Approaches and Constraints in the Simulation of Solar Systems

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Active and passive solar designs work on the basis of complex interactions of conduction, convection, radiation, mass flows, feedback and control mechanisms which are inherently dynamic and often tightly coupled. Historically the appraisal of such designs has been done in the context of one domain i.e., fabric, plant or flow analysis, with the other facets of the design handled as abstractions with limited interaction with the core domain. An improved approach for multi-domain problems is to allow the user to approach all facets of design at a similar level of detail and to allow analysis at several levels of granularity. This paper will deal with how such a task might be approached within the context of a dynamic simulation tool, what constraints are imposed on the process and the future of simulation in mixed domain design.

INTRODUCTION

Active and passive solar designs work on the basis of complex interactions of conduction, convection, longwave and shortwave radiation, mass flows, feedback and control mechanisms. Such processes are inherently dynamic and since they are often tightly coupled their interactions can be important to the performance of the design. This makes it difficult to appraise the performance of such designs unless the user has acquired intuitive skills via past work or has access to analysis tools. Analysis tools are particularly important in the case of larger buildings where the value added might be substantial but where uncertainty is not tolerated.

Although the professions have a number of analysis tools to assist in the design process, many of these impose limitations on the user in terms of fixed assumptions, simplified models of the various interactions and processes or a sequential or steady-state rather than simultaneous and dynamic treatment.

Another characteristic of many analysis tools is that they focus on the building or plant or mass flow side of the overall problem domain.

- In the first approach the influence of the plant system is more or less neglected by over-simplification of the plant; it was/is common practice to base the estimation of energy consumption on some presumed, imposed indoor air temperature profile. Most building side tools require as input rates of infiltration and how much air flows between rooms - parameters which are not easily established.
- In the second approach the complex building energy flow paths are usually grossly simplified, and the building (or each building zone) is commonly regarded as just another component which in this case imposes a thermal load on the plant.
- In the third case, boundary conditions are usually fixed and analysis is focused on a moment of time. This isolation of flow precludes integrated control with plant systems and valuable feedback to the fabric solution.

Passive solar heating and passive cooling designs are predicated on the dynamic interplay of the microclimate, building fabric, fenestration and the movement of air. Active solar designs introduce plant and control systems but rarely outside the context of a building. Ignorance of any facet of such designs makes it difficult to predict overall performance.

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We want to start from the principle that building, plant and mass flow ought to be approachable at similar levels of complexity and detail while taking into account all major fluid flow and heat transfer couplings. Clearly, the ability to model in detail all aspects of the energy performance of a building increases the potential for realistic assessments of complex design problems. This paper will deal with how this task might be approached, what constraints are imposed on the process and the future of simulation in mixed domain design.

THE SIMULATION TOOL

This paper will use as its point of reference the ESP-r building, flow and plant simulation environment (Clarke 1985). It may be characterised by:

- a research orientation, with the objective to simulate the real world as rigorously as possible and to a level which is consistent with current international research practice.
- an intention of taking fully into account all building and plant energy and mass flows and their inter-connections.
- the provision of a rich set of descriptive elements at several levels of granularity from which the user may evolve models.
- the source code being available to the research community.
- a well documented system: it is heavily commented within the code itself, it comes with training and inbuilt tutorial material, and there is an extensive manual which is updated on a regular basis (Aasem et al. 1993).

ESP-r is a finite volume program in which data describing the problem (geometry, constructions etc) is transformed into a matrix of state-space equations and the flows of energy and mass in the fabric, plant components and mass flow networks are solved.

It treats mass flow via a user defined network of flow paths which is populated by components such as cracks, ducts, pipes, windows, doors, filters, fans, pumps and dampers. At each timestep, mass balance is solved for the network based on current boundary conditions, temperatures, control logic, buoyancy and pressure distributions. The mass flows are taken by the solver and their energy implications merged into the fabric and/or plant system solution.

Plant systems are treated as networks made up of a number of nodes. These nodes represent discretised regions of individual components connected together to form the whole network. Energy and mass transfers are accounted for by the dynamic models representing each single/multi-node component. At each time-step and for each component, the coefficients in the energy and mass balance equations are evaluated for each node and then the whole network is solved simultaneously for temperatures and mass flows.

