PRACTICAL SIMULATION OF BUILDINGS AND AIR-CONDITIONING SYSTEMS IN THE TRANSIENT DOMAIN

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ABSTRACT

This thesis is concerned with the deployment of energy simulation and modelling as a tool for achieving energy conservation measures in buildings. It deals with overcoming the barriers to practical application of simulation to complex building and plant systems using a state-of-the-art energy simulation environment so that its full potential can be delivered to the profession.

A simulation approach which treats the building and the plant as an integrated dynamic system has been pursued. A historical review of one energy simulation environment, ESP-r, employing this approach is presented. The barriers to practical simulation in the ESP-r system are pointed out and the resulting development areas are outlined.

The theory underlying the simultaneous approach to plant modelling is addressed in detail. Issues concerning the efficient solution of plant networks and numerical stability to the solution are addressed.

Modelling of some common components encountered in air conditioning systems is presented. The modelling technique which is based on the control volume principle and used in the development of component models with a varying degree of detail, is elaborated. The installation procedure of new components within the ESP-r system is described. The method adopted in importing TRNSYS type components within the ESP-r system is explained.

The issues related to validation are addressed and are applied using a comprehensive validation methodology consisting of analytical, code and theory checking, inter-model comparison and empirical methods.

Application of the new features and enhancements carried out on the ESP-r system are presented. Different plant arrangements which resemble real systems are simulated based on both hypothetical and consultancy applications.

Issues related to future trends in building energy simulation are addressed especially in relation to: the development of a centralized library of components expressed in a neutral model format; the modular approach to model construction under a knowledge-based environment such as the EKS; and the application of an intelligent front end to simulation.

In conclusion, not only the practical application potential and robustness of the ESP-r system to plant simulation have been increased, but also its energy saving potential. However, in order to build on the achievements of the present study, more work is required in two areas. One is concerned with the modelling of refrigerant related components and the simulation of plant systems with more sophisticated control features, while the other is concerned with alleviating the problem of data availabilty through the implementation of a common library of components.

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CHAPTER 1
Introduction

1.1 Energy and buildings

At the beginning of the industrial age, fuel was cheap and plentiful. The development of devices to transfer heating or cooling energy to interior spaces of buildings enabled significant changes in building design practices. This meant that buildings equipped with suitable mechanical systems could be built for any climate. As a result the demand for energy has increased sharply requiring steps to be taken to legislate for energy conservation measures.

1.1.1 Energy conservation in the IEA countries

Conservation became a significant element of energy policy in member countries of the International Energy Agency (IEA)[1] at the time of the oil crisis of 1973-1974. This was demonstrated by the financial commitment of some IEA countries to intensify research and development in the area of alternative energy sources in order to reduce the dependency on oil imports. It is for this reason as well as for economic, environmental and social reasons, energy conservation became an important and necessary element in the overall energy policy of member countries of the IEA. However, it was concluded by the countries involved that alternative energy sources can not by themselves eliminate the growing risk of imbalance between supply and demand. The importance of energy conservation was demonstrated by the objective set by IEA energy ministers in October 1977: to hold down oil imports to 26 million barrels a day (mbd) by 1985.

The IEA also indicated that energy conservation should receive increased attention for the following reasons (IEA 1987):

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[1] Australia, Austria, Canada, Denmark, Germany, Greece, Ireland, Italy, Japan, Luxembourg, the Netherlands, New Zealand, Norway, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States of America are the member countries of the IEA.

- It is an economically attractive method for reducing oil import dependency.
- It results in the preservation of resources.
- It is consistent with environmental protection.

One common feature between Western Europe countries, Canada and United States of America is that buildings account for a very large proportion of the total energy consumed (CIB 1976, IEA 1989). When these countries are taken together, buildings consume about 40 percent of the total annual primary energy[2]. The bulk of the energy is consumed in the operation of space heating and cooling, ventilation, hot water, cooking, lighting and electrical appliances. It was also suggested (CIB 1976) that there are two major policy implications of these findings. The first is that buildings should constitute a priority target for energy conservation research and practical action. The second implication is that the planning of future energy consumption in new and existing buildings must be undertaken in conjunction with the planning of the level of future energy supply.

1.1.2 Energy conservation: National perspectives

In the United Kingdom, a similar energy utilisation pattern is experienced by the building sector. According to the statistics published by the department of energy (DOE, 1978), the energy consumed by end-users in buildings account for 40% of the total energy supplied. The energy usage in buildings is usually by heating systems for space and water heating. It was realised that a significant energy saving potential exists in such heating systems, especially if their efficiency was increased through the use of improved control, by the better matching of equipment to loads and by proper maintenance. It was also suggested that in addition to improving the efficiency of such systems, it is also equally important to reduce the rate of increase in the need for useful energy by means of thermal insulation of existing buildings, by designing new energy efficient buildings and by improving energy management.

1.1.3 Energy conservation in less developed countries

In contrast to the realisation of energy conservation in IEA countries, there is also a consensus amongst oil rich countries to legislate for energy conservation. For instance, the state of Kuwait, a leader in the Middle East for promoting and legislating for energy conservation practices, realised the

[2] Primary energy is the gross calorific value of the fossil fuels: coal, oil and natural gas or the equivalent of nuclear and hydro-electricity.

benefits of energy conservation not from the point of view of the balance between energy supply and demand, but rather from an economical and environmental standpoint. Kuwait has a hot and arid climate with occasional high humidity. The mean of the daily maximum and minimum dry bulb temperatures for the months from June to September are in excess of 40°C and 30°C respectively for coastal areas. Inland areas experience more of a desert climate with maximum and minimum mean temperatures, for same months, of 44.6°C and 27.1°C respectively. The cooling season is thus long and extends over eight months of the year with air conditioning required on a 24 hour per day basis for most of the season. Cooling degree-days for coastal areas amount to around 2800°Cday/yr to a base temperature of 20°C, higher than any of the North American cities listed by Sherman (1986). Over the past few years, electricity for air conditioning represented 60-70% of the peak load.

Figure 1.1 Sectoral consumption of electrical energy in Kuwait (MEW, 1989).

Figure 1.1 shows the sectoral consumption of electrical energy. It can clearly be seen that the domestic sector has the highest share of this energy. In addition, there has been an escalating increases in the demand for electrical energy and in the national cost for energy production. Currently, over 90 % of the generated electricity is subsidised by the government, imposing a large financial commitment. After the recent events of the Gulf war of 1991, in which a substantial amount of financial and energy resources were destroyed, there is an even greater awareness about the benefits gained from reducing the rate of increase in energy demand. It is for these reasons that the government of Kuwait continues to encourage the development of a code of practice for energy conservation in buildings.

1.2 Approaches to energy conservation

It is clear that there is a global consensus about the potential for energy conservation in buildings. To fully exploit this potential, there has to be some means by which conservation can be achieved and sustained. Some of the most important conservation measures taken to date by IEA countries include:

- publicity campaigns aimed at increasing the public awareness towards the need to save energy and to provide guide lines on how this can be done.
- building codes laying down minimal thermal parameters for new buildings.
- incentive schemes for retrofitting existing buildings.

In the development of these energy conservation measures, tools which can provide a thorough understanding of the complex energy and mass flows that occur in dwellings are of paramount importance. With the advent of powerful and inexpensive digital computers, a tool which is gaining popularity is simulation and modelling. In the approach the building is represented by digital information which can be processed for different energy utilisation scenarios in order to optimise performance at acceptable cost. Such a tool can also be applied at the design stage and prior to the construction of the building. For instance, for a given building design, issues related to the effect of thermal insulation; interaction of heating systems with building spaces; window orientation; and many others, on the thermal response of the building, can be investigated to obtain an energy efficient building design. Other important applications are concerned with the development of a code of practice for energy conservation in buildings. With such application, simulation and modelling tools are used to predict the thermal response of buildings when subjected to different energy conservation strategies so that rules and regulations can be established for the construction of new buildings. The other benefit of utilising such tools is that no additional capital is required since the investigation can be carried out on an imaginary building.

1.3 Conceptual building energy performance models

Many conceptual models have emerged since the realisation of the importance of modelling of building performance as a design tool. Baird (et al, 1984) indicated that most early models tend to fall into three main categories; engineering models, architectural models and energy models. Most engineering models are concerned with the energy consuming devices of buildings. They deal with a simple single building which may consist of energy consuming functions. Dubin and Long (1978) defined those functions as heating, cooling, lighting, power of equipment and domestic hot water. Integration in such models is achieved on the system level only. There is no integration with the building system.

Unlike engineering models which are concerned with predicting cooling or heating load requirements of a building, architectural models are concerned with the prediction of the indoor temperature resulting from a given configuration of the building fabric. Banham (1969) identified three modes of environmental management for architectural models: the conservative mode, the selective mode and the regenerative mode. The conservative mode is concerned with the application of massive constructions to dampen the external fluctuations in temperature and hence reduce the amplitude of inside temperature fluctuations. The selective mode is concerned with the selection of desirable climatic elements while rejecting undesirable elements. For instance, a window in a building admits daylight and solar heat gain while preventing rain and cold air from entering the inside space. The regenerative mode is concerned with the use of energy derived from non-renewable energy sources such as associated with artificial lighting and air-conditioning. Markus and Morris (1980) suggested a model of climate, building, shelter and people based on the concept of continuity of space and on the second law of thermodynamics. It comprised two overlapping environments. The first environment consists of a resource environment and a shelter system, while the second environment contains the human system and a resulting controlled environment. Their model illustrated the links between the building occupants and the use of fossil fuels.

Engineering and architectural models allow the effects of external climate, the building fabric and energy consuming systems to be taken into account. One element missing here is the influence of occupant on the overall energy performance of buildings. Occupants can directly alter systems performance through controllers and can also contribute to building casual gains and these changes can greatly affect the thermal response of buildings. Brander (1980) made use of the three basic systems which he designated as energy systems, non-energy systems and human systems. The energy system is analogous to the engineering model described above and the non-energy system is analogous to the architectural model. Both these systems are controlled by human systems such as working hours, thermostat settings and occupant behaviour. Occupant behaviour determines how the energy system is effected by the non-energy system such as drawing curtains and opening windows. In addition, occupants can directly effect the energy system by changing thermostat settings. The interaction of these three systems must be taken into account for any useful energy model.

The interacting energy flow paths encountered in buildings and their environmental control systems was illustrated by Clarke (1985) (see Figure 2.1). It can be seen that a complex multi-domain system exists in which there is simultaneous interaction between the different energy flow paths, the controls and the occupants. This indicates that in order to have a building energy model which is capable of representing the real world as closely as possible, the thermal interaction between the different domains must be represented. With such models, a building design strategy, similar to that shown in Figure 1.2, is envisaged. This can be contrasted with the design strategy adopted by a number of present energy modeling systems in which the design process is divided into two distinct stages, one stage concerned with predicting the energy requirements to satisfy the demands of the building activity, the other concerned with the modification of these energy requirements by the operating characteristics of the plant to give the energy actually consumed. The new design strategy allows for the modelling of a combined building/plant configuration in a simultaneous manner so that the problems associated with plant under/oversizing to match the load requirements of the building is minimised. In addition, the building/plant interaction allows for more realistic control strategies to be implemented in order to optimise performance.

1.4 Objectives of current research

The premise of this thesis is that where building energy models are to be used for the development of a code of practice for energy conservation in buildings, a model which offers an integrated, dynamic simulation is preferrable over simpler models. This is because a code of practice is expected to lay out the rules and regulations governing the application of thermal insulation, size and type of glazing, type of building materials, shading, ventilation, air infiltration, control and plant load requirements in the construction of new buildings, based on the calculations and predictions of the energy model. In this respect, the present research is a follow up of research activities undertaken by the Kuwait Institute for Scientific Research (KISR) in using an energy model for the development of such a

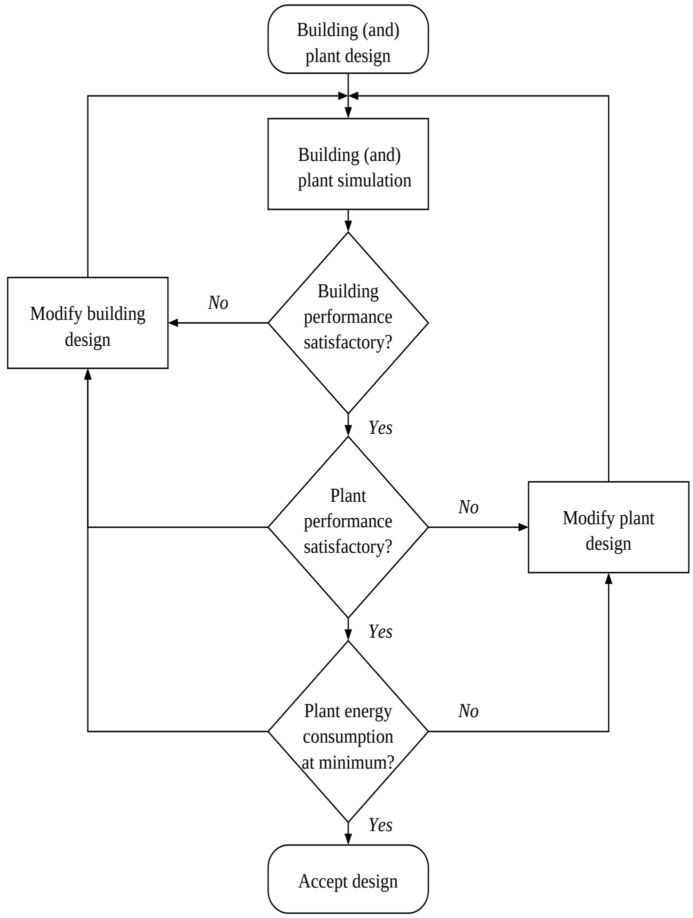

Figure 1.2 Design process in a combined building/plant simulation.

code of practice (MEW, 1983). However, in order to utilise an energy simulation model in such application, a number of existing barriers in contemporary models must be overcome so that a practical application to the simulation of combined building and HVAC systems can be attained. The HVAC systems considered for the present study are similar to those used in Kuwait (eg. air-conditioning systems).

Chapter 2 describes an energy simulation environment employing state-of-the-art techniques for the dynamic, integrated simulation approach. The system capabilities at the commencement of the present research with respect to plant simulation are described. The theory underlying the approach to plant simulation of this system is then elaborated in Chapter 3. Chapter4 then examines the commonly occuring air conditioning systems and identifies the essential components for which mathematical models are developed and installed.

Chapter 5 is concerned with the issue of validation with respect to individual plant components, whole plant networks and combined building and plant systems. Application of the extended system is illustrated in Chapter 6 in which a number of case studies of varying complexities are presented. Chapter 7 addresses new development issues in building energy simulation and finally Chapter 8 describes the conclusions drawn from the present research and identifies the areas requiring further work.

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CHAPTER 2
Energy Simulation in Buildings

2.1 Heat and mass flow regimes in buildings.

The combined building, plant and control systems were described by Clarke (1985) as follows:

> "The building, plant and control elements can be viewed as regions of vastly different time constants, with complex spatial and temporal relationships. Such system can be thought of as a network of time varying resistances and capacitances subjected to varying temperature differences. Rooms and constructional elements are volumes of fluid and solid matter characterised by thermophysical properties such as conductance and capacitance, and variables of state such as temperature and pressure. Super-imposed on this are the time dependent, perhaps non-linear flow-paths which interact in a complex manner"

The processes illustrated in Figure 2.1 are summarised in Table 2.1. Surface convection represents the heat flow from an opaque surface to an adjacent fluid. This process occurs on both the internal and external surfaces of a building wall. The external convection process is influenced by the surface finish, wind speed and direction, whereas the internal convection process is influenced by the forced air flow injected by the mechanical system serving the building zone and in the absence of a mechanical system, is influnced by the buoyancy driven natural convection. Inter-surface longwave radiation represents the amount of radiation, which is a function of surface temperatures, emitted from one surface to other visible surfaces and is influenced by surface emissivity and geometry. The intensity of shortwave radiation on a surface is a function of time, surface geometry and position of the sun relative to the geographical location of the building. The magnitude of shortwave radiation penetrating an opaque surface is influenced by the surface absorptivity and in the case of transparent surfaces, is influenced by surface absorptivity, transmissivity and reflectivity. Shading caused by external obstructions to the sun ray path affects the amount of solar radiation intensity on the external surface of an opaque element and the amount of shortwave radiation penetrating a transparent element such as a window with overhang. In addition, the amount of solar radiation penetrating a transparent surface and the internal surfaces receiving this radiation are a function of the angle of incedence of the solar

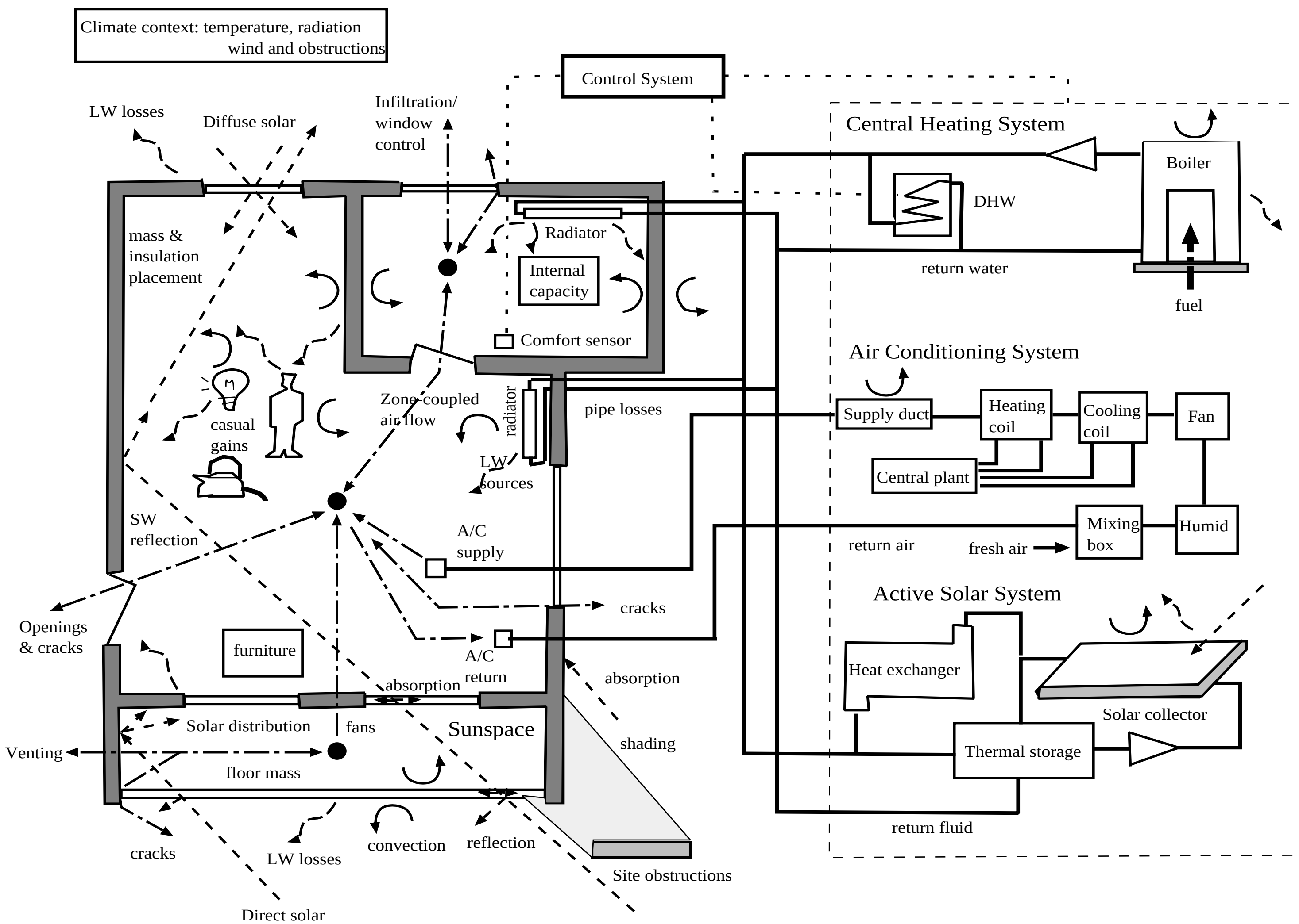

Figure 2.1 Energy flow paths in buildings (Clarke 1985)

Table 2.1 Temporal processes in buildings

Process	Caused by	Influenced by
Surface convection	Buoyancy and mechanical forces	surface finishes, geometry and temperature distribution
Inter-surface longwave radiation exchanges	temperature differences	geometry and surface finish
Surface shortwave gains	date dependent sun path	site location and conditions, building geometry and the transmittance, absorptance and reflectance characteristics of constructional materials.
Shading and insolation	surrounding and facade obstructions	site topology and cloud conditions
External surface longwave exchanges		sky conditions and the degree of exposure of the site
Air movement in the form of infiltration, zone-to-zone air exchange and intra-zone circulation	temperature and pressure differences	leakage distribution, occupant behaviour and mechanical phenomena
Casual gains (stochastic processes associated with internal heat sources)	people and equipment	social and comfort factors
Plant interaction in the form of convective, radiant or mixed heat exchange	thermostat setting	control action and occupant response
Control action involving distributed sensing and actuation, various response characteristics and the processing of a vast array of signals	building/plant system thermal reponse	occupant response
Moisture effects	internal generation processes and air migration from outside	weather and occupants
Movable features such as window insulation and solar screens.	internal comfort level	weather and occupants

radiation and the geometry of the transparent surface as well as the geometry of the internal surfaces. The process of air flow within buildings is affected by the building resistance to the uni-directional air leakage between outside to inside, by the amount of air being circulated between building zones and also by air circulation within each zone. The amount of air leakage between the outside and the inside of the building is influenced by the external air boundary conditions (such as wind speed, pressure and air temperature), and by the internal air temperature and pressure. There is also the process of casual heat gain from lighting fixtures, equipments and people. This heat gain will constitute both radiative and convective components. The process of plant interaction with building zones affects their thermal comfort and can be caused by the action of a thermostat sensing and monitoring the zone air condition. The thermostat setting can be influenced by the building occupants or by the action of an automatic control mechanism. Control processes are caused by the response of a plant system to the dynamically changing internal conditions. The plant response is influenced by the stream of signals being constantly fed back to the various controllers which according to some control action, actuate the appropriate control variable. Moisture transfer processes are not only caused by internal generation processes and air migration from outside but also by the condition of the air being injected to the zone by an air conditioning system. In buildings it is also common to find movable features which can be used to control the effect of certain parameters on the indoor air, such as solar radiation and ambient air. Such features are influenced by social factors and by occupant comfort level.

It is obvious that accurate dynamic modelling of the processes mentioned above is quite complex and the method required was described by Clarke (1985) as follows:

> "Dynamic modelling methods will be required to integrate a large number of equation types whilst respecting the integrity of the total system: parabolic partial differential equations are used to represent solid materials requiring detailed conduction modelling; ordinary differential equations can be used to represent lumped thermal property regions of lesser significance, or surface interfaces undergoing simultaneous conduction, convection and radiation exchanges; non-linear empirical equations (perhaps complex), or, perhaps, partial differential equations, will represent fluid flow; and a number of algebraic relations will define control loops, time-dependent thermophysical properties and regional heat injection (from solar radiation for example)."

From the early 1960's until the late 1980's, there have been many modelling approaches to such complex problems. These range from manual methods, in which the complexity of the real system is reduced in order to lessen the computational overhead and the input demands on the user, to highly sophisticated approaches in which mathematical models are constructed to represent the interactions observed in reality as close as possible.

The evolution of design tools, from the traditional to the present day simulation approach, is summarised in Table 2.2.

Table 2.2 Energy model evolution (Clarke 1988)

1st Generation (Traditional)	Handbook orientated Simplified Piecemeal	<=== | |	Indicative Application limited Difficult to use |
2nd Generation	Dynamics important Less simplified Still piecemeal	| | ====| | |	Feedback loop increasing integrity vis-a-vis the
3rd Generation (Current)	Field problem approach Move to numerical methods Integrated view of energy sub-system Heat & mass transfer considered Better user interface Partial cabd integration	| | | Feedback loop ====| | | | |	real world | | | leading to | |
4th Generation (Next)	CABD integration Advanced numerical methods Intelligent knowledge based Advanced software engineering	| | | <===	Predictive Generalised Easy to use

First generation models focused on a simple ’handbook’ approach, which is piecemeal in that no coupling between the various discrete calculation was made. For example a steady state U-value calculation may be conducted to evaluate envelope heat loss, a look-up table may then be used to determine an allowance for zone solar gain, and finally a degree-day relationship may then be used to predict long term energy requirements. In such calculations, many assumptions are encompassed in order to simplify their application. In addition, the calculations are based on steady-state, uni-directional wall heat flow which rarely occurs in the real world.

Second generation models took into account the temporal aspect of energy flow especially in the case of elements with large time constant such as in multi-layered constructions. Analytical methods such as the response factor, time or frequency domain were applied based on the assumption that the building system is linear and possess heat transfer properties which are time invariant. Modelling integrity remained low because of the decoupling and simplifying assumptions applied to the flow paths. While the problem encountered with first generation models related to quantifying transient heat conduction through multi-layered constructions was overcome by second generation models, a number of new problems emerged. These include the need for powerful fast computers, an extensive input data set is required to define building geometry and the need for more appropriate user interfaces.

In recent years, numerical methods in third generation models have played an increasingly important role in the analysis of heat transfer problems. Numerical methods can be used to solve complex, time-varying problems of high and low order. All fundamental properties are assumed to be time dependent and coupling between the temporal processes is accounted for. The method allows for high integrity modelling; differential equation-sets, representing the dynamic energy and mass balances within combined building and plant networks are solved simultaneously and repeatedly at each (perhaps variable) time-step as a simulation is conducted under the influence of control action. Modelling integrity has been increased so that the system is more representative of reality and is easy to use because of improved graphical I/O user interface. The highly transient nature and dynamic response of HVAC equipment is now fully taken into account.

With reference to Table 2.2, the present work is in line with the third generation modelling approach. Some aspects from which a link to next generation models may be established are also considered (see Chapter 7). The emphasis was placed on the heat and mass flow simulation of coupled buildings, plant and control systems. This area received little attention since third generation models began to emerge. Most of the work at the early stages of development was focused on the relation between building and energy consumption (eg. Clarke 1977). For example, it was customary to base the estimation of energy consumption on some imposed indoor air temperature derived from the use of an ideal control. In the next stage of the development process, some emphasis was placed on the plant side of the simulation (eg. McLean 1982, Tang 1985), however, in this work the building energy flow paths were simplified and the building zone was regarded as another component imposing thermal load on the plant. Hensen (1991) pointed out that neither approach is adequate for the majority of problems which are affected by the thermal interaction of building structure and auxiliary system. His work was focused on approaching both building and plant on equal levels of complexity and detail while taking into account all major fluid flow and heat transfer coupling. The present work focuses on a similar approach with the emphasis on the simulation of real complex and large systems coupled to multi-zone buildings and on overcoming the problems associated with the simulation of such coupled systems.

A number of existing energy simulation programs utilise different approaches to the handling of building and plant systems. Sowell (1991) pointed out that software for building simulation can be categorised into detailed modular simulators, such as TRNSYS (1983) and HVACSIM+ (1985), and whole-building simulators, such as DOE-2 (1981) and ESP-r (1993). This categorisation is not accurate because the ESP-r system can also be used for detailed plant simulation. TRNSYS and HVACSIM+

were specifically developed for the simulation of plant systems employing a sequential solution method in which the output from one component is used as an input to the next, and as a result are well established for plant simulation. DOE-2, on the other hand, is based on the weighting factor method (Stephenson and Mitalas 1967, Kusuda 1969) which represents a compromise between simpler methods (1st generation models) and the more complex complete energy balance calculation methods (3rd generation models). There are two limitations with such an approach. The first is that non-linear processes such as convection and radiation must be linearly approximated because of the superposition principle implemented in the evaluation of the weighting factors. The second limitation is that system properties, such as film coefficients and distribution of incident radiation on surfaces, are time invariant. In addition to these limitations, the building and plant systems do not interact dynamically. ESP-r on the other hand, can be considered as a third generation energy simulation environment in which a modular-simultaneous approach is adopted to handle the interaction between the building, the plant, flow systems and controls. Each of the simulation environments mentioned above make use of a customised technique to handle component modelling with respect to plant simulation. For example, in TRNSYS each component model is represented by an algorithm with pre-defined input/output parameters. In ESP-r, equation-based component models are implemented for the simultaneous solution of the whole system. As a result of these differences, the effort of researchers and developers is being diverted from reaching a common objective, the fourth generation models. For this reason, some attempts were made to overcome these problems as was demonstrated by Hanby and Clarke (1987). In their work, a catalogue of available HVAC plant component models in the UK was compiled to form a basis for collaboration in model and algorithm development. Other steps were taken by ASHRAE to prepare an annotated bibliography of HVAC component models (Yuill and Wray 1990). Current research undertaken by a number of institutes, is aimed at eliminating the problem of model portability between different simulation environments. This resulted in a Neutral Model Format (NMF, discussed in Section 7.1) to describe a component model irrespective of the host simulation environment (Sahlin et al. 1992). Other issues under research are concerned with the 'Atomic Approach' rather than the component based approach to plant modelling. This involves the identification of the energy and mass flow processes in common HVAC systems and the representation of these processes as a primitive parts (atoms) (Chow 1993). It is then possible to create a component from the topological definition of these atoms within a knowledge-based environment such as the EKS (see Section 7.2).

In view of the literature discussed above, it was concluded that with respect to plant simulation using a third generation model, no investigation was carried out to examine the practical application of such models to plant simulation. Most of the work was devoted towards the development of a solution method and towards the development of component models supporting such methods. Attainment of practical simulation is important if the main objective is to deliver the plant simulation power of third generation models to the profession. It is for this reason the research applied in this thesis was concentrated on the practical application of simulation, using third generation models, to plant simulation.

