Integrated Building Simulation: State-of-the-Art

J A Clarke, J Hensen, M Janak

ESRU, University of Strathclyde, 75 Montrose Street, Glasgow G1 1XJ, Scotland

http://www.strath.ac.uk/Departments/ESRU/

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 documented with examples. The importance of the interoperability is discussed in the area of air flow, multi-dimensional conduction, lighting, CFD, and power flow modelling. 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.

Introduction

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 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 (Clarke 1995), not least the complete absence of a standard building product model and any means to manage inter-program transactions. To elaborate on the current state-of-the-art, this article summarises the capabilities of one modelling system, ESP-r.

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.

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 1). The PM's function is to co-ordinate problem definition and give/receive the data model to/from the support applications. Most importantly, the PM supports an incremental evolution of

[1] IBPSA: International Building Performance Simulation Association (http://www.mae.okstate.edu/ibpsa/)

designs as required by the nature of the design process.

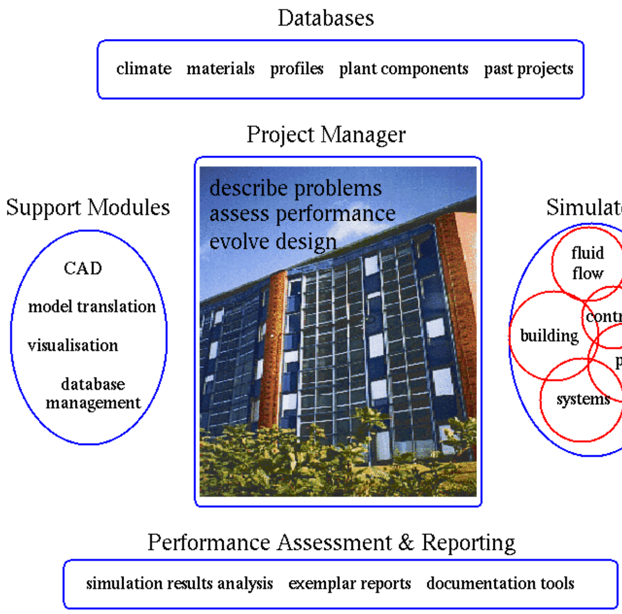

Figure 1: Architecture of ESP-r showing the central Project Manager and its support tools.

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 severities. 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 2 - 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.

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 2 - right).

As required, component networks are now defined representing HVAC systems (Aasem 1993, Chow 1995), distributed fluid flow (for the building-side air or plant-side working fluids) (Clarke and Hensen 1990, 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.