The system has evolved significantly in recent years (e.g. Hand and Clarke 1993, Hensen 1991, Aasem 1993) and has been influenced by observations of its use in architectural and engineering practices, other research groups, and as a medium for teaching building and plant systems. Recently its research bias has been tempered by use as an in-house consulting tool. Validation has become an increasingly important topic: of particular note is the model validation work of passive solar systems undertaken within the European PASSYS project (Jensen 1993).

While admitting that the individual domain analyses are far from perfect, it is the **interaction** between domains that is emerging as a particularly powerful agent in the design process. Indeed, recent work which has combined fabric, mass flow and plant systems gives every indication of producing temperature, flux and flow patterns that might be expected in practice. It now becomes possible to contemplate the optimisation of the relationship between design elements as well as the components themselves.

CONSTRAINTS

There have been a number of historic constraints on the use of simulation programs, such as their computing demand, the need for access to workstations, the steep learning curve and the difficult transition between the ubiquitous 'toy' exemplars vendors distribute to real problems.

The limitations related to computing demand have essentially fallen away - workstations are commodity items and are competing with the high-end of the personal computer market. Graphic user interfaces and window managers have become common, intuitive and robust.

The learning curve is less than it once was not only because of the evolution in interfaces but due to a mature set of support facilities to aid in simulation project management, quality assurance and training (Hand and Clarke 1992). This allows not only complex problems to be evaluated but for models to evolve significantly over a limited timescale. Rather than using simulation at the end of the design process it is possible to employ it much earlier and iteratively within the design.

In the context of active solar systems the use of simulation tools has been constrained by the dearth of plant and flow components, the often complex controls required and typically immature support facilities and hostile interfaces. Recent work has broadened the range of plant components, introduced levels of representative complexity, improved the speed of the solver and eased the descriptive task somewhat. Instead of having to be a dedicated plant modelling expert it is now possible for experienced users to venture into this problem domain.

Of course, there is always room for improvement. With respect to solar systems, current research is focused on developing controller types which are better suited to solar systems and whose logic is based on multiple sensors. Component models required include a stratification sensitive water tank, rock bed and evaporative coolers. Currently mass flow is calculated for air and water - the addition of other transport fluids would be of benefit.

For passive solar design ESP-r is quite mature in the facilities offered and in the analysis which can be performed. Currently outstanding issues are increasing the resolution of the external longwave environment and introducing two and three dimensional heat flow facilities. There are also several mass flow descriptive elements such as large openings and single-sided ventilation which await international research efforts.

The constraints are predominantly concerned with the need to gain experience with progressively more complex problem types and problems which combine the various domains. Currently there are many more exemplars relating to fabric and/or mass flow than plant systems, so a greater effort is required to master the facilities related to plant systems.