The ESP-r system (Clarke, 1985; Aasem et al. 1993) was chosen as the energy simulation environment on which the present study was based because ESP-r is a third generation model with strong links to future models. ESP-r features were described by Hensen (1991) as follows:

> "- It is a research orientated environment, with the objective to simulate the real world as rigorously as possible and to a level which is consistent with current international research practice.
>
> - It sets out to take fully into account all building & plant energy and mass flows and their inter-connections.
>
> - It provides a rich set of descriptive elements at several levels of granularity from which the user may evolve models to be simulated.
>
> - The source code is available to the research community.
>
> - The system is well documented: it is heavily commented within the code itself, it comes with training and built-in tutorial material, and there is an extensive manual which is updated on a regular basis."

What follows is a description of the ESP-r system structure and a review of its development history.

2.2 Structure of ESP-r

ESP-r is controlled by the Energy Systems Research Unit (ESRU) at the University of Strathclyde. Several research groups are now working with the system. In North America for example, the model is established at Lawrence Berkeley Laboratory, at the National Institute of Standards and Technology and at the Northwest Pacific Laboratory. In Europe, the system is being evolved and applied at several research centres throughout the Community since its selection by the European Commission as a reference program for building energy simulation. (As an aside, the "r" signifies the system's research focus). As shown in Figure 2.2, the ESP-r system comprises three principal modules: a *Project Manager* to help the user to incrementally evolve a description of the problem; a *Simulator* to model a problem comprising building, plant, flow and control components; and a *Results Analyser* which enables the simulation predictions to be interrogated in a variety of ways and transferred to other 3rd Party programs. The Simulator, in turn, is built from distinct technical subsystems which can be evolved separately to make the R&D process more efficient.

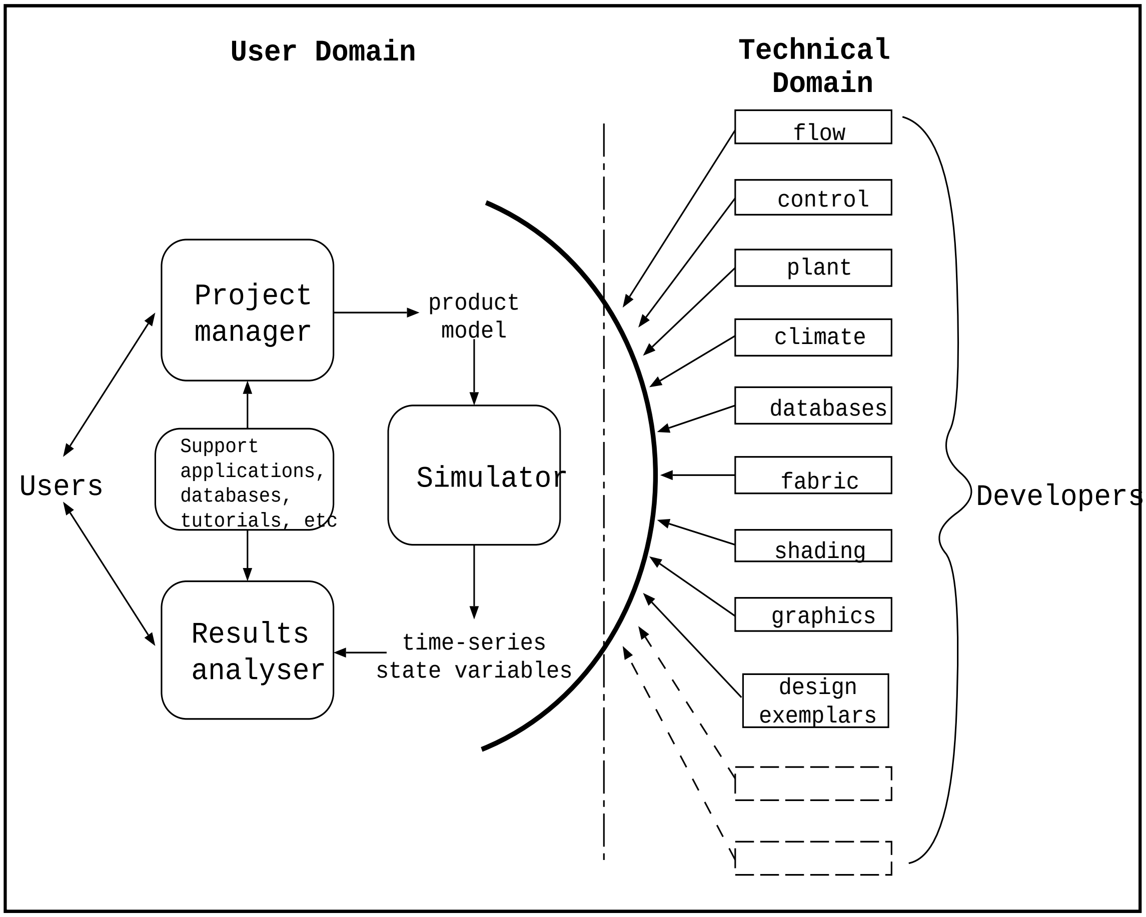

Figure 2.2 The ESP-r System structure.

ESP-r was described elsewhere (Jensen, 1993) as follows:

"ESP-r is a state-of-the-art energy modelling environment which supports the performance assessment of proposed building designs 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 subsystem simultaneously and in the transient domain. Indeed, 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. At an early design stage a model such as ESP-r is particularly powerful since it can be used to quantify the performance impact of the site, building geometry, constructional schemes, plant options and control - all factors which have considerable impact on operational performance and costs. Then, at the more detailed design stage, the model allows the designer to focus on the issues of critical environmental control and energy efficiency.

ESP-r considers a building and its plant as a collection of small finite volumes. These finite volumes represent the various regions of the building and plant between which energy and mass can flow. Throughout a simulation, these energy and mass flows are tracked as they evolve under the influence of the climatic boundary conditions, the 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 technique ensures that all regions of the building are correctly connected across space and time so that any excitation will have the correct causal effect.

For each finite volume and at each computational time-step, energy and mass conservation equations are generated and passed to a central numerical solver where the equations representing the entire problem are integrated in an essentially simultaneous manner (in fact by several solvers, specialised for each sub-system, working in tandem). The coefficients of these equations are developed as a function of the various heat transfers associated with shortwave and longwave radiation, surface convection, casual gains, leakage behaviour and so on. Thus, within ESP-r there are a number of algorithms present to address these heat transfer mechanisms."

Before ESP-r reached this state of maturity, there have been continuous enhancements carried out through its development history. For instance from 1974 until 1977 a building side research prototype with numerical and response function approaches was first created. Then during the period from 1978 to 1982 the modelling infrastructure based on the numerical approach (because of its flexibility) was reworked in terms of problem definition, database management and validation research. Further refinements to its technical engine were carried out between 1983 and 1985 to allow for air flow modelling and the development of a plant simulation infrastructure. In addition, issues concerning its implementation in practice research were considered and software sales and consultancy services were established. During 1986 and 1988, the plant and control modelling capabilities were extended and the system was used for PASSYS[1] Phase I validation project. During this period, it was selected to be the CEC reference simulation model and became the technical basis of Energy Design Advisory Service (EDAS). Between 1989 and 1991, further technical refinements were carried out to the plant side and to the modelling of flows. The number of avilable plant components was increased and the system could handle the heat and mass flow simulation of building and plant systems. From 1991 until the present, the system was subjected to further validation work in conjunction with the PASSYS Phase II project. More plant and flow components were added in addition to the redesign of a new Project Manager front-end.

In addition to the various developments mentioned above, future research issues and developments are currently being investigated by a number of postgraduates at ESRU and include: application of computational fluid dynamics (CFD); effect of non-linearities in thermal conductivity; 3D dynamic heat flow in corners to study the effect of thermal bridging; application of advanced energy management controls and enhancement of control treatment to the mixed building, plant and flows problem.

2.3 Status at project commencement and development areas

ESP-r has undergone substantial changes since the commencement of the research reported in this thesis. This is reflected in the new structure of the system as shown in Figure 2.2. In the past, the main energy simulator, incorporated building, plant and mass flow modules which made it difficult to execute development work efficiently, especially when there are a large number of developers involved. It was realised then that in order to simplify the development process the structure should be changed to accommodate developers changes which tend to occur frequently. The new structure has greatly reduced the replication of some routines which are used by a number of modules. Furthermore,

[1] The PASSYS (for Passive Solar Components and Systems Testing) project set out to develop a test methodology by which the thermal performance of existing and new passive solar building components may be evaluated. The project spanned the period 1987 to 1992 and involved 30 research teams in 10 European countries (see Appendix 1 of PASSYS II).

researchers are now able to test their development on the appropriate module. For example, if changes were made to enhance the plant capabilities only, then a researcher would test these changes on the plant simulator module before they are added to the main building, plant and flows simulator. Similarly for building and mass flows. The module which incorporates building, plant and mass flows is also available for simulations which require a detailed energy analysis of the combined building, plant and mass flows problem.

It was stated earlier that the main objective of the research applied in this thesis was the attainment of practical applications of simulation to plant simulation. The brief historical background of the ESP-r system outlined in the previous section indicated that the system is well established in the building side and has been used extensively in practice research and in consultancy levels. Whereas in the plant side, no attempt was made to exploit and enhance its practical application potential to combined building and plant simulation. This is an important aspect if the aim was to deliver the full power of third generation models to the profession.

With respect to plant simulation, the ESP-r system at project commencement was capable of simulating simple networks because of the limitations imposed by the structure of the system. A number of essential components required for the simulation of air conditioning systems did not exist, for example, the available components were less than those listed in Table 4.1. Some components, such as the mixing box, humidifier, fan, were already installed, existing and new components related to wet central heating systems, such as boilers, radiators, were later modified and developed by Hensen (1991) as part of his PhD contribution to ESP-r. In addition, the system structure did not allow for detailed modelling of components comprising a large number of control volumes, the maximum number of control volumes supported then was limited to seven. The controllers available then were of the basic proportional type and did not support other modes such as proportional, integral and derivative. The plant component database structure was inadequate and required restructuring to allow for more extensive data description of components. The plant network definition process was not interactive and access to plant components related attributes from the plant component database was not supported. Although a plant result file could be generated from a plant simulation, there was no means available to access and analyse the results. The system was not stable in that there were technical deficiencies within the plant simulation infrastructure. The plant solver implemented was unsuitable for the solution of plant networks because it imposed a limitation on the total number of equations and it was not capable of utilising the resulting system matrix equation topology so that more efficient solvers can be implemented. Because of the ability of the ESP-r system to simulate the building and the plant at different frequencies, a suitable simulation time step could only be determined on the basis of trial and error because no time-step control features were available.

As a result to this preliminary research, the following main development areas were identified:

- To increase the number of component models in the plant component database using a state conservation approach.
- To implement new techniques which allow some control on the accuracy of the solution of the combined building, plant, mass flows and control systems.
- To enhance existing plant control capabilities to cater for conventional and non-conventional systems.
- For the simulation of complex systems, a more efficient plant solver was needed which is more efficient in both speed and storage of matrix coefficients.
- To change the ESP-r structure to allow the simulation of plant networks consisting of a large number of multi-node components. This will make detailed modelling of components with a large number of nodes representing their internal regions possible, such as the multi node boiler described by Tang (1985). In addition, such changes will also allow for a detailed analysis to be carried out on specific components, such as the temperature distribution in a tube fin and the fluid flow inside a heat exchanger.
- An improved user interface to allow the definition of complex plant networks and to improve the structure of the plant component database so that it can be used in conjunction with this user interface for the automatic generation of mass flow networks for a particular plant network.
- An improved results recovery utility for analysing plant components performance making use of advanced graphical I/O user interface.

It should be mentioned that simulation of systems can cover a wide number of components which will make it difficult to achieve the main objectives set for the present work. For this reason, emphasis was placed on the thermal interaction of buildings, air-conditioning systems, mass flows and control as will be shown in the following chapters.

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CHAPTER 3
Approach to Plant Simulation

At the early stages of development in the field of plant simulation, programs such as the DOE-2 (1981) were capable of performing such simulation using a system-based approach. The program had a number of predefined systems (such as solar systems, auxiliary heating systems, dual duct systems and so on) from which the user can chose. This made the simulation model inflexible and difficult to manage because of the possible variations within each system. The next development in this field was the modular component-based approach. Within the approach it is assumed that all plant systems can be made up of components connected in series and parallel to form a network. Each component serves a certain purpose so that the function of the overall system can be achieved. A system may also contain a number of control loops which impose control over some variables in order to maintain the condition of the working fluid at a certain level.

Currently available energy simulation models attempt to tackle these systems using different methods. In TRNSYS, for example, a sequential approach is adopted in which each component is replaced by some equivalent input/output relationship so that when connected to comprise a system, the output from one component becomes the input to the next as illustrated by Figure 3.1. Other models such as ESP-r, adopt a simultaneous approach in which a set of algebraic equations representing the energy and mass flow transfers for all components in a system are assembled in one matrix, Figure 3.2, and then solved simultaneously for temperature and mass flow rates. With the first approach, problems are encountered in the following situations:

- With strongly coupled equation models where the performance of one component depends on the performance of another. For instance, Kleinbach (et al, 1993) attempted to compare TRNSYS simulation results with experimental data for a system comprising a solar storage tank, a collector and a pump. His findings were that the equations describing the performance of the collector and tank were strongly coupled in that if the tank model predicted an incorrect temperature returned to the collector, then the collector model added an incorrect value of useful energy, resulting in an incorrect collector output temperature.

- When attempting to develop neutral components for algorithmic type models in order to overcome model portability between different simulation environments. For instance, it was pointed out by Sahlin et al. (1992), who devised the Neutral Model Format (NMF) architecture to allow the use of a component model irrespective of the host simulation environment, that component models with differing input/output parameters (such as is the case with TRNSYS), it is difficult to arrive at one model format since each different component must be assigned different number of input and output variables. This contradicts the main objective of the NMF, which is to remove the input-output connotations from the problem.

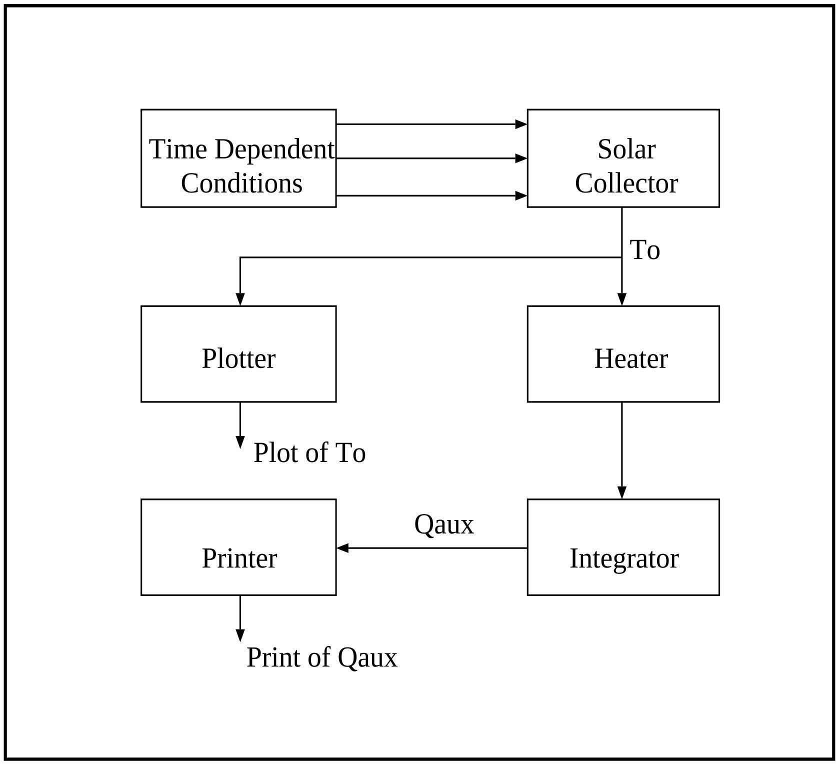


Figure 3.1 Representation of a plant network with the sequential approach

Since in the simultaneous approach the plant system matrix to result is the system linking protocol, then the problems associated with equation coupling can be overcome (as will be seen later) by correct implementation of iterative methods to the simultaneous solution. With regards to NMF, the simultaneous approach is compatible since the models are represented by continuous equations with common inter-component link types. This issue is addressed in greater detail in Section 7.1 in conjunction with an energy simulation model employing the simultaneous technique, such as ESP-r.

Simultaneous plant modelling involves, at its most complex, the representation of plant components by discrete nodal schemes and the derivation of energy and mass flow equation sets which represent whole system, inter-node exchanges over time and space dimensions. In the following sections, the theory underlying the modular component-wise approach of ESP-r and the simulation technique adopted, as it has evolved over the last decade (Clarke 1985, Mclean 1982, Tang 1985, Hensen 1991, Aasem 1993), will be explained in greater detail.

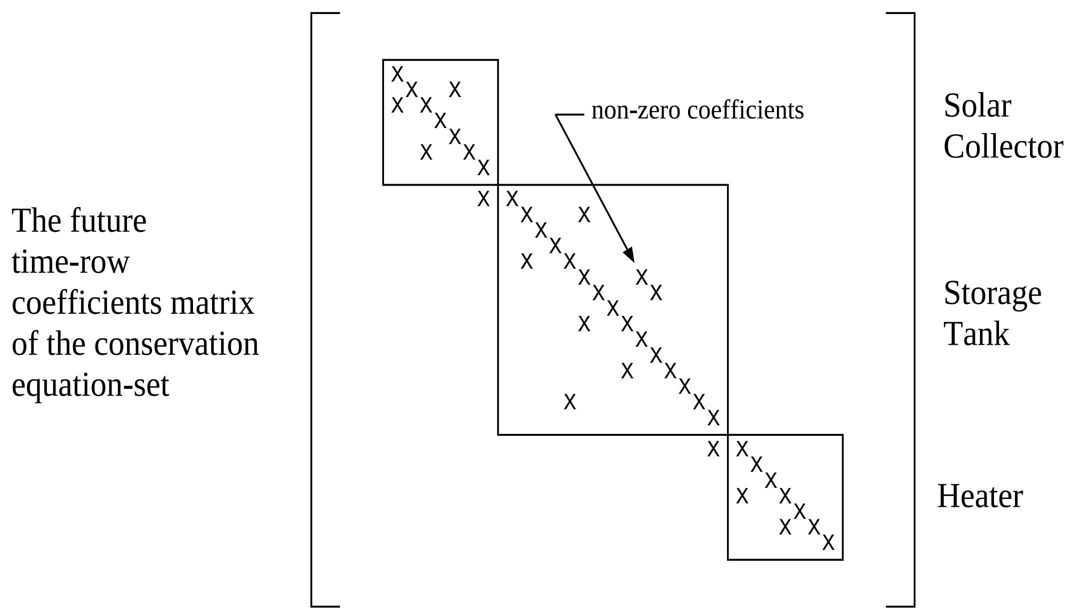


Figure 3.2 Representation of a plant system matrix equation with the simultaneous approach

3.1 Components

In the simultaneous plant modelling approach, a component can be represented by a discrete nodal scheme with each node representing a uniform control volume. Each component is then described by a set of "state" equations which are derived by application of the concepts of mass and energy conservation applied to the control volume. In the context of plant modelling of air conditioning system, quantities such as enthalpy and moist air (two phases) mass flow rate are of interest. For this reason the modelling parameters selected to represent state were temperature, first phase mass flow rate and second phase mass flow rate. The type of system being considered determines the number of state variables required. For example in a wet central heating system the state can be represented by temperature and first phase mass flow rate. Whereas with an electrical device, temperature alone is used to represent the state. A component may be linked to one or more components from which it receives a mass or heat flow as shown in Figure 3.3. In this figure component i is made up of two nodes (i1 & i2) connected to components j and k respectively. Component i also exchanges heat with the surrounding environment. The figure also shows that components do not have to have similar nodal schemes. For example, the model for component i consists of 2-nodes whereas component j and k are single nodes. This means that a detailed multi-node model and a simplified single node model can be intermixed although the connected nodes must have the same fluid types.

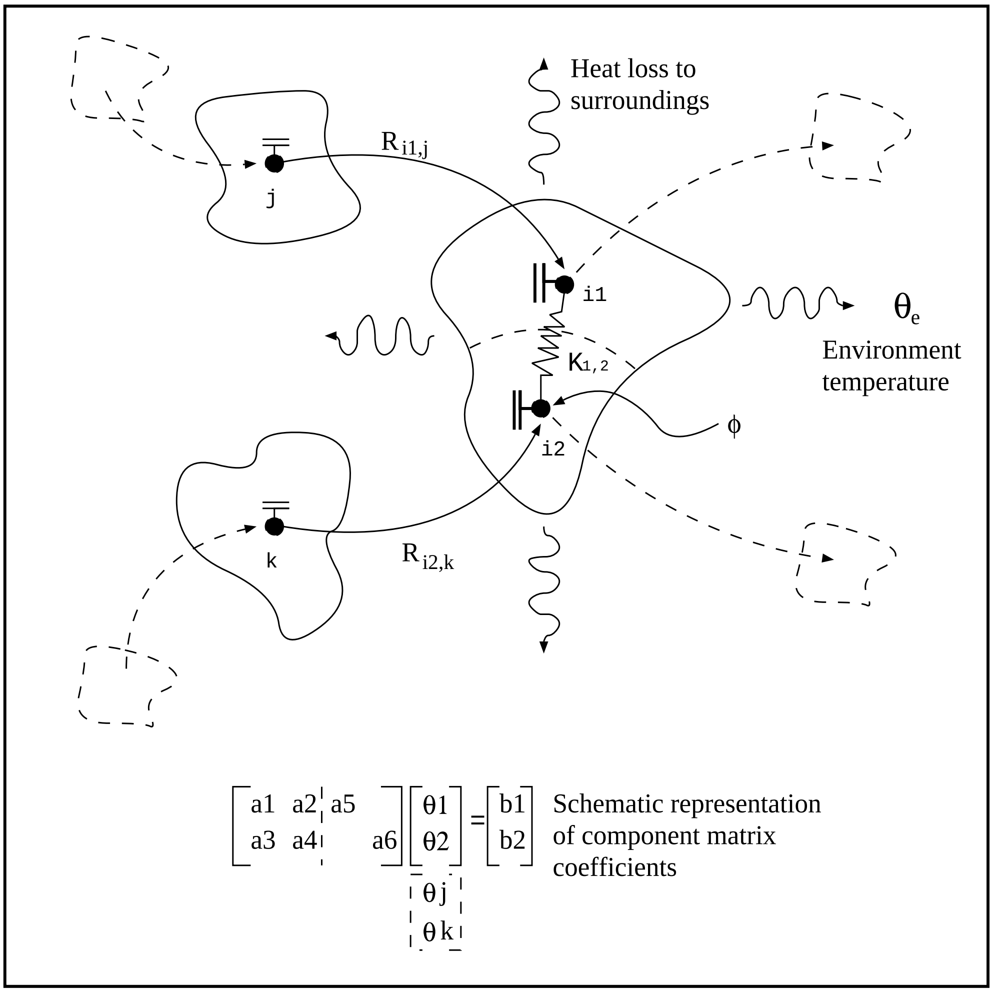


Figure 3.3 Representation of components using the control volume concept.

The energy balance for nodes i1 and i2 are

$$C_{i1,j}(\theta_j - \theta_{i1}) + K_{1,2}(\theta_{i2} - \theta_{i1}) + UA(\theta_e - \theta_{i1}) = \frac{\overline{c}_{i1}\ M_{i1}\ \delta\theta_{i1}}{\delta t} \tag{3.1}$$

$$C_{i2,k}(\theta_k - \theta_{i2}) + K_{1,2}(\theta_{i1} - \theta_{i2}) + UA(\theta_e - \theta_{i2}) + \phi_{i2} = \frac{\overline{c}_{i2}\ M_{i2}\ \delta\theta_{i2}}{\delta t} \tag{3.2}$$

where:

$$C_{i1,j} = R_{i1,j}\dot{m}_{d,j}c_{pa} + R_{i1,j}\dot{m}_{v,j}c_{pv}$$

$$C_{i2,k} = R_{i2,k}\dot{m}_{d,k}c_{pa} + R_{i2,k}\dot{m}_{v,k}c_{pv}$$

The above equations may be solved by approximation using the finite difference method. Consider the energy balance equation 3.1, the explicit form of this equation is

$$C_{i1,j,t}(\theta_{j,t} - \theta_{i1,t}) + K_{1,2,t}(\theta_{i2,t} - \theta_{i1,t}) + UA_t(\theta_{e,t} - \theta_{i1,t})$$

$$= \frac{\overline{c}_{i1}\ M_{i1}\ (\theta_{i1,t+\Delta t} - \theta_{i1,t})}{\Delta t} \tag{3.3}$$

The implicit form is

$$C_{i1,j,t+\Delta t}(\theta_{j,t+\Delta t} - \theta_{i1,t+\Delta t}) + K_{1,2,t+\Delta t}(\theta_{i2,t+\Delta t} - \theta_{i1,t+\Delta t}) + UA_{e,t+\Delta t}(\theta_{e,t+\Delta t} - \theta_{i1,t+\Delta t})$$

$$= \frac{\overline{c}_{i1}\ M_{i1}\ (\theta_{i1,t+\Delta t} - \theta_{i1,t})}{\Delta t}\quad . \tag{3.4}$$

Equal weighting of the explicit and implicit finite difference forms of equations 3.3 and 3.4 and introducing a weighting coefficient α, gives

$$\alpha\left\{C_{i1,j,t+\Delta t}(\theta_{j,t+\Delta t} - \theta_{i1,t+\Delta t}) + K_{1,2,t+\Delta t}(\theta_{i2,t+\Delta t} - \theta_{i1,t+\Delta t}) + UA_{t+\Delta t}(\theta_{e,t+\Delta t} - \theta_{i1,t+\Delta t})\right\}$$

$$+\,(\alpha - 1)\left\{C_{i1,j,t}(\theta_{j,t} - \theta_{i1,t}) + K_{1,2,t}(\theta_{i2,t} - \theta_{i1,t}) + UA_t(\theta_{e,t} - \theta_{i1,t})\right\}\quad .$$

$$= \frac{\overline{c}_{i1}\ M_{i1}\ (\theta_{i1,t+\Delta t} - \theta_{i1,t})}{\Delta t} \tag{3.5}$$

Following the same approach fo the energy balance equation of node 2 (Equation 6.2):

$$\alpha\left\{C_{i2,k,t+\Delta t}(\theta_{k,t+\Delta t} - \theta_{i2,t+\Delta t}) + K_{1,2,t+\Delta t}(\theta_{i1,t+\Delta t} - \theta_{i2,t+\Delta t}) + UA_{t+\Delta t}(\theta_{e,t+\Delta t} - \theta_{i2,t+\Delta t}) + \phi_{i2,t+\Delta t}\right\}$$

$$+ (\alpha - 1) \left\{ C_{i2,k,t}(\theta_{k,t} - \theta_{i2,t}) + K_{1,2,t}(\theta_{i1,t} - \theta_{i2,t}) + UA_t(\theta_{e,t} - \theta_{i2,t}) + \phi_{i2,t} \right\}$$

$$= \frac{\overline{c}_{i2}\ M_{i2}\ (\theta_{i2,t+\Delta t} - \theta_{i2,t})}{\Delta t} \quad . \tag{3.6}$$

With reference to Figure 3.3, the coefficients a_1 and a_4 are the thermal capacitance terms and are refered to as the self coupling coefficients. The coefficients a_2, a_3, a_5 and a_6 are the inter-node thermal conductance terms and are refered to as the cross coupling coefficients. The coefficients b_1 and b_2 are the known present values and are refered to as the right hand side coefficients. From equations 3.5 and 3.6 the following self coupling, cross coupling and right hand side coefficients are defined:

$$a_1 = \left\{ -\alpha\ (\ C_{i1,j,t+\Delta t} + K_{1,2,t+\Delta t} + UA_{t+\Delta t}) - \frac{\overline{c}_{i1} M_{i1}}{\Delta t} \right\} \theta_{i1,t+\Delta t}$$

$$a_2 = \alpha\ K_{1,2,t+\Delta t}\theta_{i2,t+\Delta t}$$

$$a_3 = \alpha\ K_{1,2,t+\Delta t}\theta_{i1,t+\Delta t}$$

$$a_4 = \left\{ -\alpha\ (\ C_{i2,k,t+\Delta t} + K_{1,2,t+\Delta t} + UA_{t+\Delta t}) - \frac{\overline{c}_{i2} M_{i2}}{\Delta t} \right\} \theta_{i2,t+\Delta t}$$

$$a_5 = \alpha\ C_{i1,j,t+\Delta t}\ \theta_{j,t+\Delta t}$$

$$a_6 = \alpha\ C_{i2,k,t+\Delta t}\ \theta_{k,t+\Delta t}$$

$$b_1 = \left\{ (\alpha - 1)\ (\ C_{i1,j,t} + K_{1,2,t} + UA_t) - \frac{\overline{c}_{i1} M_{i1}}{\Delta t} \right\} \theta_{i1,t}$$

$$- (\alpha - 1)\ K_{1,2,t}\theta_{i2,t} + (\alpha - 1)\ C_{i1,j,t}\theta_{j,t}$$

$$- (\alpha - 1)\ UA_t\theta_{e,t} - \alpha\ UA_{t+\Delta t}\theta_{e,t+\Delta t}$$

$$b_2 = -(\alpha - 1)\ K_{1,2,t}\theta_{i1,t}$$

$$+ \left\{ (\alpha - 1)\ (\ C_{i2,k} + K_{1,2,t} + UA_t) - \frac{\overline{c}_{i2} M_{i2}}{\Delta t} \right\} \theta_{i2,t}$$

$$- (\alpha - 1)\ C_{i2,k,t}\theta_{k,t}$$

$$- (\alpha - 1)\ UA_t\theta_{e,t} - \alpha\ UA_{t+\Delta t}\theta_{e,t+\Delta t}$$

$$- (\alpha - 1)\ \phi_{i2,t} - \alpha\ \phi_{i2,t+\Delta t} \quad .$$

The terms $\dot{m}_{d,j}$ and $\dot{m}_{d,k}$ can be evaluated by two different methods. In the first method all mass flows in the network are evaluated without taking into account pressure losses due to flow resistance imposed by some components. This is done by solving simultaneously the algebraic set of all mass balance equations in a network from the available information regarding the mass diversion ratios in the diferent branches of the network. In the second method a mass flow solver can be invoked to evaluate mass flows in all connections based on the relationship (usually non-linear) between the flow through a connection and the pressure difference across it. In the latter case, a number of mass flow component types are defined with each type having some mass flow and pressure relationship. A connection in the plant network can then reference the appropriate flow component as shown in Figure 3.4.

