to control electric lighting.

This ESP-r/Radiance integration improves the simulation of:

- Solar and internal heat gains
- Thermal and visual comfort
- Energy and cooling consumption

This "time step integration" of daylight calculation into thermal dynamic simulation provides an improvement of simulation results but is a little more time consuming due to the ray-tracing algorithm used for daylight calculation. This methodology is more appropriated for small simulation period and/or for complex glazing systems that can not be simulated with accuracy using the split-flux method.

4.2 Experimental Data Sets

As an example, consider a calibration exercise using an experimental dataset provided by the Belgian Building Research Institute (BBRI). The dataset comprised:

* 15 minute averages of climate parameters (ambient temperature, global and diffuse horizontal irradiance, global south-facing vertical irradiance at the component, wind speed and direction, longwave horizontal irradiance, longwave vertical irradiance at the component).

* 15 minute averages of internal PASLINK test cell thermal conditions (mean air temperature, service room temperature, pseudo-adiabatic shell temperature, net heating or cooling input).

Because relative humidity data were missing, and because ESP-r's sky temperature algorithm requires it, an average constant value was assumed. Based on the subsequent level of agreement between ESP-r and measurements (especially at night-time when this effect should be most visible), it was decided that this parameter does not play a critical role.

4.3 PASLINK Test Cell Model

The PASLINK test cells consist of two rooms. The test room is highly insulated and is separated from the service room by a well insulated wall. The test room allows for changeable components on the south-facing facade, and is basically a calorimeter, with the capability of allowing for very precise measurements of heat exchanges (both gains and losses) through test components.

The BBRI test cells are fitted with internal pseudo-adiabatic shells in which compensation heating controls the background heat losses from the test room. Figure 4 shows a PASLINK test cell as located at BBRI, together with test cell environmental control and test component schemes.

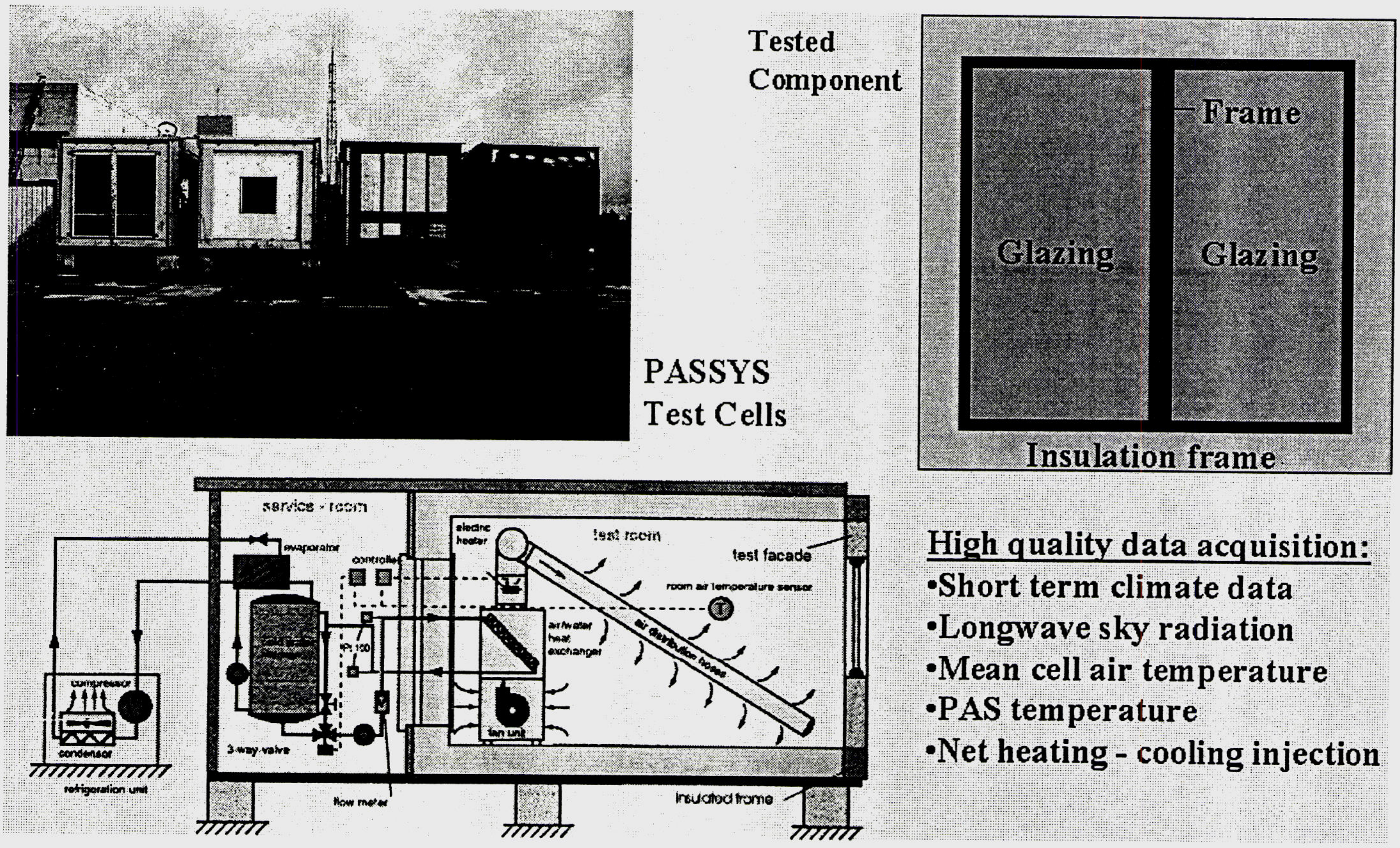


Figure 4: PASLINK test cell.

4.4 Advanced Glazing Model

The south wall of the PASLINK test cell was fitted with a component to house the advanced glazing and supporting frame as shown in Figure 5. Table 5 summarises the dimensions of the advanced glazing component and the three monitored glazings.