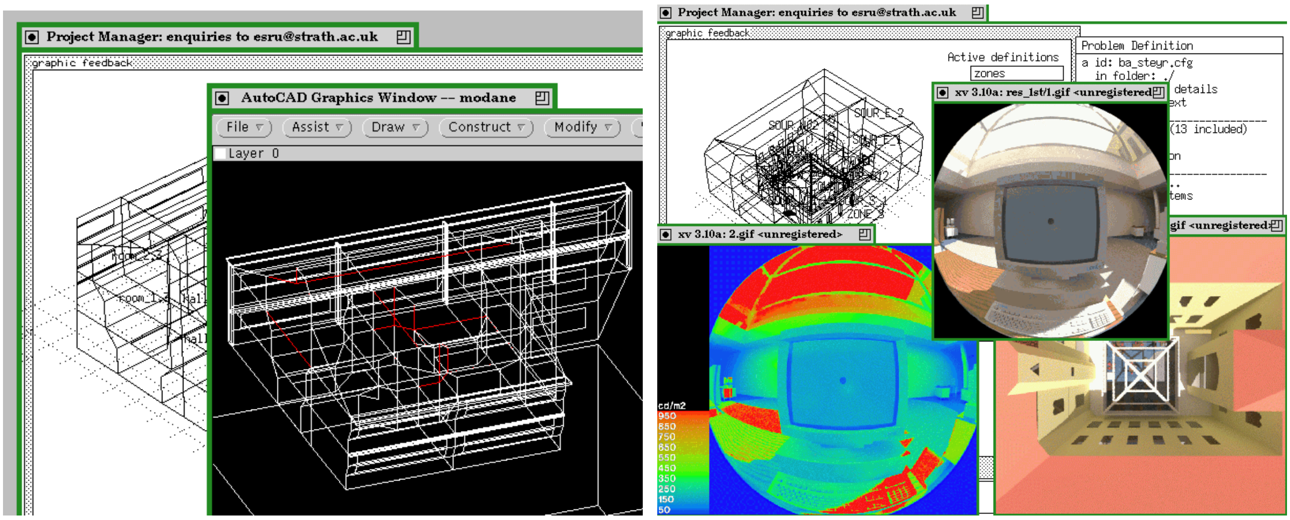

Figure 2: Defining problem geometry using AutoCad (left) and using RADIANCE to quantify luminance for a visual comfort/impact assessment or illuminance as input to a lighting controller (right).

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, associate these components with building zones, manage building-side components such as blinds, and 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 (Negra~o 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 3) so that the design and its performance can be assessed without having to commission further simulations. This record can be maintained locally or via the World Wide Web.