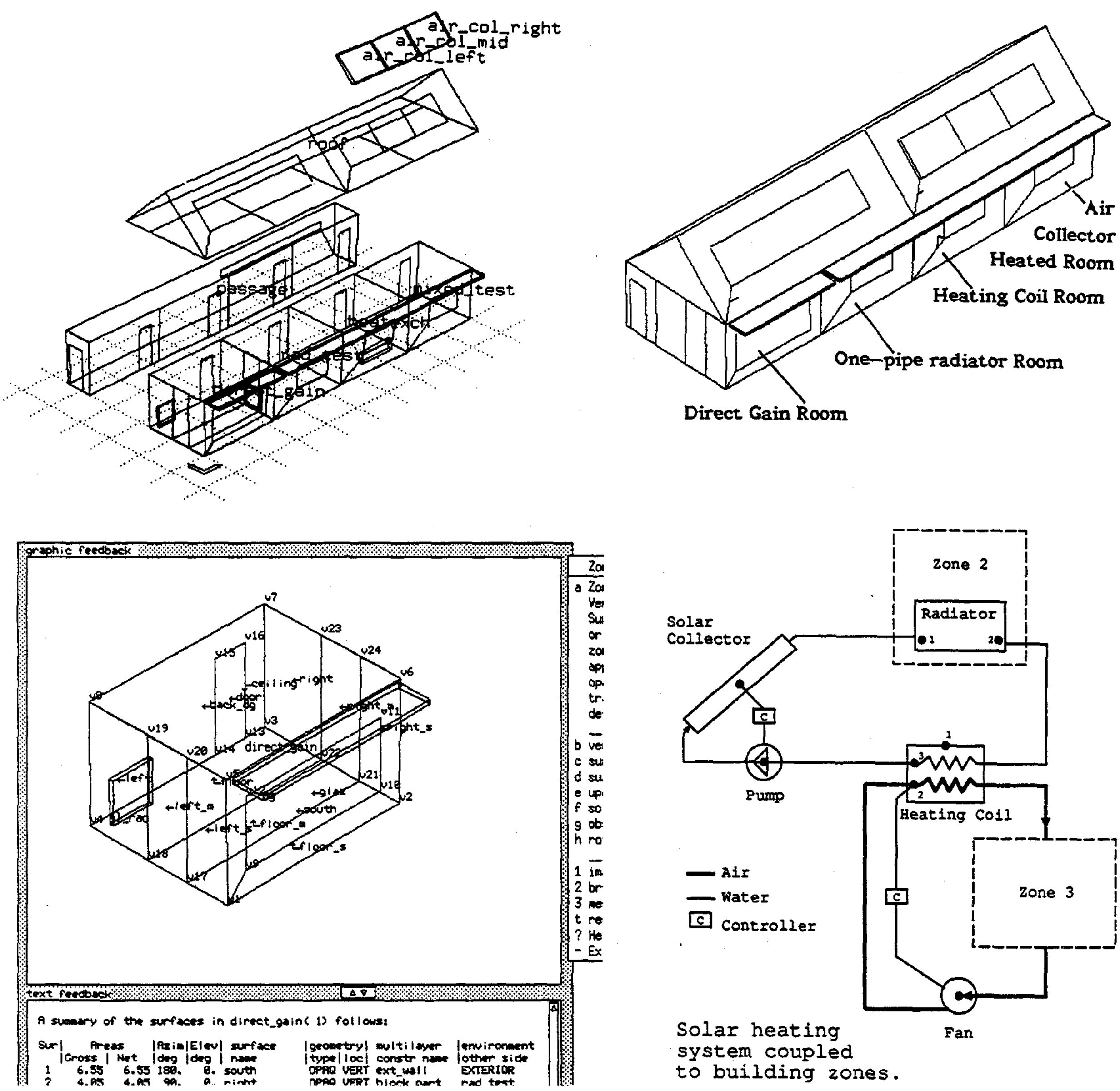
EXEMPLAR AND METHODOLOGY

To demonstrate the fitness of dynamic simulation for multi-domain simulation problems such as solar systems, a portion of a building including several active and passive solar design strategies (Figure 1) was taken and a model created which includes simultaneous treatment of building fabric, water and air mass flow networks, detailed plant components and interprocess control. The rationale for this model is the need to determine the *essence* of the building and the performance parameters required to appraise the various design strategies. In the following paragraphs the reasoning behind the evolution of the model is provided.

The first scheme in the left room ("direct gain room") is to use direct solar gain as much as possible with an oil filled electric radiator as a backup heating source. The middle two rooms are heated via a solar sourced wet central heating system and the right zone ("air collector heated room") via an air solar collector.

The wet central heating system is composed of a $10m^2$ liquid solar collector feeding a nominal 1kW radiator in the "one-pipe radiator room", a fan-coil unit in the "heating coil room", a variable speed pump (sensing collector temperature) and then back to the collector.