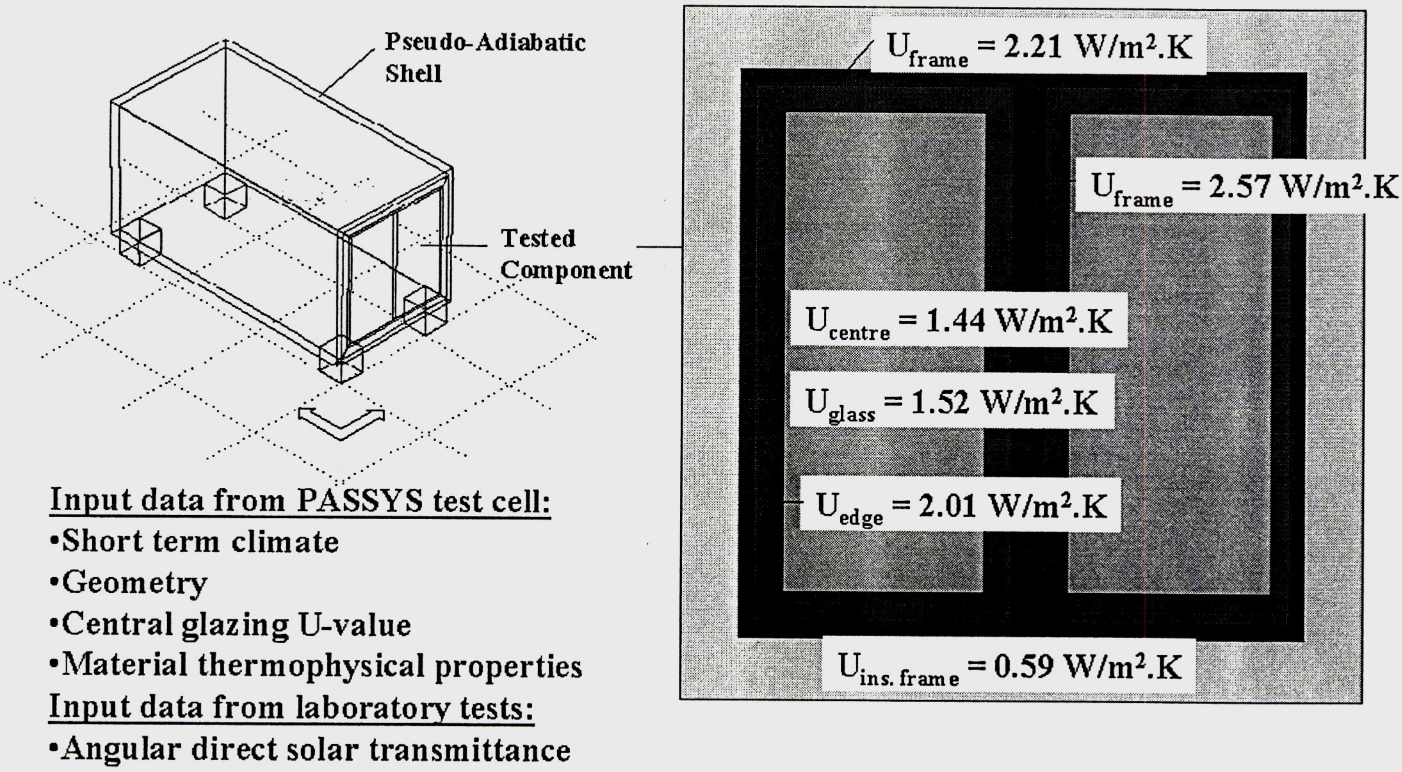


Figure 5: ESP-r model of PASLINK test cell with advanced glazing component.

Element	Area	Centre U-Value (*W/m2.K*)		
	(*m2*)	Glazing 1	Glazing 2	Glazing 3
Insulating frame	1.27	0.50	0.59	0.49
Frame-perimeter	-	2.16	2.21	2.37
Frame-middle	0.67	2.54	2.57	2.60
Centre of glass	3.53	0.94	1.47	1.15
Edge of glass	0.76	1.49	2.01	1.95
Glass	4.30	1.02	1.52	1.30
Total	6.25			

Table 5: Summary of the advanced glazing components

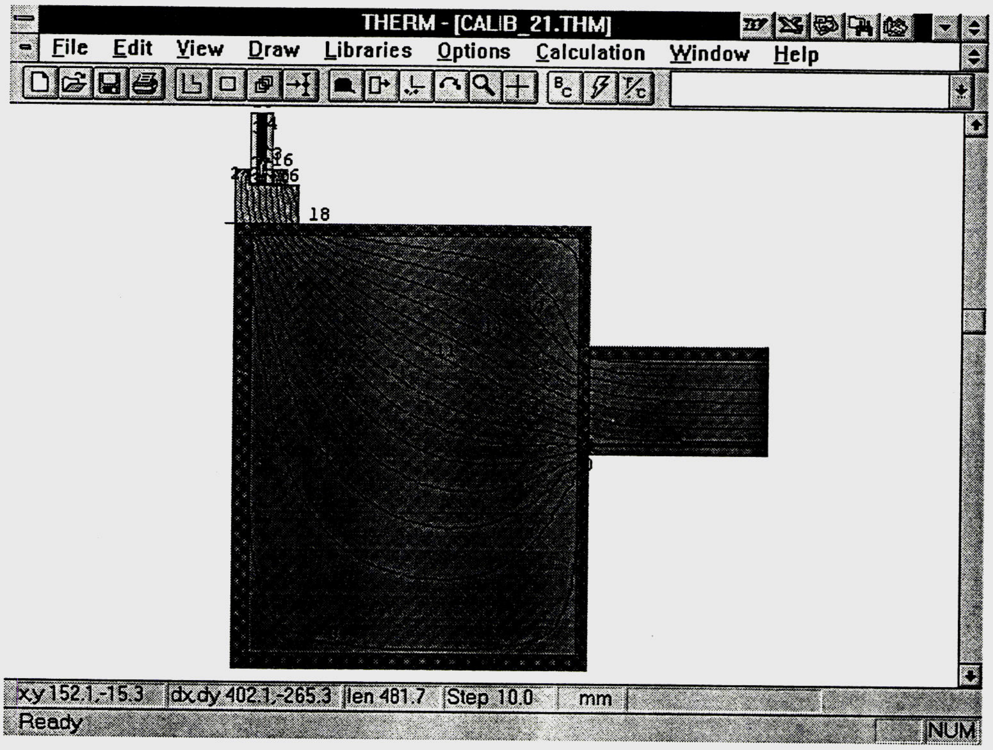
The three glazing systems were selected to typify the range of possibilities as follows.

Glazing 1 - Pilkington triple glazing unit. Triple glazing unit with external clear float pane (6mm), mid pane clear float pane (4mm) with low emissivity coating ($\varepsilon = 0.176$ at #3) and internal clear float pane (6mm) with low emissivity coating ($\varepsilon = 0.176$ at #5). Gaps filled with argon (16 mm). Table 6 gives the associated optical data.

Glazing 2 - Saint-Roch solar control double glazing unit. Double glazing unit with external clear float pane (6mm) with solar control coating ($\varepsilon = 0.040$ at #2) and internal clear float (6mm). Gaps filled with argon (12 mm). Table 7 gives the associated optical data.

Glazing 3 - Glaverbel solar control diffusing double glazing unit. Double glazing diffusing unit with external clear float pane (6mm) with solar control coating ($\varepsilon = 0.030$ at #2) and internal laminated diffusing pane (6mm). Gaps filled with argon (15 mm). Table 8 gives the associated optical data.

The centre pane U-values were taken from Pilkington hotbox tests (Jones & Pye 1997) while the effects of multi-dimensional heat conduction within the frame and at the glass edge was modelled by the THERM 2D heat conduction program for window frames (Finlayson et al 1996). Figures 6 and 7 give examples of the 2D analysis showing heat transmittance values for different component parts.



