Current Building Systems Modelling Potential of ESP-r

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ABSTRACT

This paper describes the current status of the ESP-r simulation environment with respect to modelling and simulation of systems in buildings. Following an overview of the underlying philosophy and the overall structure of the system, ESP-r's integrated approach to building and plant modelling is elaborated with a worked example.
The paper finishes with indicating current system simulation developments and concludes that an integral approach to a building with associated systems is now possible and ready to be applied on a wide scale in engineering education and research, as well as in practice.

1. INTRODUCTION

Apart from the general need for energy efficiency and protection of the environment, building designers and environmental engineers encounter a vast range of additional "problems" in everyday practice. To name just a few examples: in **offices** phenomena like "Sick Building Syndrome" and trends like: atria, climate facades, displacement ventilation combined with cooled ceilings; in **houses** increasing levels of occupants comfort expectancy; in **industry** (indoor) air quality issues; in **conversions** where existing buildings have to house completely different functions (eg industrial buildings converted into apartments); etc.

So which is the system we are actually trying to address? The whole of building form and fabric, control systems, environmental issues and methodical design comprises a very wide area. Many of the above indicated problems are in fact caused by the complexity due to interactions between the various sub-fields. These interactions are indicated in Figure 1. Obviously this diagram is merely a gross simplification of reality, because in the real world this is a n-dimensional problem involving the 3-dimensionality of building and plant, the dimension of time, and the dimension of the various aspects like: thermal environment, air quality, lighting, acoustics, etc.
As illustrated for the thermal aspects only, the indoor environment is determined by a number of sources acting via various heat and mass transfer paths. The main sources may be identified as outdoor climate, occupants (casual heat gains), and the auxiliary system which may perform heating, ventilating and / or air-conditioning (HVAC) duties. These sources act upon the indoor environment via various heat and mass transfer processes such as conduction, solar transmission, long wave radiation exchange, convection, airflow, and flow of fluids within the plant system. Within the overall configuration as sketched, several energy sub-systems may be identified, each with their own dynamic thermal characteristics: occupants (very complicated dynamic systems themselves), building structure, and auxiliary systems. The cycle periods of the excitations acting upon the system are also highly diverse. They range from something in the order of seconds for the plant, via say minutes in case of the occupants,

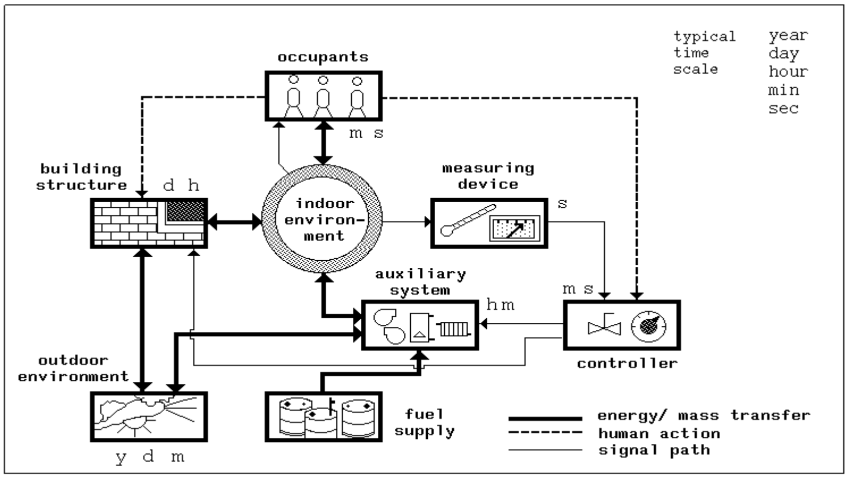


Figure 1 The building as an integrated, dynamic system

to hours, days and year for the outdoor climate.

Many design problems (for example fabric design, comfort or condensation assessment, control system appraisal, plant system analysis, etc.) can only be meaningfully assessed when treated as a sub-set of some complex set of interactions. In other words, a piecemeal approach, in which a particular region is considered in isolation, is often inappropriate and potentially misleading.

Having identified the problem domain and the need for an integral approach, we are now able to state our objective: evaluation of building performance while treating the building (including its distributed flow paths), environmental control system(s), and occupants as an integrated, dynamic system.
The remainder of this paper dwells on one particular simulation system, enabling the above, by first outlining the system and then elaborating the integral approach by means of a worked example.

2. OUTLINE of ESP-r

ESP-r is a building energy modelling environment which supports performance assessment of design solutions (for either newly build or alterations of existing stock) incorporating traditional and/or low energy features. The approach is intended to allow users to conduct a high integrity, first principle appraisal whilst modelling all aspects of the energy subsystems simultaneously and in the transient domain. In common with other simulation programs, the ESP-r approach is markedly different from traditional methods in that it aims to represent all relevant phenomena, and to process these phenomena simultaneously so that the inter-relationships are preserved. Essentially, this is achieved by establishing sets of conservation equations for different spatial regions and arranging for the integration of these equations over time. In this way the energy and mass flows are tracked - throughout a simulation - as they evolve under the influence of climatic boundary conditions, occupancy effects inside the building, constraints imposed by any control action and by the potentially time-dependent inter-volume links (representing for example damper, valve, window or door movement).
The theories employed by ESP-r to represent heat transfer and fluid flow, and the numerical techniques used to achieve equation integration, are detailed elsewhere (Clarke 1985, Hensen 1991).

Figure 2 summarizes the ESP-r system. Essentially, the system consists of two distinct parts corresponding to the user's and researcher's viewpoints.
Typically, users require considerable assistance with the specification of a design hypothesis and its evolution in the light of poor performance indications. These functions are provided by a *Project Manager* which supports the specification of design problems in terms of:

Figure 2 The ESP-r system: user and researcher viewpoints

- 3D building geometry with attribution in relation to opaque and transparent constructional materials, surface finishes, occupancy, lighting schemes, air leakage distribution, with superimposed events to represent phenomena such as window opening, shading device positioning and electric light switching.
- Plant specification in terms of networks of connected components representing the thermodynamic processes which result in the pressure and temperature differences causing heat transfer between, and the flow of, the working fluids.
- Control system specification in terms of a list of control loops, possibly nested, constructed from *sensor->action->actuator* relationships, each one valid over a given time interval.