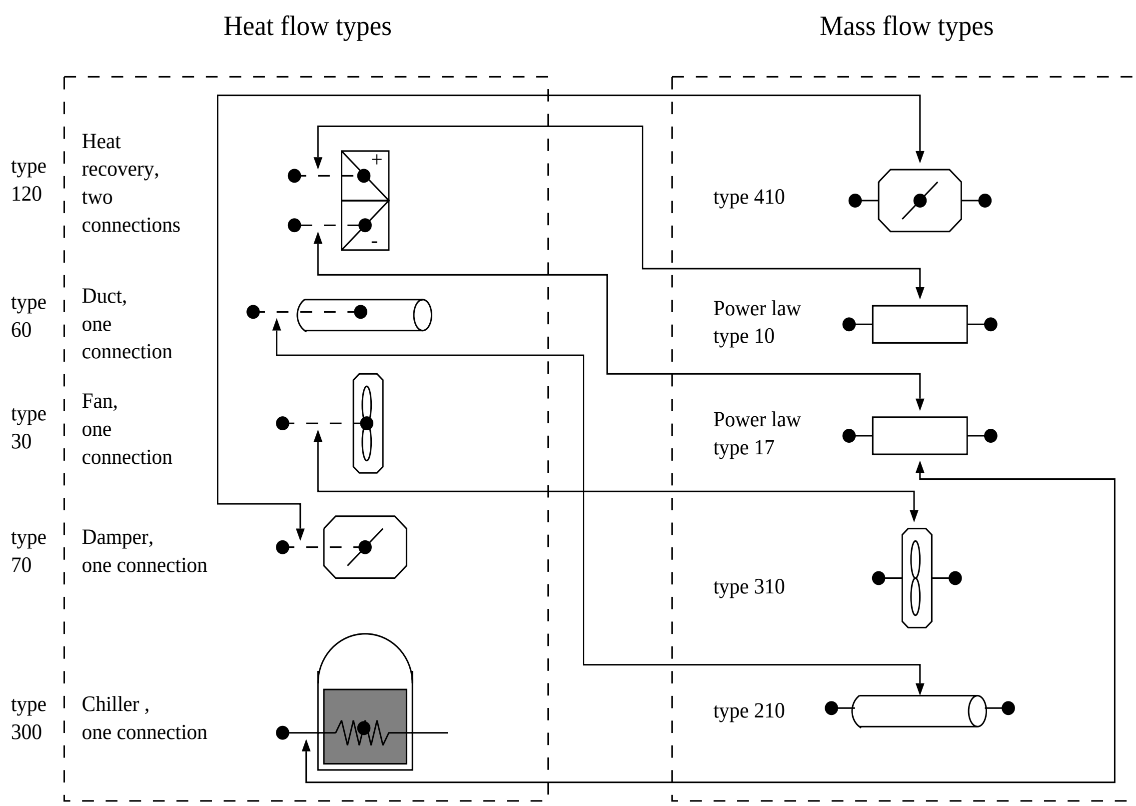


Figure 3.4 Linking of heat flow types to mass flow types.

Linking of heat flow types to mass flow types can be achieved by defining the appropriate mass flow type for each connection a heat flow node expects. For example, a single node duct expecting one connection, can reference a flow conduit mass flow component so that in case a mass flow solver is incorporated in the simulation, the mass flow in that connection will be evaluated based on the mass flow and pressure relationship as defined for a flow conduit. Clearly it can be seen that a great deal of information and data is required for each individual component (such as number of nodes, number of connections each node expects, mass flow type for each connection, fluid type in each node, component parameters and so on). One way to manage such data efficiently is to make use of a data base containing relevant information associated with each component. At present, data entry for a component is of the form given by Table 4.10 in Section 4.5. With reference to this table, items 5 to 10 contain data describing component matrix topology and number of possible connections to a component. This data allows the mapping of component equation coefficients in the overall matrix network and also the mapping of each connection to a mass flow component if the mass flow solver is invoked. The data contained in these entry forms is utilised in four different stages of the simulation process: plant component and network definition; establishing the network matrix and generating the matrix coefficients; and extracting additional output for some components.

3.2 Modelling of plant networks

The modelling approach is essentially a three stage process: system subdivision into a number of elemental uniform finite regions; the establishment of an equivalent characteristic equation-set, one equation for each node and state variable; and the simultaneous solution of the established equations for each state variable. To appreciate the implementation of these stages in detail, consider the example of an arbitrary system as shown in Figure 3.5. This system comprises four single node components connected together to form a closed loop. The source of mass flow is initiated by component 2 and some heat generation q_4 takes place in component 4. The dashed lines around each component indicate that they may have a different containment temperature denoted by θ_{e1}, θ_{e2}, θ_{e3} and θ_{e4}.

3.2.1 System discretisation

This entails the subdivision of each component into a number of control volumes, each one being represented by a node. Thus, a detailed model of a particular component might comprise ten nodes, whereas a simple model for the same component might comprise a single node similar to the case shown in Figure 3.5. Alternative difference schemes can be used for a certain problem, higher accuracy being achieved if the higher order of central difference is retained. However, care has to be taken in choosing a finite difference scheme since some high order schemes can introduce numerical instability. The penalty for a multi-nodal scheme is that the time consumed in developing such detailed models becomes large. Further, when using multi-node components in complex systems, both the memory requirements and execution time will increase. In ESP-r, the mathematical models containing the nodal scheme and thermal and mass flow behaviour of each component are installed in the form of subroutines called coefficient generators. The function and structure of a coefficient generator is described in detail in the following section.

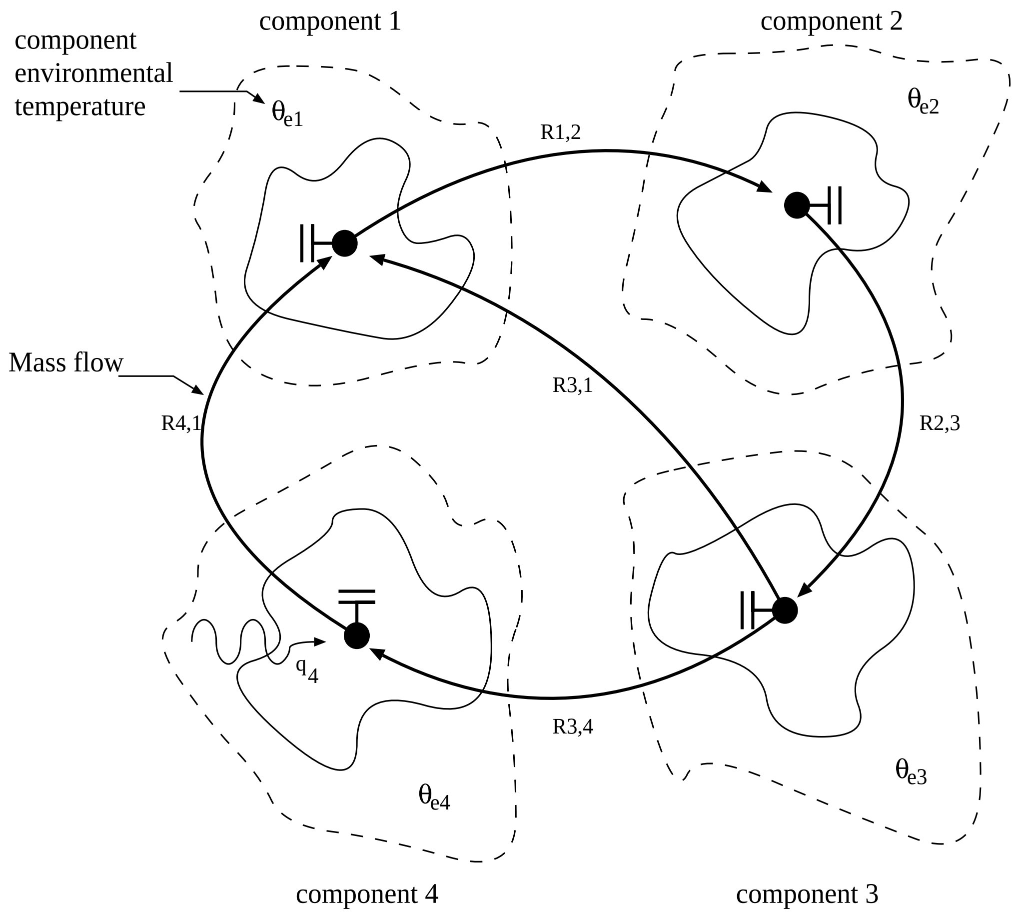


Figure 3.5 Plant layout of arbitrary system.

3.2.2 Establishment of characteristic equations

It was stated earlier that the parameters defined in the present research for modelling HVAC systems were temperature, first phase mass flow rate and second phase mass flow rate. In this section the equations describing each parameter are derived. The total number of equations derived for a component will depend on the number of nodes used to model that component. For example, for a three node component model, a total of nine equations will emerge, three describing the temperature variable (one for each node), three describing the first phase mass flow rate variable and three describing the second phase mass flow rate variable. To further elaborate on the derivation of these equations, consider the following energy system matrix derived for the system shown in Figure 3.5:

$$\begin{bmatrix} A_{11} & & A_{13} & A_{14} \\ A_{21} & A_{22} & & \\ & A_{32} & A_{33} & \\ & & A_{43} & A_{44} \end{bmatrix} \begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \\ \theta_4 \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix}$$

Figure 3.6 Schematic representation of system energy matrix.

The system matrix shown in Figure 3.6, indicates that since each component was represented by a single node, then only four energy balance equations are required. Following the same procedure outlined in section 3.1 for the derivation of energy balance equation coefficients, the coefficients for each component can be evaluated as follows:

for component 1:

$$A_{11}\theta_1 + A_{13}\theta_3 + A_{14}\theta_4 = b_1 \tag{3.7}$$

where

$$A_{11} = \alpha(-C_{14,t+\Delta t} - C_{13,t+\Delta t} - UA_{t+\Delta t}) - \frac{M_1\bar{c}_1}{\Delta t}$$

$$A_{13} = \alpha C_{13,t+\Delta t}$$

$$A_{14} = \alpha C_{14,t+\Delta t}$$

$$b_1 = \left[(1-\alpha)(C_{14,t} + C_{13,t} + UA_t) - \frac{M_1\bar{c}_1}{\Delta t}\right]\theta_{1,t}$$

$$+\left[(1-\alpha)(-C_{13,t})\right]\theta_{3,t}$$

$$+\left[(1-\alpha)(-C_{14,t})\right]\theta_{4,t}$$

$$+\left[(1-\alpha)(-UA_t\theta_{e1,t}) + \alpha(-UA_{t+\Delta t}\theta_{e1,t+\Delta t})\right]$$

for component 2:

$$A_{21}\theta_1 + A_{22}\theta_2 = b_2 \tag{3.8}$$

where

$$A_{21} = \alpha C_{21,t+\Delta t}$$

$$A_{22} = \alpha(-C_{21,t+\Delta t} - UA_{t+\Delta t}) - \frac{M_2\bar{c}_2}{\Delta t}$$

$$b_2 = \left[(1-\alpha)(C_{21,t} + UA_t) - \frac{M_2\bar{c}_2}{\Delta t}\right]\theta_{2,t}$$

$$+\left[(1-\alpha)(-C_{21,t})\right]\theta_{1,t}$$

$$+\left[(1-\alpha)(-UA_t\theta_{e2,t}) + \alpha(-UA_{t+\Delta t}\theta_{e2,t+\Delta t})\right]$$

for component 3:

$$A_{32}\theta_2 + A_{33}\theta_3 = b_3 \tag{3.9}$$

where

$$A_{32} = \alpha C_{32,t+\Delta t}$$

$$A_{33} = \alpha\ (-C_{31,t+\Delta t} - C_{32,t+\Delta t} - UA_{t+\Delta t}) - \frac{M_3\bar{c}_3}{\Delta t}$$

$$b_3 = \left[(1-\alpha)(C_{31,t} + C_{32,t} + UA_t) - \frac{M_3\bar{c}_3}{\Delta t}\right]\theta_{3,t}$$

$$+\left[(1-\alpha)(-C_{32,t})\right]\theta_{2,t}$$

$$+\left[(1-\alpha)(-UA_t\theta_{e3,t}) + \alpha(-UA_{t+\Delta t}\theta_{e3,t+\Delta t})\right]$$

and for component 4:

$$A_{43}\theta_{3+}\ A_{44}\theta_4 = b_4 \tag{3.10}$$

where

$$A_{43} = \alpha\ C_{43,t+\Delta t}$$

$$A_{44} = \alpha\ (-C_{43,t+\Delta t} - UA_{t+\Delta t}) - \frac{M_4 \bar{c}_4}{\Delta t}$$

$$b_4 = \left[(1-\alpha)(C_{43,t} + UA_t) - \frac{M_4 \bar{c}_4}{\Delta t} \right] \theta_{4,t}$$

$$+ \left[(1-\alpha)(-C_{43,t}) \right] \theta_{3,t}$$

$$+ \left[(1-\alpha)(-UA_t \theta_{e4,t}) + \alpha(-UA_{t+\Delta t} \theta_{e4,t+\Delta t} \right]$$

$$+ \left[(1-\alpha)(-q_{4,t}) + \alpha(-q_{4,t+\Delta t}) \right] .$$

The system matrix shown in Figure 3.6 is simple for the example considered here. For more complex arrangements involving multi-node components and recirculating loops, such as the dual duct system shown in Figure 6.16, Chapter 6, the schematic of first phase mass balance matrix has a more complex matrix structure as shown by Figure 3.7.

Terms like q_4 and UA in the energy balance equations can be included in the known right hand side vector if they can be evaluated by independent component models (such as is the case with single node models). This is indicated in the $q_{4,t+\Delta t}$ and $UA_{t+\Delta t}$ terms of the b vector. Alternatively, a multi-node detailed model of a component can be considered in which case the q and possibly the UA terms can be moved to the future time row side of the energy balance equation.

Similar to the system energy matrix, two system mass balance matrices may be derived for first phase and second phase mass flow rates. The structure of these two matrices is identical except for the case where there is a mass flow source component as will be shown for component 2 of the current example. The general mass flow matrix for example of Figure 3.5 is:

$$\begin{bmatrix} E_{11} & & E_{13} & E_{14} \\ E_{21} & E_{22} & & \\ & E_{32} & E_{33} & \\ & & E_{43} & E_{44} \end{bmatrix} \begin{bmatrix} \dot{m}_1 \\ \dot{m}_2 \\ \dot{m}_3 \\ \dot{m}_4 \end{bmatrix} = \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \end{bmatrix}$$

A mass balance, component by component for the dry air and vapour separately will yield at any time t:

for component 1

$$E_{11}\dot{m}_{d(1,t)} + E_{13}\dot{m}_{d(3,t)} + E_{14}\dot{m}_{d(4,t)} = f_{d,1} \qquad (3.11a)$$

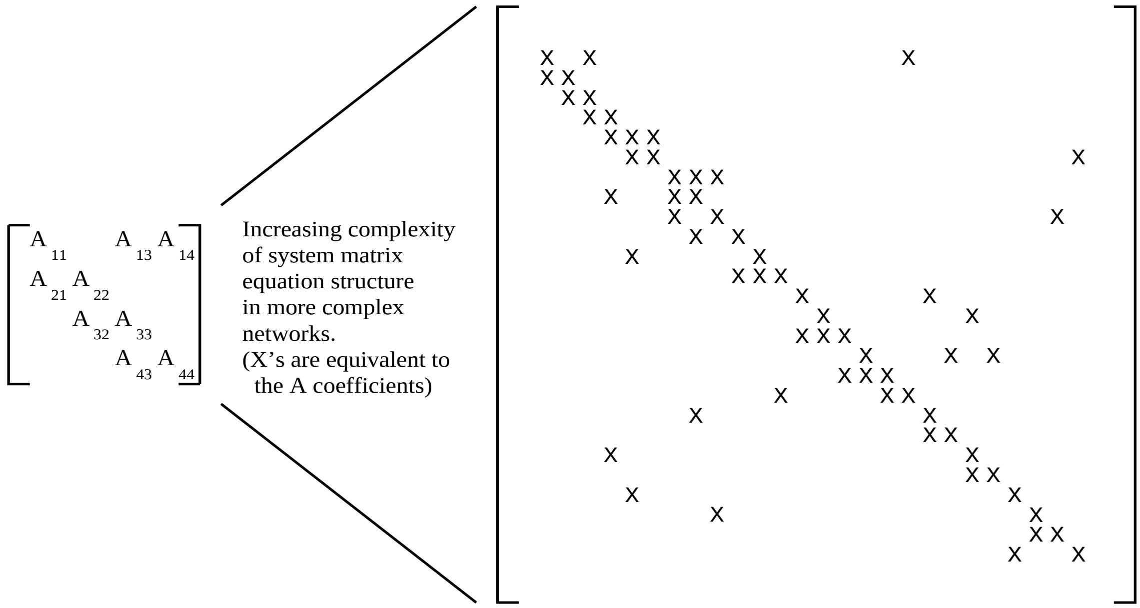


Figure 3.7 Schematic representation of a dual duct system mass flow matrix

$$E_{11}\dot{m}_{v(1,t)} + E_{13}\dot{m}_{v(3,t)} + E_{14}\dot{m}_{v(4,t)} = f_{v,1} \tag{3.11b}$$

where

$E_{11} = 1$

$E_{13} = -R_{13}$

$E_{14} = -R_{14}$

$f_{d,1} = 0$

$f_{v,1} = 0$

for component 2

$$E_{21}\dot{m}_{d(1,t)} + E_{22}\dot{m}_{d(2,t)} = f_{d,2} \tag{3.12a}$$

$$E_{21}\dot{m}_{v(1,t)} + E_{22}\dot{m}_{v(2,t)} = f_{v,2} \tag{3.12b}$$

where

$E_{21} = -R_{21}$

$E_{22} = 1$

$f_{d,2} = \dot{m}_{source} - R_{21}\dot{m}_{d(1,t)}$

$f_{v,2} = 0$

for component 3

$$E_{32}\dot{m}_{d(2,t)} + E_{33}\dot{m}_{d(3,t)} = f_{d,3} \tag{3.13a}$$

$$E_{32}\dot{m}_{v(2,t)} + E_{33}\dot{m}_{v(3,t)} = f_{v,3} \tag{3.13b}$$

where

$E_{32} = -R_{32}$

$E_{33} = 1$

$f_{d,3} = 0$

$f_{v,3} = 0$

for component 4

$$E_{43}\dot{m}_{d(3,t)} + E_{44}\dot{m}_{d(4,t)} = f_{d,4} \tag{3.14a}$$

$$E_{43}\dot{m}_{v(3,t)} + E_{44}\dot{m}_{v(4,t)} = f_{v,4} \tag{3.14b}$$

where

$E_{43} = -R_{43}$

$E_{44} = 1$

$f_{d,4} = 0$

$f_{v,4} = 0$.

Where $\dot{m}_d$ denotes mass flow rate of dry air (kg/s) and $\dot{m}_v$ denotes mass flow rate of vapour (kg/s).

In order to solve the algebraic set of equations for temperatures or mass flow rates, there has to be a way by which the coefficients in each equation can be calculated. This can be achieved by a coefficient generator installed for each component and capable of calculating these coefficients based on the component model. A typical coefficient generator is shown in Figure 3.8. The component sub-matrix coefficients are calculated from the built-in model which could either be of a simple algorithmic type or of a complex multi-node representation. In either case, component parameters representing its thermophysical properties, dimensions and its environment and other simulation parameters concerning simulation time-step, will be used to calculate essential quantities, such as heat transfer coefficients, fluid flow velocity, thermal resistances and so on, which will be used later in the calculation of the coefficients. It was shown earlier that for the same component, different equations were derived for temperature, first phase mass flow rate and second phase mass flow rate state variables. The coefficients in the derived equations are also expected to be different (eg. energy equation coefficients are different from mass flow equation coefficients). Within ESP-r, the modular-simultaneous approach is employed by which each state is solved for independently but in a manner which is equivalent to a simultaneous solution. This approach has proved to be flexible in terms of handling and administrating of the overall system matrix. This means that in situations where a solution for all state variables is required (eg air-conditioning system where fluid temperature and relative humidity is of interest), coefficients for the equations concerning the same state variable being processed must be calculated by the coefficient generator of each component so that these coefficients can then be assembled in the overall plant system matrix for the simultaneous solution phase. In ESP-r this is achieved by dividing the coefficient generator into three parts, each part is concerned with calculating the equation coefficients for the appropriate state variable equations, so that it can be instructed on which state variable equation coefficients to be generated. Referring to the equations derived above, the generated coefficients for the temperature state variable for component 1 are A_{11}, A_{13}, A_{14} and b_1, whereas the coefficients for the first phase mass flow rate state variable for the same component are E_{11}, E_{13}, E_{14} and f_1.

Note that the mass balance equation for the source of mass component (ie. Equation 3.12a) reduces to ($\dot{m}_2 = \dot{m}_{source}$) which ensures that the delivered mass flow rate is as specified and is not affected by leakages in the system. This will satisfy the matrix structure in which one equation is required for each state variable per node. With this in mind, mass flow balance is maintained in closed loop systems such as the one shown in Figure 3.5. Some problems will arise in open loop systems (such as an air-conditioning system) in which there is an outside air duct intake and return air. Consider the open loop system shown in Figure 3.9 where component 2 is the source of mass, it can be seen that because the mixing box inlet is not a source of mass, some means is required to evaluate the mass flow rate available through this component. This can be achieved by having the mixing box inlet duct phase mass flow rate can be evaluated from the product of the humidity ratio and the first phase mass flow rate. The concept of the fictitious, mass-less component was developed to cope with more complex plant networks exhibiting a number of recirculated loops and inlet and exhaust arrangements.

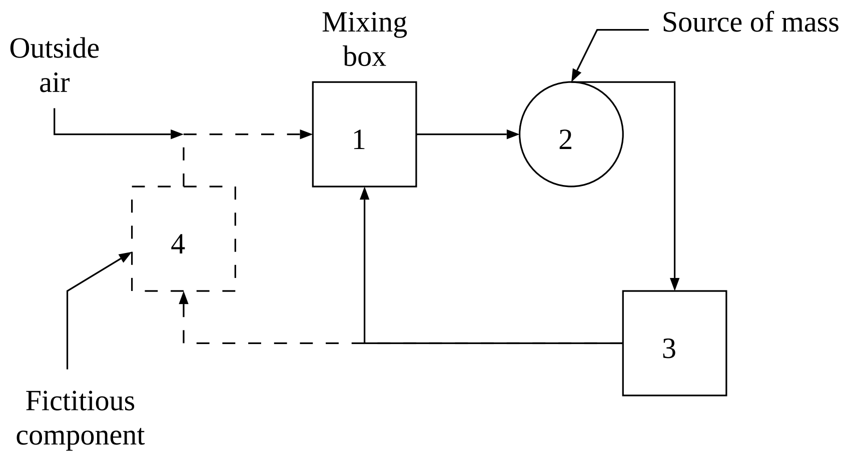


Figure 3.9 Use of fictitious component in open loop systems

If a mass flow network was incorporated within the simulation then the problems associated with open loop systems no longer exist because the flow network is effectively a closed loop system with boundary condition terminators. It can therefore predict the inlet duct conditions from knowledge of pressure and temperature difference between the duct node and the outside boundary node.

3.2.3 Construction and solution of overall system matrix

The overall matrix equation for a plant network is usually highly sparse as shown in Figure 3.10. It is not therefore efficient in terms of computer storage and computational time to attempt to solve such equations using conventional matrix reduction techniques. This was experienced with an application where a building comprising twelve zones was simulated with a plant network consisting of 23 components and a total of 26 equations (nodes). For this problem the time step for the building simulation was 20 minutes weheras for the plant simulation it was chosen to be 2 minutes. This problem can be overcome by adopting a different technique which allows for compact storage schemes of these non-zero coefficients.

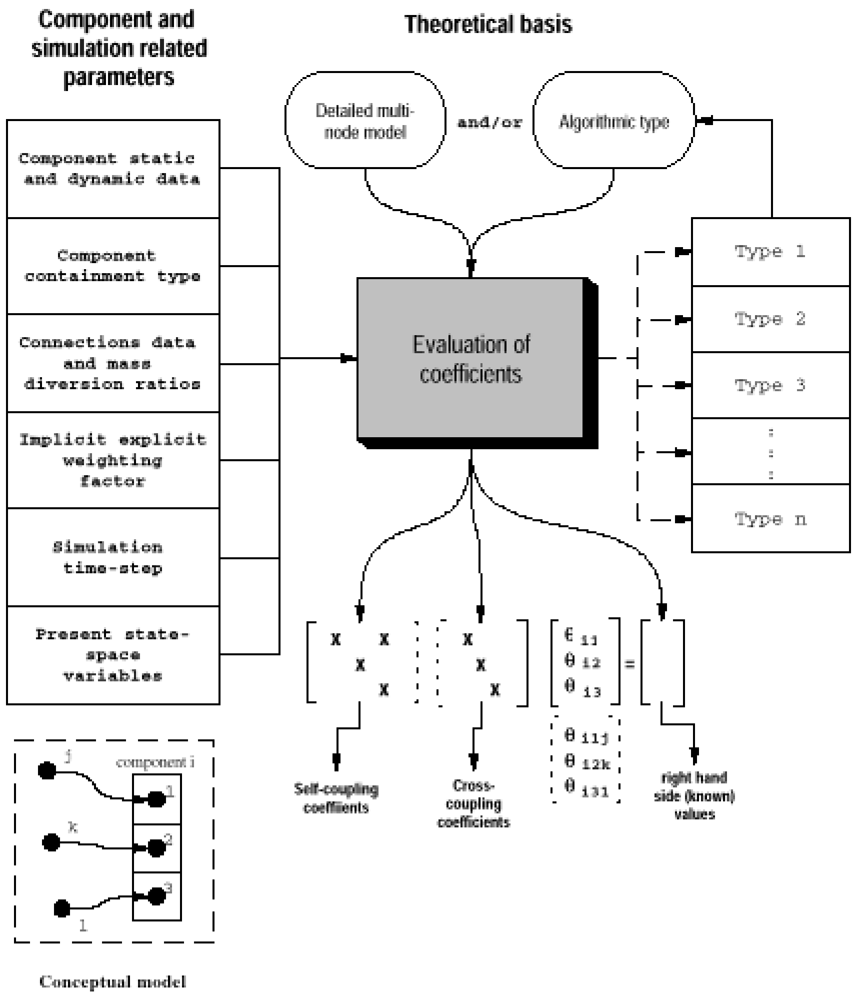


Figure 3.8 Structure and function of a coefficient generator

connected to some fictitious, mass-less component (dotted component 4) which receives its mass flow rate from the exhaust duct to form a closed loop system. Its purpose is to ensure that mass flow balance in open loop systems is maintained. An outside connection type can then be defined so that the air entering the inlet duct has a dry bulb temperature and humidity ratio of the prevailing climate. Thus the first phase mass flow rate entering the mixing box inlet duct component is now defined and the second

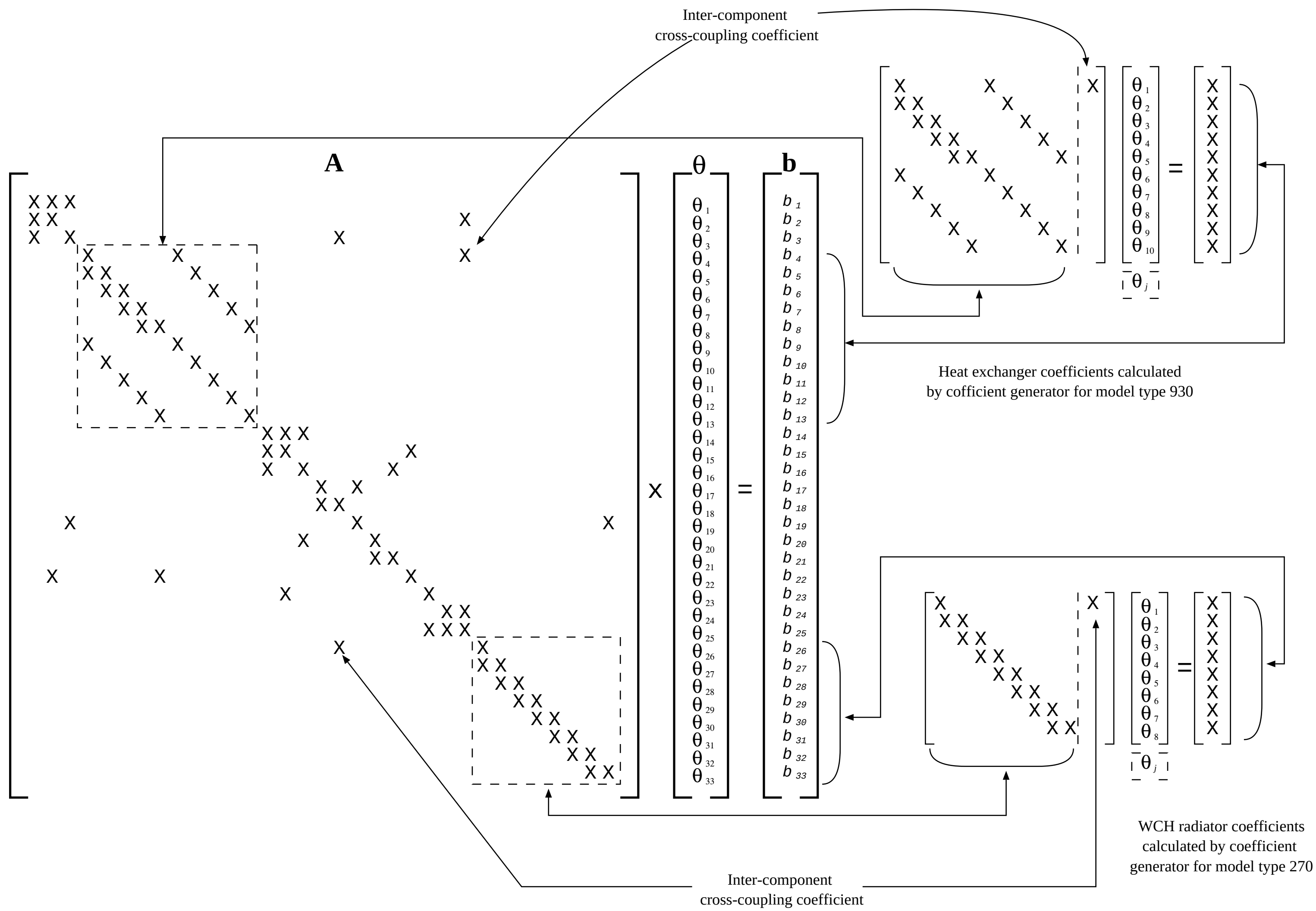


Figure 3.10 Plant system matrix formed by connecting the components of a plant network.