xy 152.1,-15.3 | dx,dy 402.1,-265.3 | len 481.7 | Step 10.0 | mm

Ready | NUM

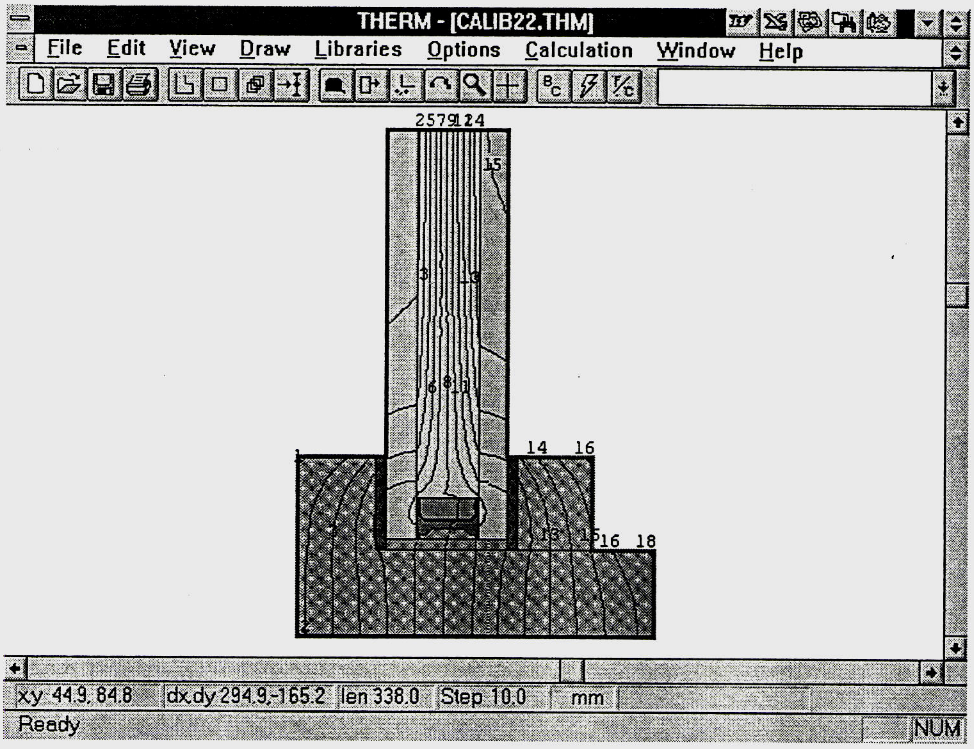
$U_{centre} = 1.44$ W/m².K

$U_{edge} = 2.01$ W/m².K

$U_{frame} = 2.21$ W/m².K

$U_{ins. frame} = 0.59$ W/m².K

Figure 6: 2D conduction analysis of frame detail.



$U_{centre} = 1.44\ W/m^2.K$

$U_{edge} = 1.99\ W/m^2.K$

$U_{frame} = 2.57\ W/m^2.K$

Figure 7: 2D conduction analysis of glazing-frame detail.

Property	Angle of incidence (°)				
	0	40	55	70	80
Solar direct transmittance	0.350	0.325	0.300	0.200	0.066
Solar absorptance #1	0.166	0.183	0.200	0.222	0.217
Solar absorptance #2	0.151	0.158	0.160	0.147	0.106
Solar absorptance #3	0.104	0.106	0.098	0.072	0.036

Table 6: Optical properties for Glazing 1.

Property	Angle of incidence (°)				
	0	40	55	70	80
Solar direct transmittance	0.285	0.265	0.235	0.157	0.073
Solar absorptance #1	0.368	0.390	0.400	0.391	0.332
Solar absorptance #2	0.033	0.035	0.036	0.035	0.029

Table 7: Optical properties for Glazing 2.

Property	Angle of incidence (°)				
	0	40	55	70	80
Solar direct transmittance	0.238	0.183	0.150	0.108	0.050
Solar absorptance #1	0.368	0.390	0.400	0.391	0.332
Solar absorptance #2	0.033	0.035	0.036	0.035	0.029

Table 8: Optical properties for Glazing 3.

The angle dependent direct solar transmittance was derived from laboratory tests carried out at the Fraunhofer Institute (Platzer & Kuhn 1997), while the solar absorptance data was determined using the WIS program (Dijk & Goulding 1996).

