INTEGRATED SIMULATION FOR BUILDING DESIGN:
AN EXAMPLE STATE-OF-THE-ART SYSTEM

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ABSTRACT: This paper outlines the current state-of-the-art in integrated building simulation. The ESP-r system is used as an example where integrated simulation is a core philosophy behind the development. The current state and future developments are illustrated with examples. It is argued that for building simulation to penetrate the profession in the near future, there is a need for appropriate training and professional technology transfer initiatives.

KEYWORDS: building energy simulation, integrated simulation

1. BACKGROUND

Many buildings are still constructed or remodelled without consideration of energy conserving strategies that could, in many cases, be incorporated in a cost-effective manner. For example, it is estimated that nearly 80% of new commercial buildings constructed each year are of 2,000 square meter or less in size. These buildings, as well as most single- and multi- family residential buildings, are generally designed and constructed by builders or design-build contractors, without the benefit of computerised building energy analyses and equipment sizing. To provide substantial improvements in energy consumption and comfort levels, there is a need to treat buildings, with their individual subsystems, as complete optimised entities - as indicated in Figure 1 - not as the sum of a number of separately designed and separately optimised components.
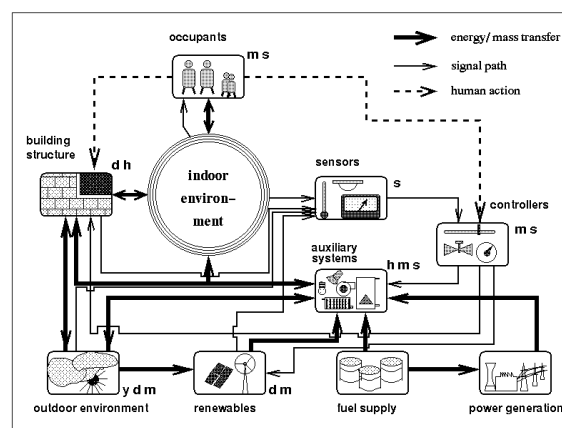

Figure 1 The building as an integration of energy systems

Building simulation is ideal for this because it is not restricted to the building structure itself but includes the indoor environment, while simultaneously taking into account the outdoor environment, mechanical, electrical or structural systems, and traditional and renewable energy supply systems. Building simulation can be used to characterise and assess proposed new equipment and system integration ideas, and to aid in the identification of such ideas. Simulation can thus be used for building analysis and design in order to achieve a good indoor environment in a sustainable manner, and in that sense to care for people now and in the future.

Although a number of sophisticated computer programs have been developed in recent years these are typically used by researchers, engineers concerned with very large building projects and for code compliance (usually translated to simpler computer or worksheet form). It is paradoxical that although architectural practices for larger firms have moved to computer design programs for the physical elements of buildings and building systems (piping, ductwork, etc.) there has been little effort by the design community to learn and apply energy analysis as a standard part of the design process. This is generally left to "specialists" at HVAC consulting firms after the building has been defined.

Since there are real opportunities to affect the building energy use through tradeoffs in building siting, orientation, spatial definition and envelope configuration, waiting until these have been completed, and perhaps even the HVAC and other systems are defined, can result in missed opportunities for energy savings.

Although most practitioners will be aware of the emerging building simulation technologies, few as yet are able to claim expertise in its application. This situation is poised to change with the advent of:
- performance based standards;
- societies dedicated to the effective deployment of simulation - such as IBPSA[1] ;
- appropriate training and continuing education;
- and the growth in small-to-medium sized practices offering simulation-based services.

