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BUILDING ENERGY AND AIR FLOW SIMULATION
(and the PHOENICS connection)

An information/discussion paper prepared for CHAM seminar "Fire & Smoke Hazard Analysis and Energy Conservation in Buildings."

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SUMMARY

This paper outlines the complexity of the building energy modelling problem and describes the ESP program and, in particular, its air flow modelling capabilities.

The issue of 'technology transfer' is highlighted and mention made of the recently established RIAS Energy Design Advisory Service, a Government-funded technology transfer initiative to provide Scottish building designers with subsidised access to advanced energy simulation technology.

Three 'case studies' from EDAS work are presented, outlining some of the practical applications of the ESP program.

Finally, the emerging possibility of combining the functional capability of models such as ESP and PHOENICS, giving building designers and researchers a range of exciting new opportunities, is mooted.

INTRODUCTION

The quadrupling of world oil prices in 1973 highlighted the need for minimising energy consumption. In response, many countries embarked on programmes promoting more frugal use of finite energy resources. In the UK, for example, a Specially Promoted Programme (SPP) on energy in buildings was instigated by the Science and Engineering Research Council (SERC). Part of this programme concerned itself with the development of simulation-based appraisal models capable of dealing with the complex dynamic nature of building energy sub-systems.

As a consequence of this SPP, and other initiatives, a number of powerful models have emerged. Such models seek to replace traditional simplified design methods. One such model is the ESP system, developed since the mid-seventies at the ABACUS CAD Unit, University of Strathclyde. The complexity of the building energy modelling problem and the approach adopted by the ESP system are described in this paper.

THE COMPLEXITY OF BUILDING ENERGY SYSTEMS

Consider Figure 1, which shows aspects of the energy sub-system as encountered within buildings and their environmental plant and control systems. Such a system can be thought of as an elaborate network of time-varying resistances and capacitances subjected to varying temperature differences. Superimposed on this network is a complex set of interacting energy flowpaths, including :-

- **Surface convection** as caused by buoyancy and mechanical forces and influenced by geometry and surface finishes.
- **Inter-surface longwave radiation exchanges** as caused by temperature differences and influenced by geometry and surface finishes.
- **Surface shortwave solar gains** as caused by the date dependent sun path and influenced by site location and conditions, building geometry and the transmittance, absorptance and reflectance characteristics of constructional materials.
- **Shading and insolation** as caused by surrounding and facade obstructions and influenced by site topology and cloud conditions.
- **External surface longwave radiation exchanges** as influenced by sky conditions and the degree of exposure of the site.
- **Casual gains**, those stochastic processes associated with internal heat sources such as people, lights and equipment and influenced by social and comfort factors.