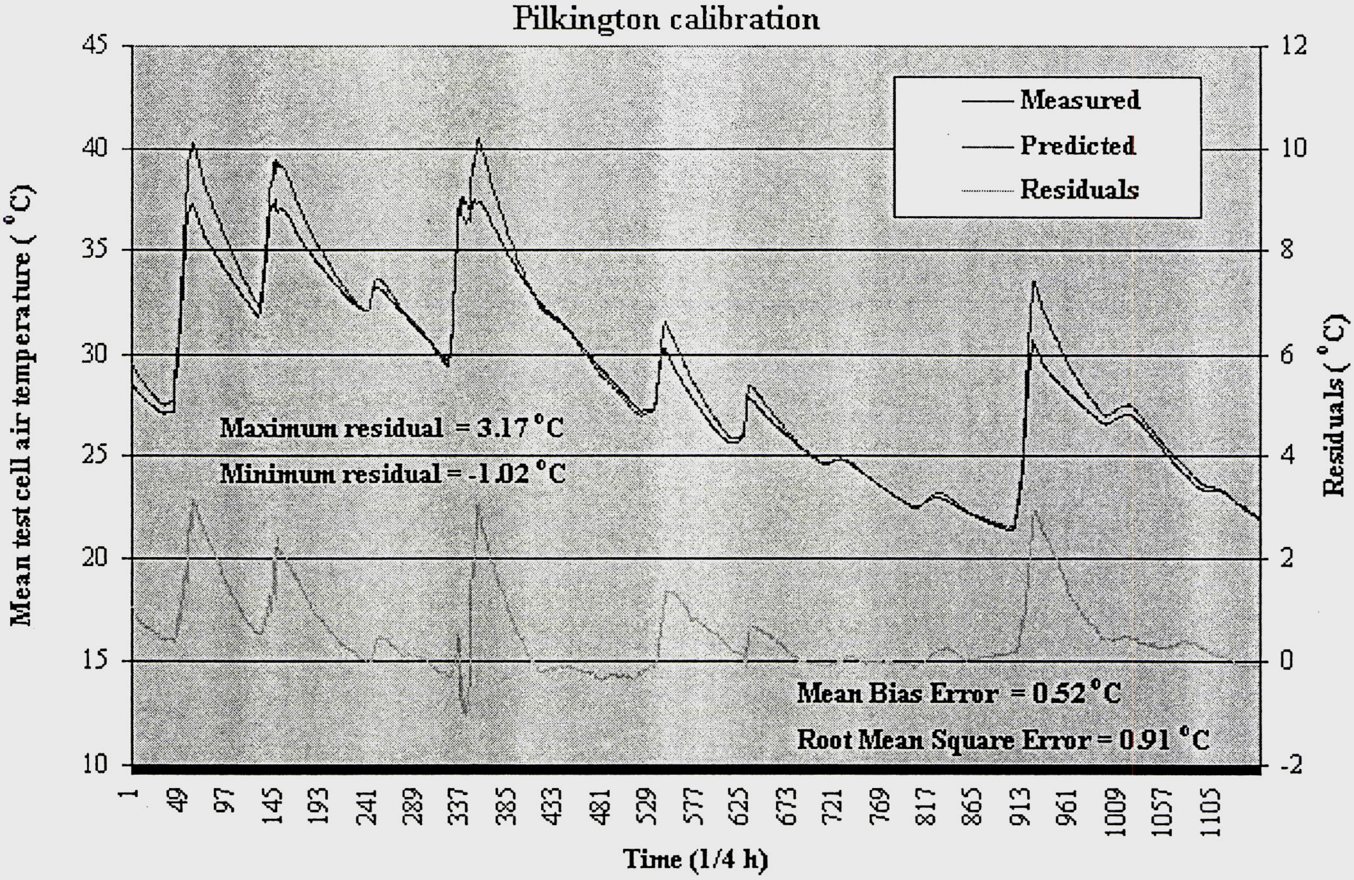
4.5 Calibration Results

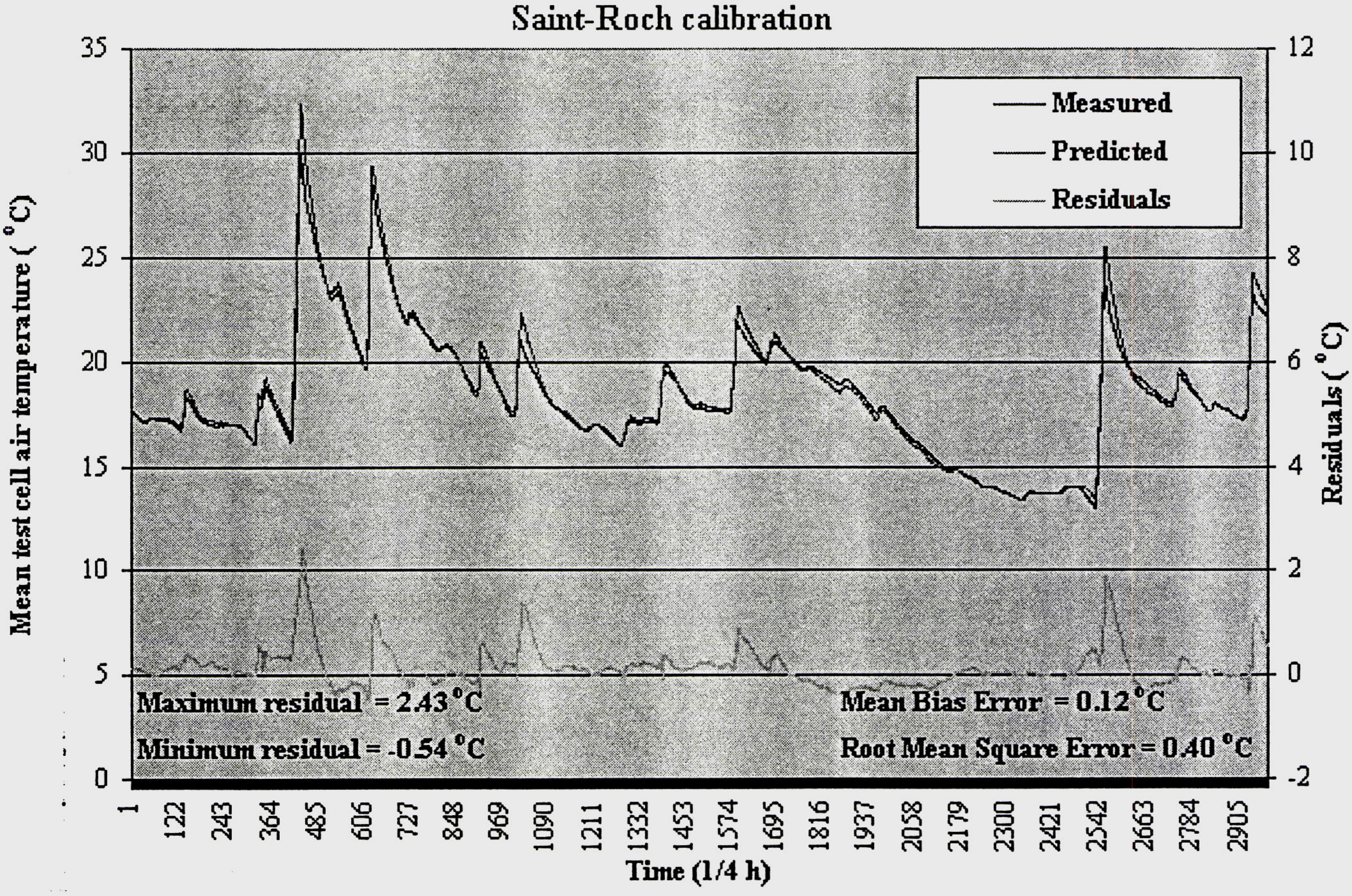
Table 9 summarises the results from a comparison of the measured mean test cell internal air temperature with the predicted value. Figures 8 to 10 show this comparison together with error analysis results for the three glazing systems.

Error	Glazing 1 °C	Glazing 2 °C	Glazing 3 °C
MBE	0.52	0.12	-0.02
RMSE	0.91	0.40	0.16
MaxR	3.17	2.43	0.69
MinR	-1.02	-0.54	-2.72

MBE: Mean Bias Error
RMSE: Root mean Square Error
MaxR: Absolute maximum residual
MinR: Absolute minimum residual

Table 9: Measured versus predicted mean test cell air temperature.





Figures 8 and 9: Glazing 1 and Glazing 2 calibration results.

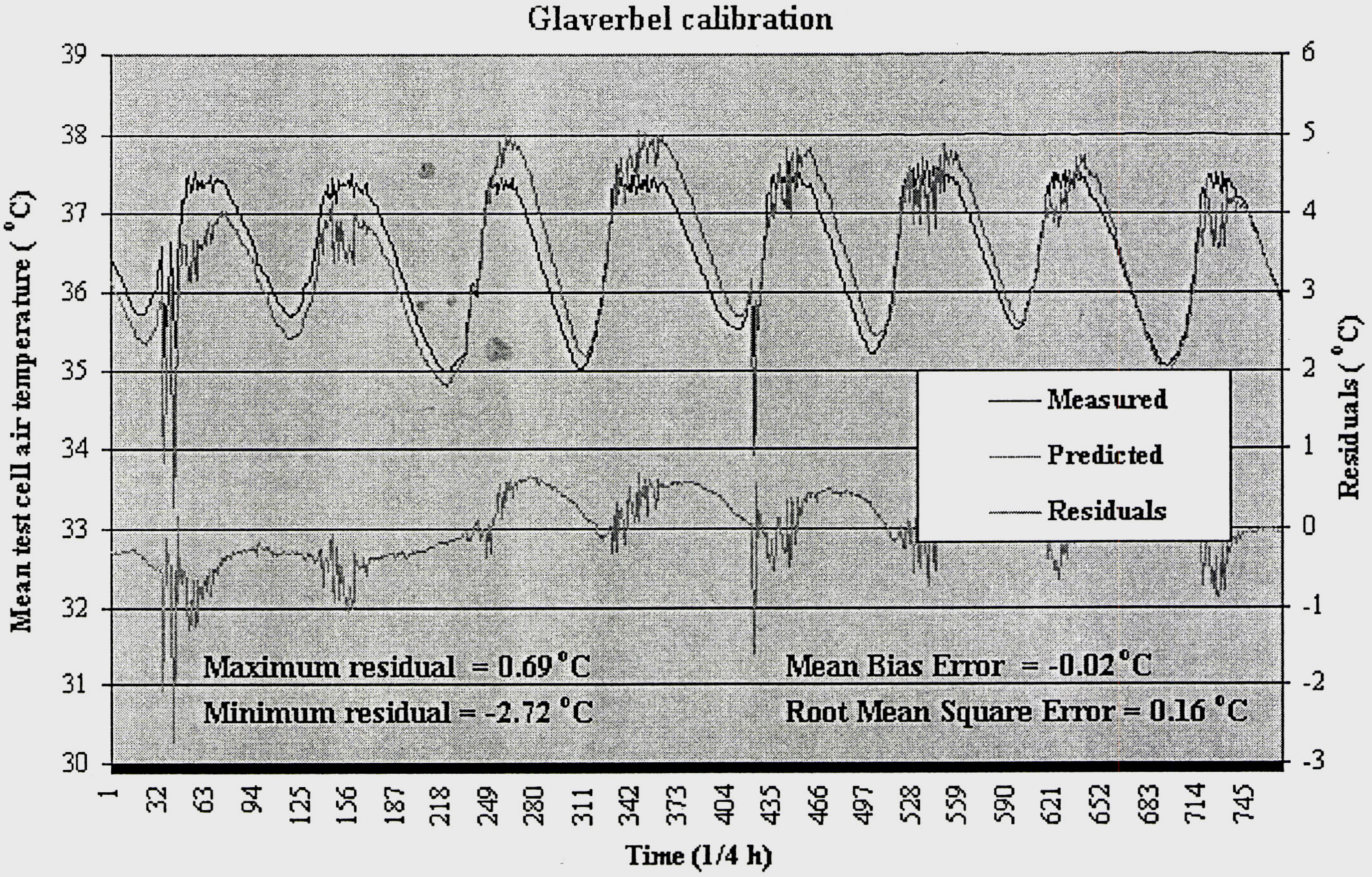


Figure 10: Glazing 3 calibration result.