One thing is clear: as the technology becomes more widely applied, the demands on simulation programs will grow. While this is welcome, in that demand fuels development, it is also problematic because the underlying issues are highly complex. Although contemporary programs are able to deliver an impressive array of performance assessments, there are many barriers to their routine application in practice. Four main issues, which must be addressed, are:
- Firstly, since all design assumptions are subject to uncertainty, programs must be able to operate on the basis of uncertainty bands applied (automatically) to their input and output data. Such a facility is currently under development for ESP-r (Macdonald 1996) so that performance risk may be assessed on the basis of prediction ranges resulting from uncertainty considerations applied to the input (design) parameters.
- Secondly, validation and calibration testing procedures must be agreed and routinely applied as the modelling systems evolve in response to user requirements.
- Thirdly, program interoperability must be enabled so those design support environments evolve in response to inter-disciplinary design needs. This was the goal of the EC's

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[1] IBPSA: International Building Performance Simulation Association - http://www.ibpsa.org

COMBINE project (Augenbroe 1992) in which a prototype Intelligent, Integrated Building Design System was developed (Clarke et al 1995).

- Finally, a means is required to place program development on a task-sharing basis in order to ensure the integrity and extensibility of future systems. This was the objective of the EPSRC funded Energy Kernel System (Clarke et al 1992), which sought to eliminate the inefficient theoretical and software de-coupling of current programs.

In terms of the building life cycle, currently modelling and simulation is mainly restricted to the detailed design phase. However there is a definite need for use of modelling and simulation both in earlier and later stages. Practitioners need early stage, strategic design tools. Modelling and simulation should be incorporated. Modelling and simulation can also play important roles in commissioning, auditing, control and maintenance of building systems.

To elaborate on the current state-of-the-art, the following sections summarise the capabilities and demonstrates an application of one modelling system, ESP-r[2].

2. ESP-r SYSTEM - AN EXAMPLE OF STATE-OF-THE-ART

The ESP-r system (Clarke 1985) has been the subject of sustained developments since 1974. The aim, now as always, has been to permit an emulation of building performance in a manner that a) corresponds to the reality, b) supports early-through-detailed design stage application and c) enables integrated performance assessments in which no single issue is unduly prominent. ESP-r is available under research (cost-free) and commercial (low cost) license from the University of Strathclyde. In both cases source code is made available.
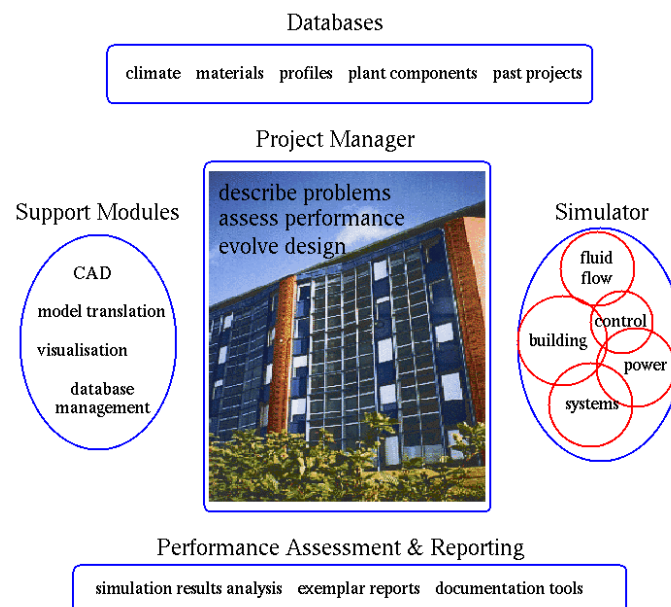

Figure 2 Architecture of ESP-r showing the central Project Manager and its support tools.

ESP-r comprises a central Project Manager (PM) around which is arranged support databases, a simulator, performance assessment tools and a variety of third party applications for CAD, visualisation, report generation, etc. (Figure 2). The PM's function is to co-ordinate problem definition and give/receive the data model to/from the support applications. Most

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[2] Environmental Systems Performance - research

importantly, the PM supports an incremental evolution of designs as required by the nature of the design process.

The typical starting point for a new project is to scrutinise and make ready the support databases. These include hygro-thermal and optical properties for construction elements and composites, typical occupancy profiles, pressure coefficient sets for use in problems involving air flow modelling, plant components for use in HVAC systems modelling, mould species data for use with predicted local surface conditions to assess the risk of mould growth, and climate collections representing different locations and severity. ESP-r offers database management for use in cases where new product information is to be appended.