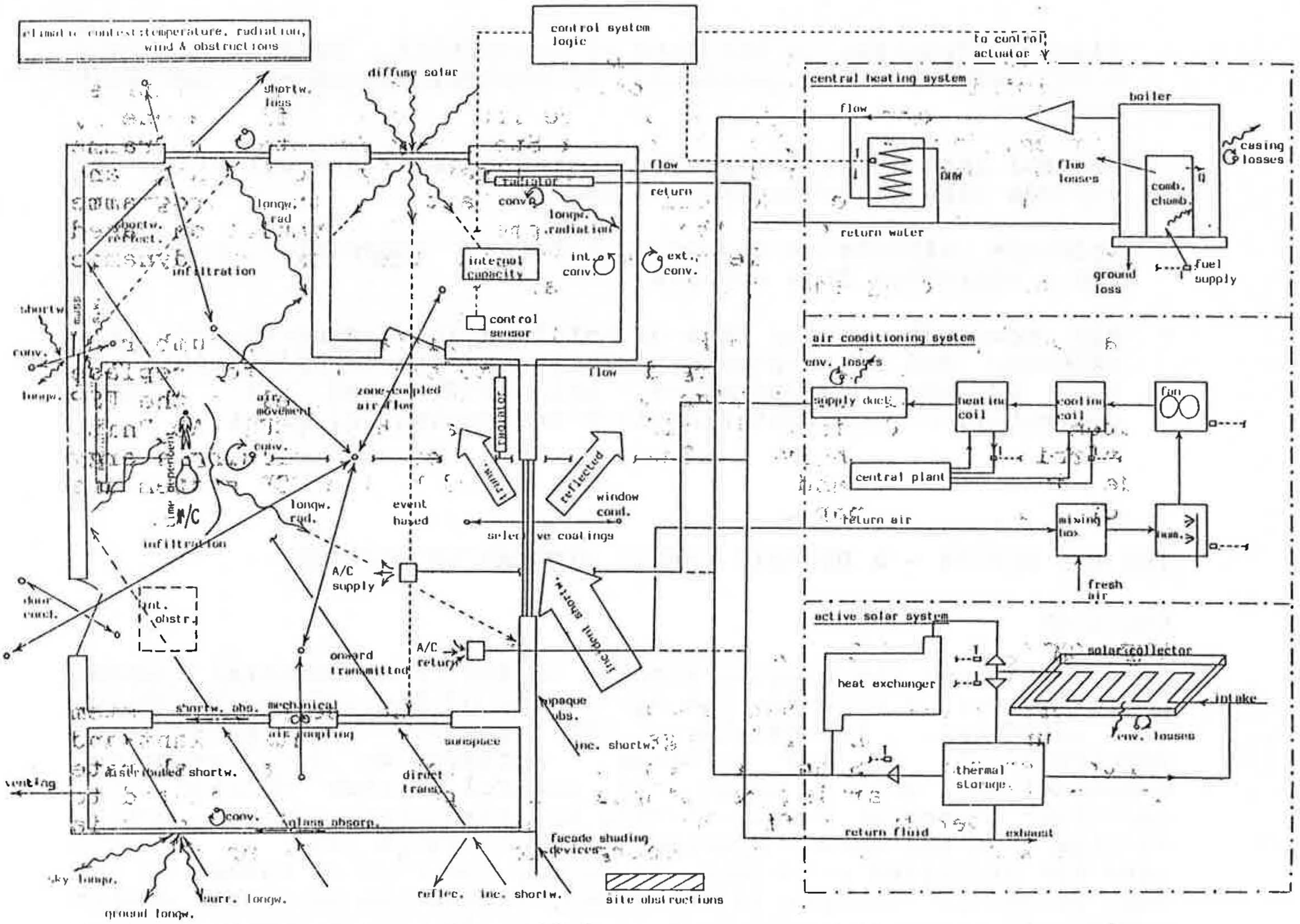


FIGURE 1 : The complexity of building energy flowpaths.

- **Plant interaction** in the form of convective, radiant or mixed heat exchange and influenced by control action and occupant response.

- **Control action** involving distributed sensing and actuation and various response characteristics.

- **Moisture effects** as caused by internal generation processes and a migration from outside.

- **Air movement** in the form of infiltration, zone-to-zone air exchange and intra-zone circulation as caused by temperature and pressure differences and influenced by leakage distribution, occupant behaviour and mechanical plant.

THE ESP SYSTEM - A DYNAMIC ENERGY SIMULATION PACKAGE

Overview

Figure 2 shows the program modules of ESP (Environmental Systems Performance); a tool for the simulation of the energy behaviour of buildings. Essentially, ESP allows the interactive specification of any building, defined by its geometry, construction, usage, plant and control system details. The resulting computer model can then be 'simulated' against actual varying weather data, providing results which give an insight into the predicted behaviour, in energy and comfort terms, of the real building. Changes to the model, reflecting potential design modifications, can easily be made and their effect assessed.

Theoretical basis

Within ESP all heat and mass flow-paths (as identified in Figure 1), and flow-path interactions, are assigned a counterpart mathematical equivalent in an attempt to emulate the reality. The entire system, however specified, is then contained within a single numerical framework. The theoretical basis of ESP is fully described elsewhere (Clarke 1985). What follows is a summary overview.

At program run time, a building and its plant, as described by the user, is made discrete by subdivision into a number of interconnecting, finite volumes. These volumes then possess uniform properties which can vary with time. Volumes represent homogeneous and mixed material regions associated with room air, room surface and constructional elements on the building side, and component interface heat transfer on the plant side. It is not uncommon to have as many as 250 such volumes per building zone, with around 5 volumes per plant component. Then, for each of these finite volumes in turn, and in terms of all surrounding