As can be seen from Table 9 and Figures 8-10, Glazings 2 and 3 show good agreement (i.e. low MBE and RMSE values) while Glazing 1 shows a lower level of agreement.

It was concluded that the long term predicted performance for all three glazings was in acceptable agreement with the corresponding measured data. On the other hand, larger errors are apparent over short periods. This indicates a trend for overprediction of the peak internal air temperatures in the free floating regime. In the cooling regime, this would lead to an overprediction of the peak cooling capacity.

It was further concluded that all models were well calibrated with respect to the overall thermal resistance, with good agreement between measurements and predictions during non-sunny periods. All overpredictions are therefore related to sunny periods and/ or times of higher internal air temperatures.

While there are possible explanations for the overprediction which deserve further research, the results of the calibration were deemed acceptable given that the observed overpredictions of peak temperatures should not influence the relative inter-comparison of the different glazing systems.

In summary, the following conclusions were drawn.

* The models of all three advanced glazings gave rise to acceptable long term residuals (measurement - prediction), with mean bias errors of -0.02°C to +0.52°C.

* The models of Glazings 1 and 2 show a tendency to overpredict the mean internal air temperature, with a mean root squared error of +0.40°C to +0.91°C during periods with high solar irradiance. This effect is more pronounced in the case of the triple glazing system (Glazing 1).

5 CASE/ DESIGN STUDY APPRAISALS

This section reports on the outcome of applying ESP-r/ RADIANCE to the case/ design study buildings. In each instance the essential tasks comprised

- establishing a base case model of the building;
- establishing a corresponding reference model for comparative purposes;
- selecting representative boundary conditions for simulation;
- extracting performance data which characterises overall, multi-variate performance;
- conducting sensitivity analyses to determine opportunities for daylight systems optimisation.

The simulation outcomes in for each case/ design study are elaborated in Appendices 1 through 9. What follows is a summary of the impacts of advanced glazings on each performance category as judged by comparing the reference and base case models.

5.1 Installed Capacity

The impact of advanced glazing on installed capacity was observed to depend on the context as follows.

Heating Capacity: Moderate Impact

- A moderate impact on maximum heating capacity was observed in some cases, with reductions of the order of 5% to 8% noted:
    - in offices where the peak heating capacity is dominated by ventilation air preheat;
    - in office spaces with high casual heat gains, and therefore low heat demand'
    - in buildings such as schools and offices where the dominant heat loss paths are infiltration and/ or opaque fabric conduction.

Heating Capacity: High Impact

- * A high impact on maximum heating capacity was observed in some cases, with reductions of the order of 20% noted:
    - in highly glazed spaces with low infiltration rates.

Cooling Capacity: Moderate Impact

- * A moderate impact on maximum cooling capacity was observed in some cases, with reductions of the order of 11% noted:
    - in offices with effective structural solar shading.

Cooling Capacity: High Impact

- * A high impact on maximum cooling capacity was observed in some cases, with reductions of the order of 30% to 60% noted:
    - in highly glazed spaces where a major component of the heat gain is due to direct and indirect solar gain;
    - in mid-European coastal climates where the central ventilation plant cooling loads are moderate due to the lower ambient summer temperatures in summer. Note that in such climates the lower U-Value of solar control glazings will tend to increase the peak cooling capacity (e.g. by up to 5%) because of the reduction in the heat loss. This may not occur in warm climates.

5.2 On Annual Energy Requirements

The impact of advanced glazing on annual energy requirements was observed to depend on the context as follows.

Heating Energy: Low Impact

- * A low heating energy saving, of the order of 0.6% to 9%, was observed in the same cases as listed above under *Heating Capacity: Moderate Impact.*

Heating Energy: Moderate Impact

- * A moderate heating energy saving, of the order of 10% - 18%, was observed in the following cases:
    - in buildings retrofitted with low U-value triple glazed system;
    - in highly glazed spaces with low U-value, solar control glazing to strike an effective balance between thermal and solar control.

Cooling Energy: Moderate Impact

* A moderate cooling energy saving, of the order of 10% - 14%, was observed in buildings where effective structural solar shading is applied.

* In mid-European coastal climates, low U-value, solar control glazing tends to increase the cooling energy requirement (e.g. by up to 11%) because of the reduced heat loss.

Cooling Energy: High Impact

* A high cooling energy saving, of the order of 51% - 74%, was observed in buildings where the principal cooling load component is due to the solar gain through the glazing. In such cases, solar control glazings therefore have the potential to deliver significant energy savings.

Lighting Energy

* Lighting energy was reduced by up to 7%, and increased by up to 10%, depending on degree to which the advanced glazing component changed the visible transmittance.

5.3 On Thermal Comfort

The impact of advanced glazing on thermal comfort was observed to depend on the context as follows.

* Low U-value glazing delivers significant increases resultant temperatures during in winter, generally maintaining temperatures within the comfort zone.

* Low U-value glazing causes moderate increases in resultant temperatures during summer, generally increasing the overheating tendency.

* Solar control glazing significantly decreases the resultant temperature in summer, generally maintaining temperatures within the comfort zone.

5.4 On Daylight Availability

All advanced glazing systems only marginally decreased the daylight availability.

5.5 On Visual Comfort

* Light redirecting and diffusing systems were observed to significantly improve visual comfort. The optimum arrangement will offer distinct redirecting or diffusing properties while maintaining high visible transmittance and allowing dynamic solar control.

* Glare control through the use of low visible transmittance glazing must be balanced by occupant viewing requirement.

5.6 On Demand Profiles

No advanced glazing was capable of temporally shifting the demand profiles although significant quantitative reductions were achieved.

5.7 Overall Observations

The project has demonstrated a need for smart glazing systems which facilitate the following control actions.

* Dynamic thermal transmittance adaptation as a function of the prevailing heating and cooling demands and thermal comfort requirement.

* Dynamic optical transmittance adaptation as a function of the prevailing solar gain, daylight penetration and visual comfort requirement.

* Variable daylight redirection.

* Control strategies to manage the complex and dynamic interactions between the window, shading and lighting systems.