Although the procedure for problem definition is largely a matter of personal preference, it is not uncommon to commence the process with the specification of a building's geometry using a CAD tool. ESP-r is compatible with the AutoCad (Autodesk 1989) and XZIP (Stearn 1993) systems, either of which can be used to create a building representation of arbitrary complexity (Figure 3 - left).

After importing this building geometry to the PM, constructional and operational attribution is achieved by selecting products (e.g. wall constructions) and entities (e.g. occupancy profiles) from the support databases and associating these with the surfaces and spaces comprising the problem. It is at this stage that the simulation novice will appreciate the importance of a well-conceived problem abstraction, which achieves an adequate resolution while minimising the number of entities requiring attribution.
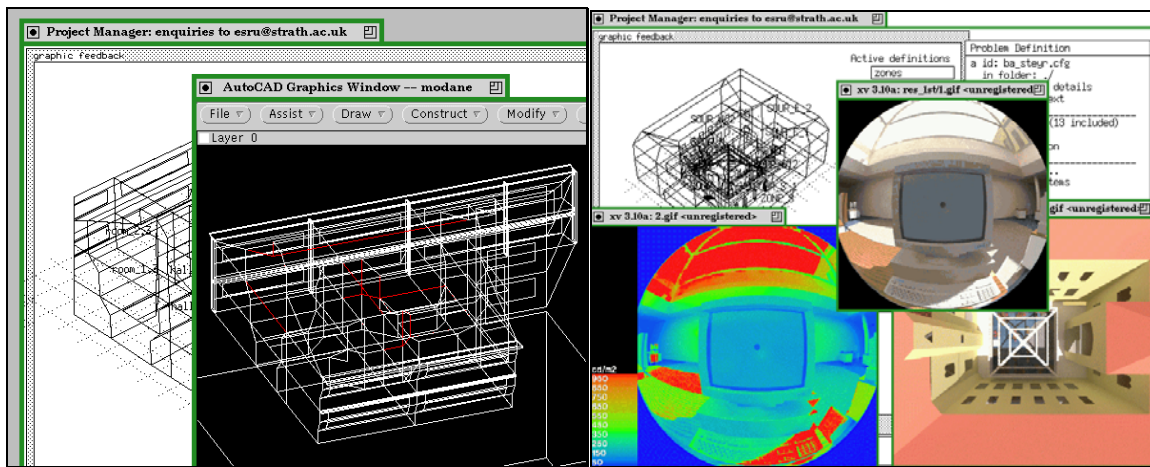
Figure 3 Defining problem geometry using AutoCad (left) and using RADIANCE to quantify luminance for a visual comfort/impact assessment or illuminance as input to a lighting controller (right).

The PM provides coloured, textured physically correct images via the RADIANCE system (Ward 1993) and wire-frame photomontages via the VIEWER system (Parkins 1977), automatically generating the required input models and driving these two applications (Figure 3 - right).

As required, component networks are now defined representing HVAC systems (Hensen 1991, Aasem 1993, Chow 1995), distributed fluid flow (for the building-side air or plant-side working fluids) (Hensen and Clarke 1991, Hensen 1991) and electrical power circuits (Kelly

1996). These networks are then associated with the building model so that the essential dynamic interactions are preserved.

Control system definitions can now proceed depending on the appraisal objectives. Within ESP-r this involves the establishment of several closed or open loops, each one comprising a sensor (to measure some simulation parameter at each time-step), an actuator (to deliver the control signal) and a regulation law (to relate the sensed condition to the actuated state). Typically, these loops are used to regulate plant components, to associate these components with building zones, to manage building-side components such as blinds, and to co-ordinate flow components (e.g. window opening) in response to environmental conditions. Control loops can also be used to change portions of a problem with time (e.g. substitute alternative constructions) or impose replacement parameters (e.g. heat transfer coefficients).