When specifying a problem, the *Project Manager* offers users access to on-line databases of constructional materials, plant components, profile prototypes, optical properties, pressure coefficients and climatic sequences of differing severity. In this way the input burden is minimized. Where possible, inputs are achieved through graphical interaction, with customized tools invoked automatically by the *Project Manager*. For example, AutoCad can be used to specify building geometry, while an icon manipulation program has recently been added to assist with the definition of plant and flow networks.

Researchers, on the other hand, are usually concerned to extend modelling functionality and accuracy by experimenting with alternative algorithms. This requires a mechanism for working with source code which does not oblige the researcher to be knowledgeable about all aspects of the system. With ESP-r this has been achieved by compartmentalizing the source code into technical domains as shown in Figure 2. A researcher interested in plant modelling, for example, need only work with the source code relating to that domain. Software engineering tools and a good practice procedure for software development (Hensen 1991a) are then employed to control the integration of the different domains into the ESP-r Simulator. At the present time this mechanism is supporting an expansion in the number of organizations actively developing ESP-r. (The system is currently used for education and research at universities and research centres in over 20 countries world-wide.)

Starting from such an existing platform offers vast advantages for any individual research group. The most important ones are: (1) as an individual group it is not necessary to have expertise in all areas, (2) areas not addressed within a specific research project will still be state-of-the-art, (3) as more people are using the system, any bugs or flaws are likely to surface sooner, (4) common tasks like development of training/ tutorial material becomes a shared burden, and (5) results transfer to the international research community is implicit and therefore very efficient.

3. A WORKED EXAMPLE

Application of this integral simulation system can best be demonstrated by means of a realistic case study. The case presented here concerns the modelling a small building at a site near London. Air conditioning is achieved with a single-zone system with re-circulation. A control strategy has been suggested to keep the air temperature and relative humidity of the main zone within certain limits. Simulation is employed to assess this proposed control strategy.

Building

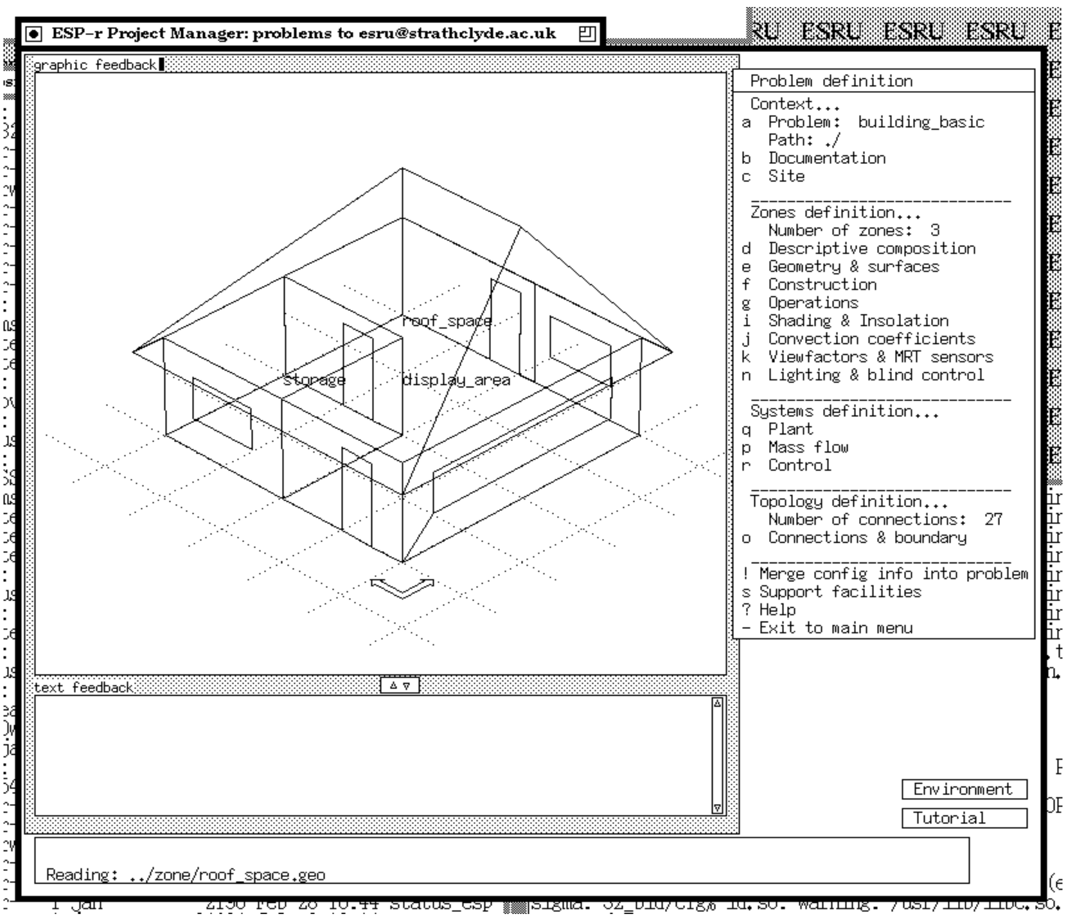


Figure 3 Definition of the building model

The building model comprises three zones, each representing a distinct area of the building. The three zones being: display area, storage, and roofspace. The building is shown in Figure 3. The display area is occupied during normal working hours (9 - 17), with the resulting latent and sensible energy gains due to people and equipment described within the problem description files. To keep the problem relatively simple, time dependent air infiltration and inter-zonal ventilation flow have been pre-defined in this case. Alternatively we might have defined the building’s air leakage distribution in terms of cracks, vents, doors, openings and external surface wind pressure coefficients. In that case the mass flow simulation module would have solved - during each simulation time-step - the airflow due to wind and temperature effects (as elaborated in Hensen and Clarke 1991).

At simulation time, the building so defined is made discrete by subdivision into a number of interconnecting, finite volumes. These volumes then possess uniform properties which can vary over time, and represent homogeneous and mixed material regions associated with room air, room surface and constructional elements. For this particular problem the number of such volumes is about 190. Then, for each of these finite volumes in turn, and in terms of all surrounding 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 represent the state of one finite volume as it evolves over some small interval of time. 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 of some user-specified simulation period. In support of equation-set generation, many algorithms are required to compute such information as solar and casual gains, sky and ground temperatures, heat transfer coefficients and so on.