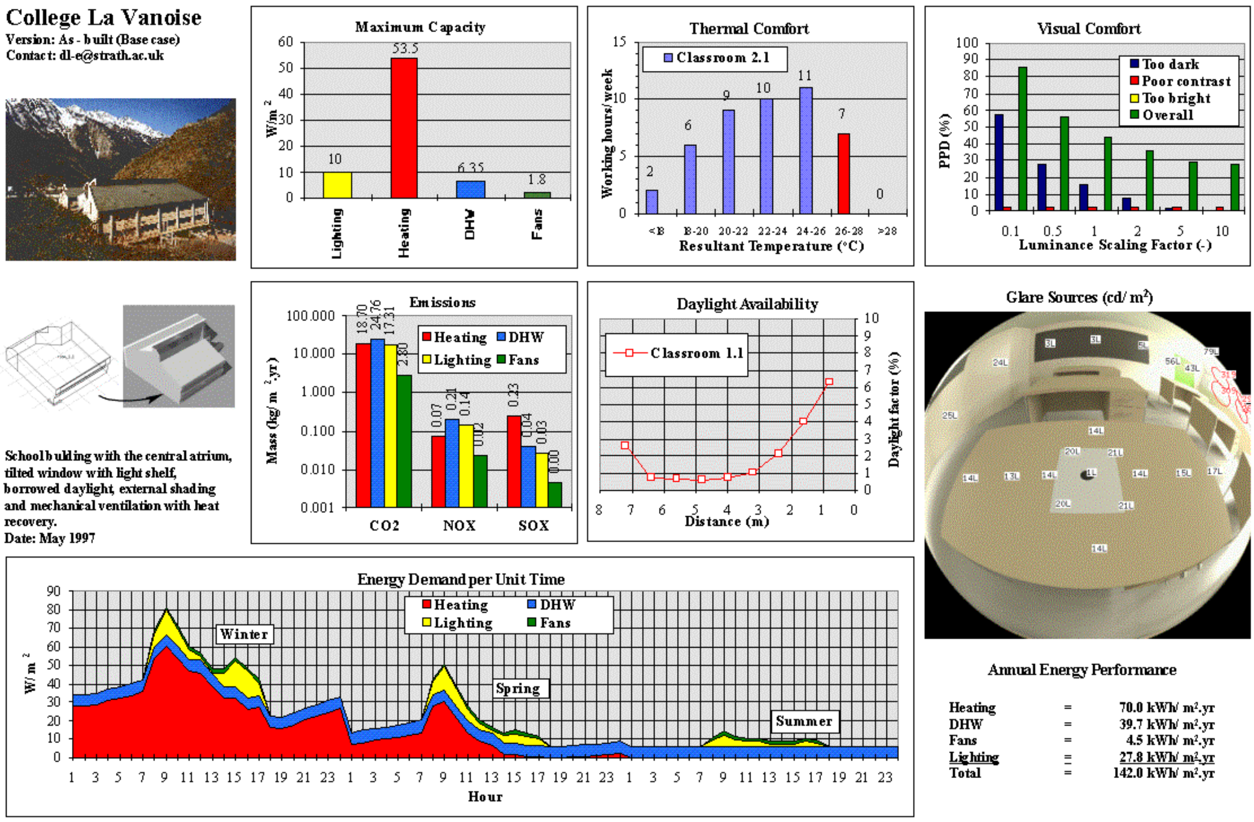

Figure 3: An integrated performance summary giving details on seasonal fuel use, environmental emissions, and thermal/ visual comfort.

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. For problems involving daylight utilisation, the Simulator can invoke the RADIANCE system in direct coupling or daylight coefficient mode (Clarke and Janak 1998) to quantify the time varying internal illuminance distribution for input (via a sensor) to an artificial lighting control loop. 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 3), 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.

The PM also offers model management whereby past designs are stored as fully attributed 3D models. Several exemplar sets are included with ESP-r to assist with application training (Hand and Hensen 1995). These sets range from simple problems demonstrating basic model construction, through real scale designs, to systems involving special components such as photovoltaic cells, advanced glazing or displacement ventilation. Several notable European buildings are also available as on-line exemplars. Some typical exemplars include:

- An office block with natural ventilation represented as a multi-zone system with an air flow network superimposed (Figure 4 - left). Typical application: summertime temperature estimation against postulated occupant interactions and weather severities.
- An air handling plant with temperature and humidity modulation serving spaces requiring critical environmental control (Figure 4 - right). Typical application: component sizing, alternative layout appraisal and control system tuning.
- A house with enhanced resolution around a thermal bridge and explicit construction moisture flow. Typical application: estimation of condensation and mould growth risk (Figure 5 - left), with appraisals of the potential of various retrofits to alleviate problems.
- A large factory space with radiant heating and a CFD domain grid. Typical application: assessment of spatial temperature distribution to achieve workplace comfort at minimum energy consumption (Figure 5 - right).
- An office with photovoltaic facade and electrical network. Typical application: appraisal of facade power generation and heat recovery potential, and a comparison of autonomous utilisation versus grid connection.
- A school employing daylight utilisation and artificial lighting control. Typical application: assessment of the electrical power reduction potential and checking that any reduction is not being achieved at the expense of other performance parameters such as thermal and visual comfort and heating fuel consumption.

Before simulation programs can be routinely applied in practice, there are four main issues which must be addressed. 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 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 that design support environments evolve in response to inter-disciplinary design needs. This was the goal of the EC's 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 programs.

Technology transfer and implementation

Let us 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. We have argued in this paper the importance of this technology and how it will benefit in an economical and environmental context.

However many people in the field are not yet aware of this. For alleviating this problem and thus for moving this technology into the everyday working practice of engineers and architects several initiatives and approaches take place, as indicated below for the case of Slovakia.