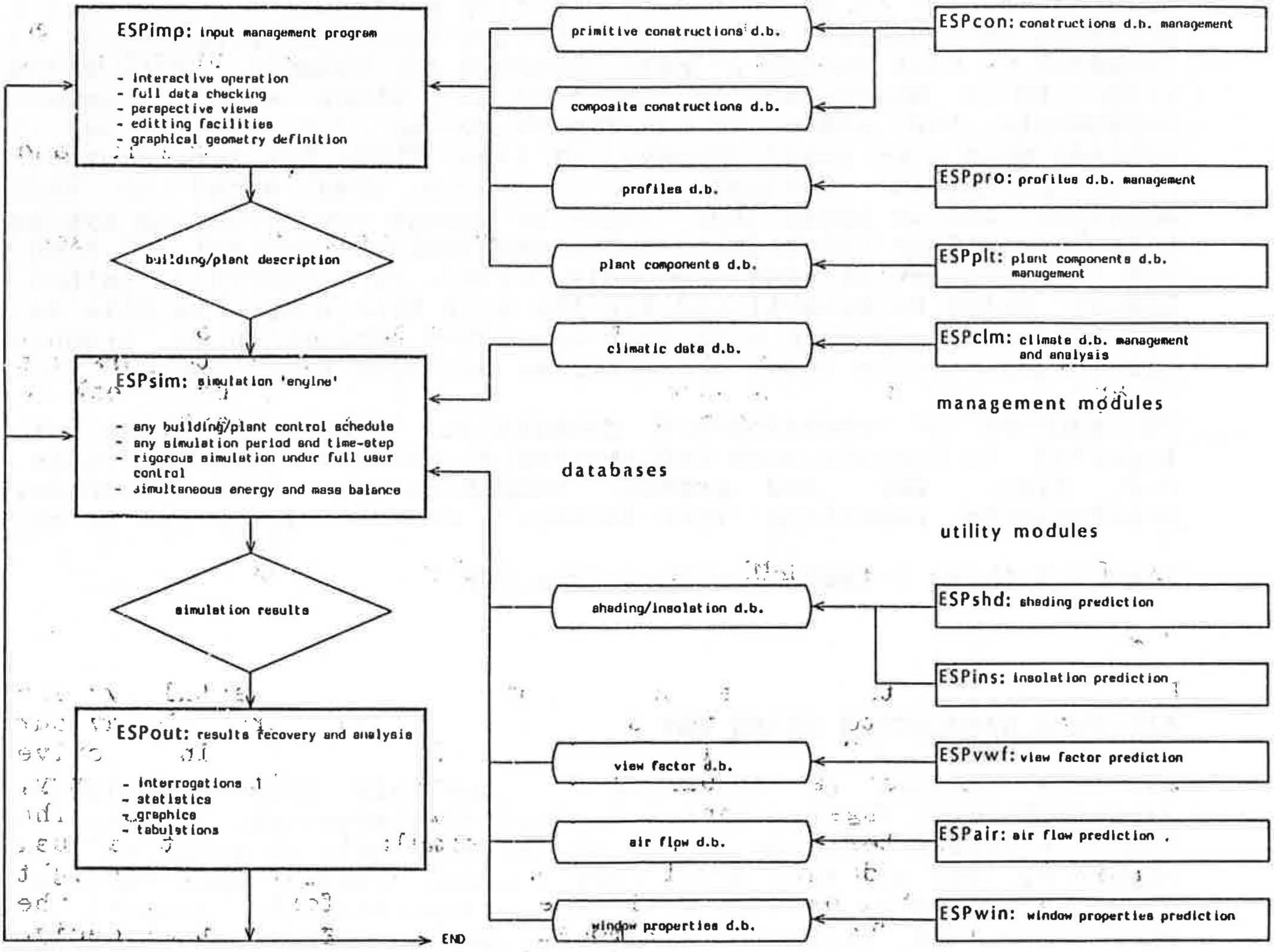


FIGURE 2 : The ESP system – a suite of interrelating, interactive program modules covering data input, database management, utilites, simulation and results analysis.

volumes deemed to be in thermal or flow contact, a conservation equation is developed in relation to the transport properties of interest - heat energy or mass exchange for example. This gives rise to a whole system equation-set where each equation represents the state of one finite volume (or space) as it evolves over some small interval of time. These are termed state-space equations. Control equations are then added to this equation set to prescribe, limit or impose conditions on system behaviour. Once established for a particular increment in time, the equation-set is simultaneously solved, by a numerical method, before being re-established for the next time-step. In this way ESP time-steps through some user-specified simulation to produce simulation results which characterise building performance.

In support of equation-set generation, many algorithms are required to compute such information as solar and casual gains, air flow, sky and ground temperatures, heat transfer coefficients, radiation 'view factors', control states and so on.

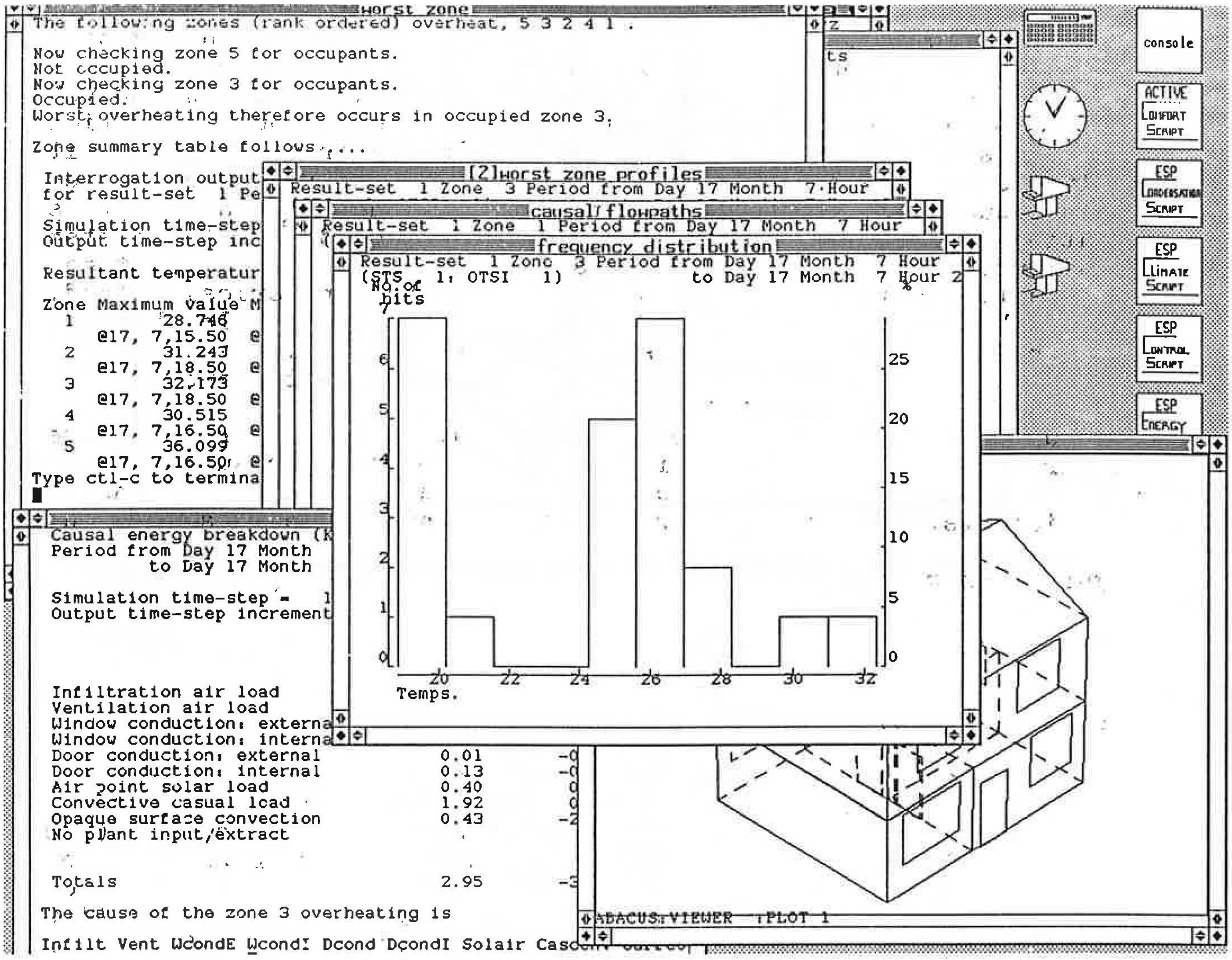
Figure 3 shows a typical output from ESP.