- ESP-r defines a thermal zone as a volume of well mixed air bounded by surfaces, to which various casual gains, controls and mass flows can be applied. Each of the rooms in Figure 1 should thus be treated as a thermal zone.
- Being a 'Passive Solar Design', the temporal interaction with the sun is of interest, particularly in the direct gain room. Viewing the building model from the sun's position at different times of the day confirms that an hour by hour shading and internal insolation distribution analysis is required in all south facing rooms and that subdivision of the floor and partitions is justified in the direct gain room.
- Infiltration is via crack flow at each of the windows as well as soffit vents in the roof. There are also grills in the doors so intra-zone flows are possible. ESP-r allows the user to define a schedule of flows, but in the absence of measurements it is appropriate to have the system determine dynamic flow patterns.
- Because there is no air conditioning in the model it is likely that occupants would choose to open windows if the room exceeds a comfortable temperature. In this model, partially open windows are represented as common orifice flow components with the inbuilt on/off controller used to compose a window opening scheme.
- In addition to the window opening strategy, the heating coil room and air collector heated room also have an extract fan. In combination this would result in the extract fan being switched on first and then, if the room continued to overheat, the window would be opened. The user has the choice of describing the fan as a flow inducer with a pressure/flow curve or approximating it as a volume flow component (for initial sizing).



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A summary of the surfaces in direct_gain( 1) follows:

Sur|     Areas    |Azim|Elev| surface       |geometry| multilayer  |environment
   |Gross | Net   |deg |deg | name          |type|loc| constr name |other side
 1    6.55   6.55 180.   0. south          OPAQ VERT ext_wall      EXTERIOR
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Figure 1: Building, flow and plant details

- To represent the air solar collector an encapsulated representation, such as a plant component, or an explicit representation could be used. The latter has been chosen since this allows all of the internal and external shortwave and longwave radiation and thermal mass to be explicitly treated. There will be a temperature gradient across the air collector and this has been approximated by representing the collector as three adjacent zones.
  To operate the collector, three nodes and a fan have been included within the mass flow network and linked to the air node of the air collector heated room. This level of resolution should provide a reasonable indication of how such a system would perform. If higher resolution was required, the collector could be further subdivided.
- To demonstrate an encapsulated rather than explicit representation, the liquid solar collector is a single node plant model based on the flat plate solar collector algorithm described in the TRNSYS manual (TRNSYS, 1983). In this case the amount of energy transferred to the collector water is evaluated by the algorithm and then used in the energy balance equation to calculate component temperature.
- The single pipe radiator is represented by a dynamic two node plant model in which the capacitance nodes are coupled to the inlet and outlet connections. An eight node model is also available but because the object of this example is focused on the thermal interaction between plant and building zones rather than on the accuracy of the individual models, it was decided that the two node radiator model is adequate.
- The electric oil-filled radiator component in the direct gain room is included to provide backup heating and is represented by a single node model. The maximum output from this radiator is 700W. While an ideal control could have

been used, the choice of a plant component means that the timelags associated with the heater are taken into account.

- The heating coil component is represented by a 3 node liquid-to-air model. The first node represents the solid material, the second represents the air and the third node represents the water in the coil. The coil is fed by the radiator return water. The water pump maximum flow rate is 0.055kg/s when the collector water temperature is above 35°C. The air flow through the coil is supplied by a single node fan controlled by a proportional controller sensing the coil air node temperature. The fan maximum flow rate is $0.06m^3/s$ when the air temperature in the heating coil exceeds 18°C.

The period selected for the simulation was 25-26th April with boundary conditions from the 1967 Kew (London) climate collection, plus an appropriate start-up period. The building time-step was 15 minutes while the time-step for the plant was taken as 90 seconds.

Putting aside the fact that this particular juxtaposition of design elements is arbitrary, it omits storage components and auxiliary heating and is unlikely to win any design awards, it is a fair test of a thermal simulation tool.

DISCUSSION

Figure 2 shows the variation of component temperatures with time. It can be seen that the water temperature is highest at the solar collector and gradually decreases as the water flows through the water radiator, where heat is transferred to the one-pipe radiator room, and through the heating coil in the heating coil room where more heat is transferred to the incoming air.

Figure 3 shows that the fan and the pump are delivering maximum flow rates when both the water temperature at the solar collector and the air temperature at the heating coil are at the desired temperature. No flow is established when there is no useful heat energy to be transferred to the zones.