Plant

In keeping with early design investigations ESP-r provides a level of plant systems which are ‘ideal’ in their representations ie. they have no inertia or time dependent characteristics, and operate on the building side only.

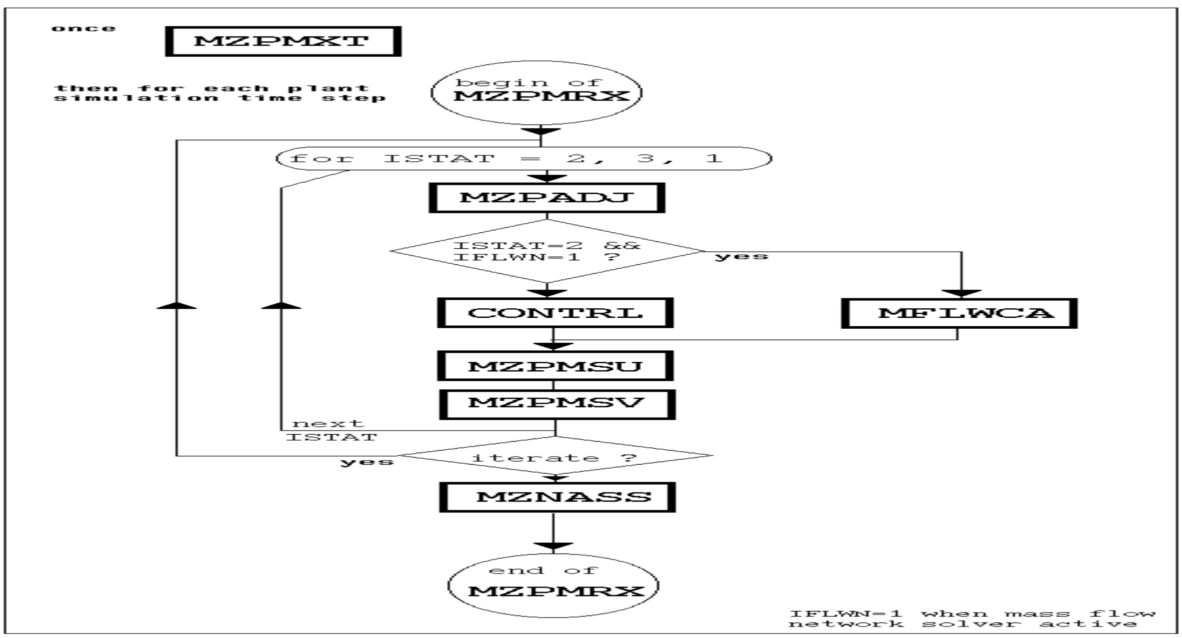


Figure 4 Diagrammatic representation of solving the plant system matrix for energy balance (ISTAT = 1), 1st phase mass balance (ISTAT = 2), and 2nd phase mass balance (ISTAT = 3); see Table 1 for brief explanation of various subroutines; IFLWN indicates whether the mass flow network solver is active.

However the system also provides a much more detailed level of plant simulation, using a modular-simultaneous technique. In this case system plant system modelling is achieved by a modular, component-wise approach. Each plant component is made discrete by subdivision into one or more interconnected finite volumes. For each finite volume (or node) up to three conservation equations are developed to

represent heat and mass transfer. In case a node represents a solid region there is only one equation (heat), for a node representing water there are two equations (heat + water flow), and for a node representing air there will be three equations (heat + dry air + water vapour).
The plant model is a combination of individual component models forming up to three complete sets of simultaneous state-equations for the whole system, for which a solution is found by means of efficient matrix equation solvers and a procedure as indicated in Figure 4 and Table 1.

Table 1 Main subroutines involved in solving plant system matrices

Subroutine	Description
MZPMXT	accesses the plant components database and extracts the data needed to establish the templates for the plant network energy, 1st phase mass, and 2nd phase mass balance. Checks that component connections are legally defined, initialises data arrays, and in case the encapsulated version of *mfs* is active: resets the mass diversion ratios to unity, and checks plant/mfs connection mapping regarding fluid types
MZPMRX	controls setting up, solution and results assignment of the plant energy (ISTAT = 1), 1st phase mass (ISTAT = 2), and 2nd phase mass (ISTAT = 3) matrix equation at each plant simulation time step
MZPADJ	organises the information which defines each inter-component coupling. This data is required by the component nodal equation coefficient generators in order to calculate the inter-component connection coefficients. Checks whether mass flows are in the assumed direction (ie. the coefficient generators implicitly assume each connection's mass flow rate ≥ 0. Establishes plant component containment temperatures, if defined to exist
CONTRL	determines plant control status based on most recent available results, by invoking appropriate control routine for each active plant control loop for current time step
MFLWCA	controls the fluid flows calculation for each simulation time step: sets climate variables, temperatures for nodes corresponding to plant components or building zones, sets boundary nodes temperature and/or wind pressure. Calculates fluid densities and connections stack pressure difference. Solves the fluid flow network mass balances; transfers fluid flow simulation results to results file. Establishes and transfers building side air flow and plant side fluid flows
MZPMSU	sets up the plant matrix equations by calling the appropriate matrix coefficient generators, and locating generated equation coefficients in the network matrix
MZPMSV	solves the plant matrix equation. A sparse matrix solver is invoked to solve the matrix equation $\mathbf{A} \cdot \theta = \mathbf{b}$ or $\mathbf{E} \cdot \dot{\mathbf{m}} = \mathbf{f}$ for the solution vector θ or $\dot{\mathbf{m}}$ in terms of the known vector $\mathbf{b}$ or $\mathbf{f}$. The solution vector is then relocated in the future time-row state-space variable array.
MZNASS	adjusts all plant related history variables

For the current case-study it was decided to use one of the most common and effective approaches to controlling temperature and relative humidity within a zone: pre-heat the air, pass it through an air washer where it undergoes adiabatic saturation, and then to re-heat it to the temperature at which it is to be supplied to the zone. The pre-heating and adiabatic saturation processes will permit the relative humidity in the zone to be controlled and re-heating allows the temperature therein to be properly regulated during winter conditions.