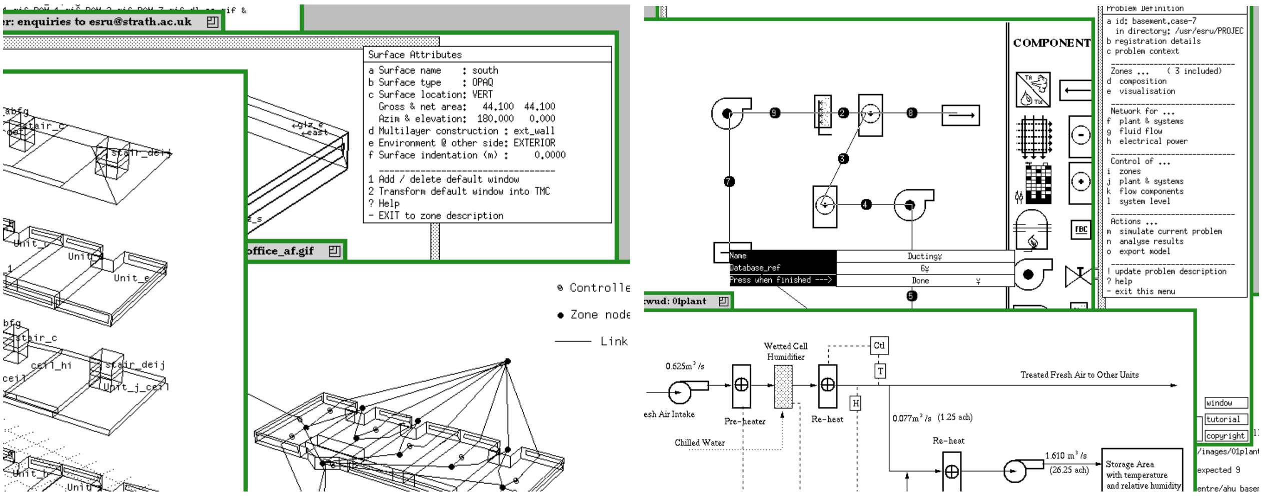

Figure 4: Defining an air flow network (left) and defining a plant system (right).

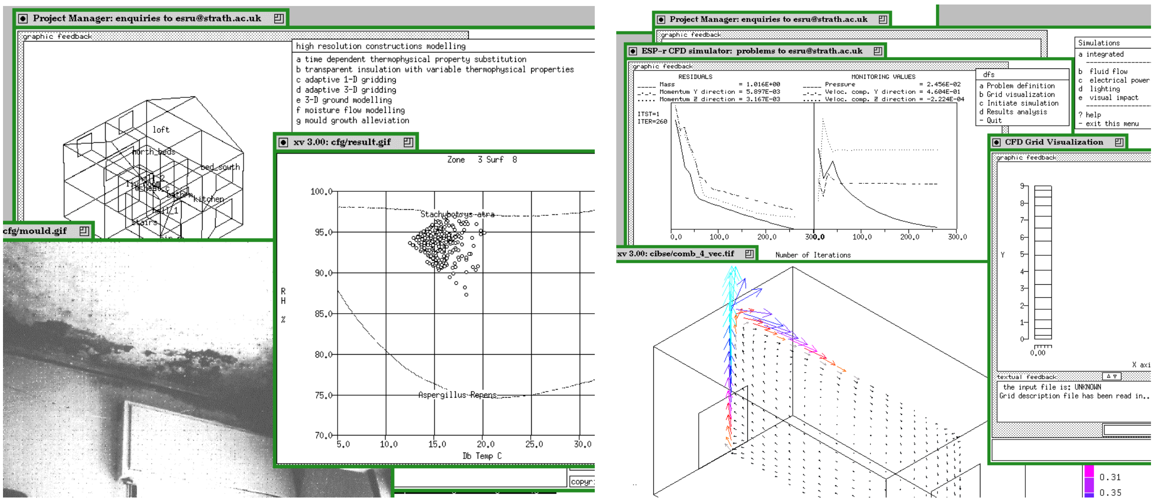

Figure 5: Predicting mould growth (left) and undertaking an integrated CFD analysis (right).

- Training of the next generation of engineers. This takes place in the universities and other educational institutes by introducing new classes and updating existing classes. One such project has been recently carried out in Slovakia under EC Tempus project scheme (Hensen et. al. 1998).
- Training of practitioners in order to enable them to use the technology. A first attempt to achieve this in Slovakia, is actually a spin-off of the above referenced Tempus project.
- Making people more aware of the benefits of the technology. This is, for example, achieved by presentations at conferences such as this. A more structural approach is through the establishment of IBPSA Slovakia, the Slovak chapter of the International Building Performance Simulation Association. IBPSA is a not-for-profit international society of building performance simulation researchers, developers and practitioners, dedicated to improving the built environment. IBPSA was founded to advance and promote the science of building performance simulation in order to improve the design, construction, operation and maintenance of new and existing buildings world-wide.

Acknowledgements

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