AIR FLOW SIMULATION USING ESP

In the context of this paper, the air flow simulation capabilities of ESP are worthy of further discussion. ESPair is the air flow prediction module of the ESP suite of programs (see Figure 2). The air flow model uses a nodal network, mass balance approach to flow simulation, and incorporates the results of analytical and experimental techniques to prescribe the flow field. Sometimes referred to as a 'zonal technique', ESPair can be classified as an 'intermediate' model. This was deemed to be an approach ideally suited to the modelling of infiltration and zone-coupled air movement within ESP.

Using the air flow model, a nodal network description of the distributed leakage within a building (e.g., cracks around doors and windows, general openings, air bricks, etc.) may be constructed. Figure 4b, for example, shows the air leakage distribution network generated for the 10 zone house ESP model described in Figure 4a. The network can be considered as a number of interconnected spaces, or zones. Connections between zones represent air flow-paths. Mechanical air handling plant (e.g., fans, filters, ducts, bends, etc.) may be superimposed on the network.

Network simulation proceeds as follows. At each simulation time-step, zone or space temperatures are obtained directly from ESP's energy calculations. Because the characteristic flow equations are non-linear, a Newton-Raphson iterative solution technique is employed to determine internal zone pressures and hence mass flow rates. The model calculates pressures on zone external surfaces as a function of surface pressure coefficients and prevailing



```
The following zones (rank ordered) overheat, 5 3 2 4 1 .

Now checking zone 5 for occupants.
Not occupied.
Now checking zone 3 for occupants.
Occupied.
Worst overheating therefore occurs in occupied zone 3.

Zone summary table follows....

 Interrogation output
 for result-set  1 Pe

 Simulation time-step
 Output time-step inc

 Resultant temperatur

 Zone Maximum Value M
   1         28.746
      @17, 7,15.50  @
   2         31.243
      @17, 7,18.50  @
   3         32.173
      @17, 7,18.50  @
   4         30.515
      @17, 7,16.50  @
   5         36.099
      @17, 7,16.50  @
Type ctl-c to termina
```

```
Result-set  1 Zone  3 Period from Day 17 Month  7 Hour
```

```
Result-set  1 Zone  1 Period from Day 17 Month  7 Hour
```

```
Result-set  1 Zone  3 Period from Day 17 Month  7 Hour
(STS  1: OTSI  1)               to Day 17 Month  7 Hour 2
```

```
 Causal energy breakdown (K
 Period from Day 17 Month
         to Day 17 Month

 Simulation time-step =   1
 Output time-step increment



 Infiltration air load
 Ventilation air load
 Window conduction: externa
 Window conduction: interna
 Door conduction: external              0.01      -0
 Door conduction: internal              0.13      -0
 Air point solar load                   0.40       0
 Convective casual load                 1.92       0
 Opaque surface convection              0.43      -2
 No plant input/extract


 Totals                                 2.95      -3

The cause of the zone 3 overheating is

Infilt Vent WcondE WcondI Dcond DcondI Solair Cas
```

FIGURE 3 : Example ESP output – obtained from running an automated design appraisal methodology for comfort assessment on a Whitechapel MG-1 workstation.

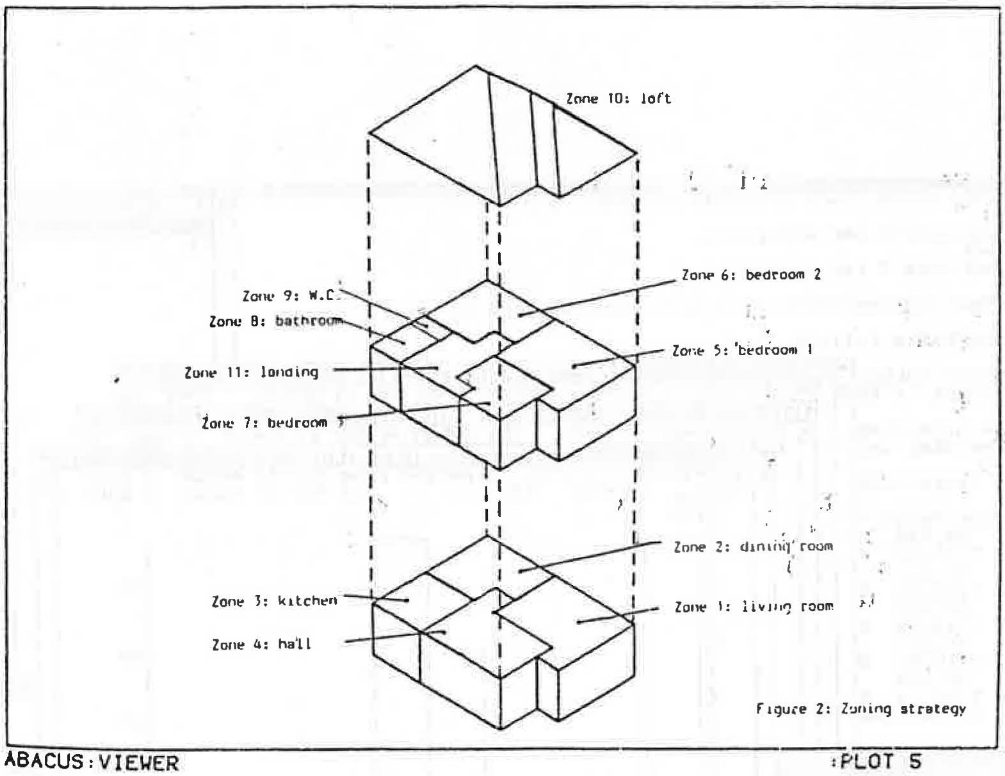


Figure 4 a : 10 zone ESP domestic house model. Shown exploded.