For specialist applications, the resolution of parts of the problem can be selectively increased, for example:

- ESP-r's default one-dimensional gridding scheme representing wall conduction can be enhanced to a two- or three-dimensional scheme to better represent a complex geometrical feature or thermal bridge (Nakhi 1995).
- A one-, two- or three-dimensional grid can be imposed on a selected space to enable a thermally coupled computational fluid dynamics (CFD) simulation (Negrao 1995, Clarke et al 1995).
- Special behaviour can be associated with a material, e.g. electrical power production via crystalline or amorphous silicon photovoltaic cells (Clarke et al 1996).
- Models can be associated with material hygro-thermal properties to define their moisture and/ or temperature dependence in support of explicit moisture flow simulation and mould growth studies (Anderson et al 1996).

The PM requires that a record be kept of the problem composition and to this end is able to store and manipulate text and images which document the problem and any special technical features. It is also possible to associate an integrated performance summary with this record (Figure 4) so that the design and its performance can be assessed without having to commission further simulations.

The problem - from a single space with simple control and prescribed ventilation, to an entire building with systems, distributed control and enhanced resolutions - can be passed to the ESP-r simulator where, in discretised form, the underlying conservation equations are numerically integrated at successive time intervals over some period of time. Simulations, after some minutes or hours, result in time-series of "state information" (temperature, pressure, etc.) for each discrete region.

ESP-r's results analysis modules are used to view the simulation results and undertake a variety of performance appraisals: changes to the model parameters can then follow depending on these appraisals. While the range of analyses are essentially unrestricted, interrelating the different performance indicators (Figure 4), and translating these indicators to design changes, is problematic because of the lack of performance standards and the rudimentary level of simulation scholarship and training.

3. EXAMPLE APPLICATION: DESIGN OF EMBEDDED ENERGY SYSTEMS

The Lighthouse Building, designed by Charles Rennie Mackintosh, is the centrepiece of Glasgow's celebrations as UK City of Architecture and Design 1999. This refurbished city centre building is of major architectural significance. A specially configured portion of the building serves as a showcase for state-of-the-art technologies that demonstrate the integration of complimentary passive and active renewable energy components at the urban scale.

While a more complete description can be found in (Clarke et al. 1999), the following sections outline the design process undertaken and the system configuration adopted to achieve:
i)   lowest practical energy demands (without compromising building functionality),
ii)   sizing of the embedded micro-scale generation systems to match a significant portion of these demands, and
iii)   appraise the options for electrical power supply.

3.1 Renewable energy systems

Implementation of renewable energy systems at the local level can be fraught with technical problems. When undertaking such tasks within an urban environment adds additional problems to a project such as impact on building aesthetics and most importantly, planning requirements which impair system performance. After careful consideration, the renewable energy systems deemed suitable and chosen for this demonstration were categorised as: type (i) are those that reduce energy demands and type (ii) are those that generate electricity to meet some of these demands. The 3 passive (type i) components were:
1) advanced glazings, including a triple glazed, double low-e coated, argon filled component, a light redirecting component and a variable transmission component;
2) daylight utilisation through illuminance based luminaire control; and
3) transparent insulation with integral shading.

The 2 active systems (type ii) consisted of:
1) facade-integrated photovoltaic cells with heat recovery; and
2) roof mounted, ducted wind turbines with integral photovoltaic aerofoils.
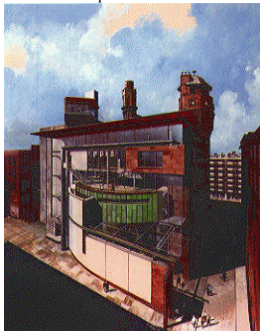
Based on detailed energy simulations using the ESP-r system, it was concluded that the passive components had the potential of reducing annual energy demands by up to 64%, relative to an initial best practice compliant design hypothesis. It was also concluded that the active components had the potential to match a significant portion of the residual demand.
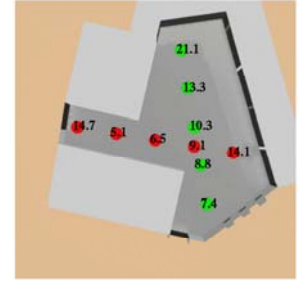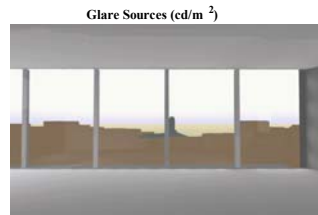
3.2 Evaluation methodology