The system network for the current case consists of 14 components describing the major items of plant of a typical year-round, single-zone system. The components required to create the system are: pre-heat and re-heat coils, cooling coil, supply and return fan, air washer, mixing box, and ducts. The models which were used in this case all originate from the IEA Annex 10 work (1988). The system layout is shown in Figure 5; the corresponding energy balance matrix is shown in Figure 6. For the current case-study, the mass flow balance matrices for dry air and water vapour will have a similar lay-out, but obviously different coefficients and right hand side values.

The pre-heat and re-heat coils are one-node flux control heating coils, the maximum output of each coil is 3.5 kW. The cooling coil is also a relatively simple flux control model with a maximum capacity of 1 kW. If a greater level of granularity is required in the simulation the described components can be replaced by the more detailed 3-node models also available in the plant component database, where a

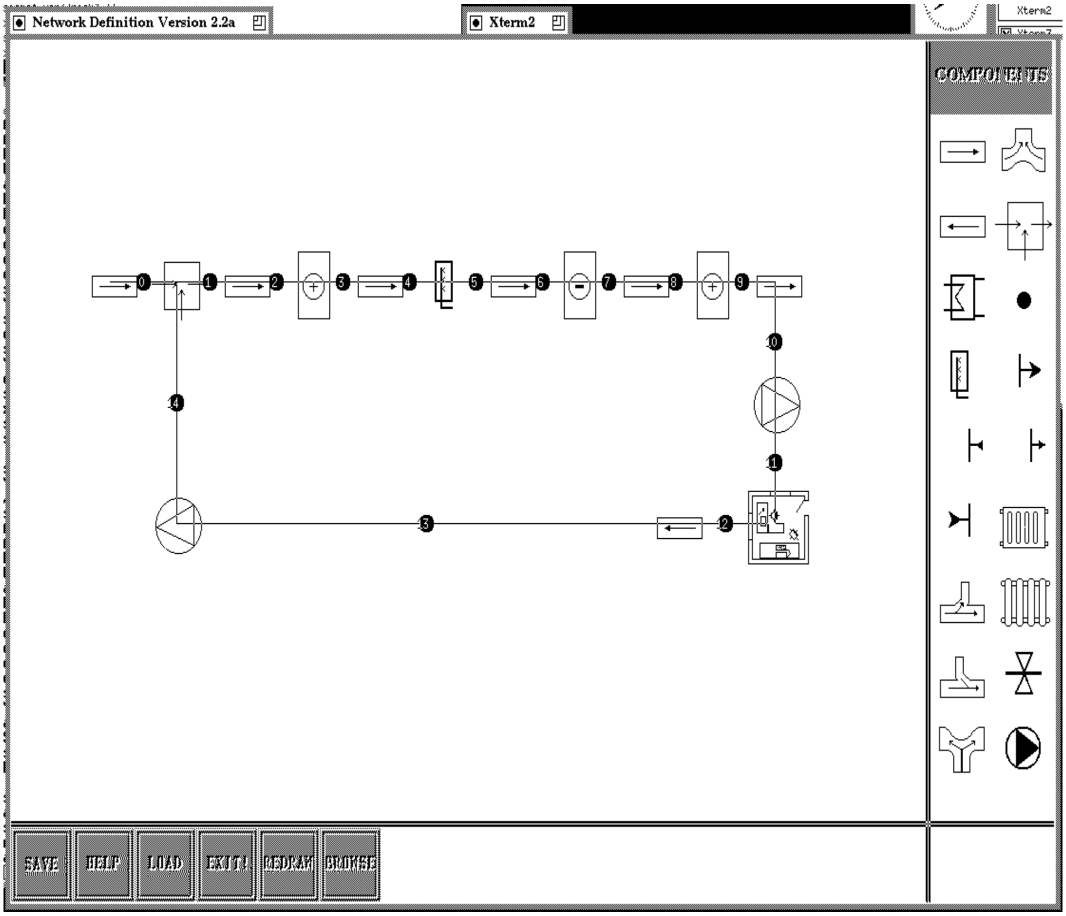
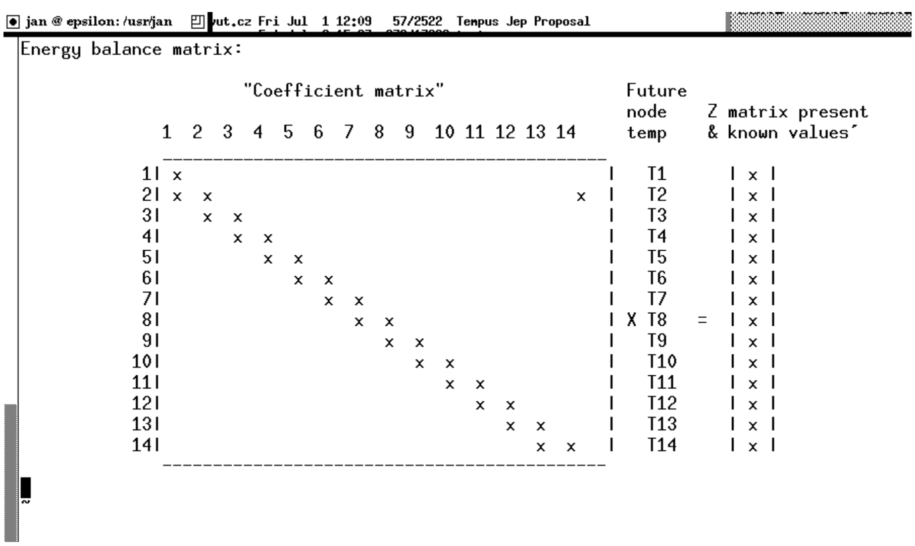


Figure 5 Definition of the air-conditioning system



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Energy balance matrix:

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      ___________________________________________
    1| x                                         |    T1        | x |
    2| x  x                                   x  |    T2        | x |
    3|    x  x                                   |    T3        | x |
    4|       x  x                                |    T4        | x |
    5|          x  x                             |    T5        | x |
    6|             x  x                          |    T6        | x |
    7|                x  x                       |    T7        | x |
    8|                   x  x                    |  X T8    =   | x |
    9|                      x  x                 |    T9        | x |
   10|                         x  x              |    T10       | x |
   11|                            x  x           |    T11       | x |
   12|                               x  x        |    T12       | x |
   13|                                  x  x     |    T13       | x |
   14|                                     x  x  |    T14       | x |
      ___________________________________________
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Figure 6 Energy equations matrix lay-out for the plant system fluid flow rate to the heater/ chiller unit is controlled as opposed to flux.