One approach would be to hold the location of the non-zero coefficients within the overall matrix in two one-dimensional indexing arrays which point to the row and column position of every coefficient, with the coefficient value then stored compactly in a one dimensional array. However the introduction of new non-zero coefficients during the reduction phase of the matrix will require their location to be determined prior to the solution of the matrix equations. Before explaining how this can be achieved, it is essential to elaborate on how the overall matrix equation topology is determined for a particular plant network.

The total number of coefficients for a component model can be determined from the information contained in the plant component database. Some of these data relate to the number of non-zero coefficients in the component defining matrix equation, and to the number of inter-component connections each node expects. The total number of coefficients is therefore the total sum of these plus the right hand side coefficients. For example, the total number of coefficients for the 2-node arrangement shown in Figure 3.3, is

4 (a1, a2, a3 & a4) + 2 (a5 & a6) + 2 (b1 & b2) = 8

The 'a' coefficients are located in the overall coefficient matrix relating to the future time-row whereas the 'b' coefficients are located in the right hand side, known time-row vector. The flowchart shown in Figure 3.11 describes the procedure involved in constructing the system overall matrix for a plant network. At run-time the ESP-r simulator makes available essential data for each component, such as the number of sub-matrix non-zero coefficient, the number of inter-component cross-coupling coefficients; and the location of the first coefficient of this component within the row and column index arrays. This information can then be used to transfer the coefficients calculated by the coefficient generator to the overall system matrix equation as shown in Figure 3.10. Once the system matrix equation is constructed, the next step is to determine the location of new non-zero elements which result from the decomposition of the LHS matrix to its upper triangular component during the solution phase. Further elaboration on this phase of the solution procedure is given in the following section.

Jennings (1985) has shown that the computational time when solving an n by n matrix using standard techniques, is proportional to n^3, where n is the number of equations to be solved. This will make the execution of large order problems time consuming. For example in the context of the plant modeling approach described here, the computational time per time-step is proportional to $3\ n^3$, because there are three state variables to be solved. In addition, there is usually a number of possible iterations

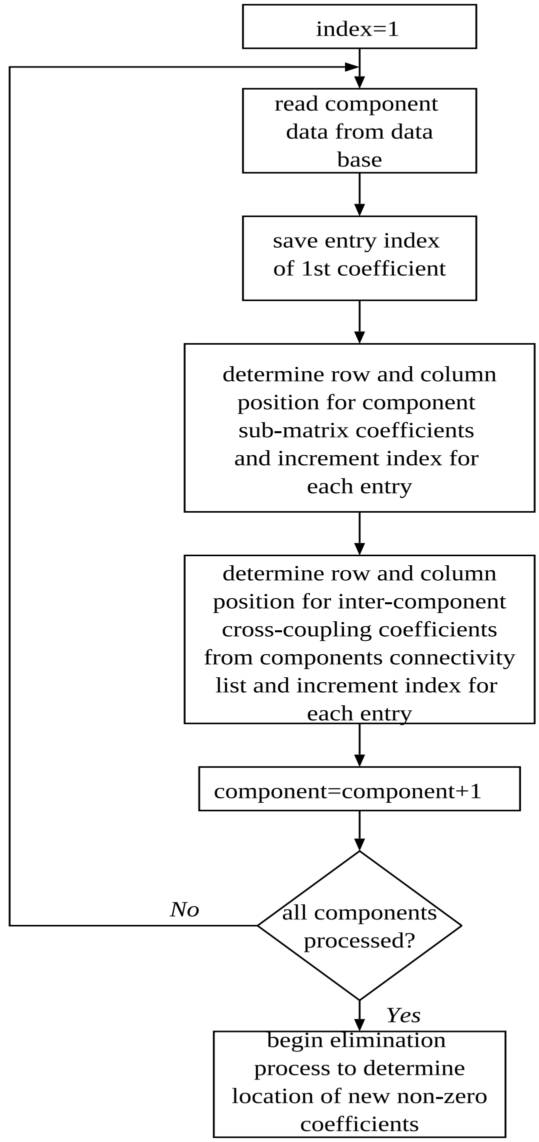


Figure 3.11 Procedure for establishing location of component coefficients in overall system matrix.

to be carried out at each time-step in order to reach a satisfactory solution for situations where there is coupling between the state variables. For this reason, the highly sparse nature of the overall plant matrix is made use of in order to reduce both the computation time and storage requirements. The method described here assumes that the overall matrix is non singular in that there are no identically zero diagonal coefficients and that the matrix topology remains the same throughout the simulation. Consider a set of five simultaneous equations obtained for the particular plant network as shown in Figure 3.12.

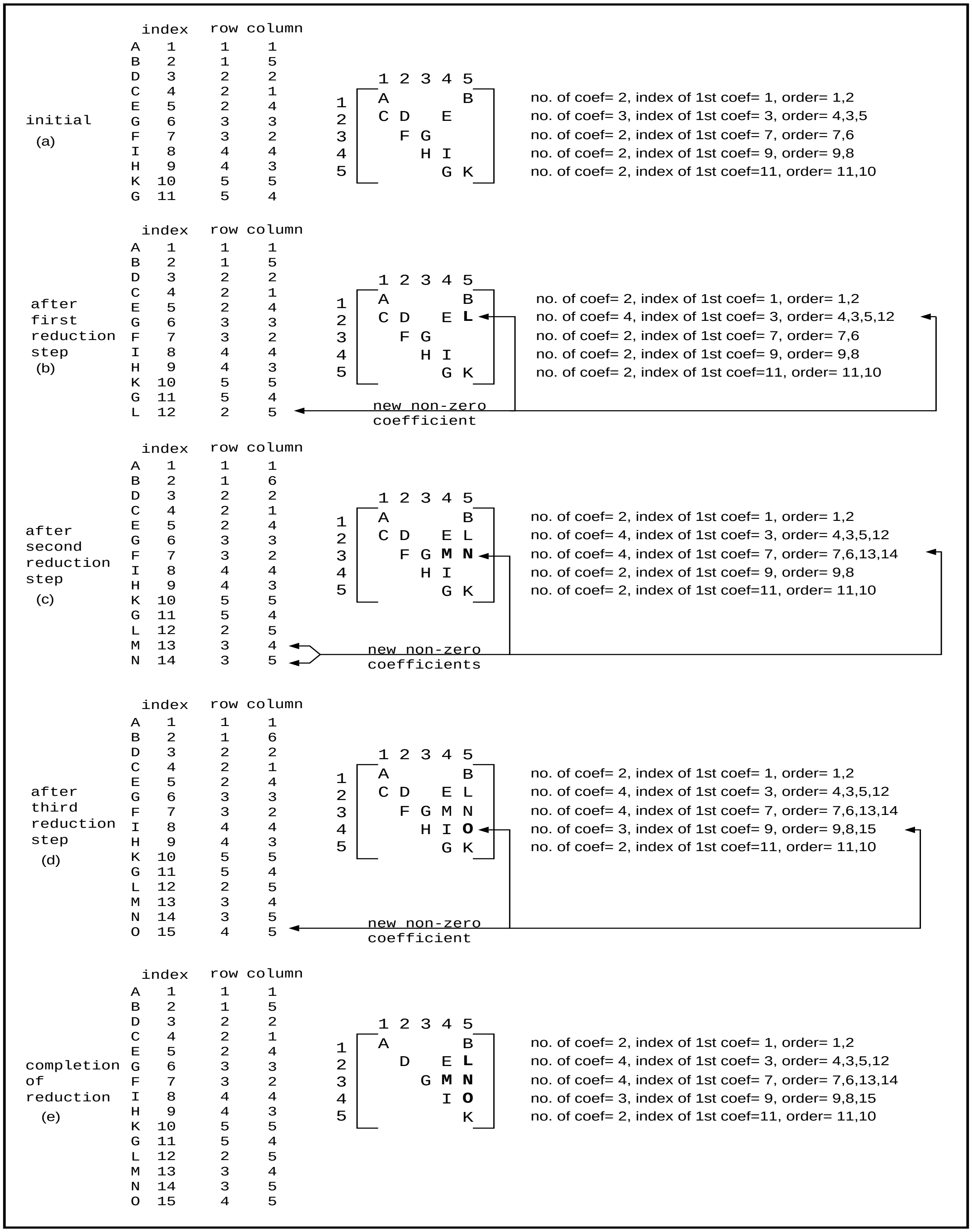


Figure 3.12 Space allocation for new non-zero elements introduced during the elimination process.

The row and column indexing arrays for the non-zero coefficients were established from the procedure described earlier. The first Gaussian elimination step will produce extra non-zero coefficient (L) as shown in Figure 3.12b and the final reduced form will contain non-zero coefficients as shown in Figure 3.12e, four of which (L, M, N and O) will have been introduced during the elimination. Storage for these extra non-zero coefficients can be accounted for by updating the row and column arrays at each reduction step as indicated by ’row’ and ’column’ entries. In order to determine if an equation is to be reduced at each reduction step, it is possible to scan through the row and column indexing arrays to see if a non-zero coefficient is located in the column to be reduced. A better way to do this is to optimise the order of the coefficients for each equation according to their column number. This can be achieved by introducing one more array (IX say). Array IX can hold two data items for each equation, such as total number of non-zero coefficients and the position of the first coefficient in the row and column arrays. However, because the position of the matrix coefficients are randomly stored in the indexing arrays, then another array (IY say) can be introduced which will hold row wise and column sorted index entries, which point to the row and column arrays. In this case, instead of the index defined for the IX array pointing to the row and column arrays, it will point to the correct location in array IY to indicate the start of the non-zero coefficient for the equation concerned. This is illustrated in Figure 3.12 by the text to the right of the matrix. This method is highly optimised for speed in that it executes the solution phase with minimum computational time requirements mainly because only the non-zero coefficients are processed. Note that the storage for extra non-zero coefficients produced by the Gaussian elimination and the construction of the IX and IY arrays, can be done only once and prior to commencement of the simulation. This is achieved by simulating the Gaussian elimination process without actually performing the arithmetical operations. The effect of the scheme described above is that only the non-zero coefficients are processed which is identical to the scheme adopted for the building side.

A comparison between the performance of the older ESP-r plant-side solver, which is also based on Gaussian elimination technique, and the method described above is shown in Figure 3.13. This graph was constructed from a simulation of a plant network consisting initially of twelve components with a total number of 14 equations (nodes). Results for three more simulations were obtained where the number of equations in each case was increased by the initial number of equations (ie 28, 42 and 56 equations respectively). The simulations were carried out for a one day period with a one day start up. In all cases the time-step value was taken to be six minutes. The results correspond to ESP-r running on

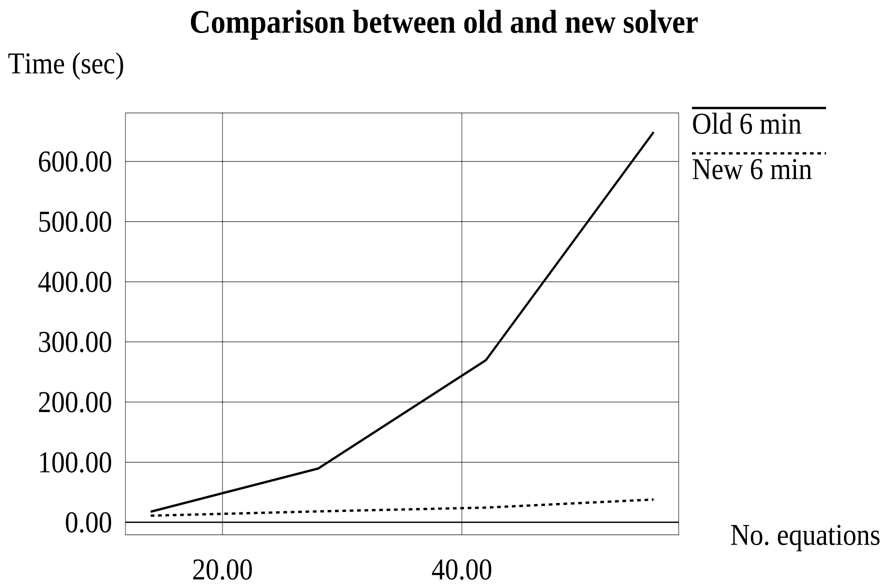


Figure 3.13 Solver performance comparison.

a SUN SPARC 1+ workstation. As can be seen, the increase in computational time with respect to the number of equations solved in the case of the compact matrix solver, exhibits a linear relationship, whereas the results obtained from the previous solver, exhibit a power law relationship. It can also be seen that the new solver is ideal for situations where a large number of equations are required to be solved.

In addition to the three state variables (eg. temperature, first phase mass flow rate and second phase mass flow rate), it is also possible to establish within ESP-r an additional mass flow network to represent the actual mass flow rates in the connections of the flow network. The predicted mass flow rate values are then transferred from the flow simulator to the plant simulator at each time-step so that they can be used in the evaluation of components state variables. It is therefore possible to simulate components which have no mass flow rates such as a direct electric heater or an oil-filled electric radiator. In this case only energy balance equations will be established and solved for the temperature state variable. However, if a system requires all state variables to be evaluated then the order of formation of the matrix equation is to establish and solve the system matrix for the 1st phase mass flow rate and then to establish and solve the system matrix for the 2nd phase mass flow rate and, finally, to establish and solve the system matrix for temperature. It is possible to start matrix formation in any order, however the reason for the order given above is that the dependency of energy balance on mass flow rate is much stronger than the other way around. For example, the energy balance equations for components in which fluid flow occurs are a function of the fluid mass flow rate. If the temperature was to be evaluated first, then there is a possibility that the solution might diverge or more likely take longer to converge because it will be based on 'unreal' mass flow rate values. Moreover, if a mass flow network is incorporated in a simulation, then the connections flow rates are first calculated before any of the other state variables are evaluated. The reason for this is that the mass flow diversion ratios in the inter-component connections are time dependent and must be evaluated before proceeding with the energy balance equations. In some situations, it is not possible to have inter-nodal component connections such as in a multi-node component where a node might represent a solid and another node represent a fluid. In this case there is no fluid flow between the two nodes. This implies that in order to calculate the mass flow rates for all nodes in a plant network, the mass balance system matrix must be solved regardless of whether the mass flow solver was invoked or not.

It can be seen that at any given time-step a maximum number of four matrices need to be solved in a plant simulation. Although it is entirely possible to combine energy and mass balance equations into one matrix and to solve it simultaneously, it is more practical in terms of matrix elements storage requirements and administration to handle each state variable's matrix equation separately. Moreover, for non-linear systems it is not possible to establish a combined matrix equation since the coefficients depend on state variables. In cases where there is strong coupling between two different matrix equations (i.e if the cooling flux of a cooling coil depends on the water mass flow rate state variable) then both values of the water mass flow rate must be matched in order to find a true simultaneous solution of the plant matrices. This is achieved by invoking an iteration process in which the values of the variable concerned for the current and the previous iteration are compared to ensure that the difference is within the tolerance specified by the user. The iteration is invoked when the coefficient generator marks a variable involved in the inter-matrix coupling. This is further illustrated in the flowchart shown in Figure 3.14. Consider the case where for some component model, the magnitude of the heating flux is to be evaluated based on the fluid temperature passing through it. In order to ensure that the correct fluid temperature is used, inside the coefficient generator for this component model the temperature state variable is marked for iteration so that after the overall temperature state variable matrix equation is solved, the fluid temperature in the component considered will be compared with that from the previous iteration to check if the difference is within the specified accuracy.

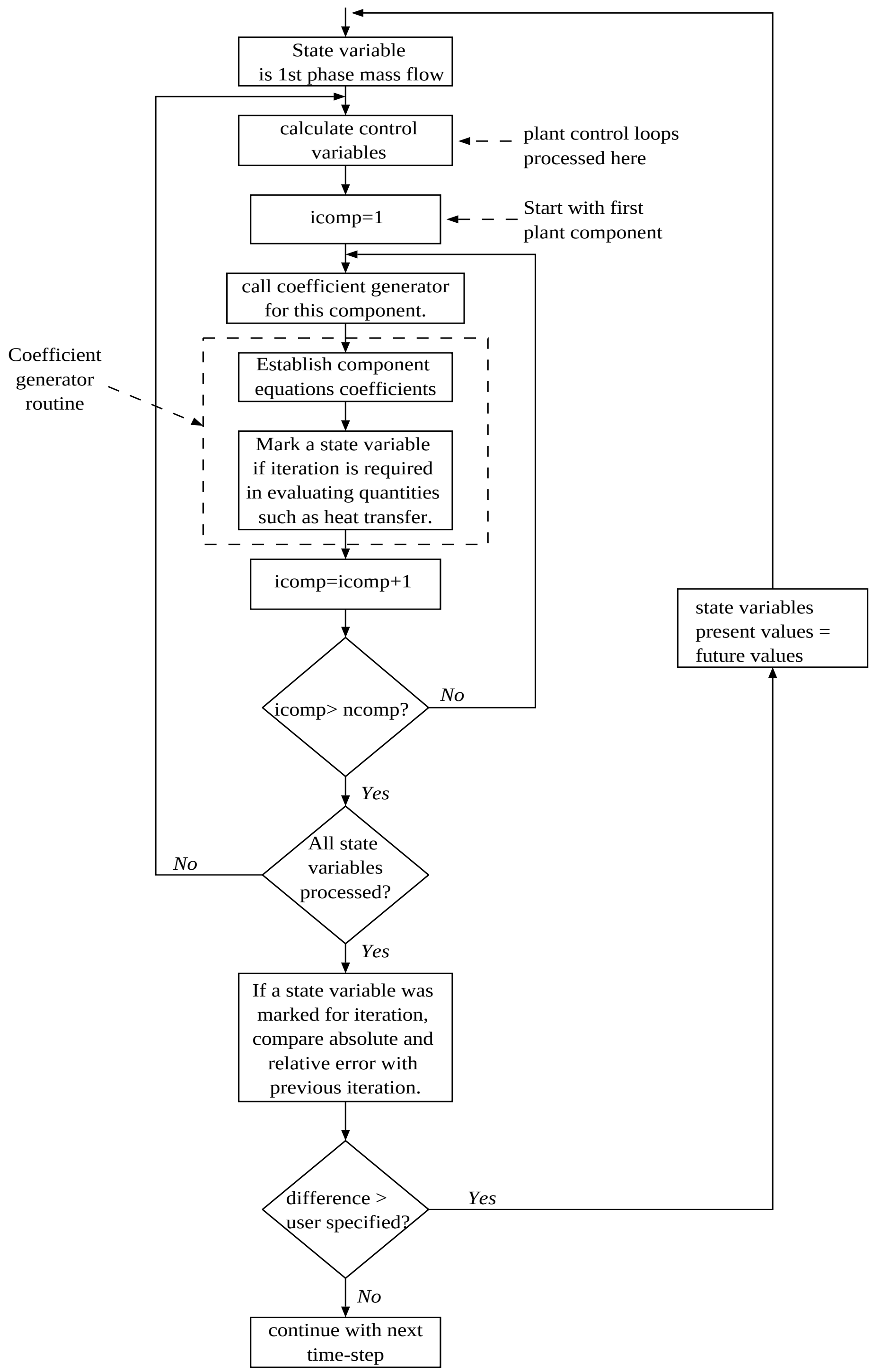


Figure 3.14 Structure of plant simulator incorporating a direct/iterative method.

3.3 Control

Because of the dynamic nature of buildings and plant systems and because of the continuously changing climatic conditions, it is not possible to have a system which can be used to maintain an indoor space at a certain comfort level without imposing some control on its operation. Systems comprise a number of components and each can change the condition of the working fluid differently. For example in an air conditioning unit, a humidifier increases the moisture content of the incoming air whereas a cooling coil not only reduces the temperature of the air passing through it but also dehumidifies it. Control can be imposed on the amount of moisture injected to the air and can also be imposed on the amount of cooling provided by the cooling coil. It is therefore the action of one or more controllers which determines the final condition of the working fluid. In ESP-r a number of control loops can be defined to act on the required plant components. It is emphasised that these control loops are not built into the component models but are free standing to allow for flexibility of use. Essentially, a control loop comprises a sensor, a controller and an actuator. The sensor measures the quantity or physical property to be controlled, termed the control variable. The controller interprets the input signal from the sensor and provides appropriate output to the actuator. The action taken depends on the design of the controller which could be of a proportional type, could include a derivative and/or integral action or could take another more sophisticated form such as in optimal controllers, adaptive controllers and rule-based controllers. The actuator provides the motive power to the final control element in response to a signal from the controller. A control loop can be used with a component if that component has a predefined control variable. For instance a fan has a volume flow rate which may be controlled using an appropriate control law. Similarly, the heat flux in a cooling coil can also be defined as being a control variable. The control loops routines also check to see if a control loop is used to actuate the correct control variable. For example, a control law which actuates heat flux can not be used to actuate volume flow rate of a fan.

Figure 3.14 shows that if a control loop was defined for a component, the control routine for the corresponding control loop is first executed in order to evaluate the physical quantity being controlled (eg, volume or mass flow rates, heat fluxes, damper position, ON/OFF signal ..etc). In situations where a mass flow network is defined for a particular plant configuration, then control imposed on the mass flow will be handled by the mass flow solver through some predefined mass flow components such as a mass flow corrector or an ideal open/closed flow component.

Available control laws in ESP-r are shown in Figures 3.15.a 3.15b and 3.15c. As can be seen, each control loop requires a sensor and an actuator definition. In this definition the sensor location and actuator location is also specified. For example, a temperature sensor may be located in a zone or in a plant component and control law 1 may be used to actuate the heat flux of a heating coil. Note that in specifying the actuator location for a plant component, reference must be made to the component and to the control variable defined for that component since more than one control variable can be defined for one component. For a detailed explanation on how sensors and actuators are defined in ESP-r, the reader should refer to (Aasem et al, 1993).

The actual property sensed by the sensor and actuated at the actuator is controlled by the controller. Table 3.1 lists the currently available options.

Table 3.1 Currently supported plant controller types

Index	Sensed property	Actuated property
0	temperature	heat flux
1	temperature	flow rate
2	enthalpy	heat flux
3	enthalpy	flow rate
4	1st phase mass flow rate	heat flux
5	1st phase mass flow rate	flow rate
6	2nd phase mass flow rate	heat flux
7	2nd phase mass flow rate	flow rate
8	additional plant output	heat flux
9	additional plant output	flow rate
10	relative humidity	heat flux
11	relative humidity	flow rate
12	temperature	variable expecting numerical value
13	enthalpy	variable expecting numerical value
14	1st phase mass flow rate	variable expecting numerical value
15	2nd phase mass flow rate	variable expecting numerical value
16	additional plant output	variable expecting numerical value
17	relative humidity	variable expecting numerical value
18	temperature	mass diversion ratio
19	enthalpy	mass diversion ratio
20	1st phase mass flow rate	mass diversion ratio
21	2nd phase mass flow rate	mass diversion ratio
22	additional plant output	mass diversion ratio
23	relative humidity	mass diversion ratio

Controller types 18-23 can be used to modify the mass diversion ratio of a branch in the network. Typical application of this is when using a damper to control the flow rate. The sensor type used in conjunction with control law type 0 is redundant in that its value is not made use of within the control routine since its main function is to set the control data for the component to zero to shutdown the plant.

However a sensor must still be specified in order to maintain compatibility with other controllers. Control law 6 is a function generator and can be applied in situations where a component dynamic response is to be investigated in response to a change in fluid temperature or mass flow rate. It can also be used to examine the response of the whole system as a result of a change in the value of some parameter based on the function type selected. Table 3.2 lists the function types on offer and the data required with each type.

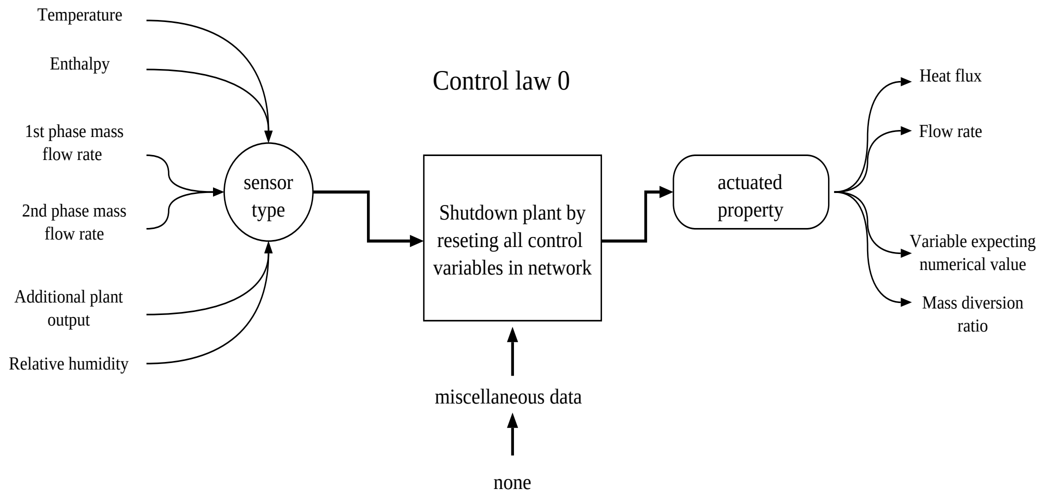
Table 3.2 Function types on offer by control law 6

Type	item 1	item 2	item 3	item 4	item 5
Step function	1	start time (hours)	finish time (hours)	maximum	minimum
Ramp function	2	start time (hours)	finish time (hours)	maximum	minimum
Square sine wave	3	maximum	minimum	frequency	-
Square cosine wave	4	maximum	minimum	frequency	-
Triangular wave	5	maximum	minimum	frequency	-
Saw-tooth wave	6	maximum	minimum	frequency	-
Sine wave	7	maximum	minimum	frequency	phase shift (hours)
Cosine wave	8	maximum	minimum	frequency	phase shift (hours)
Sensed property	9	increment or decrement	-	-	-

With control law 6, the actuated property can be a temperature, a mass flow rate, heat flux or any property required by a control variable. With this controller, additional output from a component, such as heat loss to the surroundings, can be sensed and used to actuate a control variable of some other component. A typical situation for this application is when one component is rejecting heat inside another.