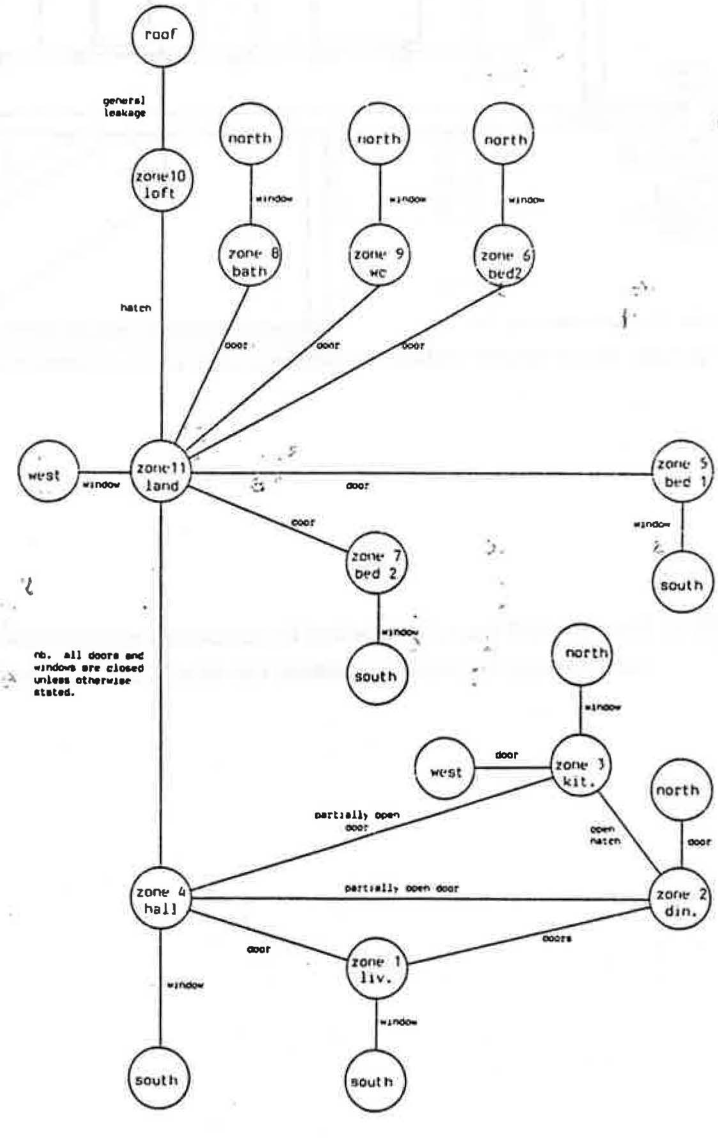


Figure 4 b : Air leakage distribution network for 10 zone house model.

wind velocity and direction; this defines the boundary condition of the problem.

The iterative solution technique involves the following stages. Arbitrary initial pressures are assigned by the model to internal spaces and the flow equation set solved simultaneously. The air mass flow to each zone is then solved and any deviation of the sum from zero is termed the flow or residual error. A small pressure modification is then applied to the zone with the largest residual error. Having modified the space pressure, the equation set is re-solved and the space with the worst residual error corrected as before. This procedure continues until the worst residual error is acceptable. The speed of convergence depends upon the permissible pressure and mass balance tolerances, the number of zones and connections, and the size and nature of these connections.

TECHNOLOGY TRANSFER

General

One of the most important issues facing emerging simulation models is that of technology transfer, i.e. use of the technology in practice. At the present time, several initiatives are underway which are designed to encourage such use.

In the UK, for example, a subsidised professional service, the RIAS Energy Design Advisory Service (EDAS), has recently been formed to help architects and engineers effectively apply simulation techniques. The concept underlying EDAS and the range of services it offers are outlined below.

Also in the UK, an association known as the Building Environmental Performance Analysis Club (BEPAC), has been formed Bloomfield 1987) to address the issues of model use in practice. With a membership drawn from both private and public sector organisations and academia, part of the Club mission is to critically examine the relevance, reliability, applicability and modus operandi of current modelling systems. The Club caters for all aspects of building environmental appraisal, and includes a special interest group concerned with air movement in buildings (Hammond 1988).

In North America a similar organisation - the International Building Performance Simulation Association (IBPSA) - has been incorporated to pursue similar objectives. And in Europe, another initiative in this area is currently being discussed.

The RIAS Energy Design Advisory Service

The Royal Incorporation of Architects in Scotland (RIAS), the professional body representing Scottish architects, have recognised the need to establish an independent Energy Design Advisory Service (EDAS) based on the use of advanced simulation modelling. The venture is funded jointly by the Scottish Development Agency and the Energy Efficiency Office (through the Building Research Establishment Energy Conservation Support Unit - BRECSU). Officially launched in September 1987 by its chairman, Sir Monty Finniston, EDAS is a two-year project which is being appraised as a prototype for a service which could, eventually, be made available to building designers throughout the UK.