The evaluation procedures adopted adheres to a standard performance assessment method (PAM) (Clarke et al 1996) whereby computer simulation is used to determine the multivariate performance of an initial model of the building (in this case corresponding to current best practice design). The multivariate performance data are then presented in the form of an integrated performance view (IPV) as shown in Figure 4. The model is then modified by incorporating one of the renewable technologies and the overall performance re-assessed. In this way, the contribution of both passive and active renewable technologies, applied separately or jointly, may be assessed and the different possible permutations compared.

Lighthouse Viewing Gallery

Version: Base case
Contact: ESRU
Date: Sep-97

Viewing gallery base case model, double glazing in all windows. No lighting control
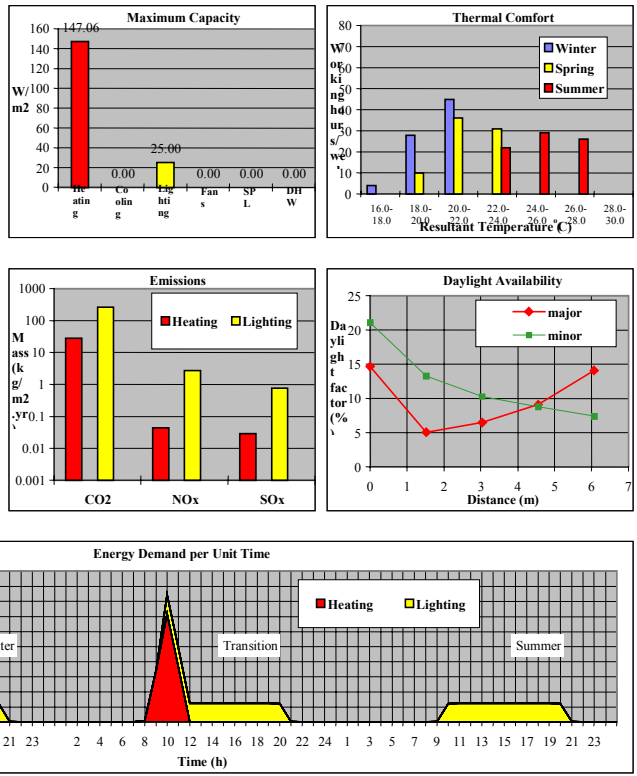
Maximum Capacity (W/m2)
Heating 147.06, Cooling 0.00, Lighting 25.00, Fans 0.00, SPL 0.00, DHW 0.00

Thermal Comfort — Working hours/week vs Resultant Temperature (°C)
Winter, Spring, Summer

Emissions — Mass (kg/m2.yr), Heating / Lighting
CO2, NOx, SOx

Daylight Availability — Daylight factor (%) vs Distance (m)
major, minor

Glare Sources (cd/m²)

Energy Demand per Unit Time (W/m2)
Heating, Lighting — Winter, Transition, Summer — Time (h)

Annual Energy Performance

Heating:	118.29 kWh/m².a
Cooling:	0.00 kWh/m².a
Lighting:	100.10 kWh/m².a
Fans:	0.00 kWh/m².a
Small PL:	0.00 kWh/m².a
DHW:	0.00 kWh/m².a
Total:	**218.39 kWh/m².a**

Figure 4: Performance Appraisal of Initial Design

3.3 Energy demand reduction techniques

The initial design concept for the Lighthouse Building refurbishment consisted of an insulated steel clad facade, insulated lead sheet roof, extensive use of double glazing and a slate covered concrete floor slab with external insulation. The building services comprised embedded floor heating, halogen display lighting and natural ventilation from vented slot windows.