3.4 Coupling of building and plant

As well as dealing with plant matrix equations as described earlier, there is typically a building matrix equation which has to be processed in order to evaluate the final effect of the integrated, dynamic thermal interaction of all building and plant processes. As described by Clarke (1985), it is possible to



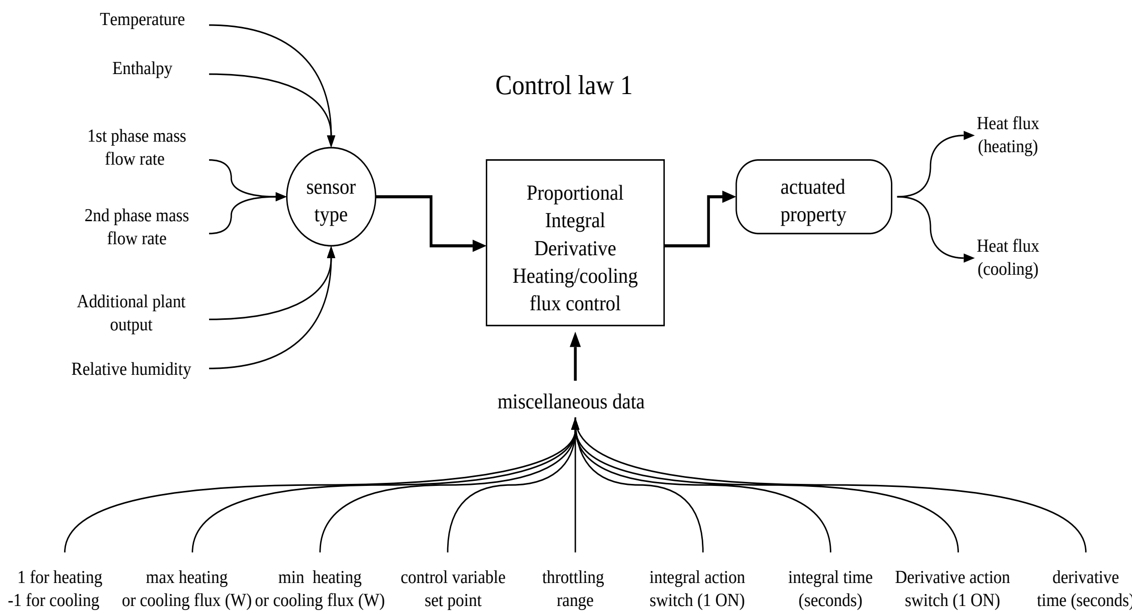
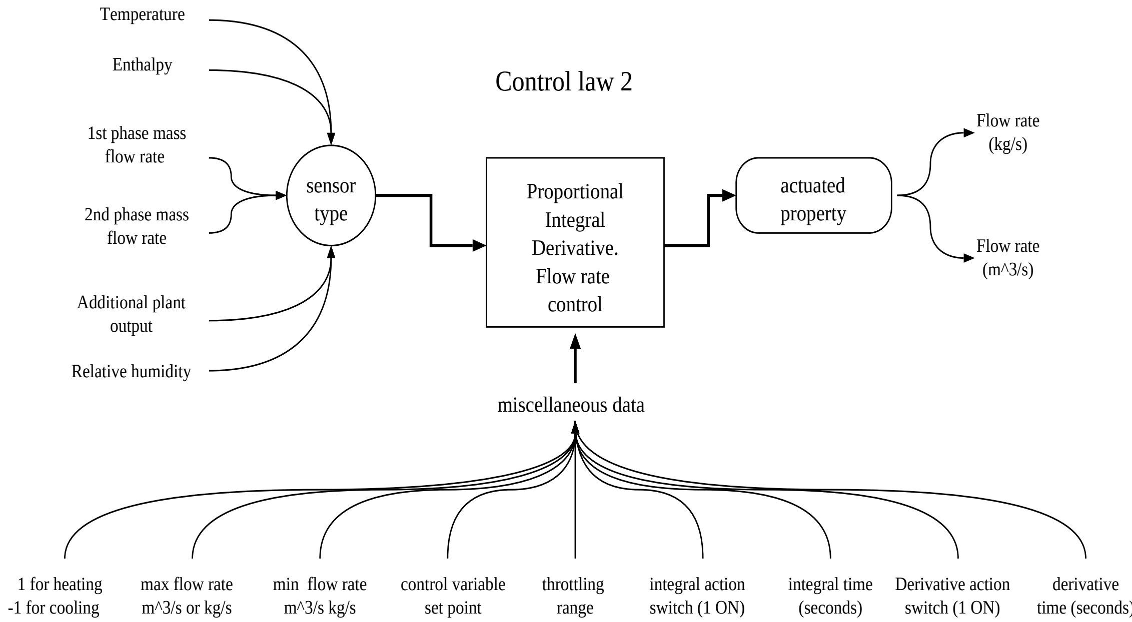


Figure 3.15a Control laws on offer in ESP-r.



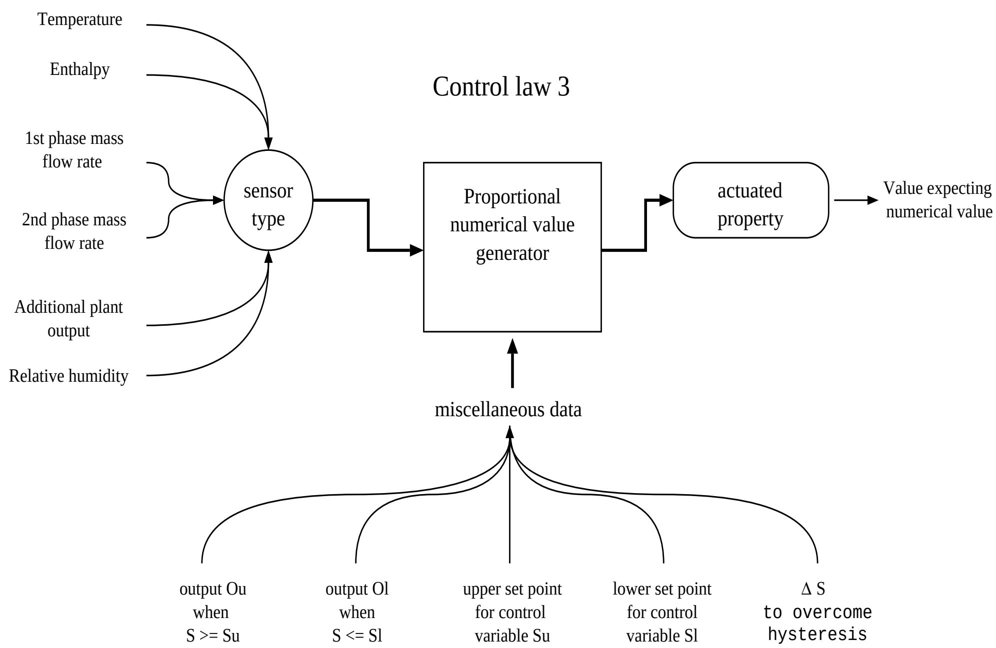
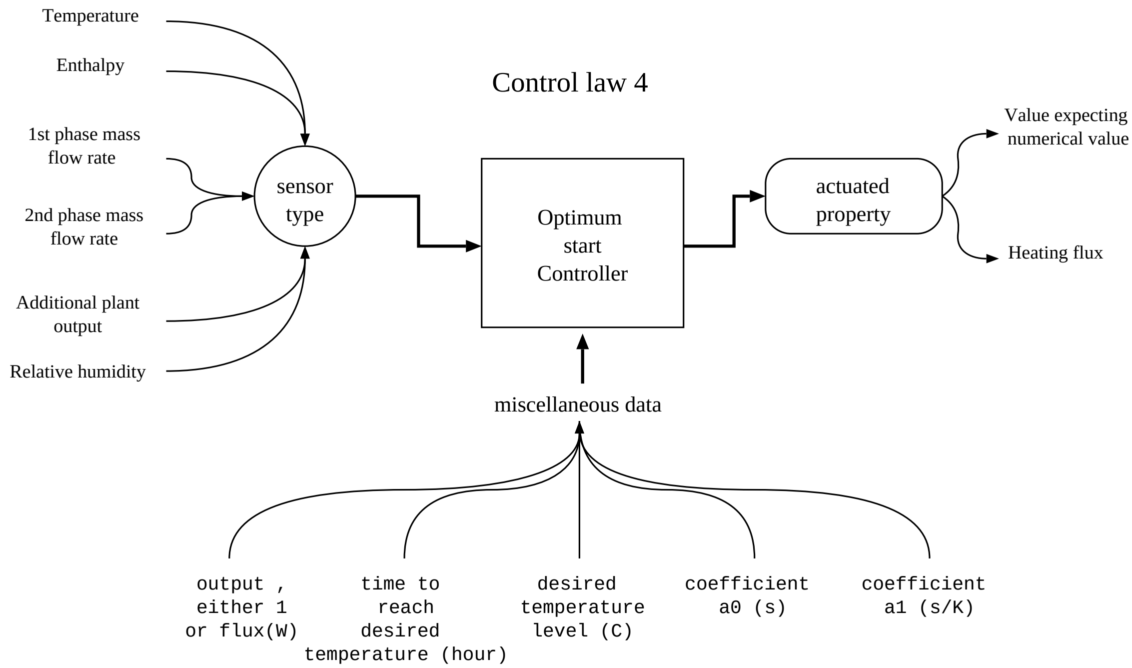


Figure 3.15b Control laws on offer in ESP-r.



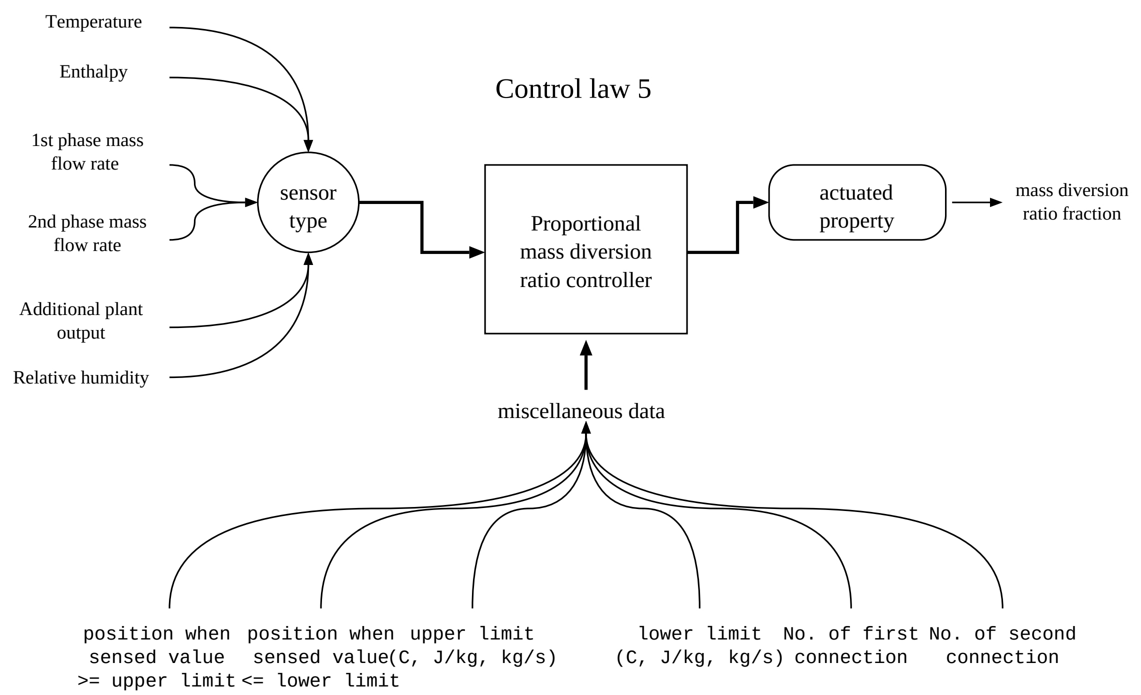


Figure 3.15c Control laws on offer in ESP-r.

solve the overall system matrix equation, resulting from the combination of the matrix equations for the building and plant, plant phase mass balances and a mass flow network, simultaneously. In ESP-r, the modular simultaneous approach is employed in which each system sub matrix equation is solved separately. This is favoured over the solution of the combined matrices for the following reasons:

- The known topology of the building sub-system matrix equation means that intelligent solvers can be used which only process the filled elements within the sub-system matrix. For a plant system in particular the matrix topology is known only at run time while the building-side matrix topology is often known from the problem description. For both cases, this approach significantly reduces computational time and encourages the adoption of compact storage schemes for the filled elements which also reduces memory storage requirements.
- For heavy building structures, a relatively large time-step can be used. Whereas for plant systems with fast response, small time-step value can be used.
- Separate matrices are simpler to administrate in terms of evaluation of coefficients for characteristic equations.
- The complexity involved in handling and processing the combined overall system matrix is eliminated.

The problems encountered with the modular simultaneous approach, such as the evaluation of highly coupled processes, can be eliminated through iteration applied to the entire system. For example, in a building and plant configuration, the building matrix is first processed to give zone temperatures. The plant matrix is then processed to determine the cooling load requirements based on the previously calculated zone temperatures. In order to ensure that the correct zone temperatures are used, the iteration process must continue until the difference between the present and previous zone temperature values are within an acceptable accuracy level.

Interaction between a plant and a building can be accounted for by specifying the intra-zone interaction point. In terms of the control volume technique, this interaction point is represented by one or more nodes. A node could be located at an air point indicating that energy is added to or extracted from the zone air convectively. For most air conditioning systems, this is an appropriate choice since heating or cooling is enacted by convection exchange. The interaction point can also be an intra-construction node allowing for plant injection or extraction within storage regions. This would be appropriate in situations where there is some device embedded within a construction such as with underfloor heating systems or electrical storage units. If the containment for a plant component (a radiator say) was defined to be a building zone, then the radiator heat emission can also interact with the zone air point by convection, as well as with zone inside surfaces by radiation. In other words a radiative and convective split can also be allowed for if such situations arise.

The heat injected to the zone air (ϕ_p (W)) with the plant interaction point located at the zone air can be expressed by the following equation:

$$\phi_p = \dot{m}_a \, C_p(\theta_s - \theta_a) \tag{3.15}$$

where $\dot{m}_a$ is the dry air mass flow rate entering the zone (kg/s) , C_p is the specific heat of air at constant pressure (J/kg K), θ_s is the component node temperature (°C) and θ_a is the zone air temperature (°C). It was explained by Clarke (1985) that a zone matrix equation is reduced to produce a set of whole-system 'characteristic equations' (referred to as CE's) which relate control nodes to the required nodal plant interaction. Equation 3.15 can then be solved simultaneously with the following zone characteristic equation:

$$B\theta_a + C\phi_p = D \tag{3.16}$$

where B, C and D are the modified coefficients (Clarke 1985), to give the following expression:

$$\phi_p = \frac{(\theta_s - \frac{D}{B})}{(\frac{1}{\dot{m}_a C_p} - \frac{C}{B})} \quad . \tag{3.17}$$

For the case where a component containment was defined to be a building zone, for example a radiator inside a building zone, then the evaluation of ϕ_p will be based on a component's theoretical model (i.e coefficient generator for the radiator component).

Note that in both heat transfer calculation methods, θ_a can be calculated by direct use of equation 3.16, or in the case where there is a mix of radiant/convective plant flux, then the B, C and D coefficients are modified to account for the correct proportion of convective/radiative split.

In ESP-r, building and plant interaction is achieved by the use of special building control functions, the structure of which is shown in Figure 3.16. As can be seen, a number of miscellaneous data items must be specified in order to define the plant and building interaction points. A choice between convective and mixed radiative/convective heat transfer can be made by specifying the

3.5 Numerical methods.

When the differential equations representing heat and mass balances within a building/plant network are reduced to linear algebraic equations for matrix equation processing, It is then possible to obtain accurate results even when considering non-linear processes or when there is cross coupling between equations. This is achieved by iteration applied to the entire building/plant equation-set. For the cross coupling case, consider the $C_{t+\Delta t}$ terms of the energy balance equations (3.5 and 3.6) which are a function of the future time-row mass flow rates. In this case an iterative approach may be adopted in which future-time C is evaluated based on the most recent value of the mass flow rate. The entire plant matrix equation is then solved for the new values of the mass flow rate. If the difference between new and old mass flow rates is not within an acceptable tolerance, then the new mass flow rate values are used for the next iteration. For the non-linear case, consider the linearised heat transfer coefficients which are to be determined from future-time row surface temperatures (i.e not yet computed). Iteration can also be applied here by successive substitution of surface temperatures until an acceptable tolerance is reached. It is also possible to overcome these problems by using small time-step values for the simulation instead of iteration. The most obvious disadvantage with using such time-steps is the increase in simulation time and also in results storage requirements. It is nevertheless possible to implement time-step reduction schemes based on user specified criterion. These time-step reduction schemes control how the simulation time-step is to be modified at run time for each hour so that the required accuracy is obtained with minimum simulation execution time. Time-step reduction schemes were implemented in ESP-r using the concept of time-step controllers.

Winkelmann (1986) defined the purpose of time-step controllers as:

> "the underlying idea behind a time-step controller (TSC) is that processes can occur in a building with a wide range of characteristic time variation. For example, earth-contact heat conduction varies very slowly with time, with time constants of days or weeks; heat conduction through exterior walls, solar gain through windows, infiltration and ventilation loads follow fairly closely the time change rates of climatic variables, which can vary significantly over periods of tens of minutes to a few hours; equipment cycling on and off and transients caused by set-point changes can have characteristic times of minutes or seconds. To account for this range of variability, a detailed simulation should allow adjustable time-steps".

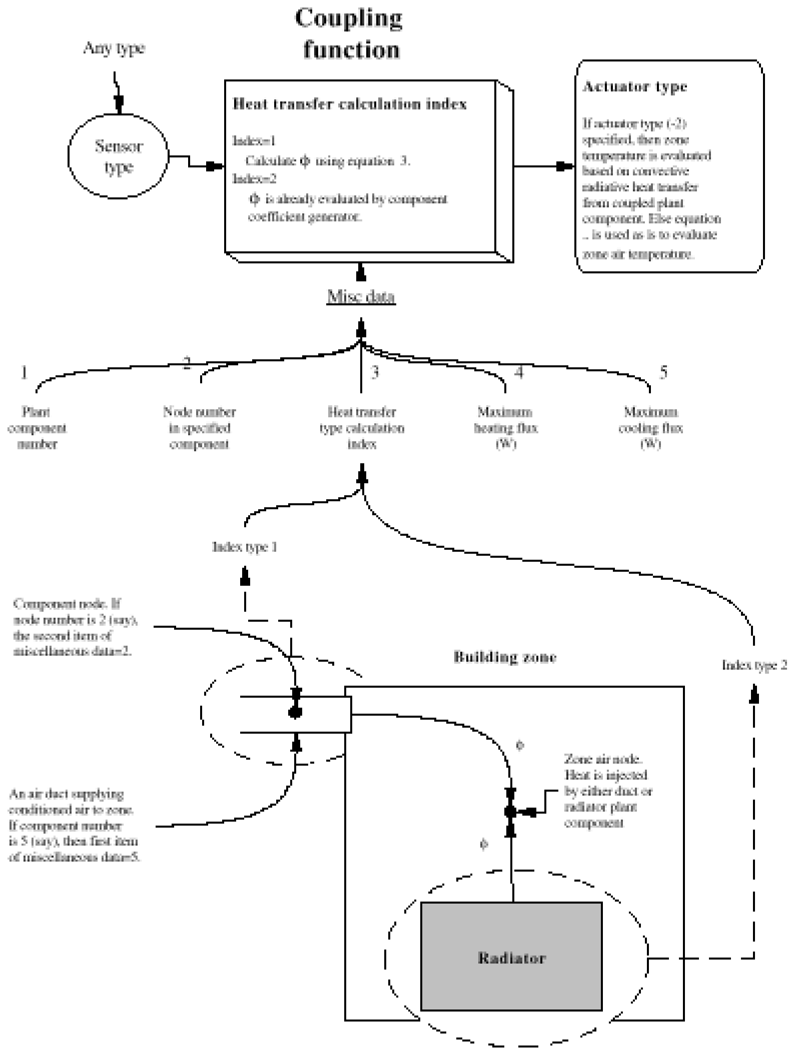


Figure 3.16 A building function for coupling of building and plant

Appropriate index for the third miscellaneous data item. The fourth and fifth data items ensure that the calculated ϕ_π is within this range.

In order to employ this feature to ESP-r, a number of issues, discussed in the following section must first be considered.

3.5.1 General simulation time-step considerations

The structure of the main numerical solver in ESP-r is shown in Figure 3.17. As can be seen, the simulation starts with the required number of days, 24 hours for each day and the required number of building time-steps within each hour. Then for each building time-step, the simulation steps through each zone for which the matrix equation is reduced to produce a whole-system characteristic equations (CEs) relating control nodes to the required nodal plant interaction. Before this subroutine is called, some terms which are not expected to change during the simulation are first calculated. These are coefficients of temperature terms relating to nodes in thermal contact within each construction in a building and coefficients of heat generation terms of the same nodes. Another important term is the time-step value for the plant. With regard to calculating the plant time-step value, it can also be seen from Figure 3.17 that for every building time-step, there are NTSTPP plant side time-steps. This means that the following relationship holds:

$$\Delta t_p = \frac{3600}{NTSTEP * NTSTPP} \quad (seconds) \tag{3.18}$$

where Δt_p is the plant simulation time-step, *NTSTEP* is the number of building time-steps per hour and *NTSTPP* is the number of plant time-steps per building time-step. For a simulation involving both building and plant simulation, it is therefore necessary to modify these time-step dependent terms every time NTSTEP is required to be changed by some time-step controller. This is true if only building time-step control was active. In the case where time-step control was required on plant side then only Δt_p will be affected.

Although it is possible to save the simulation results at different time-step values, it was decided that in order to keep the results file as small as possible, it is essential to have these results saved at a fixed time-step. This implies that if a time-step controller was active and that *NTSTEP* was changed, then simulation results must be transferred at the original *NTSTEP* value (specified by the user during the simulation parameter definition phase). A time-step controller (hereafter referred to as a TSC) can achieve this by halfing the time-step (i.e doubling *NTSTEP*) and then performing a check to see if result transfer is required at the present time-row. Expressed in FORTRAN, the statement may look like:

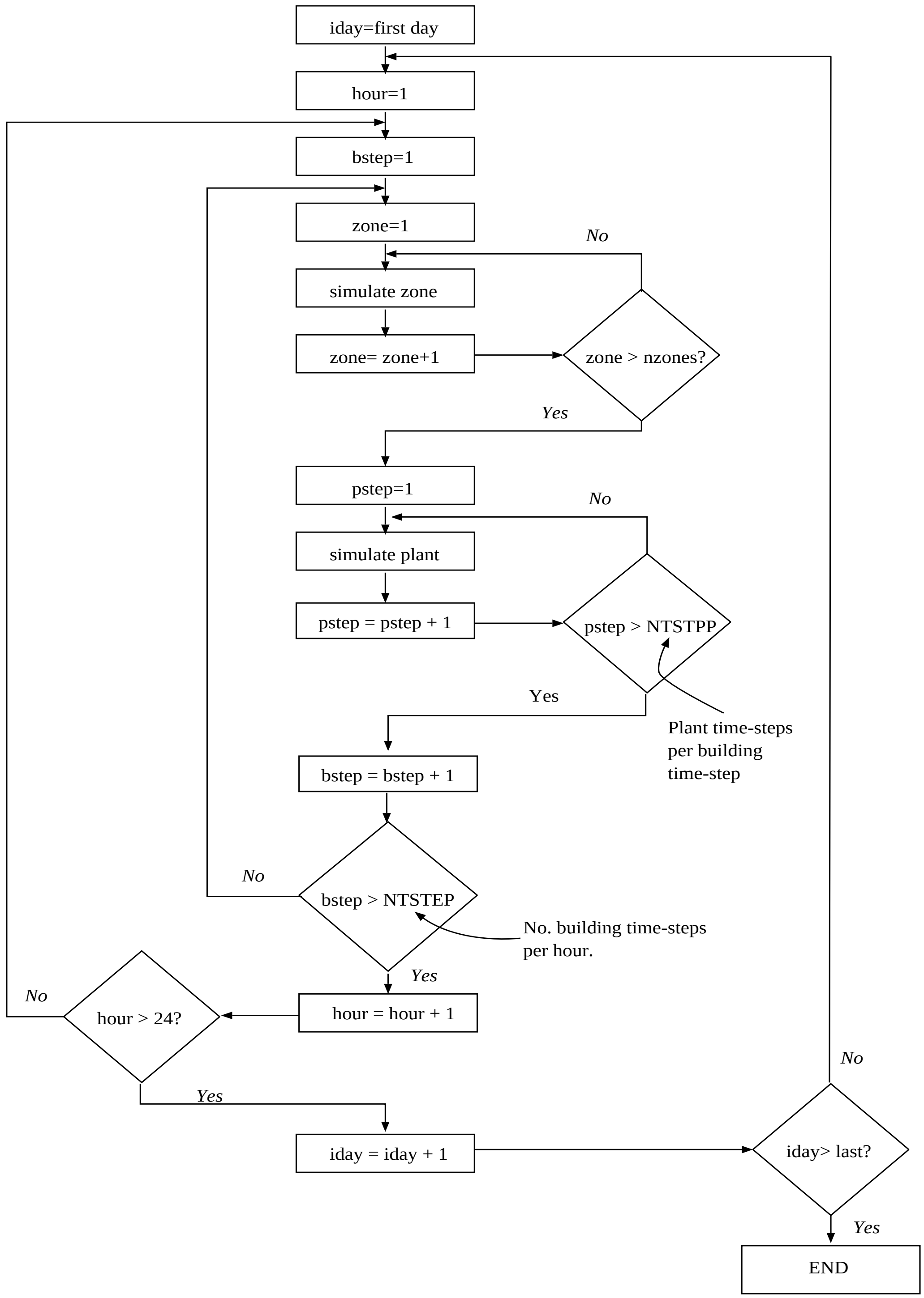


Figure 3.17 Diagrammatic representation of simulation structure for a combined building and plant domain in ESP-r.

IF (AMOD(float(k),float($NTSTEP_{new}$ / $NTSTEP_{orig}$)).EQ.0.0)

where k=1..$NTSTEP_{new}$, $NTSTEP_{new}$ is as evaluated by the TSC and $NTSTEP_{orig}$ is the original user specified value. Note that if a TSC simply increments $NTSTEP_{orig}$ instead of doubling its value , for example if $NTSTEP_{orig} = 2$ (30 minutes time-step) then for $NTSTEP_{new=}$ 3 (20 minutes time-step), the above test will fail for k=1 and 2, and simulation results will only be transferred when k=3. For this reason it is essential to have the time-step value halved. In this case for $NTSTEP_{orig} = 2$ and $NTSTEP_{new=}$ 4, the above test will be true for k values of 2 and 4 (i.e 30 and 60 minutes). Moreover, the other effect of halfing the time-step is to reach convergence with the minimum number of iterations.

3.5.2 Available time-step controller types

Some of the following time-step controllers directly modify the simulation time-step and some may be used to impose iteration on the solution. The main intention is to provide numerical control features which can be applied in the solution of non-linear systems and in situations where a time-step value which produces accurate results is not known beforehand. Moreover, some types may be used to reduce the transient effects of a thermostat when switched on, while other types can be used with stiff plant systems (i.e systems with components of widely different time constants).

3.5.2.1 Building type 1: The boundary condition look-ahead method

This type is suitable in situations where the rate of change in a climatic variable is relatively large, such as in the case of direct normal radiation under cloudy skies. In ESP-r the following climatic variables are supported:

- Dry bulb temperature (°C)
- Direct normal (or global horizontal) radiation (W/m^2)
- Diffuse horizontal radiation (W/m^2)
- Wind speed (m/s)
- Wind Direction (degrees clock-wise from north)
- Relative humidity (%).

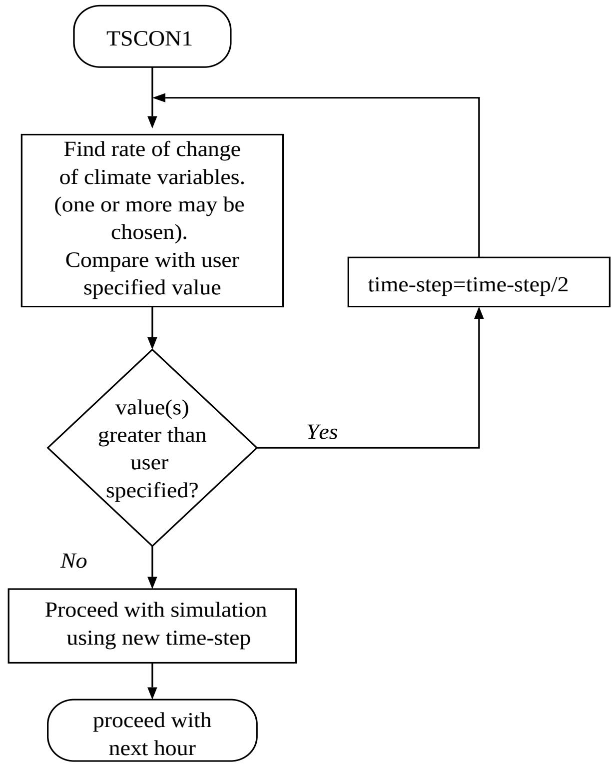


Figure 3.18 Flow chart for boundary condition change rate time-step controller

All data is assumed to act on the hour, with linear interpolation for smaller time-steps. This climatic data is available in a separate binary file. For the required simulation period, the climatic data is read at each hourly interval and the present and future time-row climatic data for the current time-step are evaluated. The rate of change for any climatic variable can be evaluated and if it is greater than the user-specified threshold value, the time-step is halved. This process is repeated until either the rate of change condition is satisfied or the maximum number of repetitions specified by the user is reached. The new time-step value is then used in the numerical solution. More than one climatic variable can be specified. In this case, time-step reduction will occur if the above condition is not satisfied by any climatic variable.

3.5.2.2 Building type 2: The iterative with time-step reduction method

This type is suitable when simulating large multi-zone buildings where a suitable time-step is not known prior to the simulation and the use of a small time-step will result in excessive results file size and computational time. With this type the building's dynamic response is used to determine whether more iterations are required. It is also suitable for buildings of light construction in which the time constant is small and might introduce instability to the solution if a relatively large time-step value was chosen.

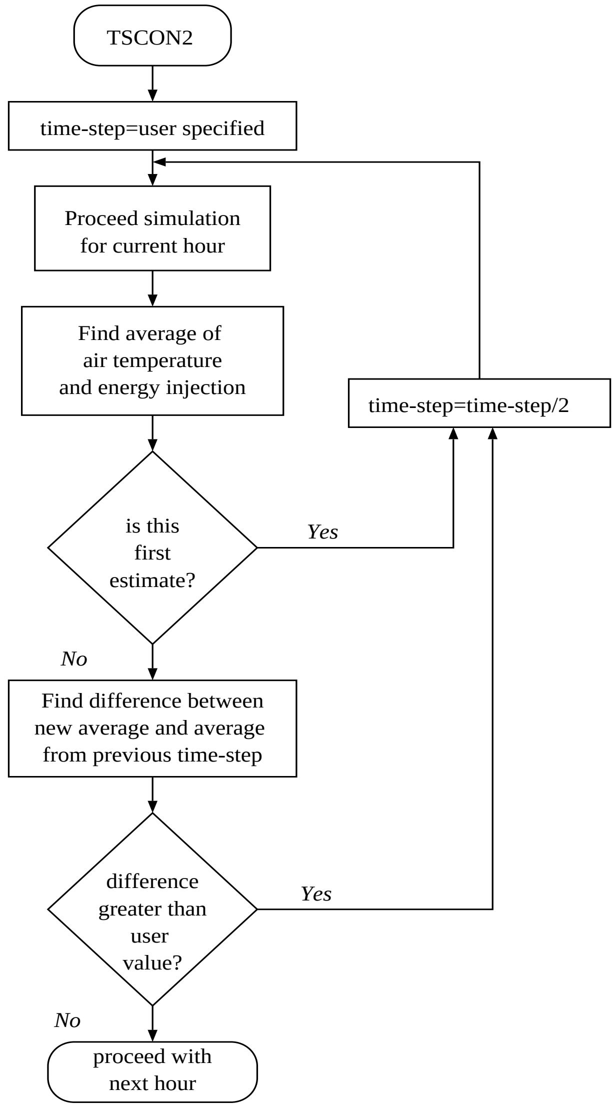


Figure 3.19 Flow chart for iterative with time-step reduction time-step controller

At each hourly interval, the numerical solution is proceeded using the initial time-step value. The time-step is then halved and, for the same hourly interval, another run is made. This iterative process is repeated until either the difference evaluated for the control variable(s) is within the user-specified threshold value or the number of iterations reaches the user-specified maximum. The difference evaluated for a control variable is that between its average value at the current time-step and its average value at the previous time-step. The following control variables were implemented (others could be added):

- Zone air temperature (°C)
- Air node energy injection (W/m^2).