The air washer (or spray humidifier) in the system can either be uncontrolled (ie fixed moisture addition) or be controlled to vary the water flow rate according to a certain strategy.

The intake and extract in the network provide a constant volume flow rate of 0.4 m^3/s to and from the conditioned space; this corresponds to an air change rate of about 5 ACH. The supply air has a constant fresh air content of 20%, with the remainder made up from re-circulated zone air.
Similar to the remark above regarding building side airflow due to infiltration and ventilation, alternatively we might have decided to define the flow behaviour of the system in terms of pressure-flow characteristics by selecting appropriate models for the various plant components (ie fan, mixing box, duct, etc). In that case the mass flow simulation module would have solved - during each simulation time-step - the airflow through the system.

Controls

In ESP-r a control loop is defined by: sensor location, actuator location, and control law. A control loop is not static but has a temporal dimension so that it can change as a function of time. A sensor exists to measure some variable for transmission to the control law representing the active controller. The control variable may be any nodal state variable active within a simulation, an outdoor condition, one of the plant component additional variables, or some derived combination of the previous. Actuators exist to transmit the output of a controller to some building zone or plant component, usually to reduce the deviation of the sensed control variable from some user-specified set point. Actuator locations can be set to any building side node (air, surface, mixed, intra-construction), or some plant component participating in a simulation.
A control law is an algorithm which represents the logic of some controller. Its purpose is to translate (algorithmically) the sensed condition to the actuated state in terms of the control system characteristics, for example: building pre-heat, fixed heat injection or extraction, PID control, optimum start controller, etc. (For each control loop, in addition to specifying sensor, actuator, and control law data, the user has to specify items such as: periods of validity and operation, component output capacity, set point, throttling range, etc,.)
At each time-step as a simulation proceeds, the nodal property detected by the sensor is fed to the control law algorithm, which then acts to fix or limit some other nodal property, via the actuator node, prior to matrix reformulation for the current time-step. In this way, simulation control is achieved on the basis of some function of a prevailing control point.

At an early design stage it is useful to be able to conduct simulations on the basis of the assumption of ideal control. This allows factors such as energy efficiency to be improved by the systematic adjustment of the building design parameters against the expectation of ideal comfort conditions. Subsequently, after a near optimum design has been arrived at, more realistic control regimes can be imposed in order to obtain a stable control system with good response characteristics. The latter is being pursued in the current case-study.

The determination of supply conditions for such a system requires the determination of values for the dry-bulb temperature and moisture content of the supply air which are required to maintain a design state in a conditioned space. The control law used in the current case-study is a psychometrically-based algorithm which establishes and re-sets (at every plant time-step) the set-points for the pre-heater, re-heater, cooling coil, and humidifier plant components. For the current system four control loops (as detailed in Table 2) are active: one each for the pre-heater, cooling coil, humidifier, and re-heater components.

Coupling Building and Plant

In a mathematical/ numerical sense, this effectively means combining the energy and flow balance matrix equations for both the building and plant. While in principle it is possible to combine all building / plant and heat / fluid flow matrix equations into one overall ‘super-matrix’, this is not done primarily because of

Table 2 Plant control loop parameters for pre-heater (1), cooling coil (2), humidifier (3) and re-heater (4); set-points for room conditions: 19 $^{\circ}C$ dry bulb temperature and 50% RH.

Description	(1)	(2)	(3)	(4)
Sensor Location:	pre-heater exit	coil exit	humidifier exit	re-heater exit
Sensed Variable:	dry bulb temp.	dry bulb temp.	relative hum.	dry bulb temp.
Actuator Location:	pre-heater	cooling coil	humidifier	re-heater
Actuated Variable:	heating flux	cooling flux	moisture injection	heating flux
Control Law:	proportional	proportional	proportional	proportional
Proportional Band:	2 $^{\circ}C$	2 $^{\circ}C$	12% RH	2 $^{\circ}C$
Output Range:	0.0 -> 3.5 kW	0.0 -> 3.5 kW	0.001 -> 0.005 kg/kg_{da}	0.0 -> 3.5 kW
Control Period:	07:00 - 18:00	07:00 - 18:00	07:00 - 18:00	07:00 - 18:00

the advantages which accrue from problem partitioning.

The most immediate advantage is the marked reduction in matrix dimensions and degree of sparsity. A second advantage is that it is possible to easily remove partitions as a function of the problem in hand; for example when the problem incorporates building only considerations, plant only considerations, plant + flow, and so on. A third advantage is that different partition solvers can be used which are well adapted for the equation types in question - highly non-linear, differential and so on.

Obviously there are often dominating thermodynamic and/ or hydraulic couplings between the different partitions. If a variable in one partition (say air temperature of a building zone) depends on a variable of state solved within another partition (say the temperature in the air supply), it is important to ensure that both values match in order to preserve the thermodynamic integrity of the system. Without going into details, two methods are offered to handle these couplings: (1) a time step control facility, and (2) iteration mechanisms.