EDAS offers a two-tier service. The first is a FREE initial consultation service. The aim is to give designers, without charge, advice and information on a variety of buildings-related energy issues appropriate to their design requirements. The second tier, a follow-on from the first, is a subsidised computer-aided energy/environmental design service. Certain aspects of a design or refurbishment project, identified in the initial consultation, might be worthy of further, more detailed analysis using computer simulation techniques. In this case, a report containing recommendations for a full analysis, the likely benefits and anticipated cost, is prepared. Should the designer proceed, a 50% subsidy is given towards the full cost of the study.

To-date, EDAS has conducted around 100 initial consultations. Twelve full studies have been undertaken.

A full account of the EDAS initiative is given elsewhere (Emslie 1988).

CASE STUDIES IN BUILDING ENERGY SIMULATION

The following summaries of three case studies, involving use of ESP, have been selected from the range of full analyses conducted to date by the Energy Design Advisory Service. Additional, more detailed information on these and other studies may be obtained from the author.

Case Study 1 : Tower Block Refurbishment - Heating and Stairwell Pressurization Appraisal.

This project involved appraisal of the pros and cons of electric storage heating and district heating, using piped low temperature hot water, in multi-storey tower blocks. Detailed simulations of various flats within the tower blocks gave quantitative information on predicted energy consumption, comfort levels and fabric condensation risk for the different heating system types against different occupancy patterns and degree of exposure to external conditions. In the case of district heating, a detailed appraisal of the thermal inertia, or 'flywheel' effect of building structure was conducted to establish whether a 'night set-back' control strategy could be employed to reduce peak heating demands, and hence reduce boiler sizes.

The issue of stairwell pressurization was raised during the study. The designers were experiencing difficulty in applying the British Standard relating to smoke evacuation using pressurization techniques (BS5588. Part 4. 1978). As a side-issue, therefore, a study was instigated to look at the application of nodal network air flow simulation techniques in the design of stairwell pressurization schemes. Using such techniques, it is possible to ensure that a given fan size will maintain sufficient pressure levels throughout the stairwell given varying conditions of wind pressure and internal buoyancy effects.

It is interesting to note that nodal network, mass balance simulation techniques have been applied to the problem of stairwell pressurization as long ago as 1979 (Irving 1979).

Case Study 2 : The Crystal Pavilion

The Crystal Pavilion is a glass exhibition building, housing displays on the subject of crystals and crystalline technology at the Glasgow Garden Festival. The structure has 'crystalline' form and the glass is painted internally in shades of blue to give a translucent effect. Being constructed entirely of glass, however, the architects (Bruce Patience & Wernham) wished to establish whether summertime overheating might occur and, if so, how it might best be minimised.

A detailed computer model of the pavilion was established. Figure 5 shows a perspective view of the model as generated via the ESP program. The 'crystalline' form can be readily appreciated. Given the obvious complexity of solar heat gain calculations, involving detailed shading studies together with accurate consideration of facade azimuth with respect to sun position for each surface, the dynamics of the problem were ideally suited to simulation appraisal.

Simulations confirmed that the pavilion, without any means of cooling, would overheat under certain summer conditions. Further simulations were therefore conducted to confirm the hypothesis that, given a suitably high air change rate, outside air could be used for cooling purposes. Another series of simulations were then performed, this time involving combined energy and air flow simulation. It was established that a 'passive' natural ventilation scheme based on 'stack-effect' (i.e. temperature difference between outside and inside) would induce sufficient air change for cooling purposes.