The overall performance of the model is shown in Figure 4 where line '1' is the temperature of the direct gain room, '2' the one pipe radiator room, '3' the heating coil room, '4' the air collector heated room, '5' the passage and '6' is the roof. The first day of the simulation is cloudy and the single pipe radiator and the air collector do not provide enough heat to bring the rooms up to 19°C. The latter does not even begin to supply heating until mid-day. The heating coil is adequate only in the afternoon and the oil filled radiator would appear to maintain the direct gain room at a comfortable level. On the second day of the simulation the solar heating is adequate for all the rooms except that the air collector is not active until 10h00.

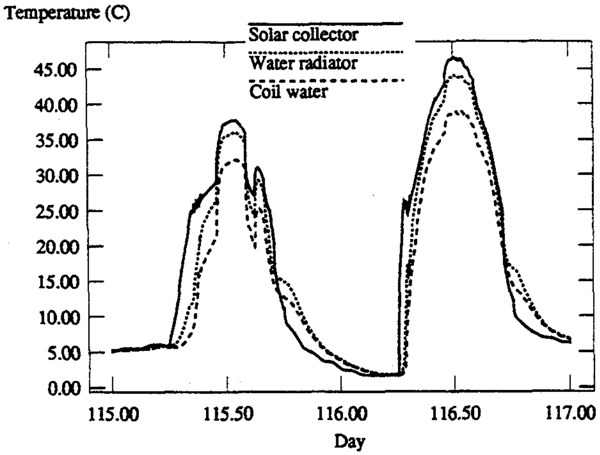

Figure 2: Variation of component temperatures.

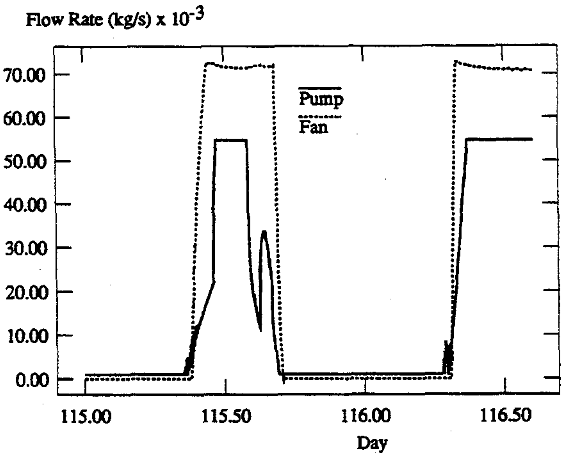

Figure 3: Variation of component flows.

The mass flows within the room heated by the air collector are shown in Figure 5. There is a background crack induced infiltration, periods where approximately $150m^3/hr$ flows from the air collector and peaks of $250m^3/hr$ on the second day. The peaks coincide with the room temperature reaching the extract fan setpoint temperature.

A particularly powerful attribute of a multi-domain simulation tool is the ability to advise the user on the various flux paths within a room (such as in the following listing), surface or plant component.

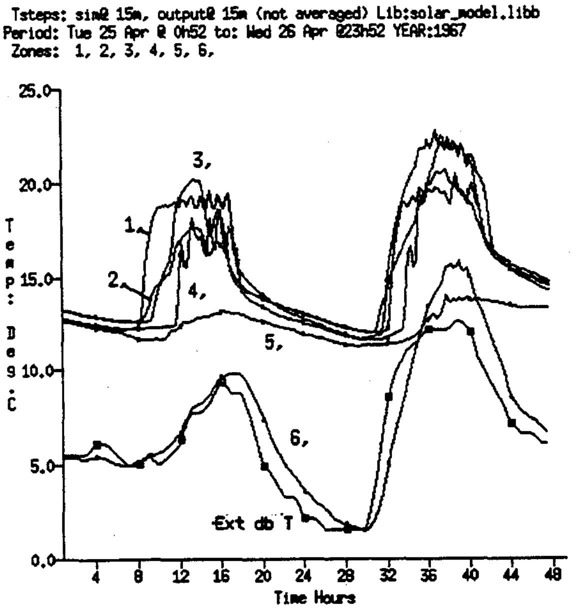

Figure 4: Room temperatures.