6 THE GLAZING DESIGN SUPPORT TOOL

To facilitate the wider dissemination of the project's outcomes, a PC-based tool, termed GDST (for glazing design support tool), has been created to allow the glass industry to estimate and demonstrate the multi-variate impact of applying a given advanced glazing component, to a given building, located in a given climate. GDST offers the following functionality:

* storage of ESP-r models of exemplar and project specific buildings;

* storage of weather data relating to typical and project specific climates;

* storage of data defining the optical and thermal properties of advanced glazing components;

* association of glazing components with buildings and buildings with climates;

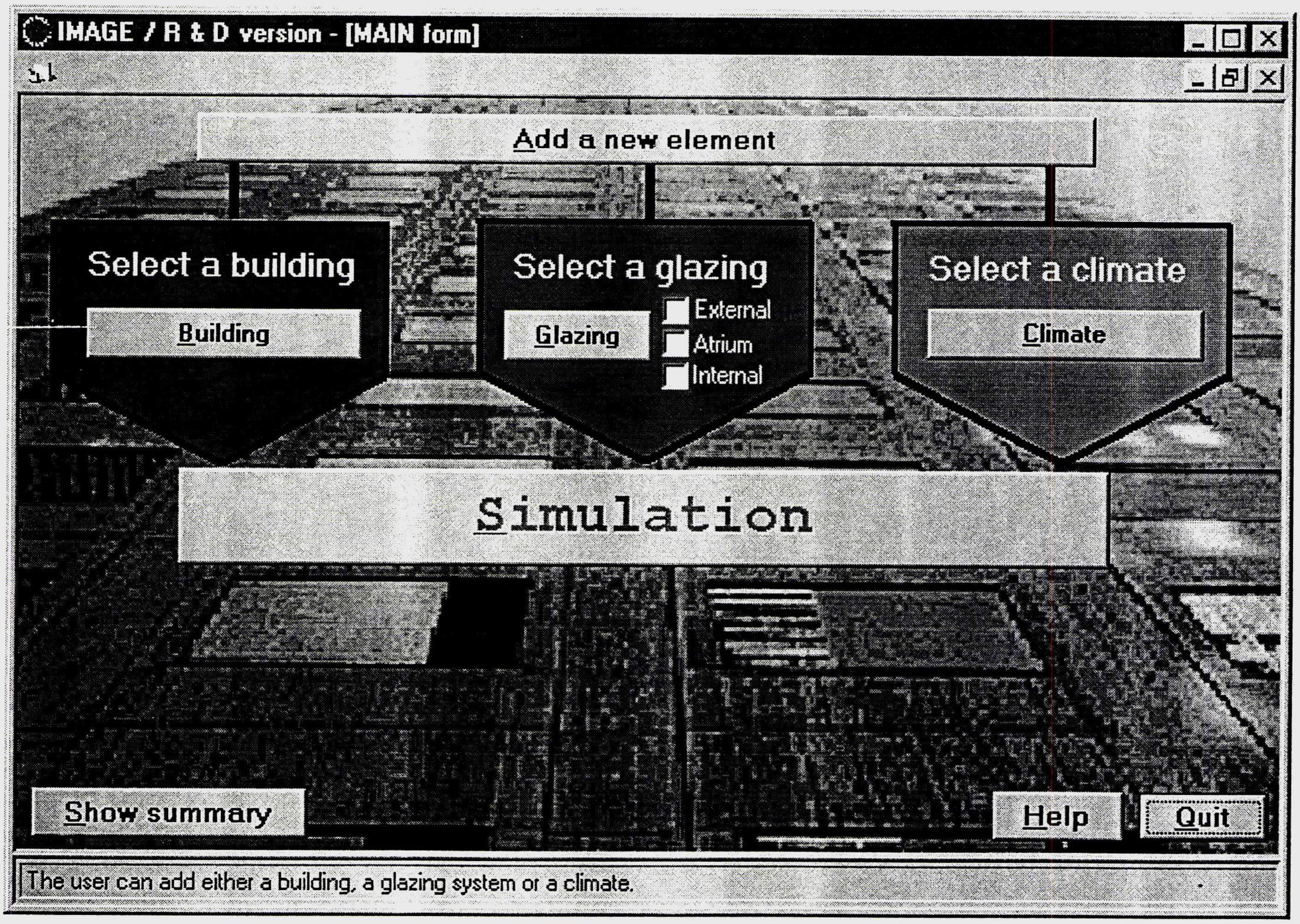
* storage and retrieval of pre-formed IPVs for specific combinations of building, climate and glazing;

* invocation of ESP-r to elaborate an IPV for a combination not previously processed.

To ensure good user requirements capture, the GDST was developed with the full involvement of the industrial partners with prototypes subjected to staged critical review.

On defining a combination of building, climate and glazing which has previously been processed (within the IMAGE project), the corresponding IPV is retrieved to give a performance summary in relation to energy use, gaseous emission and thermal/ visual comfort. It is envisaged that this mode of operation will support a company's marketing activity. Where a combination has not been previously processed, the defined problem is automatically passed to ESP-r for simulation. To support this feature, ESP-r's simulator has been ported to NT and . It is envisaged that this mode of operation will support a company's research and development activity. Thus, the GDST can be viewed as a PC-based, user-friendly interface to the ESP-r system offering a dual marketing and research mode of operation.

Figure 11 shows the tool's user interface while Figure 12 summarises the information flows between the ESP-r and GDST systems both of which have been implemented under Windows95 and NT.



The user can add either a building, a glazing system or a climate.

Figure 11: GDST interface.

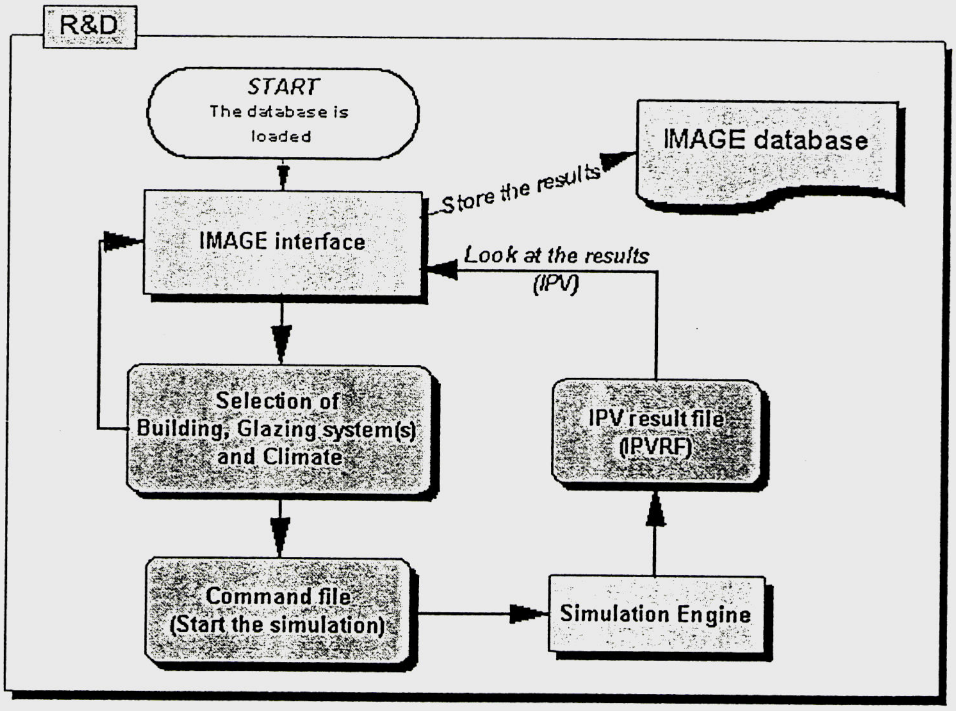


Figure 12a: Information flows between ESP-r and GDST for pre-simulated results.