More than one control variable may be specified, in which case, time-step reduction will occur if the criterion set was not satisfied by any control variable.

3.5.2.3 Building type 3: Manual time-step variation method

This type can be used in situations where the transient effects introduced because of a controller becoming active are to be minimised. In this case, a suitable time-step value can be specified before and after the control start period.

In this method the user simply specifies the number of building-side time-steps per hour for a certain period of time during the simulation run period. In order to ensure that the simulation results are transferred to the results recovery file at the original time-step value, only time-step values obtained from the following relationship are allowed:

$$NTSTEP_{new} = NTSTEP_{orig} \times I$$

where $NTSTEP_{orig}$ is the original value of the building-side time-steps per hour and I is an even integer number, 2,4,6..etc. Thus if the original NTSTEP value is 3 (i.e time-step of 20 minutes), then values of 6,12,18,..etc are equivalent to 10,5,2.5 minutes respectively.

3.5.2.4 Building type 4: Iteration without time-step reduction

To permit future time-row coefficient matrix formulation it is usually acceptable in terms of accuracy, to operate one time-step in arrears. However in cases where there are non-linearities involved, such as in the heat transfer problem mentioned at the beginning of this chapter, an alternative mechanism can be used. The future time-row values can be guessed and then used to solve the entire matrix for surface and zone temperatures. The new surface temperature values can then be used to re-establish the matrix coefficient and solve re-solution until the difference between new and old surface temperatures are within an acceptable tolerance. The following control variables are supported:

- Zone air temperature (°C)
- Air node energy injection (W/m^2)
- Surface temperatures (°C).

The user must also specify the total number of iterations allowed per time-step and the tolerance acceptable with each selected control variable. More than one control variable can be selected. In this case all tolerance must be satisfied before termination of the iterative mechanism.

Note that the time-step controller types specified above also affect the plant time-step indirectly, as was illustrated by Equation 3.18. However the plant simulation time-step is modified as a result of the transient performance of a building and not the plant. In order to allow for plant simulation time-step control, additional types were also implemented to the plant side of ESP-r.

3.5.2.5 Building type 5: Output control of results

With this type, no time-step reduction takes place. It was implemented to overcome the limitation caused by transferring building results at initial user specified time-step values rather than at the current time-step value evaluated by a TSC. This type allows the output of some variables at the current time-step value and can be used in conjunction with other time-step controllers, therefore eliminating such limitations. When used, it requires the output file name and the building zone in addition to the required output variables selected from:

- Zone temperature (°C)
- Zone energy injection/extraction (W).

Results are output to the specified file when the specified period of results transfer is reached. This file can later be used by graphical tools for further analysis.

3.5.2.6 Plant type 1: Time-step reduction based on component time constant

This type can be used for systems containing a number of components, each with different time constant characteristics (ie. stiff systems). Within ESP-r, each component time constant is calculated at each time-step in order to select the finite difference scheme which gives a stable solution (e.g. implicit, mixed implicit/explicit by user defined weighting factor, or Crank-Nicolson). The selection of the finite difference scheme is based on a comparison between the simulation time-step and the component's time constant. Typically, if the simulation time-step exceeds 63% of the component time-constant, the fully implicit formulation is used. Otherwise the default scheme (Crank-Nicolson) or the user specified implicit/explicit weighting, if active, is used. In some situations, where large variations in component time constant occur, unstable solution may persist because different finite difference schemes will be selected for individual components. This problem can be overcome if a smaller time-step is used. This time-step controller allows the user to establish the simulation time-step on the basis of: one of the following available options:

- component with smallest time constant
- component with largest time constant
- user specified component.

If the first option is selected, then before the plant simulation commences, a new time-step value will be calculated based on the component with the smallest initialvtime constant. Time-step reduction then continues at run-time until its value is less or equal to the smallest dynamic time constant. In ESP-r, because the component time constant is calculated at each time-step to account for temporal component parameters (e.g. thermal conductance), time-step reduction takes place at each building time-step. In the second control option, the same procedure is followed but now the time-step reduction is based on the largest time constant value for a particular plant system. With this option it is possible to investigate the magnitude of the difference in the plant system response when compared to that obtained from the first option. The third option allows the user to conduct more rigorous analysis based on the effect of different time constant values on the stability of the solution. Now the time-step reduction procedure will be based on the user-specified component time constant.

3.5.2.7 Plant type 2: Manual time-step reduction method

This control type is similar to building type 3 and allows the user to specify a different time-step for a given period of time. This is appropriate in situations where a control loop may be expected to introduce fluctuations in system response. Using this type it is possible to specify a time-step value during any control period so that any fluctuations are minimised. For example, for a specified control loop period which might initiate variations in flow rates, this type can be selected to be active just before the start of the control loop period, so that the specified time-step is used. In order to reduce the size of the plant results file, which could be very large when small time-steps are used, the simulation results are transferred to the results recovery file at the original time-step value. To achieve this only time-step values obtained from the following relationship are allowed:

$$NTSTPP_{new} = NTSTPP_{orig} \times I$$

where $NTSTPP_{orig}$ is the original value of the plant time-step per building time-step and I is an even integer number 2,4,6..etc. Thus if $NTSTPP_{orig}$ value is 10, then values of 20,40,60,..etc are allowed.

3.5.2.8 Plant type 3: Mixed iterative and time-step reduction method

This type may be used to investigate the solution convergence rate for a specific problem. Alternatively it may be used in situations where continuous oscillations result from the built-in iterative/direct solution approach. Such situations might arise in air conditioning systems where the cooling and heating fluxes of the cooling and heating coils are actuated based on the same air point temperature. With this method, the first solution iteration is carried out using the user specified time-step value. If another iteration is required then the time-step value is reduced (either by incrementing NTSTPP or by halfing the current time-step) and the system solution is repeated. Then in each successive iteration the time-step value is reduced and the system is solved again. This process is repeated until either the maximum number of iterations or the minimum time-step value is reached, which ever comes first. To use this type, an option may be selected from the following:

- decrement time-step
- half time-step

The first option implies that the new time-step value will be calculated from the result obtained by incrementing the number of plant time-step per building time-step (NTSTPP). Whereas in the second option, the time-step is actually halved in each iteration.

3.5.2.9 Plant type 4: Output control of results

This control type does not modify the time-step value. Instead, it allows control on the results to be output this controller type is specified for a particular period. This method allows for a targeted results recovery to take place at the current time-step rather than at the original user-specified time-step value. One useful application is when studying the dynamic response of components using small time-step values. To obtain output for the period of interest, plant time-step controller type 2 can be used to specify the required time-step for a certain control period, the type 4 controller can then be used for the same period to obtain results for each modified time-step. Type 4 can also be used with other plant time-step controller types. When this type is selected, the output file name and the plant component must be specified together with the required output variables selected from:

- node temperature (°C)
- node first phase mass flow rate (kg/s)
- node second phase mass flow rate (kg/s)
- additional output.

During the simulation, if the period specified for output is reached, then the output of the component results for the selected variables selected variables will begin, with the transfer terminating at the end of the output period. Note that the output is in 'text' format so that it can later be used by separate analysis software.

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CHAPTER 4
Air Conditioning Systems

4.1 Function of air-conditioning systems

The main function of an air conditioning system is to maintain some desired environmental conditions within a space while external conditions are continuously changing. These environmental conditions include the air purity, movement, temperature and relative humidity. The process used to deliver air to a room at a specified temperature and relative humidity consists of cooling an outdoor/recirculated air mix to a temperature below the dew point, forcing condensation to occur until the mixture has the required specific humidity, and then heating the air to the required temperature. This process is shown in Figure 4.1. The vapour is at state 1 in incoming/recirculated air mix, and is required at state 3 in the room. The temperature θ_{d2} is termed the apparatus dew point and is the temperature of the refrigerant in the case of a coil cooler battery, or the temperature of the chilled water spray in the case of a spray de-humidifier. The state of the moist air follows the state path shown by the line 1-d_2. In practice the moist air would not leave the cooler at state d_2 but at some intermediate state such as point Z. The ratio of $Z - d_2$ to $1 - d_2$ is called the coil by-pass factor. Heating the mixture leaving the cooling coil at constant pressure brings the temperature to θ_3 and the condition to that defined by 3.

Figure 4.2 shows a typical air conditioning plant arrangement consisting of a cooling coil, which can be the evaporator of a refrigeration unit, or a chilled water coil. The air washer sprays water as a fine mist to control the water content and help to clean the air. The heater, which can be the condenser of a refrigeration unit or a hot water coil, brings the air to the required temperature before delivery to the room by a fan. In many cases, the bulk of the air leaving the room is recirculated and mixed with the fresh air, while some is rejected to the atmosphere. In order that the supply should be of a consistent quality it is necessary to have automatic control of the cooler, heater and spray unit.

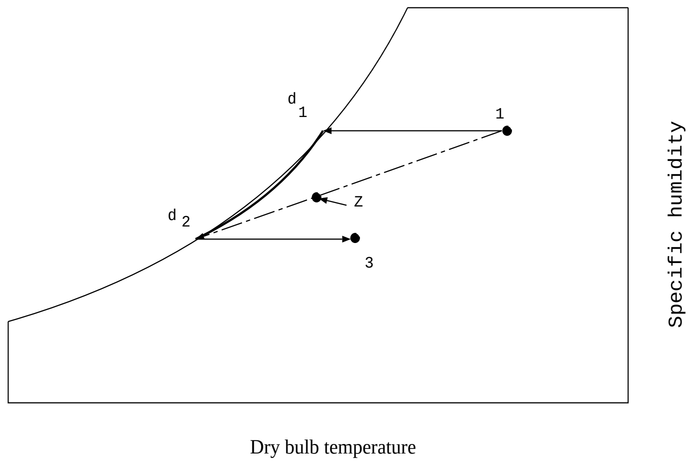

Figure 4.1 Cooling and heating processes on a psychrometric chart

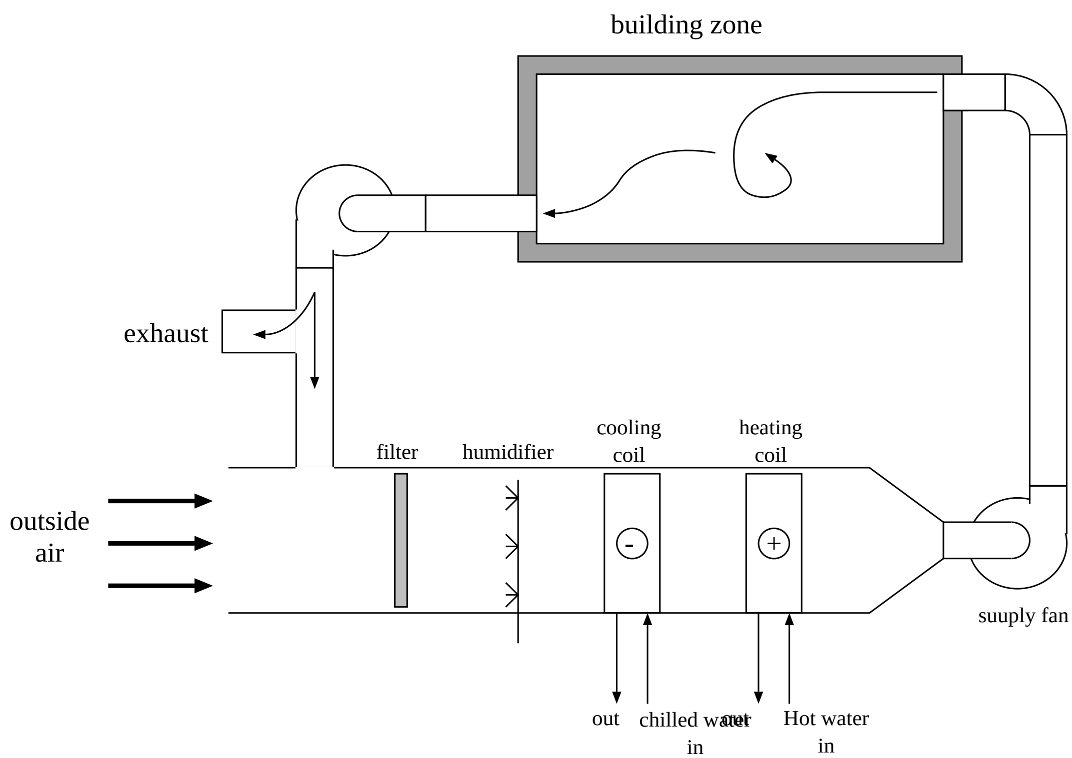

Figure 4.2 A typical air-conditioning plant arrangement

4.2 Air-conditioning systems categories

In general air-conditioning systems are categorised by how they control cooling in the conditioned space with different equipment arrangements used to accomplish specific purposes. For example, a system which provides complete sensible and latent cooling, preheating and humidification of the air supplied, with no additional cooling or humidification taking place at the zone, is classed as an all-air system. Systems which contain a central plant for pre-conditioning primary air but provide hot and cold water to terminals located at the different zones in a building are called air-and-water systems.

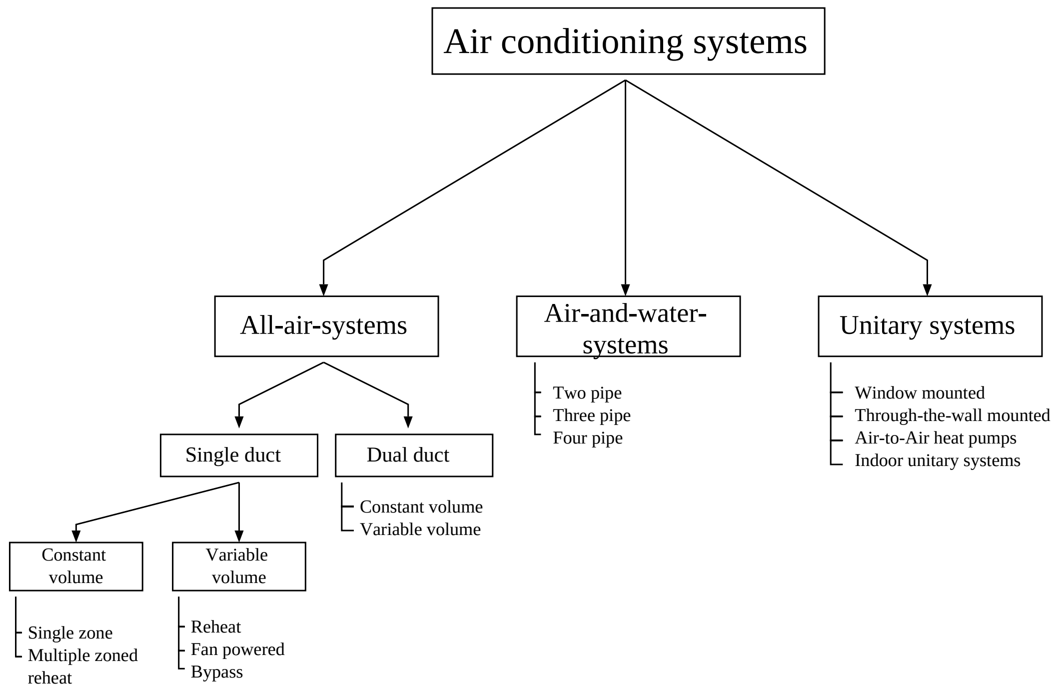

Figure 4.3 Classification of air-conditioning systems

Systems which are factory assembled into an integrated package which includes fans, filters, heating coil, cooling coil, compressors and condensers are called packaged or unitary systems. In general, all air-conditioning systems fall under three categories as shown in Figure 4.3. In the following sections, a detailed description of each system will be given.

4.2.1 All-air-systems

According to ASHRAE (1992), these systems can be classified as:

- Single duct systems, which contain the main heating and cooling coils in a series flow air path. A common duct distribution system at a common air temperature feeds all terminal apparatus.
- Dual duct systems, which contain the main heating and cooling coils in parallel flow or series-parallel flow air paths with either (1) a separate cold and warm air duct distribution system that blends the air at the terminal apparatus (dual-duct systems), or (2) a separate supply air duct to each zone with the supply air blended to the required temperature at the main unit mixing dampers (multizone).

Figure 4.3 shows further classification of systems for single duct based on the volume flow rate type connected to the zone. Considering the constant volume type, Figure 4.2 shows the system arrangement for a simple single zone air handling unit. The system consists of a heating coil, a cooling coil and a fan. The heating coil is placed before the cooling coil in order to prevent freezing.

The multiple-zoned reheat system is a modification of the single-zone system. It is mainly used when the load requirements are different for each zone. Zone reheat is provided by means of coils in the zone branch ducts. Figure 4.4 shows a variable volume arrangement. There are different types of VAV systems. The one depicted in the figure is fitted with a bypass VAV box in which the excess air is dumped to a plenum where it is mixed with the return air. This system supplies a constant volume flow rate but the zone air volume flow rate is modified by a damper which is actuated by a controller sensing the zone temperature. In other VAV systems it is possible to directly alter the fan speed by using variable frequency motor drives. Dual duct systems condition all the air in a central apparatus and distribute it to the conditioned spaces through two parallel ducts, one duct carrying cold air and the other carrying warm air. In each conditioned space or zone, a valve mixes the warm and cold air in the required proportions to satisfy the load of the space. Again, these systems are based on volume flow type, constant or variable air volume. Figure 4.5 shows a constant volume dual duct system with reheat installed upstream to the supply fan (not shown). This is similar to a single duct reheat system except that the reheat is done at the central plant rather than at each individual zone. The mixing valve in the mixing box is actuated on the basis of zone temperature. In this way, different zone requirements can be met by mixing cold and warm air through zone dampers at the dual duct box in response to zone thermostats.

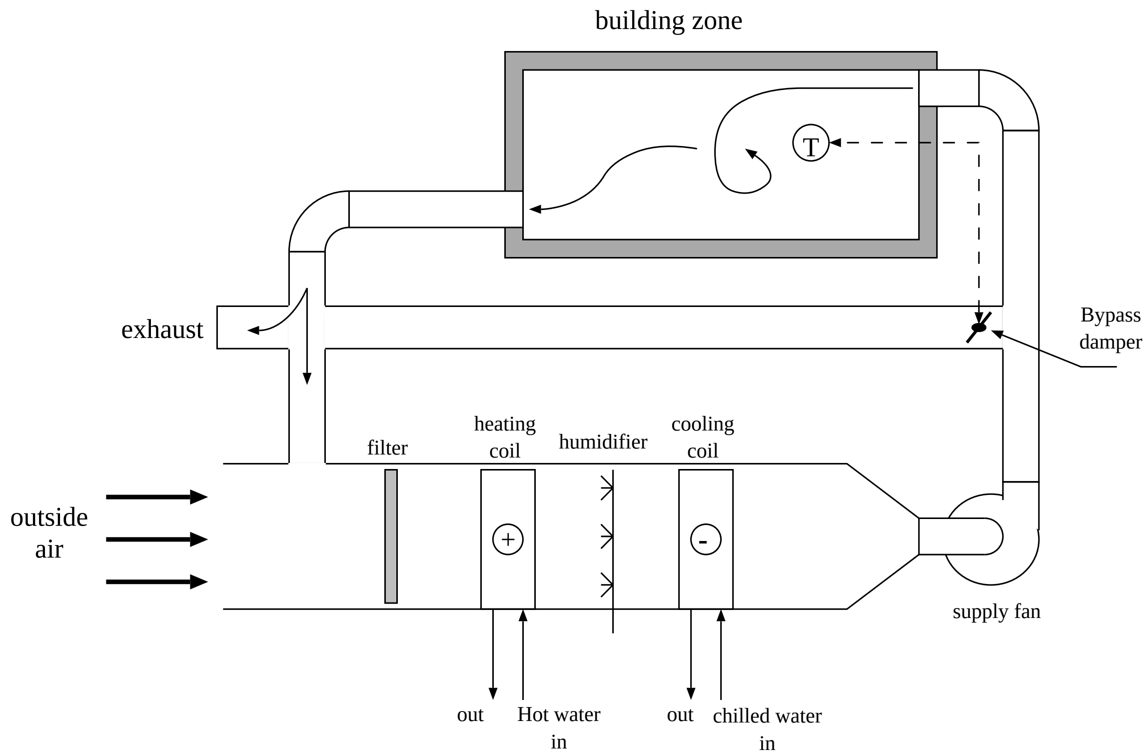

Figure 4.4 An example of a variable air volume (VAV)

Figure 4.6 shows an arrangement for a variable air volume dual duct system with two fans. This system incorporates a single duct VAV system connected to the cold duct for interior space cooling. The outside air can then be pre-conditioned by a heating coil and a cooling coil located at the inlet section. The air volume of each supply fan is controlled independently by the static pressure in its respective duct. The return fan is controlled on the basis of the sum of the cold and warm fan volumes using flow measuring device. Other VAV dual duct systems may employ a single fan instead of the dual fan system as shown. In this case, the single fan is sized for the coincident peak of the hot and cold ducts. Control of the fan is on the basis of two static pressure controllers located in the hot and cold ducts.

4.2.2 Air-and-water systems

An air-and-water system includes central air-conditioning equipment, duct and water distribution systems and a room terminal. The room terminal may be an induction unit, a fan-coil unit, or a conventional supply air outlet combined with a radiant panel. The air supply is generally of a constant

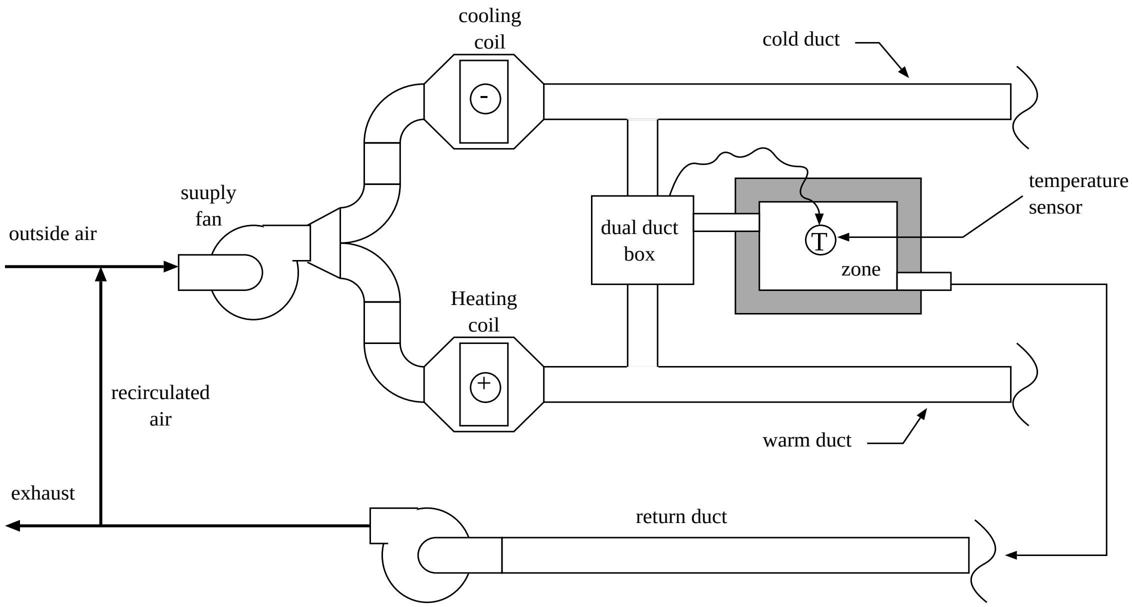

Figure 4.5 A constant volume dual duct system

volume type, termed the primary air to distinguish it from the room air (or secondary air) which is being recirculated. Air-and-water systems are mainly used to condition exterior spaces of buildings with high sensible loads and where close humidity control is not required. When this system is installed in exterior building spaces, they act to provide all required space heating and cooling needs and to provide simultaneous heating and cooling in different parts of the building during intermediate seasons.

Air-and-water systems are categorised as two-pipe, three-pipe or four-pipe systems. They are basically similar in function and include both heating and cooling capability for all year round operation. The name refers to the water distribution system. For a two-pipe system, the water is distributed by one supply and one return for either warm or cold water supply. For a three-pipe system, the water is distributed by two supplies, one for cold water and one for warm water, with one common return for both supplies. With a four-pipe system, the water is distributed by a cold water supply, a cold water return, a warm water supply and a warm water return. The two-pipe system for all year round operation requires that some changeover must take place (i.e from heating to cooling or vice a versa) which presents operational and control problems and are more costly to operate than four-pipe systems. Three-pipe systems are rarely used today because the cold and warm water blends resulting in excessive energy waste. It is for this reason that only the two and four pipe systems are explained in detail in the

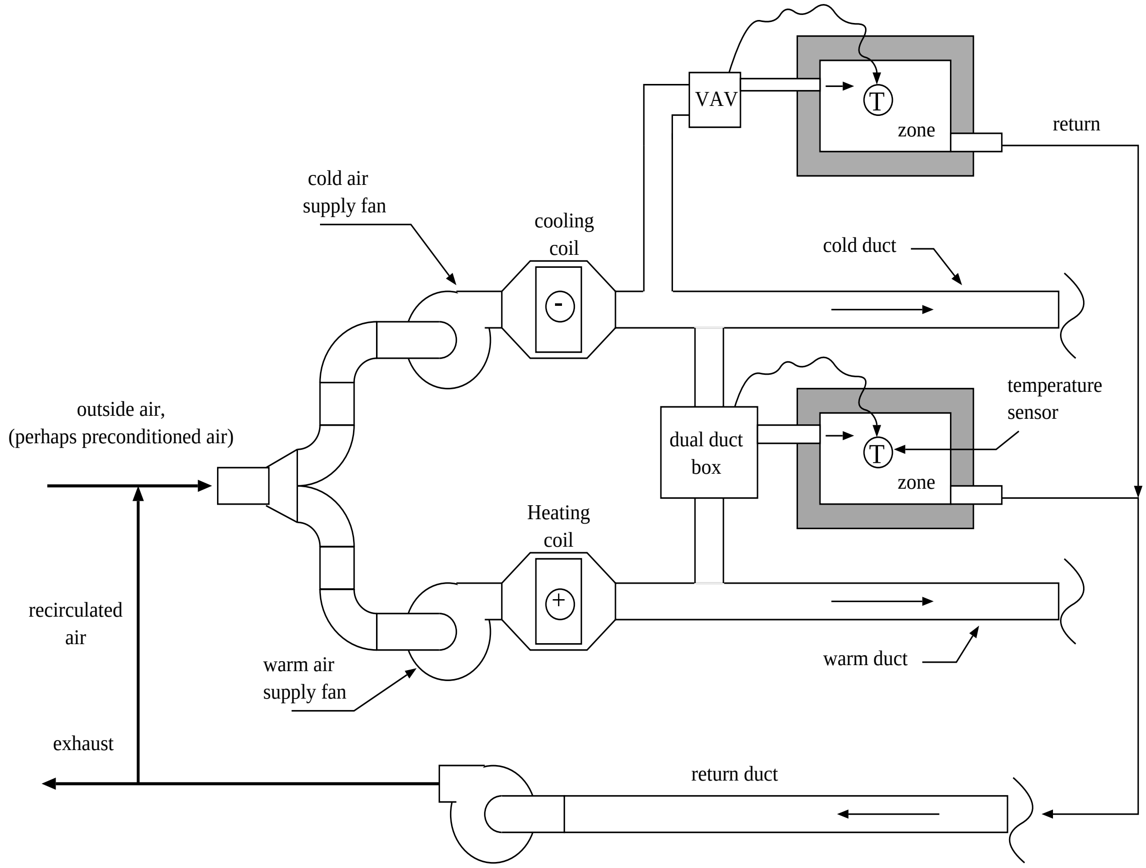

Figure 4.6 A variable air volume dual duct system

following sections.

Figure 4.7 shows the arrangement for a two pipe induction system with no changeover. This system has a constant quantity of primary air supplied at varying temperatures to each zone of the building together with chilled air at constant temperature. Heating is provided by the primary air and zone temperatures are individually controlled by actuating the chilled water flow rate through the coil of the terminal induction unit. The primary air is supplied to these induction units through specially designed nozzles which induce high velocity at the nozzle exit thus creating a pressure drop. The pressure differential between zone air and the induction unit causes the zone air (induced air) to flow through the coil attached to the induction unit. The induced air then mixes with the primary air to produce the required space condition.

Figure 4.7 A two-pipe induction system with no changeover (Sherratt 1980)

Figure 4.8 shows a four-pipe, fan coil system, consisting of terminal units with a fan to recirculate air within the conditioned space. The units can receive both hot or cold water. Room temperature control can be achieved by either actuating water mass flow rate through the coils or by damping the recirculated room air so that the required proportion of air is passed over each coil. A central ventilation plant provides the necessary amount of fresh air. This allows units to be placed anywhere inside the room. It is also possible to have a fan in the terminal units to draw fresh air directly from outside; however with this arrangement condensation may occur on the secondary coils and so a drain must be provided. Compared to the two-pipe system, the four-pipe system is simpler to operate; responds quickly to room load changes; has a better efficiency and lower operating cost; and has a high initial cost.