A number of reference models were developed to assess the contributions from alterations to glazing systems, the adoption of critical control strategies and the incorporation of various passive and active renewable energy technologies. The first reference model replaced the standard double glazing with low ε coated, argon filled triple glazing, with a centre pane U-value of 0.8 W/m^2 K. This resulted in a 58% reduction in annual heating energy and a 31% reduction in overall energy requirements (heating plus lighting). Further reductions were achieved using daylight responsive lighting control. The addition of a south facing transparent insulated (TI) thermal mass wall reduced the duration of the heating season, with the TI wall supplying the building's heating requirements during the transitional seasons, while auxiliary heating was confined to the winter period.

In comparison with the initial design hypothesis, the cumulative effect of the advanced glazings, lighting control and TI facade resulted in a 45% reduction in annual heating energy, 59% reduction in lighting energy and a 51% reduction to the overall annual energy demands.

A detailed examination of the simulation results concluded that further energy demand reductions were possible. The next evaluation case replaced the underfloor heating system with a fast response, critically controlled, convective heating system and the halogen lamps with high efficacy luminaires. In comparison with the original design hypothesis, this reference case resulted in a 58% reduction in annual heating energy demand, a 67% reduction in heating plant capacity, an 80% reduction in lighting energy demand and a 68% reduction in overall energy demand. Figure 5 details the energy savings and capacity reductions achieved when under-taking the various permutations adopted within this study.
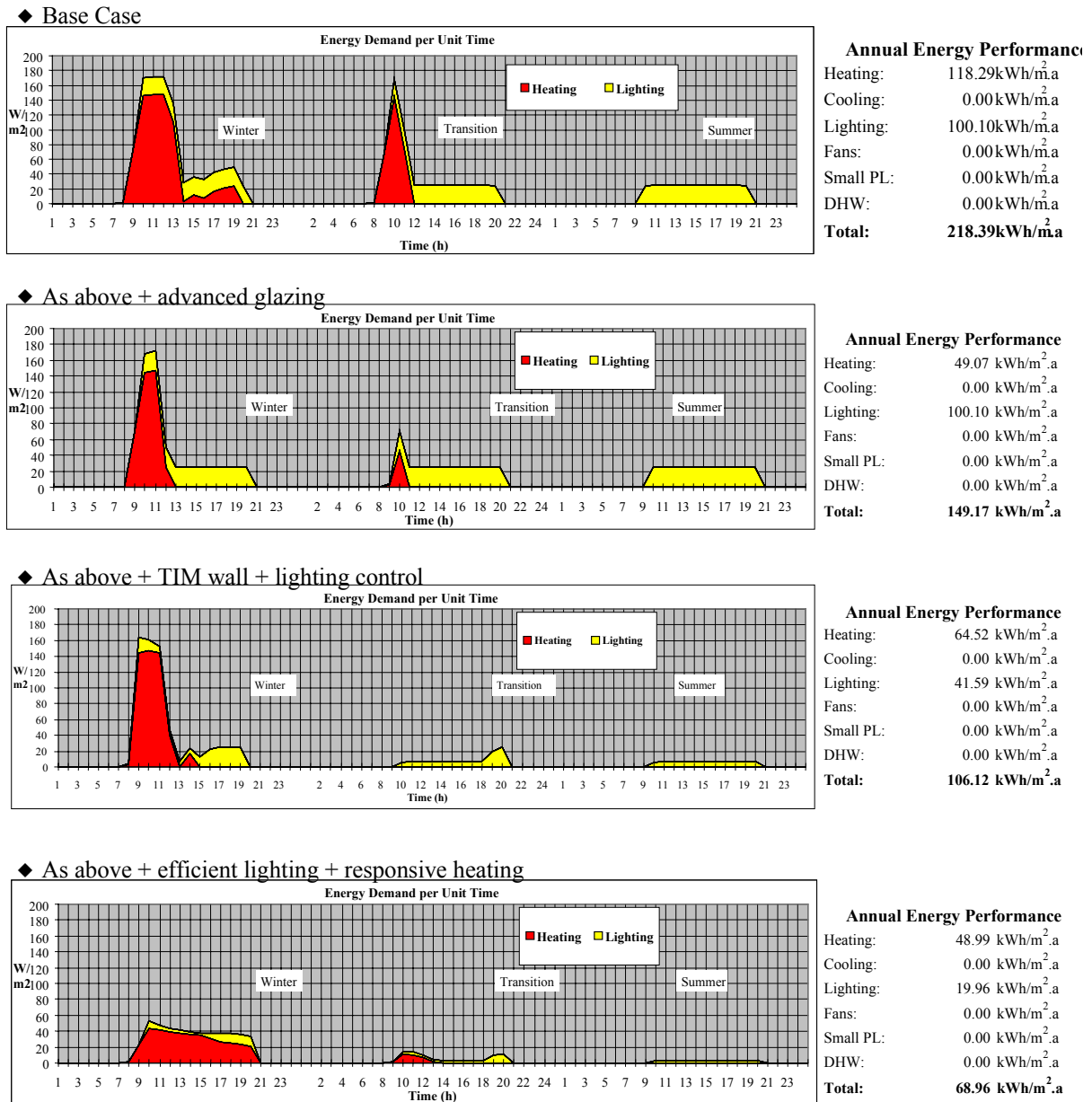
◆ Base Case