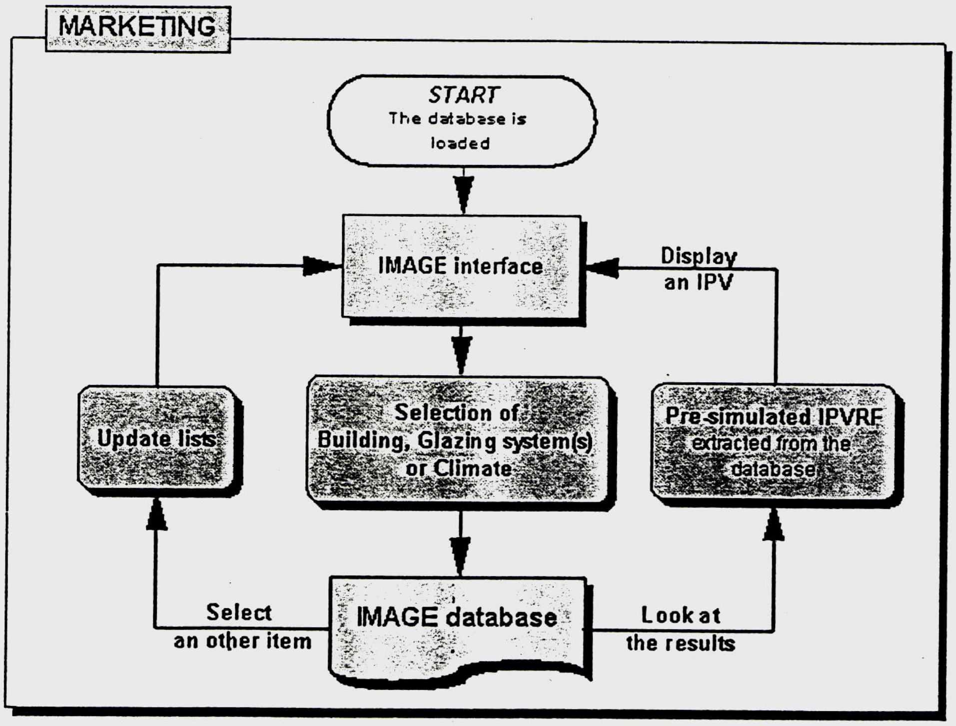


Figure 12b: Information flows between ESP-r and GDST for new simulation.

The following tasks were undertaken to facilitate the ESP-r to GDST link:

- Porting of ESP-r's core simulation engine to NT from its native Unix environment.
- Development of an "anchor point" facility for ESP-r to allow the GDST to automatically insert user-selected glazing components within building models. In the current implementation, three anchor points are supported corresponding to external windows, atria roofs and internal windows adjacent to atria.
- Establishment of a protocol to allow the GDST to control the operation of ESP-r.
- Several new IPV performance types were developed and an ESP-r to GDST transfer mechanism devised.
- Refinement of ESP-r's run-time coupling with Radiance to facilitate the simulation of daylight utilisation strategies.
- Development of a daylight coefficient method (Clarke and Janak 1998) for use in cases where direct RADIANCE coupling is inappropriate (e.g. where the number of systems state combinations is low and RADIANCE is best used in pre-simulation mode).
- Development of an ESP-r algorithm applicable to electrochromic glazing components.

Annex 10 describes the operational features of the GDST.

7 ECOBALANCE OF ADVANCED GLAZING SYSTEMS

A range of different criteria, ranging from price to technical performance to aesthetic characteristics, affect the selection of a glazing unit for a building. However, the environmental impact of a glazing element has, in the past, largely been ignored. The present study seeks to address this omission and aims to offer a reliable indicator of the environmental impact of advanced glazing technologies.

The work carried out to assess the environmental impact of advanced glazings has been divided into two parts: an 'ecobalance' study to assess the embodied energy of a glazing component in terms of its non-renewable energy content; and a thermal analysis to study the energy consumption for typical rooms in three different climates.

The non-renewable energy consumption during manufacture can be compared to the energy savings during use and a judgement made as to the environmental impact of a particular glazing application.

7.1 The Ecobalance

The first part of the work analyses in detail the ecobalance of the window (sub-divided into its main components: glazing, frame, solar protection etc.) over the whole life cycle of the unit. The selection of the elements was mainly performed according to the availability of data (EMPA 1996a , EMPA 1996b , ETH 1997a, ETH 1997b) and of detailed information concerning the complete life cycle of the component. Only components with significant market penetration have been examined and these are listed in Table 10 below.

Glazing Materials	Frames	Solar Protection
Clear Float	Wood	PVC Roll Shutter
Clear Float (for Laminated Glass)	Plywood	Fiberglass Fabric Roller Blind
PVB Layer	Aluminium	Aluminium Awning
Hard Coated Glass	PVC	Glass-integrated Venetian Blind
Clear Float (for Diffused Glass)	Wood-Aluminium	
Fiberglass Layer	Plywood-Aluminium	
TIM (Transparent Insulation Material) - Capillary structure		
Argon		
Aluminium Spacer		
TPS (Thermoplastic Spacer)		

Table 10: Window components analysed.

For each element in Table 10, a complete ecobalance has been computed for the window lifetime, i.e. 30 to 45 years. The factors taken into account include non-renewable energy consumption, global warming and acidification potential, photosmog risk and waste production.

The ecobalance allows the environmental impact of various processes to be estimated. Every window can be sub-divided into its composite materials, the main ecological parameters of which have been determined elsewhere [7] [9] [10]. The most important parameters are presented in Table 11.

Name	Abbreviation	Description	Unit
Non-renewable Energy	NRE	Total non-renewable energy: embodied energy and energy used for the fabrication, transportation, maintenance and elimination.	[MJ]
Global Warming Potential	GWP	Gas emissions responsible of the global warming process.	[g eq. CO_2]
Acidification Potential	AP	Gas emissions responsible of the acidification process.	[g eq. SO_x]
Photosmog	POCP	Photochemical ozone creation process	[g eq. C_2H_4]

Table 11: The parameters used in the ecobalance.

7.2 Basic Assumptions

In order to determine the environmental impact of the various window components, specific steps have been identified. This means the user is always aware of the different factors considered in the calculation process. The procedure is detailed schematically in Figure 1 of Annex 10.

The calculation takes as its starting point the production of the relevant raw materials (aluminium, glass, wood, etc.). The raw materials are then transported to factories and manufactured into window components. The components (the glass, the frame etc.) are then transported to the building site. The window is then assembled and installed (an allowance is made for breakage and loss). At the end of its life, each component of the window is removed and transported to its final destination (recycling centre, incineration plant or landfill site).

In all of these phases, considerable non-renewable energy consumption as well as production of polluting emissions (CO_2, SO_x, and C_2H_4) take place. In addition, waste products are produced during the fabrication, breakage and loss, replacement and disposal of the components.