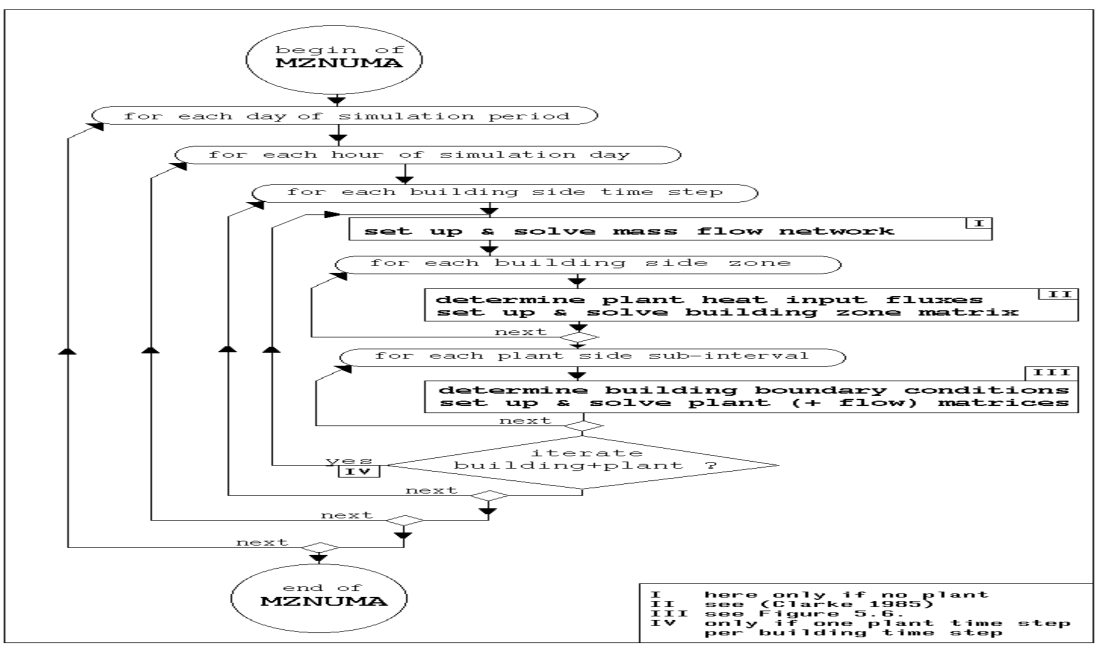

Figure 7 Indicative flow chart showing the main loops in the simulation process for a combined building and plant configuration

Figure 7 visualizes ESP-r's main numerical controller (MZNUMA) which controls the simulation process for combined building and plant configurations. As indicated in this diagram, the overall configuration simulation time increments may be smaller than one hour.† A complete configuration time step involves the evaluation of all building-side zones followed by the processing of the plant system equations. If a mass flow network is defined to exist, this is processed together with the plant system network. In case the user defined a building-only configuration, the mass flow network is processed prior to building zones.
At each overall configuration simulation time step the building- and plant-side state-space equations, and the mass flow network equations are generated and solved from up to five separate matrix equations. The building-side solution process is invoked once per user-specified time step. This process uses a matrix partitioning technique (ie. one partition for each building zone) as described by Clarke (1985). For the building, heat input or extraction by the plant are regarded as as known boundary conditions.
Since it is practice to process the plant equations at a greater frequency than building matrices (because of the different time constants), the plant matrix may be established at some sub-interval of the building time step. For the plant, the connections with the building are treated as excitations. Then the plant matrix is solved by a sparse matrix method as described above.

Division of the overall simulation problem in a building-side and a plant-side may leed to certain difficulties. When processing the building-side energy balance, heat input or heat extraction by the plant for the time step under consideration should be known. It is common practice to use plant side temperatures and mass flow rates from the previous time step in evaluating this heat exchange. When building-side control is based on a plant-side originating signal a similar time shift occurs. When processing the plant-side energy balance, the component losses are calculated with containment (perhaps building-side) temperatures which were calculated with plant-side state variable values from the previous plant time step. A similar effect may occur when plant-side control is based on a signal originating from the building-side.
One way to deal with this kind of problems, is to make use of a mechanism such as indicated in Figure 7 which could be labeled as a mixed direct/iterative solution scheme. At the indicated point in the calculation process, the plant heat input as assumed in processing the building side is compared with the plant heat emission as calculated when processing the plant side. If the difference exceeds some user specified value, the whole building and plant solution process is repeated based on the newly calculated values. If either the absolute or the relative difference between assumed and newly calculated building/plant heat exchange satisfies the user specified tolerances, the model proceeds with the next time step. In order to prohibit excessive number of iterations, the iteration process may only be enabled when the user specifies one plant time step per building time step.

Simulation

As an example of the operation and interaction of the plant and building models a few typical days in January are simulated. The climate data used represents a typical year for the South of England.

In winter psychrometric processes the active components in the plant network are the pre-heat, re-heat and humidifier.
Pre-heating serves two functions, the first is that varying the output of the heater allows control of the amount of moisture evaporated into the process air at the humidifier. The second function performed by the pre-heater is to prevent freezing of water in the humidifier.
Variation of re-heater output allows control of the supply air dry bulb temperature. The humidification process serves to offset the low moisture content of the outside air.
The display area is the focus of the simulation, with the plant attempting to control the zone dry-bulb temperature to 19 $°C$ and a relative humidity of 50%.

† Note that by choosing a time step the user implicitly decides to ignore the process dynamics within the time step

The simulation is run over the period 7-9 January. The time-step used on the building side is 15 minutes, while on the plant side the time-step is 1 minute. The time-step is kept small to capture the dynamic performance of the plant components, and also to avoid iteration problems which occur with larger plant time-steps. It should be noted that this has nothing to do with the solution process itself, but is a consequence of how the problem is defined; ie here we use flux controlled coils which means that normally the heat input or extraction will either be maximum or minimum. Now if the time-step is too large, this will cause the temperature rise or drop to be too large, resulting in oscillating behaviour.