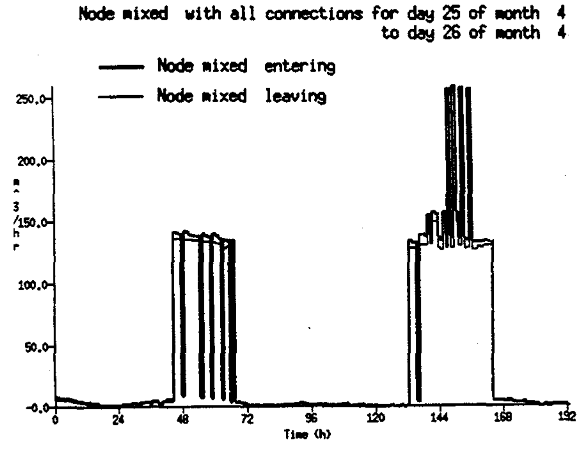

Figure 5: Flows in the air collector heated room.

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Causal energy (kWhrs) @ air point in rad_test
Tue 25 Apr @ 0h52 to: Thu 27 Apr @23h52
Tsteps: sim@ 15m, output@ 15m (not averaged)
                              Gain       Loss
Infiltration air load        0.000     -0.734
Ventilation air load          0.000     -0.060
Uncontr'd casual gains        0.000      0.000
Controlled casual gains       0.000      0.000
Opaque MLC convec: ext        0.127     -1.267
Opaque MLC convec: int        0.459     -7.562
Transp MLC convec: ext        0.105     -0.712
Transp MLC convec: int        0.000      0.000
Convec portion of plant       9.662      0.000
Totals                       10.352    -10.335
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Graphs and tables are the means by which a simulation tool "tells the story" of the design. It is the clarity of such presentations and the ability to explore flux and flow throughout a model that is particularly useful within the design process.

SENSITIVITY

Simulation is an iterative process where simulation results provide clues as to the fitness of the model as well as the performance of the design. Many users will as a matter of course go through several simulation/appraisal iterations to find optimal flow rates, setpoints and the like. It is less common, but worthwhile, to carry out sensitivity studies to verify whether the methodology and granularity of the model is appropriate.

An example would be a test to see if an ideal control is a reasonable substitute for an oil filled radiator. Figure 6 shows the temperature patterns of the two variants and Figure 7 the energy injections. The oil filled radiator inertia causes both a delay and a sawtooth temperature response. The user must decide if ideal control is a reasonable approximation in terms of a particular design problem. The ability to recover detailed performance data is an attribute of comprehensive thermal simulation tools and can be of great value in supporting such decisions.

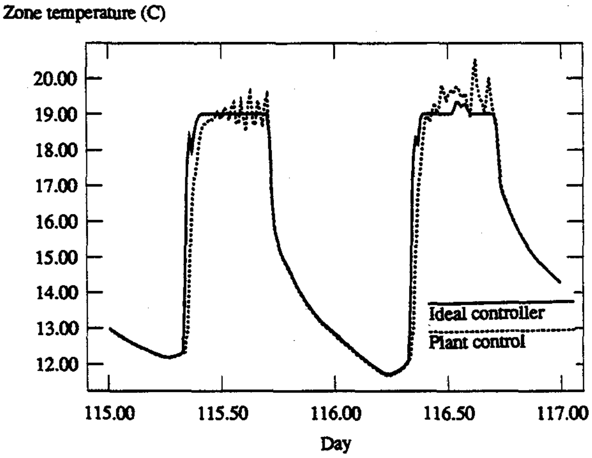

Figure 6: Direct gain temperature sensitivity.

Another sensitivity study would be to look at the changes in performance vis-a-vis solar radiation distribution. It is straightforward to substitute a fixed internal insolation distribution for the timestep based distribution. Similarly, the choices of subdividing the surfaces within the direct gain room or using an extract fan instead of a window opening scheme are based on a parametric analysis.