7.3 Thermal Balance Study

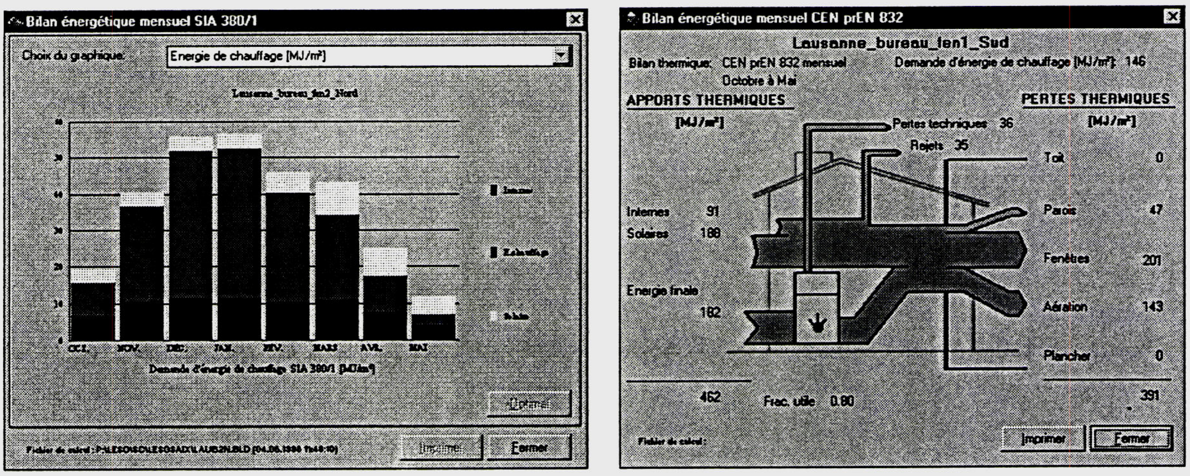
Some specific windows were chosen in order to compute their thermal balance and compare it to their non-renewable energy (NRE) consumption as shown in Table 12.

Office			**School**			**Dwelling room**	
Window index: 25% Window surface = 6.25m^2			Window index: 25% Window surface = 12.5m^2			Window index. 15% Window surface = 1.8m^2	
Window Frame Fraction: 25%							
Window 1	**Window 2**	**Window 3**	**Window 4**	**Window 5**	**Window 6**	**Window 7**	**Window 8**
U-value = 2.68	U-value = 1.70	U-value = 1.17	U-value = 2.63	U-value = 1.65	U-value =1.42	U-value = 2.60	U-value = 1.63
Double Glazing (4-12-4)	Hard Coated Double Glazing + Air (4-12-4)	TIM pane (6-12-8)	Double Glazing (4-12-4)	Hard Coated Double Glazing + Air (4-12-4)	Hard Coated Double Glazing + Argon (4-12-4)	Double Glazing (4-12-4)	Hard Coated Double Glazing + Air (4-12-4)
PVC Frame (U-value=2 W/m^{2}K)			Wood-Aluminium Frame (U-value=1.8 W/m^{2}K)			Wood Frame (U-value=1.7 W/m^{2}K)	
Fiberglass Fabric Roller Blind Utilisation factor: 0-60 %			Fiberglass Fabric Roller Blind Utilisation factor: 0-60 %			PVC Roll Shutter Utilisation factor: 0-60%	

Table 12 Glazing systems analysed for the thermal balance calculation (U-value [W/m^{2}K]).

The aim was to compare, in term of energy costs, the NRE for production/maintenance of the glazing system with the energy consumption of a room using that window with different climates and glazing orientations (global energy performances of the glazing system).

To compute the thermal balance of the glazing systems, the Lesosai4 software (LESO-PB 1996), which is based on monthly energy consumption calculation as shown in Figure 13, was used.



Bilan énergétique mensuel SIA 380/1

Choix du graphique: Energie de chauffage [MJ/m²]

Bilan énergétique mensuel CEN prEN 832

Lausanne_bureau_fen1_Sud

Bilan thermique: CEN prEN 832 mensuel Octobre à Mai

Demande d'énergie de chauffage [MJ/m²]: 146

Figure 13 Lesosai4 was used for energy consumption calculations (monthly (left) and annual results)

7.4 Results

Even if the ecological cost of an advanced window is greater than that of a standard window as shown in the ecobalance study, the energy consumption during the utilisation phase rapidly decreases in accordance with the improvement of the windows' thermal performance. The energy advantage of advanced glazing materials is clearly proved for other climates as well, even if for the Rome climate, overheating has to be avoided.
It has been shown that even if the advanced windows have a slightly higher environmental impact during their life-cycle, the difference is not significant compared to the energy gains they provide during the utilisation phase due to their insulation properties as summaries in Figure 14.

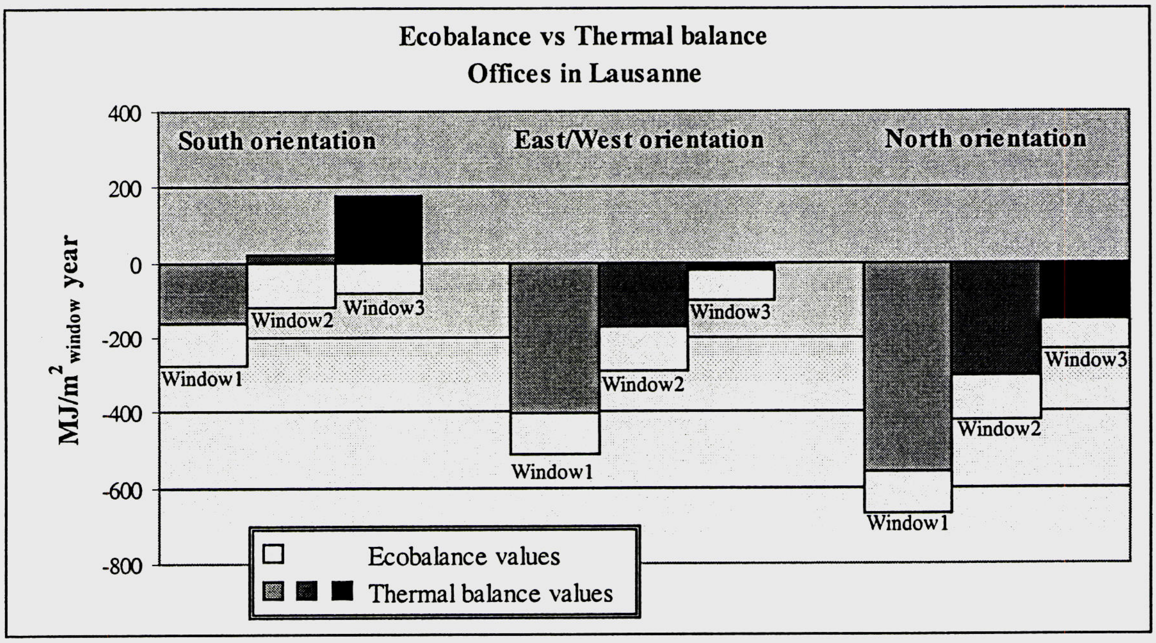


Figure 14 Ecobalance and thermal balance for offices located in Lausanne (Switzerland) for different window orientations (see Table 4 for window characteristics).

The application of advanced glazing systems already constitutes an interesting reality from the ecobalance and energy viewpoint as detailed in Annex 11.

8 CONCLUSIONS

A methodology has been developed for the detailed appraisal of advanced glazing systems when applied to existing or proposed designs. The method includes the notion of an Integrated Performance View (IPV) by which the benefits associated with a particular glazing component can be ascertained across a range of criteria. The method has been applied to 4 existing and 5 proposed buildings in order to test the applicability of advanced glazing systems across a range of design types and under realistic marketplace constraints.

In most cases examined, it was found that advanced glazing can make a significant energy saving contribution. However, in some cases this is being achieved at the expense of thermal and/or visual comfort.

To support the wider dissemination of the research outcomes, a glazing design support tool (GDST) was developed. This offers two modes of operation: a marketing support mode where IPVs for pre-formed building/ climate/ glazing combinations can be viewed, and a R&D mode where new combinations can be defined and sent to ESP-r for IPV production.

From the ecobalance viewpoint, it as been shown that even if advanced glazing systems have a slightly higher environmental impact during their life-cycle, the difference is not significant compared to the energy gains they provide during the utilization phase due to their insulation properties.

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