4.2.3 Unitary systems

These systems are factory assembled and come in various forms to meet a wide range of applications such as window air conditioners and through the wall room air-conditioners. Special arrangements are also available to cater for hospital and computer room air conditioning. Basically

Figure 4.8 A four-pipe fan coil system (Sherratt 1980)

these systems comprise a fan, filters, heating coil, cooling coil, refrigerant compressor, refrigerant side control, air-side controls and condenser. A schematic view of a typical room air conditioner is shown in Figure 4.9.

The heat from the room air is absorbed by the liquid refrigerant flowing through the evaporator. This heat is sufficient to vaporize the refrigerant before it enters the compressor. In the compressor the vapour temperature increases to a temperature higher than the outside air temperature before it enters the condenser. In the condenser the high pressure hot temperature vapour refrigerant liquefies, giving up the heat extracted from the room air to the outside air. The refrigerant then passes through a throttling valve to reduce its pressure and temperature before it enters the evaporator and repeats the cycle. The main advantage of these local plant systems over central plant systems is that they are easy to install and require no ducting or piping space allocation in a building.

Figure 4.9 A window type air-conditioning unit (ASHRAE 1992)

4.3 Identification of common components

A close inspection of the components which make up most of the air conditioning systems mentioned in the previous chapter, reveals the following common components:

- air duct
- mixing box
- fan
- heating coil
- cooling coil
- boiler
- water pump
- chiller
- heat pump

- VAV box
- three way valves
- damper
- water pipes

Chillers and heat pumps are composed of a number of sub-components such as a compressor, evaporator, condenser and throttling valve. Other components not previously mentioned are diverging junction components. The reason for not including this component in the list of common components is that in the energy balance equations derived for most components, only the receiving inter-connections are of interest. The modular nature of component models in ESP-r allows a component to be used more than once in a system and with different attributes. In the case of distribution components this means that component models can be repetitively used in a particular network to define pipes and ducts which are of different sizes and are distributed throughout the system. Once component models have been installed for the above mentioned components, then it is possible to simulate most of the air-conditioning system mentioned previously.

Table 4.1 summarizes the currently available plant component types. Some of these, which are common in air-conditioning systems, are elaborated in the following section which commences with simple single node models and before progressing to multi node formulations. The characteristic conservative equations describing other components developed by the author and other researchers are presented in Appendix A, together with the equation solution and associated component data. The table also shows that a type designation can be assigned to each component in order to distinguish between their functionality.

4.4 Mathematical modelling of plant components

This section describes the mathematical models developed for some of the more important components. Models of progressing complexity are considered in order to show how components can be modelled at different resolutions, both in terms of detail and accuracy. Further, emphasis is made on the modelling of heat flows and where possible mass flow.

Table 4.1 Currently supported plant components

Database entry	Type	Description
1	10	air mixing box or converging junction; 1 node model
2	20	atomizing humidifier; 1 node model ; water flow rate control
3	30	centrifugal fan, 1 node model ; flow control
4	40	air cooling coil; 1 node model ; flux control
5	50	air heating coil; 1 node model ; flux control
6	60	air duct; 1 node model
7	70	air duct damper; 1 node model; flow ratio control *
8	100	air cooling coil; 1 node model ; water mass flow rate control *
9	110	air heating coil; 1 node model ; water mass flow rate control
10	120	air/air plate heat exchanger; 2 node model
11	200	non-condensing domestic WCH boiler; 1 node model
12	210	domestic hot water radiator VO ˜ 2 mˆ2; 2 node model
13	220	5 m length of 15 mm WCH pipe; 1 node model
14	230	WCH pipe converging 2-leg junction; 1 node model
15	240	variable speed domestic WCH pump; 1 node model
16	250	condensing boiler & ON/OFF control; 2 node model
17	260	non-condensing boiler & aquastat control; 2 node IEA Annex X model
18	270	domestic hot water radiator VO ˜ 2 mˆ2; 8 node model
19	300	Single node water cooler with flux control. *
20	400	air cooling coil fed by WCH system; 3 node model *
21	410	air heating coil fed by WCH system; 3 node model
22	500	thermostatic radiator valve; 1 node sensor model
23	510	mechanical room thermostat; 1 node sensor model
24	900	air & water temperature source
25	910	imaginary building-like plant load *
26	280	Oil filled electric radiator; 1 node model with flux control. *
27	90	air cooling coil; 1 node (Q by type 32); water mass flow rate control *
28	670	0.5 m length of 0.01 m dia heat transfer tube, 3 node model
29	920	Fictitious boundary component; 1 node model. *
30	930	A detailed 10 node heat exchanger model; hot fluid temp control *
31	700	Flat-plate collector; 1 node model (Q by type 1) *
32	430	air cooling coil fed by WCH system; 2 node model *
* Developed during present project		

4.4.1 Single node components

As discussed in section (3.2), a plant component may be divided into a number of uniform discrete regions with each region being represented by a set of characteristic equations describing heat and mass transfer. In the case where a component is represented by one discrete region, all the mass involved (ie. solid material and enclosed fluid) is assumed to be concentrated in the one node. A free-standing component algorithm is then used to represent the performance capabilities of the component. This is further elaborated with the cooling coil model described in the following section.

4.4.1.1 Cooling and dehumidifying coils (component type 40, 90 and 100)

Currently there are three coefficient generators for the cooling and dehumidifying coils. Component type 40 allows direct cooling flux control which could be actuated by plant control law 1 (eg. proportional and/or derivative and/or integral) or the cooling flux may be assumed constant in which case no control loop would be specified for this component. Component types 90 and 100 allow cooling water flow rate control which could be actuated by plant control law 2 (eg. proportional and/or derivative and/or integral) or may be assumed fixed if no control loop is defined for these component types.

Table 4.2[1] shows the template for component type 40. The general characteristic equations for temperature, 1st phase mass flow rate and 2nd phase mass flow rate for the single node are first defined. Note that dehumidification is handled within the vapour mass balance equation which indicates that any condensate will be the difference between the vapour entering the coil and the vapour leaving. This applies only if the air temperature of the air entering the coil is equal or less than the dew point temperature. Table 4.2 also shows the formula used to calculate the coefficients for the self coupling, inter-component coupling and present term coefficients respectively. For the temperature state variable, the expressions for the coefficients were derived on the basis of an equal weighting of the implicit and explicit finite difference schemes of the characteristic energy conservation equation.

For component type 40, the cooling flux q_i is directly imported into the matrix coefficients for the energy balance equation. For component type 90 and 100, q_i has to be evaluated first. For component type 90, q_i is evaluated on the basis of empirical relationships taken from ASHRAE (1976). The empirical relationship for the total heat transfer q_t is given by

$$q_t = N_{row} A_f B_r W_{sf} \theta_{lm} \tag{4.1}$$

where N_{row} is the number of rows (depth-wise) of coil tubes, A_f is the face area of the coil (m^2), and B_r is the base rating for the chilled water coil (W/m^2) defined by

$$\frac{1}{B_r} = a_1 + \frac{a_2}{v_a} + \frac{a_3}{v_w} + \frac{a_4}{v_w^2} + \frac{a_5}{v_a^3} + \frac{a_6}{v_a^4 v_w^2} \quad . \tag{4.2}$$

[1] where θ_1 is node 1 temperature (°C), θ_j is the sending component temperature (°C), θ_e is the component's environmental temperature (°C), $\dot{m}_w^v$ is the water condensate flow rate (kg/s), H_w is the condensation heat of water (J/kg), $R_{j,1}$ is the mass diversion ratio in the connection between node j of the sending component and node 1 of the receiving component.

Table 4.2 Air cooling and dehumidifying coil (component type 40)

Characteristic balance equation		
State space variable	Node	Equation
Temperature (C)	1	$C_{1,j}(\ \theta_j - \theta_1) + UA\ (\ \theta_e - \theta_1) + q_i\ + \dot{m}_w^v H_{w=}\ \dfrac{\overline{c}M\delta\theta_1}{\delta t}$
First phase mass flow rate (kg/s)	1	$\dot{m}_{a,1} - R_{j,1}\dot{m}_{a,j} = 0$
Second phase mass flow rate (kg/s)	1	$\dot{m}_{v,1} - R_{1,j}\dot{m}_{v,j} = \dot{m}_w^v$

Generated coefficients		
State space variable	Coefficient	Equation
Temperature	1	$= \alpha\ (- C_{1,j,t+\Delta t} - UA_{t+\Delta t}\ ) - \dfrac{\overline{c}M}{\Delta t}$
	2	$= \alpha\ C_{1,j,t+\Delta t}$
	3	$= \left\{ (1-\alpha)\left[\ C_{1,j,t} + UA_t \right] - \dfrac{\overline{c}M}{\Delta t} \right\} \theta_{1,t}$ $+ (1-\alpha)\ (-C_{1,j,t})\ \theta_{j,t}$ $- \alpha\ UA_{t+\Delta t}\ \theta_{e,t+\Delta t} - (\ 1-\alpha\ )UA_t\theta_{e,t}$ $- \alpha\ q_{i,t+\Delta t} - (\ 1-\alpha\ )\ q_{i,t}$ $- \alpha\ (\dot{m}_w^v H_w)_{t+\Delta t} - (\ 1-\alpha\ )\ (\dot{m}_w^v H_w)_t$
First phase mass flow rate	1	$= 1.0$
	2	$= - R_{1,j}$
	3	$= 0.0$
Second phase mass flow rate	1	$= 1.0$
	2	$= - R_{1,j}$ for $T_{air} \geq T_{dew}$ else $= 0.0$
	3	$= 0.0$ for $T_{air} \geq T_{dew}$ else $= \dot{m}_w^v$

Component default parameters		
M	Component total mass (kg)	15.0
$\overline{c}$	Mass weighted average specific heat (J/kgK)	1000.0
UA	Overall heat loss coefficient (W/K)	3.5

Control data variables
Cooling duty $q_i(W)$

W_{sf} is the wetted surface factor given by

$$W_{sf} = b_1 + b_2\Delta\theta_1 + b_3\Delta\theta_1\Delta\theta_2 + b_4\Delta\theta_1^2 + b_5\Delta\theta_1\Delta\theta_2^2 + b_6\Delta\theta_1^2\Delta\theta_2$$

$$+ b_7\Delta\theta_1\Delta\theta_2^3 + b_8\Delta\theta_1^2\Delta\theta_2^3 + b_9\Delta\theta_1^3\Delta\theta_2^3 \quad (4.3)$$

where

$$\Delta\theta_1 = \theta_{ad,i} - \theta_{w,i}$$

$$\text{and}\Delta\theta_2 = \theta_{a,i} - \theta_{w,i} \quad .$$

$\theta_{ad,i}$ is the inlet air dew point temperature (°C), θ_{lm} is the log mean temperature difference between the air and water flow streams, evaluated from the following expression

$$\theta_{lm} = \frac{(d_1 - d_2)}{ln(d_1/\ d_2)}$$

where

$$d_1 = \theta_{a,i} - \theta_{w,o}$$

$$d_2 = \theta_{a,o} - \theta_{w,i}$$

in which $\theta_{a,i}$ is the inlet air dry bulb temperature (°C), $\theta_{a,o}$ is the outlet air dry bulb temperature (°C), $\theta_{w,i}$ is the inlet water temperature (°C) and $\theta_{w,o}$ is the outlet water temperature (°C). The coefficients $a_1 \rightarrow a_6$ and $k_1 \rightarrow k_9$ are empirical constants with values obtained from ASHRAE (1976). Equation 4.2 was developed for air velocities in the range of 1 m/s to 4 m/s and water velocities from 0.3 m/s to 2.44 m/s. Equation 4.3 is valid for $\Delta\theta_1$ from -17°C to -1.1°C and $\Delta\theta_2$ from -12.2°C to 15.5°C. The average velocities of the air and water streams are evaluated from the following respective equations

$$\bar{v}_a = \frac{\dot{m}_a}{A_f \rho_a}$$

$$\bar{v}_w = \frac{4\dot{m}_w}{\rho_w \pi d_i^2 N_{coil}}$$

where $\dot{m}_a$ is the air mass flow rate kg/s, $\dot{m}_w$ is the water mass flow rate kg/s, d_i is the coil tube inside diameter (m), ρ_a is the air density kg/m^3, ρ_w is the water density kg/m^3 and N_{coil} is the number of parallel water flow circuits. The total heat transfer q_t can also be expressed in terms of inlet and outlet water temperatures and also in terms of the inlet and outlet air enthalpies as given by the following equations

$$q_t = \dot{m}_w C_{p,w}(\ \theta_{w,o} - \theta_{w,i}) \tag{4.4}$$

$$q_t = \dot{m}_a(\ H_{a,o} - H_{a,i}) \tag{4.5}$$

where $C_{p,w}$ is the specific heat capacity of water (J/kgK), $H_{a,o}$ is the outlet air enthalpy (J/kg) and $H_{a,i}$ is the inlet air enthalpy (J/kg). Equations (4.1), (4.4) and 4.5 are solved using an iterative procedure to determine the heat transfer and outlet water and air conditions. The sensible heat transfer q_i can then be evaluated from

$$q_i = \dot{m}_a C_{p,a}(\theta_{a,o} - \theta_{a,i}) \tag{4.6}$$

where $C_{p,a}$ is the air specific heat capacity (J/kgK). q_i as obtained from Equation (4.6) is then used to evaluate the coefficients for the temperature state variable. Note that the present term coefficient contains both present and future values for q_i. The reason for this is that in order to evaluate q_i using the above procedure, the calculation must be based on previous time-step component condition. Table 4.3 shows the parameters required, together with the control variable for component type 90.

Table 4.3 Parameters and control variable for component type 90

Component default parameters		
M	Component total mass (kg)	15.0
$\bar{c}$	Mass weighted average specific heat (J/kgK)	1000.0
UA	Overall heat loss coefficient (W/K)	3.5
A_f	Coil face area (m^2)	0.25
d_i	Internal tube diameter (m)	0.015
$\theta_{w,i}$	Inlet water temperature (C)	5.0
N_{row}	Number of rows deep (-)	2.0
N_{coil}	Number of parallel coil circuits (-)	3.0

Control data variables
Water flow rate $\dot{m}_w$ (kg/s)

The evaluation of q_i for component type 100 is based on the method adopted by Holmes (1982). In his method Equation (4.1) is used in a different form as shown by the following equation:

$$q_t = \frac{\theta_{lm}}{R_L}$$

where the thermal resistance R_L (W/m^2K) is defined as

$$R_L = SHR\ R_a + R_m + R_w \tag{4.7}$$

where SHR is the ratio of sensible to total heat transfer ($\frac{q_i}{q_t}$), R_a, R_m and R_w are the air, metal and water thermal resistances respectively (W/m^2K). R_m represent the thermal resistance of the tube wall, fins and may include external and internal fouling resistances. For air and water it is usual to express their thermal resistances in terms of the heat transfer coefficient as given by the following expressions:

$$R_a = \frac{1}{h_a} \qquad , R_w = \frac{A_o}{A_i h_w} \tag{4.8}$$

in which h_a and h_w are the air and water film heat transfer coefficients (W/m^2K), respectively. The air film heat transfer coefficient depends on a number of factors (such as size and spacing of tubes; velocity of air stream in the coil; the depth of the coil and the temperature of air film). In the absence of experimental results, it is difficult to obtain an accurate relationship for the air film heat transfer coefficient. In such situations, Holmes (1988) suggested the following approximation for the air film heat transfer coefficient

$$h_a = 38\ \overline{v}_a \ . \tag{4.9}$$

In the case of the water film heat transfer coefficient, Holmes (1988) suggested that the flow can be taken as fully turbulent to yield the following expression

$$h_w = 1400(1 + 0.015\ \theta_w)\ \overline{v}_w^{0.8} d_i^{-0.2} \tag{4.10}$$

where θ_w is the mean water temperature (°C). Equation (4.6) can be used to evaluate the sensible heat transfer using the procedure outlined in the following steps:

1- Calculate inlet air enthalpy at temperature $\theta_{a,i}$ from

$$H_{a,i} = H_{a,dry} + \omega_i H_{a,vap}$$

where ω_i is the inlet moisture content (kg/kg dry air).

2- Calculate specific heat at temperature $\theta_{a,i}$ from

$$C_{p,a} = C_{p,dry} + \omega_i C_{p,vap}$$

3- Calculate the coil bypass factor from

$$B_f = e^{\left(\frac{-1}{C_{p,a}\dot{m}_a R_a}\right)}$$

4- Guess the total heat transferred q_t, perhaps from a previous value, or an estimate.

5- Calculate outlet air enthalpy from

$$H_{a,o} = H_{a,i} - \frac{q_t}{\dot{m}_a}$$

6- Calculate saturation enthalpy at coil surface temperature from

$$H_s = \frac{(H_{a,o} - B_f H_{a,i})}{(1 - B_f)}$$

7- Calculate coil surface temperature θ_s from wet bulb temperature as a function of saturation enthalpy and atmospheric pressure.

8- Calculate outlet air temperature from

$$\theta_{a,o} = B_f(\,\theta_{a,i} - \theta_s) + \theta_s$$

9- Calculate sensible heat ratio from

$$SHR = C_{p,a}\,\frac{(\,\theta_{a,i} - \theta_{a,o})}{(\,H_{a,i} - H_{a,o})}$$

10- Calculate corrected thermal resistance R_L from Equation (4.8)

11- Now evaluate q_t via a transposition of Equation (4.7)

$$X1 = \frac{SHR}{C_{p,a}\dot{M}_a R_L}$$

$$X2 = \frac{\dot{m}_a C_{p,a}}{\dot{m}_w C_{p,w} SHR}$$

$$X3 = e^{(-X1\,(1 - X2))}$$

$$X4 = \frac{(1 - X3)}{(1 - X2.\,X3)}$$

$$q_t = \dot{m}_a C_{p,a} X4\,\frac{(\theta_{a,i} - \theta_{w,i})}{SHR}$$

12 Compare new q_t with that from step 4 and if not within a reasonable tolerance return to step 5 and iterate.

13 Use $\theta_{a,o}$ from step 8 to evaluate q_i from Equation (4.6).

At this stage, q_i is used to evaluate the coefficients for the temperature state variable. The parameters used to define component type 100 are listed in Table 4.4.

Table 4.4 Parameters and control variable for component type 100

Component default parameters		
M	Component total mass (kg)	15.0
$\overline{c}$	Mass weighted average specific heat (J/kgK)	1000.0
UA	Overall heat loss coefficient (W/K)	3.5
A_o	Coil outside (air side) heat transfer area ($m^{2)}$	15.0
A_i	Coil inside (water side) heat transfer area ($m^{2)}$	0.33
A_f	Coil face area ($m^{2)}$	0.25
R_m	Coil metal thermal resistance (m^2K/W)	0.001
d_i	Internal tube diameter (m)	0.015
$\theta_{w,i}$	Inlet water temperature (C)	5.0

Control data variables
Water flow rate $\dot{m}_w$ (kg/s)

For component types 90 and 100, the calculation of the heat transfer is initiated with the present values for temperature, first and second phase mass flow rate. These values will not necessarily be identical to the future time-row values. For this reason, temperature, first and second phase mass flow rate are marked for iteration. For component type 40, the present values are used to evaluate the amount of water condensate and so in order to ensure that future time-row values are identical to present values, the second phase mass flow rate is marked for iteration.

4.4.1.2 Water chiller (component type 300)

Component types 40, 90 and 100 as described in the previous chapter, assume that there is only one external connection of type air. The cooling effect of the water is either specified explicitly or evaluated from the input parameters. These component types do not accept another external connection of a water fluid type. As will be seen later (section 4.4.2.1), multi-node cooling and dehumidifying coils allow for more than one external connection and therefore enable a more detailed simulation of heat and mass transfers. Although a boiler can be used to feed heating coils, there existed in ESP-r no component to feed chilled water to cooling coils. For this reason component type 300 was added. The template for this component is included in appendix A and will not be explained here as it takes the same form as component type 40 described previously. This chiller model allows the cooling capacity to be controlled such that the leaving chilled water may be maintained at a specified temperature. This can be achieved by specifying a control law of type 1 with PID capabilities. On the other hand, if no control loop is specified, then a fixed cooling capacity value will be assumed throughout the simulation. Since the working fluid for this component is water, then only the temperature and first phase mass flow rate state variables will be processed. The input parameters required for this component are listed in

Table 4.5.

Table 4.5 Parameters and control variable for component type 300

Component default parameters		
M	Component total mass (kg)	20.0
$\bar{c}$	Mass weighted average specific heat (J/kgK)	1000.0
UA	Overall heat loss coefficient (W/K)	15.0

Control data variables
Cooling capacity q_i (kg/s)

In practice it is usually necessary to take into account the pressure drop that occurs in heat exchangers. ESP-r's ability to incorporate a fluid flow network to simulate the flow of the different fluids makes it possible to do this. This is important if the objective is to simulate real systems accurately. For the water chiller component, this can be achieved by mapping a fluid flow component to the external connection for the chiller. With respect to water flow in the chiller, inlet water passes through an evaporator (heat exchanger) in which the heat rejected from the water will evaporate the refrigerant before it enters the compressor. As the water flows through the evaporator, some pressure drop occurs across the evaporator because of the restriction imposed on water flow by the pipe bundle and losses due to bends in the pipes. Manufacturers of heat pumps and chillers provide charts which represent the relationship between water flow rate and pressure drop. It is possible to make use of such charts to determine the input parameters for the chosen fluid flow component.

To illustrate this, consider the graph shown in Figure 4.10. This graph was extracted from Carrier's catalogue for chillers of different capacities. The graph shows water pressure drop against water flow rate. It is possible to establish from the plotted lines a relationship between pressure drop and water mass flow rate assuming the following power law relationship

$$\Delta P = C\dot{m}_w^{\alpha} \tag{4.11}$$

Equation (4.11) can be rewritten in natural logarithmic form as

$$ln(\Delta P) = \alpha\ ln(\dot{m}_w) + ln(C) \tag{4.12}$$

where α is the slope of a line and C is the point at which the line intercepts the water pressure drop axis. Rearranging Equation (4.11) gives

$$\dot{m}_w = \frac{1}{C^{\frac{1}{\alpha}}}\Delta P^{\frac{1}{\alpha}} \quad . \tag{4.13}$$

Figure 4.10 Heat exchanger water pressure drop (Carrier)

In ESP-r, mass flow component type 15 is defined as a power law component with mass flow rate given by the following relationship

$$\dot{m} = a \Delta P^{b} \tag{4.14}$$

Comparing Equation (4.13) with (4.14), it can be deduced that the coefficients *a* and *b* are described by the following relationships

$$a = \frac{1}{C^{\frac{1}{\alpha}}} \quad ; \qquad b = \frac{1}{\alpha} \ . \tag{4.15}$$

This implies that providing manufacturer’s data is available a power law component type 15 should be used with the *a* and *b* coefficients evaluated from the relationship give by Equation (4.15).

4.4.2 Multi node components

An alternative to operating with a free-standing component algorithm is to introduce a number of equations to the system matrix equation to represent the internal component processes. While in single node components, all the mass involved (ie. solid material and enclosed fluid) was assumed to be concentrated in the one node, in multi node components one node may represent the solid material, another node may represent the air while another node may represent the water and so on. By extending the nodal scheme, it is possible to extend the model's capability so that higher resolution and/or better accuracy can be attained. For example, when designing a tube fin, it may be necessary to study the temperature distribution across the fin, in this case the fin is divided into a number of discrete regions with each region assumed to be uniform and represented by a characteristic energy balance equation. It is then possible to determine the temperature distribution across the tube fin. Another example is the temperature distribution of the cold fluid across a heat exchanger (ie. from entering the heat exchanger to exiting) taking into account the fluid's velocity, time constants and thermal resistances. It is important to realise that in some situations a single node component might be adequate to consider if the aim is to study the thermal interaction with the building (such as in the case of a duct supplying air to a building zone). However, if the aim is to investigate component thermal response or to validate a component model, then multi node modelling will be required. Another situation where multi node components are of benefit is when there are more than one working fluids in a component. For example, when simulating real air conditioning systems in which a boiler feeds a heating coil to warm up outside fresh air and a water chiller feeds a cooling coil to cool the heated air, both heating and cooling coils must be modelled so that external connections to more than one fluid type is allowed.

In order to show how multi-node modelling is carried out within the ESP-r environment, the following sections describe, in detail, a two node cooling coil and a ten node heat exchanger component formulation.

4.4.2.1 Cooling and dehumidifying coil (component type 430)

The matrix coefficient generator for this component is based on a two node model as described by Holmes (1982). The first node representing the air and metal, while the second node represents the water mass inside the coil tubes. This model is intended to have two external inlet connections: one where air is the working fluid to the air node, and a water flow connection to the water node. With this component it is therefore possible to link two plant sub-networks with different working fluids.

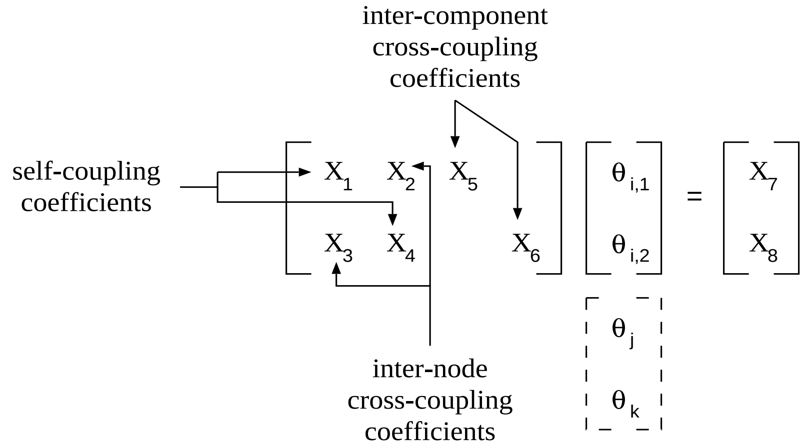

Figure 4.11 Schematic representation of energy balance matrix equation for a two node air cooling coil with two external inlet connections

The component matrix structure is shown in Figure 4.11. As can be seen, a total of eight coefficients exist with their formulation defined in the corresponding template definition of Appendix A. The first and fourth coefficients are the self coupling coefficients, the second and third are the inter-node cross-coupling coefficients, the fifth and sixth are the inter-component coupling coefficients and the seventh and eighth are the present-side coefficients. The derivations of the formulas for the temperature state coefficients were derived by equal weighting of the implicit and explicit finite difference form of the energy balance equations shown in Table 4.6 in which: $\theta_o = \theta_k - \theta_j$; $\theta_1 = \theta_{i,2} - \theta_j$; $\theta_2 = \theta_{i,1} - \theta_j$; $R_1 = \frac{1}{\dot{m}_w C_{p,w}}$; $R_4 = \frac{1}{\dot{m}_a C_{p,a}}$; $\theta = \theta_2(R_a + R_4)/R_4$; R_{mw} is the metal and water film thermal resistance (K/W) and R_a is the air film thermal resistance (K/W); $\theta_{i,1}$ is the temperature of node 1 (ie. air); $\theta_{i,2}$ is the temperature of node 2 (ie. water); θ_j is the inlet air temperature and θ_k is the inlet water temperature. The linear nature of the first and second phase mass balance equations indicates that a numerical solution is not required. The model for this component is a truly dynamic one in that no steady-state algorithm is required to calculate the heat transfer between water and air. In addition, the mass of water in the coil tubes is calculated at each time-step, since it is a function of the water stream velocity and the tube length.

This component allows the dynamics of cooling coils to be studied in response to variations in water flow rate and temperature as well as variations in the inlet air flow rate and temperature. The model has

Table 4.6 Air cooling and dehumidifying coil (component type 430)

Characteristic balance equations		
State space variable	Node	Equation
Temperature (C)	1	$\frac{\theta_1 - \theta}{R_{mw}} - \frac{\theta}{R_a + R_4} - UA\ (\ \theta_{i,1} - \theta_e) + \dot{m}_w^v H_w = \frac{\overline{c}_{i,1} M_{i,1} \delta\theta}{\delta t}$
	2	$\frac{1}{R_1}\ (\ \theta_o - \theta_1) - \frac{1}{R_{mw}}\ (\theta_1 - \theta) = \frac{\overline{c}_{i,2} M_{i,2} \delta\theta_1}{\delta t}$
First phase mass flow rate (kg/s)	1	$\dot{m}_{a,1} - R_{j,1} \dot{m}_{a,j} = 0$
	2	$\dot{m}_{w,2} - R_{k,2} \dot{m}_{w,k} = 0$
Second phase mass flow rate (kg/s)	1	$\dot{m}_{v,1} - R_{1,j} \dot{m}_{v,j} = \dot{m}_w^v$
	2	Not applicable

Component default parameters		
M	Component total mass (kg)	15.0
$\overline{c}$	Mass weighted average specific heat (J/kgK)	500.0
UA	Overall heat loss coefficient (W/K)	3.5
N_{rows}	Number of rows (-)	2.0
N_{fins}	Number of fins per metre (-)	316
f_t	Fin thickness (m)	0.00042
η_f	Fin efficiency (-)	0.77
K_t	Thermal conductivity of tube material (W/mK)	350.0
x_t	Tube spacing (m)	0.0375
d_i	Tube inside diameter (m)	0.0136
d_o	Tube outside diameter (m)	0.015
w_f	Coil face width (m)	1.5
h_f	Coil face height (m)	1.2

been enhanced so that a detailed analysis of the air film, water film and metal thermal resistances can be applied from the given coil tubing and fin geometry. In addition, the calculation of the amount of condensate is also taken into account.