Undertaking such sensitivity studies requires that either the model or some simulation parameter is changed. The user has the choice of evolving the model for each design variant and running separate simulations or representing both the base case and variant within the model by replicating and translating zones. For models of limited complex-

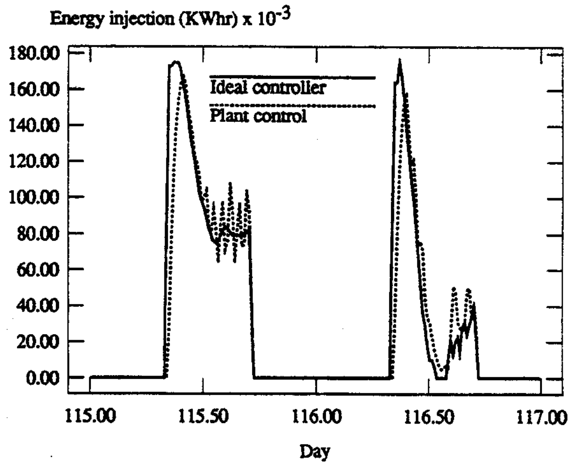

Figure 7: Direct gain energy injection sensitivity.

ity the latter technique does not usually impose much of a computational burden and the user is able to compare directly all of the state variables.

An experienced user will have acquired his/her intuition as to the use of the tool by running many such sensitivity studies. While design changes and sensitivity studies imply staff and computing resources, many require only a few moments to perform. In the current design the authors fine-tuned the flow rates and setpoints interactively by monitoring selected parameters during the simulation. Design changes such as subdividing the surfaces in the direct gain room and running a sensitivity study required on the order of twenty minutes.

CONCLUSIONS

Multi-domain design problems such as active and passive solar designs work on the basis of complex interactions of conduction, convection, radiation, mass flows, feedback and control mechanisms which are inherently dynamic and often tightly coupled. For problems of this type the paper has demonstrated an improved approach to the use of simplified or single domain design tools, based on the use of a dynamic thermal simulation tool which has the ability to treat building fabric, plant and mass flow on an equal footing.

Given the availability of increasingly powerful and inexpensive computing equipment, the computing constraints of using simulation as a design tool have essentially fallen away. While simulation continues to demand staff and training resources, the ability to assess complex multi-domain designs can lead to performance enhancements which are beyond the scope of other appraisal techniques.

It has been found that rather than constraining the user to the problem types and analysis modes implicit in a simplified or single domain tool, the user is free to define concise descriptions of the problem and to vary the level of descriptive granularity so as to focus on the essence of the problem and the interactions within a design.

It has been found that for multi-domain problems, the tool must provide unambiguous feedback as to the form, fabric and networks which constitute the model. Further, to allow the user to clarify methodology and representation issues as well as confirming the relationships between elements of the design, it is essential that the user is able to explore flux and flow throughout a model at various levels of granularity.

REFERENCES

Aasem, E. 1993. *Simulation of Buildings and Air-Conditioning Systems in the Transient Domain.* PhD Thesis in preparation, University of Strathclyde, Glasgow.

Aasem, E.; J.A. Clarke; J. Hand; J. Hensen; C. Pernot; P. Strachan. 1993. "ESP-r A Building and Plant Energy Simulation System, Version 8 Series." ESRU Publication. Faculty of Engineering, University of Strathclyde, Glasgow. (Feb.).

Clarke, J.A. 1985. *Energy Simulation in Building Design.* Adam Hilger Ltd, Bristol and Boston.

Hand, J. and J.A. Clarke. 1992. "Passive Solar Programme: ESP Support for the Performance Assessment Service, Report for Project E/5A/CON/1249/2024 Energy Technology Support Unit." ESRU Publication. Faculty of Engineering, University of Strathclyde, Glasgow. (Nov.).

Hensen J.L.M. 1991. *On the Thermal Interaction of Building Structure and Heating and Ventilating System.* PhD Thesis, Technische Universiteit, Eindhoven.

Jensen S.O. (Ed.), 1993. "Validation of Building Energy Simulation Models, a Methodology." Research Report from the PASSYS Subgroup Model Validation and Development, The Commission of the European Communities DGXII.

TRNSYS, 1983. *A Transient Simulation Program.* Solar Energy Laboratory. University of Wisconsin-Madison.