Results

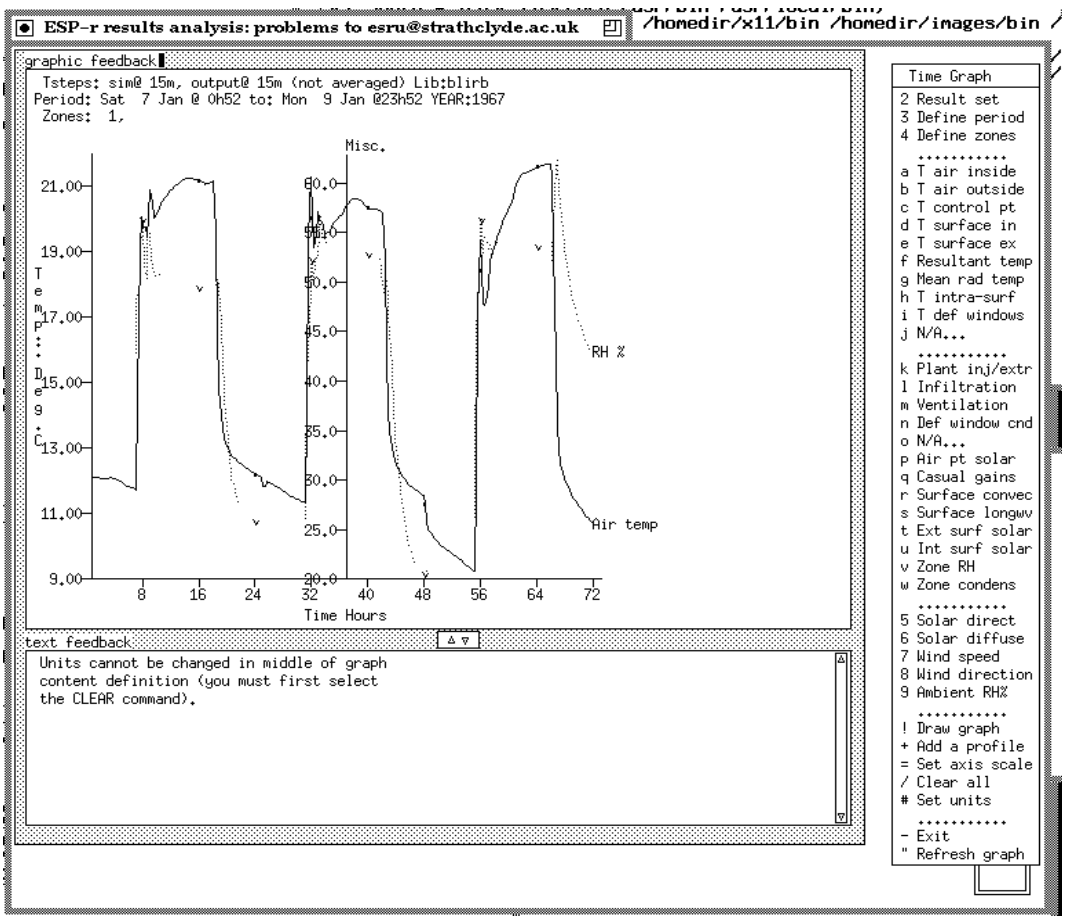

Figure 8 Results analysis module showing the zone conditions

Some of the results of the simulation process are shown in Figure 8. It can be seen from the results that the control system performance for relative humidity within the zone is good throughout the simulation period. Relative humidity is held close to the prescribed set-point of 50%. However the dry bulb temperature is consistently higher than the set-point of 19 $^{\circ}C$ for prolonged periods during the day. This can be attributed to poor controller tuning. Clearly, controller tuning parameters could be altered to reduce further such factors as overshoot and deviation from set-point.

It should be noted that - in the current case-study - the capacities for each actuated component are fixed for the duration of any particular control period. These could be altered in a dynamic manner by means of some (weather) compensating control loop. Also, controllers often tend to act in a 'conflicting' manner, e.g. cooling and humidification control is one such example. For such cases, a 'control supervisor', facility is required to resolve such conflicts. (A model for such a facility is currently under development.) Although the results might be interpreted as poor control behaviour, it is also important to note that this is due to the performance of the "real controller" rather than of the simulation tool. This example illustrates that simulation can be utilised to identify poor system performance.

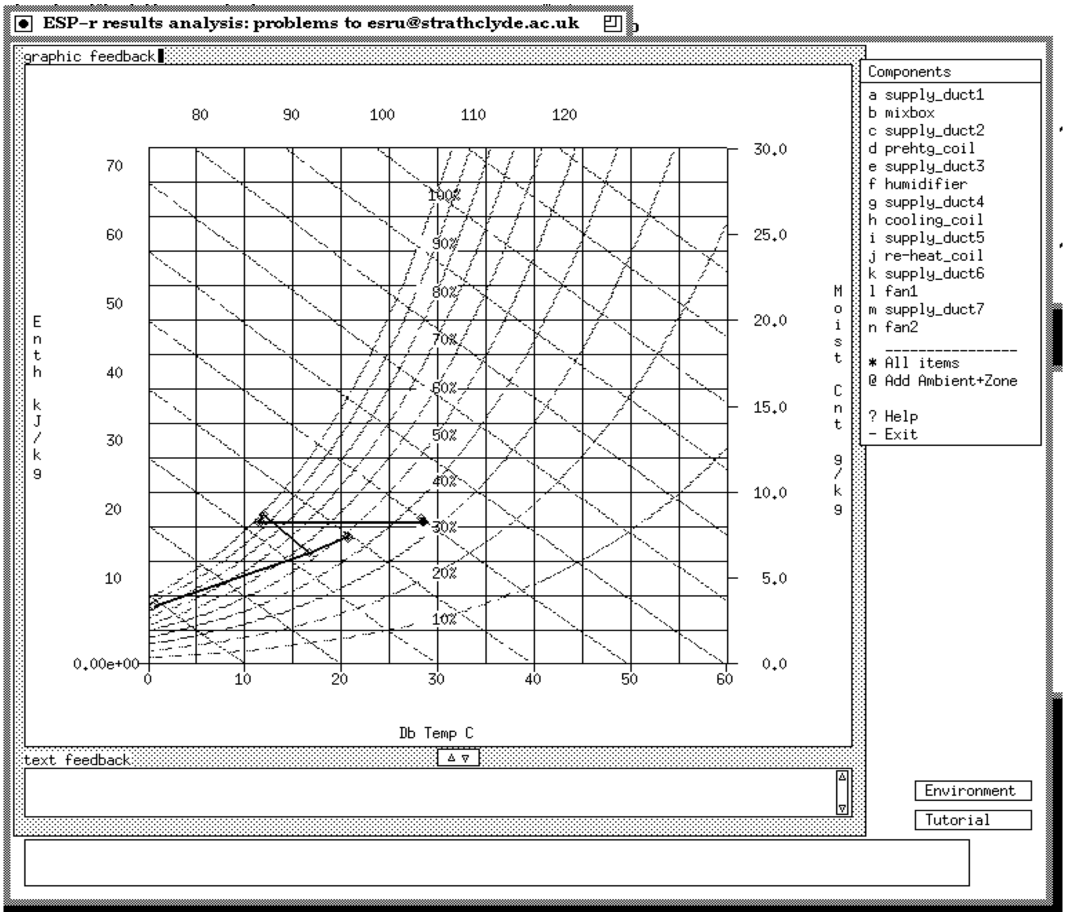

Figure 9 Results analysis module showing the psychrometric processes occurring within the plant.