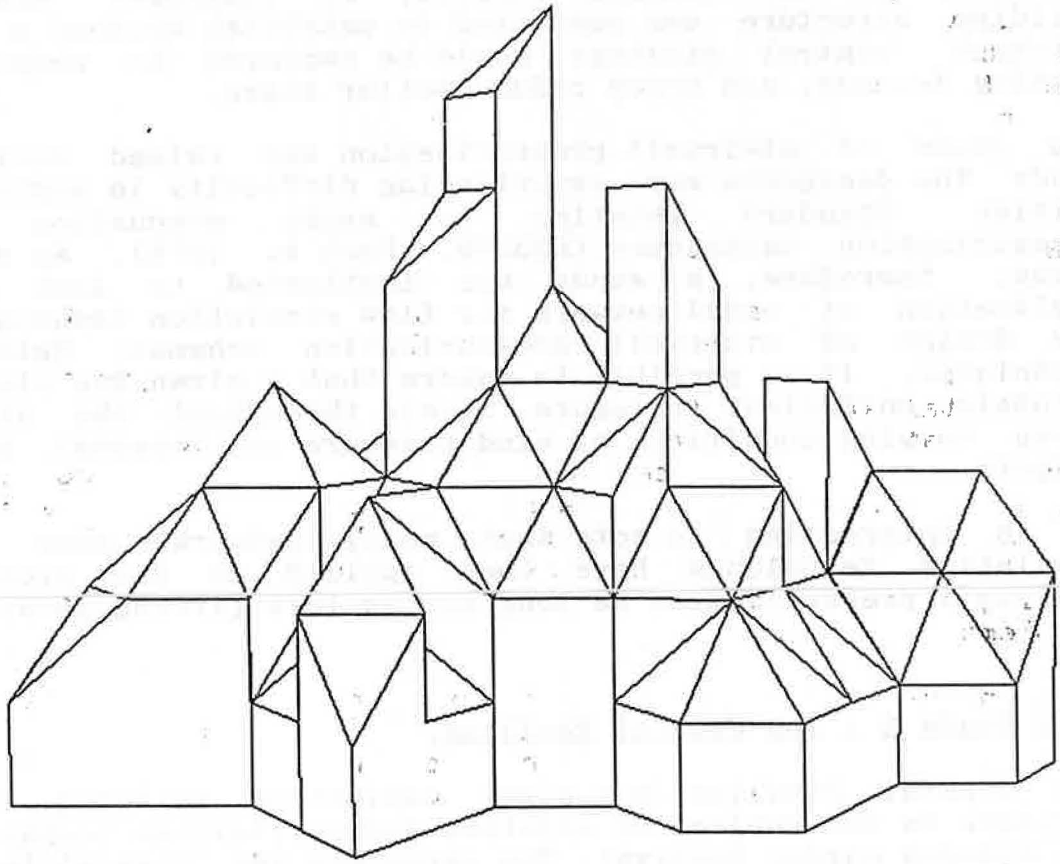


Figure 5 : The Crystal Pavilion
(Maximum height approx. 15 metres)

At the end of the day, the architects decided that the inclusion of a significant area of air-flow louvres on the glass skin would seriously affect visual aesthetics. Free standing cooling plant was therefore sized and installed. The plant has been running quite frequently since the garden festival opened in April thanks to rare, prolonged sunshine periods.

Case Study 3 : Modelling of Radiant Heating in an Ice Rink.

Complaints of excessive cold, from passive paricipants of the sport, led the owners of a curling rink to consider the possibility of some form of heating. One proposal put forward was the installation of direct gas-fired radiant heaters above the ice rink at ceiling level. Concern was expressed, however, that such a scheme might place too great a stress on the ice sheet and cause melting. Concern was also expressed that the release of substantial quantities of water into the curling hall, through direct firing of natural gas, might give rise to increased ceiling condensation with water dripping onto the ice and causing problems for curlers.

A computer model of the problem was constructed to test, at a theoretical level, the efficacy of the proposed heating. Simulations, taking full account of the complex dynamic energy flowpaths and interactions, were conducted against a range of external weather patterns and internal usage. From the simulation results, the following conclusions were drawn :-

- Under certain conditions, some melting of the ice could occur with the heating on. The integrity of the ice surface, critical to the game of curling, could not be guaranteed.

- Ceiling condensation would actually reduce on account of the higher surface temperatures prevailing when heating is on. Increased condensation would occur, however, on the ice sheet, placing additional load on refrigeration systems and necessitating an increased frequency of ice surface scraping operations.

- During colder weather, electricity costs associated with operation of the refrigeration plant would rise considerably. These costs would be in addition to the cost of running the gas heaters.

On the basis of the study results, the radiant heating proposal was rejected. An alternative scheme, comprising low temperature panel heaters situated at rink ends, was proposed, simulated and found to be a reasonable compromise. Low temperature panels are currently under trial to determine their effectiveness in use.

THE FUTURE - COMBINING THE FUNCTIONALITY OF ESP AND PHOENICS

There is plenty of evidence of an increasing need for simulation based appraisal capabilities which exceeds the individual capabilities of models such as ESP or PHOENICS. Not least in applications where time and cost factors dictate reduced dependence on experimental analysis. With the advent of high performance processors and transputer systems, computational environments now exist which would allow the functional capabilities of the two models to be combined. The availability of an advanced, easy to use, integrated energy and air flow simulation appraisal package offers the prospect of exciting new possibilities and opportunities for building designers and researchers. Such a prospect is, perhaps, a longer term goal. There are, however, two developments underway at Strathclyde University which might facilitate such a scenario :-

i) The Intelligent Front End

The Intelligent Front End (IFE) is an attempt to develop a truly ´user-friendly´ interface for, initially, building energy simulation purposes. The IFE is an intricate synthesis of user modelling, human-computer interaction techniques, contextual knowledge and the interface to the simulation application at its back-end. It is built from cooperating modules organised around a communications module, the ´blackboard´, to facilitate multiple use of information. Several other modules exist and can examine this blackboard for information, posting results back to it. Figure 6 shows the software modules comprising the IFE (MacRandal 1986, Clarke 1986). These include :-

- A **Dialogue Handler** to converse with the user in a manner which is tailored to his/her conceptual class and level of experience.
- A **Plan Recognition** module to identify the user´s performance appraisal wishes.
- A **Planner** to determine the most appropriate appraisal methodology.
- A **Building Model** to create, from information supplied by the user and the knowledge base, the data structure which describes the building under consideration.
- A **Back-End Handler** to drive the required simulation appraisal package, feeding it the necessary data. This module is the only one specifically tailored to a given program.
- And a **Knowledge Handler** to manipulate the knowledge concerning the application (building design), the domain (energy modelling for example), the appraisal software (e.g. ESP) and the user class.