Annual Energy Performance	
Heating:	118.29 kWh/m^2.a
Cooling:	0.00 kWh/m^2.a
Lighting:	100.10 kWh/m^2.a
Fans:	0.00 kWh/m^2.a
Small PL:	0.00 kWh/m^2.a
DHW:	0.00 kWh/m^2.a
Total:	**218.39 kWh/m^2.a**

◆ As above + advanced glazing

Annual Energy Performance	
Heating:	49.07 kWh/m^2.a
Cooling:	0.00 kWh/m^2.a
Lighting:	100.10 kWh/m^2.a
Fans:	0.00 kWh/m^2.a
Small PL:	0.00 kWh/m^2.a
DHW:	0.00 kWh/m^2.a
Total:	**149.17 kWh/m^2.a**

◆ As above + TIM wall + lighting control

Annual Energy Performance	
Heating:	64.52 kWh/m^2.a
Cooling:	0.00 kWh/m^2.a
Lighting:	41.59 kWh/m^2.a
Fans:	0.00 kWh/m^2.a
Small PL:	0.00 kWh/m^2.a
DHW:	0.00 kWh/m^2.a
Total:	**106.12 kWh/m^2.a**

◆ As above + efficient lighting + responsive heating

Annual Energy Performance	
Heating:	48.99 kWh/m^2.a
Cooling:	0.00 kWh/m^2.a
Lighting:	19.96 kWh/m^2.a
Fans:	0.00 kWh/m^2.a
Small PL:	0.00 kWh/m^2.a
DHW:	0.00 kWh/m^2.a
Total:	**68.96 kWh/m^2.a**

Figure 5: The energy reductions achieved by the various permutations

Implementing the above measures not only achieved a high level of demand-side energy reduction without compromising the building's thermal and visual comfort levels, but increased the effectiveness of the deployed active renewable energy systems in meeting the remaining energy demands.