Figure 9 shows the various psychrometric processes occurring within the plant when the controls are active. These processes include mixing between fresh and return air, humidification, and re-heat. The temperature of the binary mixture entering the pre-heat coil is such that pre-heating is not required in this instance. A slight amount of cooling is required to off-set a degree of over-humidification in the washer. However this could be overcome through modification of the psychrometric control algorithm such that it will allow tighter control of the humidification process.

4. CURRENT DEVELOPMENTS

As indicated in the introduction, many researchers in various locations are now working with the ESP-r environment. In most cases this concerns application and validation of the system, but in an increasing number of cases this also involves new developments. Sometimes this is adding a small feature or improving certain aspects of the system, in other cases it involves completely new modules. Often this work is done in the context of post-graduate studies.

Current developments introducing adaptive gridding techniques (enabling explicit modelling of three dimensional phenomena such as thermal bridging and constructional edge effects), variable material properties, modelling of combined heat and moisture transfer, artificial/ˆdaylight modelling, and design tool cooperation (eventually leading to integrated building design systems) are not covered in this paper.

Here we just want to indicate some developments which most pertain to system simulation in buildings.

Conjoining CFD and Building Simulation

This project (Negrao 1994) has implemented within ESP-r a CFD module capable of solving dynamic three-dimensional turbulent airflow and buoyancy effects. The model uses the widely used $k-\varepsilon$ model for representing turbulence, the SIMPLE algorithm (Patankar 1980) for linking pressures with velocities, a staggered (possibly non-uniform) grid, and an up-wind scheme to approximate the density in the velocity cells.
The CFD module is used to obtain the mass, energy and momentum state of a space when connected to a nodal network representing the distributed flowpaths throughout the building, its plant and systems. In this way the entire building system can be processed simultaneously, with increased resolution within user nominated spaces.

Plant Simulation

A continuing effort is expanding the existing plant components database. Developing or adjusting models is a difficult and time-consuming process which can be alleviated by reusing existing models. In this context ESP-r now enables incorporation of "external" models like for instance TRNSYS type models. Another mechanism is by creating a "neutral model format"-translator which will enable automatic incorporation of models written in NMF (Bring et al 1992).
In terms of the plant components database recently additional models, based on energy and mass conservation, have been added for a range of components as found in air conditioning systems (Aasem 1993), and in solar systems. In addition work has begun (Kelly 1994) on the modelling of combined heat and power (CHP) units. These component models can then be connected to define a plant system and subjected to a dynamic analysis simultaneously with the building.
Near future efforts will concentrate on the development of a power module to allow simulation of electrical loads and sources within the building model. This development, as well as augmenting plant and CHP models will also allow the simulation of building-oriented self-contained power systems containing wind, photovoltaics, power storage and other electrical power sources.

Another project (Chow 1993) is attempting to establish mathematical models for each of the physical processes that occur within plant components (boiling heat transfer, flame radiation, fluid flow, etc.) and to use these to explore the possibility of automatically constructing component models from primitive parts. If successful, this will allow all component models to be synthesized from a small number of primitive models rather than, as at present, each component requiring a unique mathematical model. In this way, it will be possible to create a simulation system which is plant-type independent while being able to handle all plant types: just as contemporary building simulators are essentially building type independent.

Control System Simulation

The objective of this project (MacQueen 1993) is to extend ESP-r's family of controllers so that they cover a broad spectrum from simple systems, such as thermostatic devices, to state-of-the-art Building Energy Management Systems (BEMS) capable of reacting to changes in both the external and internal environments associated with a building in a fully integrated way. This entails the development of new *sensor* and *actuator* models capable of multiple variable action, *control algorithms* to represent advanced sensor-to-actuator relationships and *control executives* to coordinate the above against the user specified control strategy.
Recent developments in terms of control involve both "traditional" controllers like PID, duty cycle, and cascade controllers, but also novel controller types like fuzzy logic rules-based and the use of ESP-r as a simulation-based logic controller (where ESP-r is the process model which is used to forecast future reality, and the controller algorithm is actually a set of logic statements). In terms of application the latter

facility can be used as a design tool, a commissioning aid, a fully adaptive controller with its parameters re-evaluated at every time-step, or an on-line BEMS controller (for example optimum start/stop controller or adaptive PID controller).

Validation

Significant effort is being expended, particularly in Europe, on the topic of model validation. In recent times, major contributions to the development of a coherent validation methodology have been made by for instance the International Energy Agency (Judkoff 1994) and the Commission of European Communities (CEC 1993). Because of these efforts a consensus has emerged on the components of such a methodology: review of theory and algorithms, code checking, analytical testing, inter-model (or program) comparison, sensitivity analysis, and empirical testing.
The next important step is to organize the methodology so that it can be routinely applied in practice. Within the ESP-r environment this goal is being pursued by the implementation of several validation "aids" like: CASE tools to help detect/eliminate programming errors; analytical tests which can be invoked whenever the code is upgraded; a series of on-line benchmark tests suitable for inter-program comparison; test cases for which substantial monitored data exists, and supporting the statistical comparison of predicted and monitored data; and last but not least improving user feedback through improved user interfaces and more extensive consistency and range checking.

5. CONCLUSIONS

This paper has described and demonstrated an approach for the simulation of combined heat and fluid flow in a building / plant context. Typically a model's focus is either the building or the plant side. Here we have a simulation environment of combined potential, which attempts to process the entire system in the dynamic state and to the same level of detail. The present performance of the model indicates that it is now feasible and practical to solve complex building/ plant/ flow networks on currents small computer systems. This enables an integral approach of the thermal interactions between a building, its environmental control system, the occupants, and the context.

Computer simulation using advanced and state-of-the-art models, is quickly becoming accessible to the (environmental) engineering community. It is now ready to be applied on a wide scale in engineering education and research, as well as in practice.

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