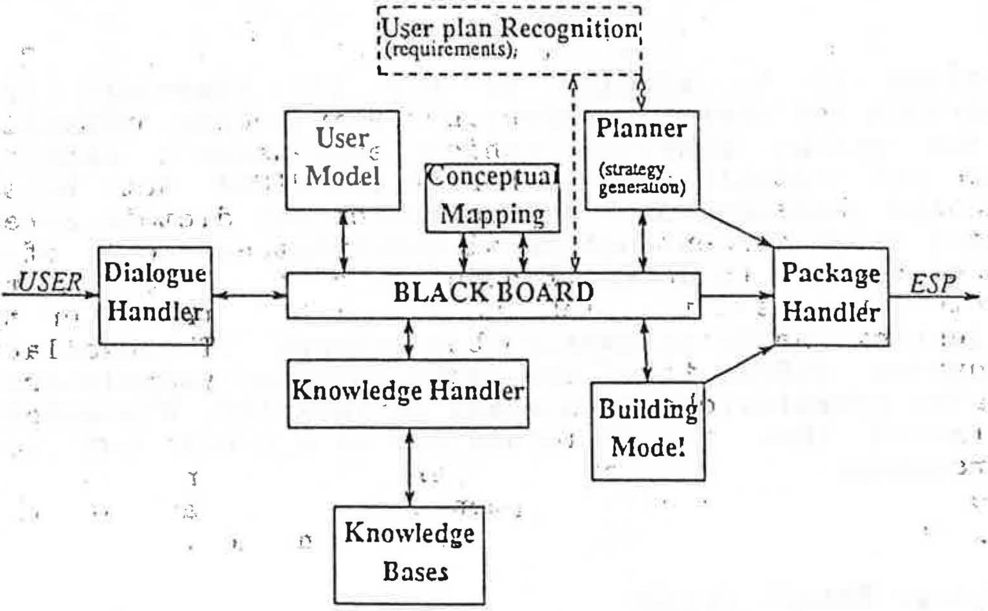


Figure 6 : Intelligent Front End Architecture.

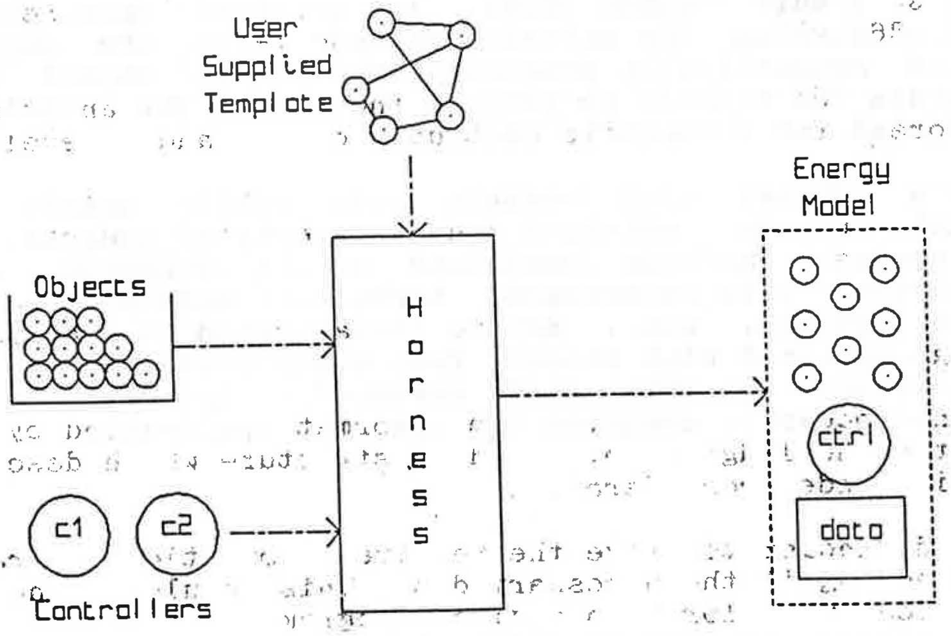


Figure 7 : The Energy Kernel System.

The functions to be handled by the IFE therefore include conversing with the user in appropriate terminology, planning how to use the energy model to achieve the user's objectives, collecting and organizing the description of the building, generating the necessary data and control input for the appraisal package and storing both the domain knowledge and the strategy knowledge to be used to drive the package.

The application could as easily be a sub-set of computational fluid dynamics (CFD), fire and smoke movement simulation for example. The appraisal package could be PHOENICS. Ultimately, it is anticipated that the IFE could act as a front end to any appraisal package.

ii) The Energy Kernel System

The Energy Kernel System (EKS) is a project which attempts to re-cast the methods of simulation in a modular manner so that building specific models can be readily configured. The EKS [Clarke 1987] is a software/hardware product which is capable of constructing a program from internal, accredited methods. Figure 7 shows the elements of the EKS.

It is imagined that a template can first be constructed to define a model in terms of its methods. This template is passed to the harness which automatically constructs the program, outputing it in the form of a multi-object model, in executable form. This is done by transferring the selected objects from the object's library, and automatically generating the control object which will coordinate the methods at program run time. The output is a program targeted for a specific machine.

The object's library will contain both public domain and proprietorial methods, obtained from a variety of sources. For example, specific methods contained within PHOENICS, e.g., equation solvers, grid generators, turbulence models, buoyancy calculations routines, etc., may be incorporated as proprietory objects. When combined with objects from other sources (e.g. ESP) it is entireley feasible that advanced, integrated flow simulation codes may be conjured for specific applications.

CONCLUSIONS

Simulation models are now emerging which are well equipped to address the microcosm of complexity which is the energy sub-system within buildings. In response, a number of Technology transfer initiatives are currently underway in an attempt to help designers effectively apply simulation technology.

In a 'future' scenario, it is envisaged that attempts will be made to further advance the appraisal capabilities of models such as ESP and PHOENICS by giving each the functional capability of the other. The Intelligent Front End (IFE) and Energy Kernel System (EKS) initiatives are seen as a means of facilitating such a scenario.

ACKNOWLEDGEMENTS

Grateful thanks to Dr Joe Clarke, Director of the Energy Simulation Research Unit and progenitor of the ESP system. His recently published papers and book on building energy simulation were the source of most of the material contained within the section on ESP and also the IFE and EKS projects.

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