3.4 Embedded renewable energy systems

Two electricity generating renewable energy technologies were appraised and subsequently accepted for incorporation within the building. These were a photovoltaic (PV) component operating in hybrid mode to give both power and heat outputs; and ducted wind turbines (DWTs) with an integral photovoltaic aerofoil section. The hybrid PV system was incorporated within the south-facing facade, while the DWTs were positioned along the south and west-facing roof edges; south-west being the predominant wind direction in Glasgow. To maximise electricity generation, a high efficiency monocrystalline silicon component was chosen for both the hybrid PV and DWT systems. Figure 6 summarises the final performance results in the form of an IPV as produced by ESP-r.
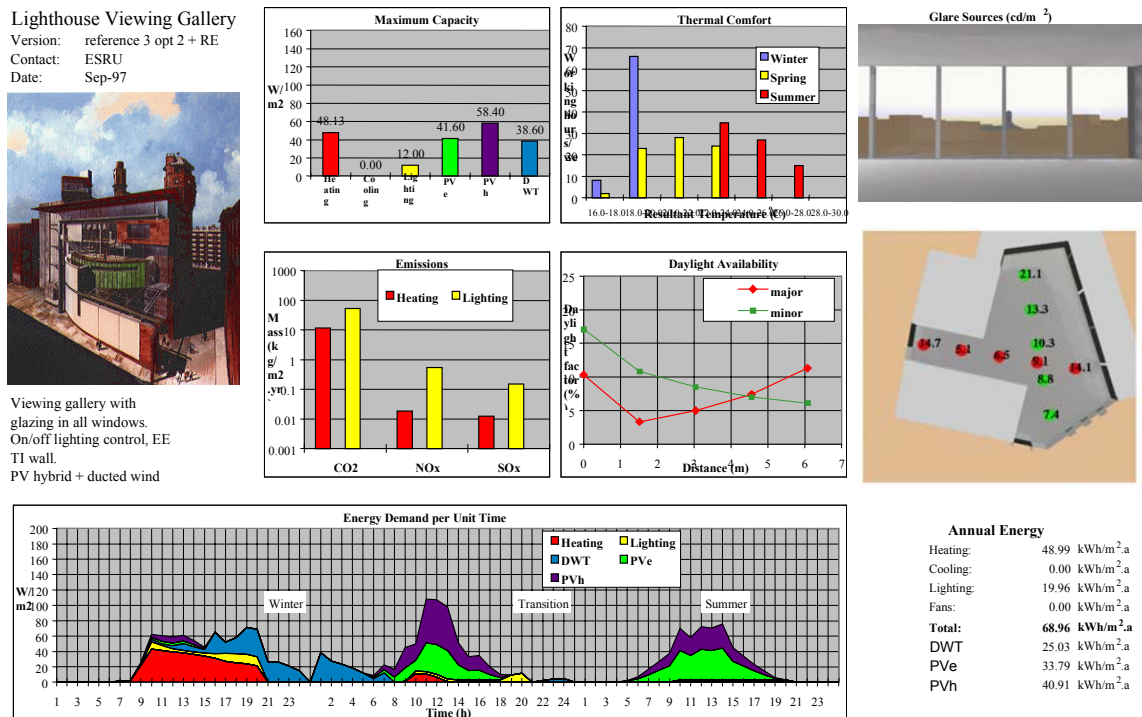

Figure 6: Performance Appraisal with Passive and Active RE Systems Applied

3.5 Results

As demonstrated, the active renewable energy systems, in conjunction with the passive renewable energy technologies, are capable of meeting the demands of the building during the spring, summer and autumn seasons. In winter, the active renewable energy systems are capable of supplying a significant proportion of the energy demands. However, an electrical storage system is required to cater for the temporal mismatch between renewable energy supply and demand since the former is largely available out with the times of building operation.

The combination of DWTs and PV components proved to be a successful matching of renewable energy systems to meet the seasonal energy demands. The DWTs produce electricity predominately during the winter period when the PV components can contribute little. Conversely, the PV components supply power predominately during the summer

period when the winds are light. The combination of the two systems gives rise to an embedded RE approach which is well suited to the climate of Glasgow.

The next stage of the project will be to monitor the performance of the development over an extended period and compare these with the predictions from the simulation model to test its robustness, and establish guidelines for efficient renewable energy based electrical power utilisation.

4. CONCLUSIONS

By means of summarising the capabilities of a particular simulation environment this paper has elaborated and demonstrated the state-of-the-art in integrated building simulation.
The case study has demonstrated the value of simulation early in the design stage of building projects.

If we divert for a moment from the specifics of a software system such as ESP-r and take a broader perspective in terms of building energy simulation in general, this paper has argued the importance of this technology and how it will benefit in an economical and environmental context. Since many people in the field are not yet aware of this, this paper has also argued the necessity of an organisation such as IBPSA. It's main role is to alleviate this problem and thus for moving this technology in everyday practice of engineers and architects.

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