The air film thermal resistance is calculated using the following expression

$$R_a = \frac{SHR}{h_a A_{ts}} \qquad (4.17)$$

where SHR is the sensible heat ratio as defined for Equation 4.7 and A_{ts} is the sum of the total surface area of all fins and the net surface area of all tubes (m^2). The air film heat transfer coefficient h_a (W/m^2K) according to Jones (1989) is given by the following expression for a staggered tube arrangement:

$$h_a = 27.42\ \overline{v}_a^{0.8} \qquad (4.18)$$

in which $\overline{v}_a$ is the air stream velocity obtained from

$$\overline{v}_a = \frac{\dot{m}_a}{A_f \rho_a} \quad .$$

where $\dot{m}_a$ is the air mass flow rate (kg/s) and ρ_a is the air density (kg/m^3) calculated at the current temperature. The coil face flow area A_f (m^2) can be estimated from the following equation

$$A_f = h_f\left(w_f - N^t_{fins} f_t\right) - \frac{A^n_{tubes}}{2N_{rows}}$$

where N^t_{fins} is the total number of fins in the coil and A^n_{tubes} is the net coil surface area (m^2). The water film thermal resistance R_w can be calculated in (K/W) from the following expression

$$R_w = \frac{1}{h_w A^s_{it}}$$

in which the water film heat transfer coefficient h_w can be evaluated from Equation 4.10 (W/m^2K) and A^s_{it} is the total inside surface area of the tubes in the coil (m^2).

The thermal resistance of the coil metal can be considered as the sum of thermal resistances of the fins and the tubes. The following expression† was used to determine the coil fins thermal resistance R_f in (K/W)

$$R_f = \frac{(1 - E_f)}{E_f} \frac{SHR}{h_a A^s_f}$$

in which A^s_f is the surface area of all fins (m^2) and E_f is the effectiveness of fin surface which is given by

$$E_f = \frac{(\eta_f A^s_f + A^s_{ot})}{A_{ts}}$$

where A^s_{ot} is the net surface area of the coil tubes (m^2). The fin efficiency η_f depends on the coil construction features. For example, the number of rows, fin thickness and tube spacing are all significant. Using fins made of copper material improves efficiency over fins made of aluminium, but the use of larger tube diameters reduces it. The thermal resistance of the tubes R_t can be calculated from

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† Standard for Forced Circulation Air-cooling and Air-heating Coils, ARI standard 410, Air Conditioning and Refrigeration Institute, Arlington, Virginia, 1972.

the following expression as given in McAdams (1954) (modified to give units in (K/W))

$$R_t = \frac{1}{A_{ot}^s} \frac{A_{ts}}{A_i} \frac{d_o}{2K_t} \ln \frac{d_o}{d_i}$$

where A_i is the total internal surface area (m^2) of the coil tubes. The total coil metal thermal resistance R_m in (K/W) is thus

$$R_m = R_f + R_t \quad .$$

The metal and water thermal resistances R_{mw} in (K/W) is therefore

$$R_{mw} = R_m + R_w \quad .$$

There are no directly controllable variables. All coil boundary conditions, such as inlet temperatures and mass flow rates, are assumed to be available from network conditions. For example, the inlet air condition might be that supplied by a fan while the inlet water condition might be that leaving the chiller water pump.

In the case where manufacturer's data for the pressure drop relate to air and water flow rates, the treatment described for component type 300 with respect to simulation of mass flows may be applied. Note that decoupled sub-systems with different working fluids are also supported. This means that for the external air connection, a flow component, perhaps a power law component, may be used with air being the working fluid. Whereas for the external water connection and assuming a similar pressure drop against water flow rate to that shown in Figure 4.10, another power law mass flow component may be defined with water the working fluid.

4.4.2.2 Heat exchanger (component type 930)

Myers (et al 1967) pointed out that the transient response of cross flow heat exchangers due to changes in the inlet temperature of the fluids is quite complex in that it involves the solution of three simultaneous partial differential equations for temperatures as a functions of time and position. The following three governing differential equations obtained from energy balances on the control volume (Δx by Δy) shown in Figure 4.12 are for the cold fluid, the hot fluid and for the wall separating the two fluids:

cold fluid:-

$$\bar{C}_c \frac{\delta \theta_c}{\delta t} + \frac{\bar{C}_c L_c}{t_{dc}} \frac{\delta \theta_c}{\delta y} + \frac{1}{R_c} (\theta_c - \theta_w) = 0$$

hot fluid:-

$$\bar{C}_h \frac{\delta \theta_h}{\delta t} + \frac{\bar{C}_h L_h}{t_{dh}} \frac{\delta \theta_h}{\delta x} + \frac{1}{R_h} (\theta_h - \theta_w) = 0$$

wall:-

$$\bar{C}_w \frac{\delta \theta_w}{\delta t} + \frac{1}{R_h} (\theta_w - \theta_h) + \frac{1}{R_c} (\theta_w - \theta_c) = 0$$

where $\bar{C}$ is the product of mass and specific heat (J/K), R is the fluid heat transfer resistance (K/W), subscripts c, h and w denote the cold fluid, hot fluid and wall separating the two fluids respectively. Subscripts dc and dh denote the dwell time (s) for the cold and hot fluids within the exchanger.

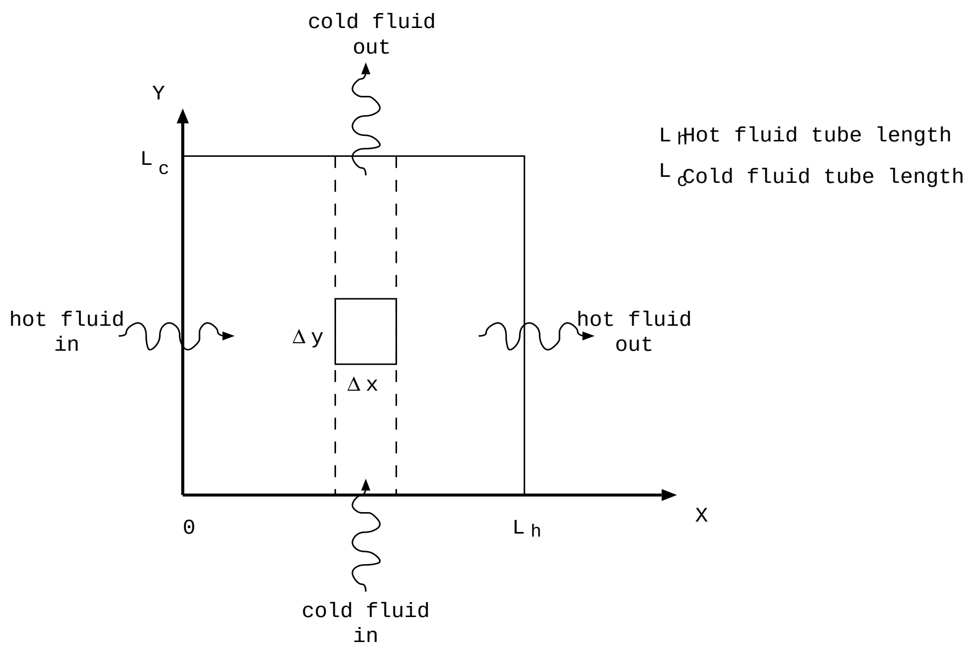

Figure 4.12 Schematic of a cross-flow heat exchanger

It is clear that if the cross flow heat exchanger component is to be modelled accurately, taking into account changes in fluid temperatures across the exchanger, a large number of nodes should be used to enable detailed analysis of each fluid and the wall temperatures. At the time when the model for the heat exchanger was being developed for the present study, there was a limitation imposed by the ESP-r system (which was later removed) that a maximum of only ten nodes may be used for one component model. For this reason, a simplified model as described by Myers (et al. 1970) was adopted. In his model, the assumption was made that in many heat exchanger applications the thermal capacitance rate of one fluid is much larger than that of the other fluid. Consequently, they can be modelled by assuming one of the fluids has an infinite capacitance rate and is always at a uniform temperature throughout the exchanger. With this assumption the differential equation for the fluid with infinite capacitance rate is eliminated and the solution becomes valid for any flow arrangement (ie. not restricted to cross flow heat exchangers).

The matrix coefficient generator for this component is based on a ten node model of a heat exchanger. The first five nodes represent the air inside the heat exchanger while the other five represent the solid material. For this component, the air is assumed to be the cold fluid and the hot fluid is assumed to be water which is at a uniform temperature in the heat exchanger. The reason for developing this model was to enable the study of the transient response of heat exchangers, evaporators, condensers, precoolers and intercoolers. Such components are common in most air-conditioning systems, and many use refrigerants as the working fluid. It was decided that by starting with a simplified heat exchanger model using air and water as the working fluid, the model could be extended to account for the dynamics of the hot fluid as well as being applied for other types of working fluids.

The energy and mass balance equations for each node are shown in Table 4.7 and the component matrix topology is shown in Figure 4.13. Note that for the solid nodes, there are no first and second phase mass flow balance equations. In deriving these equations, the following further assumptions (Myer etal 1970) were made:

- The cold fluid velocity is uniform across the flow passage.
- The heat transfer is one-dimensional (longitudinal conduction in the fluid and in the wall is assumed to be zero).
- The conduction resistance through the wall is negligible.
- The wall capacitance, thermal resistance are independent of temperature, time and position.

A total number of 35 matrix coefficients are required for this component and they are evaluated from the generated coefficients portion of this component's template definition as given in Appendix A.

This component accepts one external air connection via node 1. The air exits the exchanger at node 5 which can be used as the 'sending' node to another air node of some component. There is one

Table 4.7 Characteristic balance equations for component type 930

Characteristic balance equations		
State space variable	Node	Equation
Temperature (C)	1	$C_{1,j}(\theta_j - \theta_{c,1}) + \frac{1}{R_c}(\theta_{s,6} - \theta_{c,1}) = \frac{\overline{c}_c M_c \delta\theta_{c,1}}{5\delta t}$
	2-5	$\frac{1}{R_c}(\theta_{s,n} - \theta_{c,k}) = \frac{\overline{c}_c M_c \delta\theta_{c,k}}{5\delta t} + \frac{\overline{c}_c M_c \dot{m}_1 \rho}{5A}\frac{\delta\theta_{c,k}}{\delta x}$ $k = 2..5\ ,\ \ n = 7..10$
	6-10	$\frac{1}{R_h}(\theta_h(t) - \theta_{s,n}) + \frac{1}{R_c}(\theta_{c,k} - \theta_{s,n}) + UA(\theta_e - \theta_{s,n})$ $= \frac{\overline{c}_s M_s \delta\theta_{s,n}}{5\delta t}\quad , k = 1..5\ ,\ \ n = 6..10$
First phase mass flow rate (kg/s)	1	$\dot{m}_1 - R_{j,1}\dot{m}_j = 0$
	n=2..5	$\dot{m}_n - \dot{m}_{n-1} = 0$
	n=6..10	Not applicable
Second phase mass flow rate (kg/s)	1	$\dot{m}_{v,1} - R_{j,1}\dot{m}_{v,j} = 0$
	n=2..5	$\dot{m}_{v,n} - \dot{m}_{v,n-1} = 0$
	n=6..10	Not applicable

Component default parameters		
M_c	Total mass of cold fluid(kg)	4.0
$\overline{c}_c$	Cold fluid specific heat (J/kgK)	1000.0
M_s	Total mass of solid material (kg)	10.0
$\overline{c}_s$	Solid wall specific heat (J/kgK)	2000.0
UA	Overall heat loss coefficient (W/k)	10.0
A	Cold fluid flow area (m^2)	0.05
L	Cold fluid flow length (m)	5.0
R_c	Cold fluid heat transfer resistance (K/W)	0.05
R_h	Hot fluid thermal resistance (K/W)	0.05

Control data variables
Hot fluid temperature $\theta_h(t)$ (C)

control variable for this component, the hot fluid temperature, which may be varied according to a given function on offer by control law 6 (ie. modes 1 to 8: step, ramp, sine wave) or assigned a sensed temperature value of some other component (such as a boiler water temperature); this last option is possible using control law 6 in mode 9. In this way, the transients of the heat exchanger may be studied in response to a change in the hot fluid temperature.

When calculating nodal temperatures for the fluid air at a given time-step, the calculations are based on the temperature of node 1, for this reason the node 1 temperature is marked for iteration. A typical temperature profile for this component is shown in Figure 4.14.

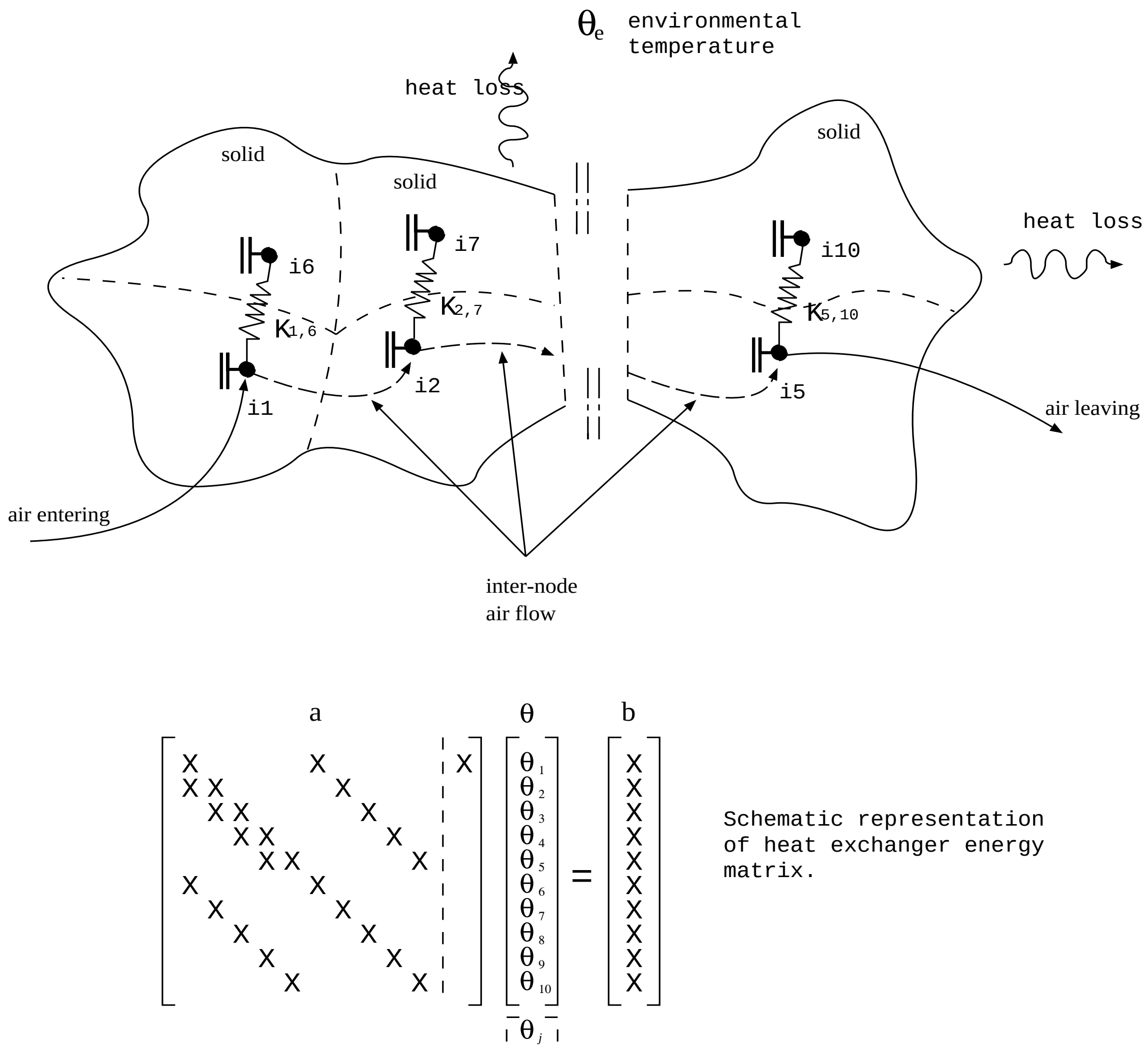

Figure 4.13 Schematic representation of control volume model and energy balance matrix equation for a ten node air heat exchanger with one external inlet connection

4.4.3 Generic algorithmic type component (800)

The main reason for developing this component is to allow the installation of algorithmic type models such as those implemented in TRNSYS. The main advantages of this approach are:

1- To cut down the time required in the development of component models which do not already exist in ESP-r.

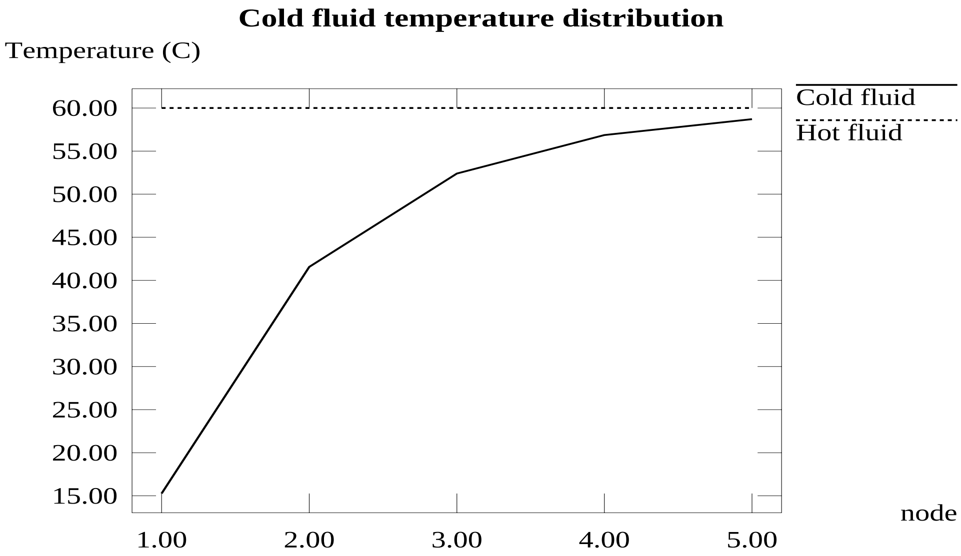

Figure 4.14 Temperature profile as function of position

2- To simplify the models by using single nodes components, where possible, and have these static algorithmic type models evaluate essential quantities such as rate of heat injection/extraction to a fluid. This quantity is then used in the energy balance equation to evaluate component temperatures.

3- Having models, which are based on the sequential approach encapsulated within a dynamic model utilising the simultaneous approach overcomes some of the problems associated with the sequential approach (see section 3 for a discussion on the sequential vs simultaneous approach to plant modelling).

4- A large number of TRNSYS type components have been subjected to validation work by numerous researchers.

The modular structure of TRNSYS makes the task of importing its component models relatively simple because each model type is treated as a ’black box’ requiring prescribed data inputs. The function of these black boxes is to simulate the functionality and internal operations of components using the supplied input data and then to generate output data associated with that component. The task of importing TRNSYS type models is then reduced to identifying the input variables required for a particular component and making use of the output variables in the energy balance equation for the dynamic model. In ESP-r there are two components at the present time which adhere to this concept:

non-condensing boiler (type 260); and a flat plate solar collector (type 700). Component type 260 is a two node representation of a non-condensing boiler with aquastat control and is discussed in detail elsewhere (Hensen, 1991). Component type 700 is a one node model based on the TRNSYS algorithm for a flat plate collector variant of the solar collector model. The following energy balance equation is used for the single node flat plate solar collector model:

$$C_{1,j}(\theta_j - \theta_1) + q = \frac{\overline{c}M\delta\theta_1}{\delta t}$$

where q is the amount of heat energy transferred to the collector water. For this component q is calculated for two water flow regimes; zero water flow rate and some arbitrary water flow rate. The calculation mode is determined by the TRNSYS algorithm for the solar collector from information passed to it by the coefficient generator as its input data.

Because the TRNSYS model uses the collector water temperature to calculate the water outlet temperature, the temperature state variable is marked for iteration.

The coefficients generator for these two components have a similar structure in that they are customised for the encapsulated TRNSYS models installed within them. A more generic structure can be arrived at if one coefficient generator existed for most algorithmic model types. For instance, for components that have one fluid type, a one node coefficient generator may be generalised to generate equation coefficients for such components. In ESP-r, the type of fluid associated with a component node is predefined in the plant component data base. This implies that although this is a generic TRNSYS type component, it can only be used for components with the same fluid type. For example there could be a generic coefficient generator for those components which only use air as the working fluid and another for those components which only use water, with yet another for components requiring the use of both fluid types such as in a heat exchanger. The latter type requires a two node coefficient generator in order to take into consideration the thermal coupling between the working fluids. For this reason, three generic components were developed to handle components with different fluid types.

In order to illustrate how TRNSYS components are utilized in ESP-r, consider a cooling coil component. The energy balance equation describing the energy transfers for a single node representation is given by Table 4.2 for component type 40. From the cooling coil model, TRNSYS type 32, the rate of heat transfer q_i can be evaluated by requesting the coefficient generator to supply the required input data which is evaluated from the most recent values for air temperature and mass flow rate. The calculated heat transfer rate q_i can then be imported to the energy balance equation so that the future air temperature can be calculated. TRNSYS components also have parameters associated with them. Unlike the input data which are time dependent, TRNSYS component parameters are fixed and describe items such as dimensions. For example, Table 4.3 lists the parameters required for the type 32 TRNSYS model. Another advantage gained from using these models under the ESP-r environment is the ability to modify such parameters if they are time dependent before they can be passed to the appropriate algorithmic model. For example, in many TRNSYS models, the water specific heat capacity is considered a constant parameter, whereas in ESP-r this parameter is calculated as a function of time.

In TRNSYS, the component parameters, input data and output data are held in the order given by Table 4.8. The coefficient generator in ESP-r is thus required to fill the appropriate arrays from data attached to this component (ie component data entry in the plant component database) and from data available from the present status of the network being processed. The output values will then be computed and returned to the coefficient generator for subsequent substitution of the desired output in the energy balance equation (eg. sensible cooling rate in the case of the cooling coil).

Table 4.8 TRNSYS type 32 configuration

Component parameters	
1	Units (1:SI, 2:English)
2	Number of rows deep
3	Number of parallel cooling coil circuits
4	Coil face area
5	Inside tube diameter
Input variables	
1	Inlet air dry bulb temperature
2	Inlet air wet bulb temperature
3	Air mass flow rate
4	Inlet water temperature
5	Water mass flow rate
Output variables	
1	Outlet air dry bulb temperature
2	Outlet air wet bulb temperature
3	Mass flow rate of air
4	Outlet water temperature
5	Water mass flow rate
6	Sensible cooling rate
7	Latent cooling rate
8	Total cooling rate

A typical data entry format for this generic TRNSYS component is given by Table 4.12. As can be seen, it is similar to that given in Table 4.10 with the exception of two more records required to distinguish the TRNSYS component model since component parameters change with different TRNSYS component types.

Table 4.9 Parameters and control variable for a generic TRNSYS component (type 800) using TRNSYS type 32 model

Component parameters	
1	Component total mass (kg)
2	Mass weighted average specific heat (J/kgK)
3	Overall heat loss coefficient (W/K)
4	TRNSYS model type (eg. 32 for cooling coil)
5	Coil face area (m^2)
6	Internal tube diameter (m)
7	Inlet water temperature (°C)
8	Number of rows deep (-)
9	Number of parallel coil circuits (-)
Control data variables	
	Water flow rate (kg/s)

A control variable is available and may be used to actuate control on the water mass flow rate feeding the cooling coil. The coefficient generator for the generic component uses the TRNSYS type number to jump to the appropriate routine to set up the input data and parameter values as required by the TRNSYS type model. Note that for the TRNSYS type 32 model it is also possible to be used in a two node ESP-r model to account for the external water connection if direct control on the water flow rate control variable is not desired. At present component type 800 has been used with TRNSYS type models which use air as the working fluid, other component types should be considered for components in which water is the working fluid and for components in which both air and water are the working fluids.

4.4.4 Packaged air-conditioning component (type 600)

It was mentioned in section 4. that unitary or packaged air-conditioning units are made up of a number of sub-components (such as fan, heating coil, cooling coil, humidifier and so on). The plant component data base contains most of these sub-components and can be used in unitary components by using a ’meta component’. Meta components can be considered as consisting of a number of sub-components connected together to perform the function of the desired component. In ESP-r, meta components can be defined and entered in the plant component database, but they don’t require a coefficient generator counterpart. The existing coefficient generators for the predefined sub-components are used. In effect, a meta component in ESP-r is treated as a sub network, however, the ability to describe such component in the plant component database allows more complex systems to be handled efficiently. For example, in a multi-zone building where an identical packaged air-conditioning unit is used for each zone, instead of repeatedly defining individual components that make up the packaged unit for each zone, one packaged unit can be defined in the plant component database and then referenced for each building zone. This will dramatically reduce input errors and the time required to define complex networks. Figure 4.15 shows how a heat pump can be defined using this concept once the individual sub-components have been installed in the ESP-r system.

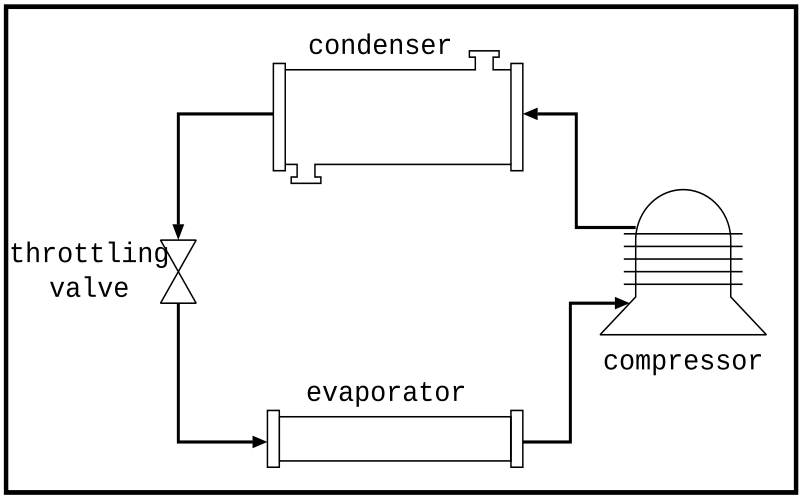

Figure 4.15 Heat pump definition from the meta component concept.

The component structure for single and multi-node components, algorithmic type components and meta components is described in greater detail in the following section.

4.5 Installing new plant component in ESP-r

The installation of new components in ESP-r differs for different component models. For example, the procedure involved in installing single and multi-node components is different from that for the TRNSYS type models, with the meta-component component procedure different again. The following sections describe the steps involved in installing a component.

4.5.1 Single and multi node components

The steps required are as follows:

1- The governing partial differential equations must be derived for each control volume considered.

2- The component description is then defined and entered in the plant component database together with any parameters to be associated with this component.

3- The coefficient generator is then installed in the ESP-r system together with the routine which assigns component data to appropriate FORTRAN array variables.

The first step involves the derivation of the energy and mass flows balance equations for each control volume of the component considered. The form of these equations is similar to that given under the ‘characteristic balance equation’ heading of Table 4.2. Equal weighting of the explicit/implicit form of the energy differential equations will allow the expressions for the self-coupling, inter-node-cross-coupling, inter-component coupling and present time coefficients to be derived. The expressions used to generate these coefficients have a form similar to that given in Table 4.2 under the ‘generated coefficients’ heading. At this stage, the theory underlying the model and all the parameters required for its implementation are known.

The second step involves component model description in the plant component database. The format of data entry is given by Table 4.10.

The variable type (item 9) is used within ESP-r to define the nature of a node and to enable fluid type connection checking. To exemplify the use of this variable consider a 3-node component model in which the first node represents the solid, the second node represents the air fluid and the third node represents the water fluid. When a connection is established between the air node and another external node of some other component, then it is possible to determine if this connection is valid from the index specified for each node. In this case, if matrix formulation is for energy balance and 2 phase mass balance state variables, the connection is valid if the index of both nodes is of type 21. Similarly, a connection to the third node is valid if the sending node is also of type 20. While for a solid, the index type for the same matrix formulation would be 29. Table 4.11a shows index values for other state variable type configurations.

The fluid flow components defined for each connection are used to build up a flow network corresponding to a particular plant configuration. This can be achieved after the plant network definition is complete so that information regarding component connections can be used together with the

Table 4.10 Component data format for single/multi node models

Number	Field	Description
1	Generic type	Generic class for component (ie. for different type of boilers this field would contain ’boilers’), maximum of 40 characters allowed.
2	Description	Terse description of component (eg. name and number of nodes), maximum of 80 characters allowed.
3	Type	Component type (eg. Single component)
4	Component code	This is an integer number which must be divisible by 10 in order to jump to the right coefficient generator subroutine.
5	Number of Nodes	This equals number of control volumes in discretised model.
6	Number of non-zero matrix elements	Total number of coefficients with non-zero value in component matrix (eg. for a two node model, this might be 2).
7	Matrix position	Position of each non-zero coefficient in component matrix (eg. this might be 1,4 for a two node model with diagonal non-zero coefficients).
8	Node connections	Number of external connections to each node.
9	Variable type	An index for each node to identify functionality in terms of supported state variable types and to define nature of a node (see Table 4.11a).
10	Connections mass flow component	mass flow component type to be used for each connection.
11	ADATA items	Number of static manufacturers data items.
12	BDATA items	Number of data items used in model theory and may be expected to be time dependent.
13	CDATA items	Number of variables which may be controlled via a control loop.
14	ADATA data	This includes a description of each item (maximum of 68 characters), default value and valid range (ie. min and max values).
15	BDATA data	This includes a description of each item (maximum of 68 characters), default value and valid range (ie. min and max values).
16	CDATA variables	This includes a description of each variable (maximum of 68 characters).
17	Additional output parameters	This field contains number of additional output parameters to be specified for this component.
18	Output parameters description	This includes a description of each additional output parameter (maximum 20 characters) and the type of each output (1-5).

specified fluid flow components to automate flow network definition. At present, flow component data is held in a separate file to simplify the implementation process in a prototype set up. The limitation of this arrangement is that once a flow component parameters have been changed, then the plant components in the data base referencing this flow component will also inherit the modified flow component parameters. An improved approach is to have these flow component parameters defined as part of the plant component definition as held in the data base.

The description of the component parameters allows a flexible structure to be adopted when it comes to component selection and plant network definition using ESP-r's plant network definition module. Further, realistic values can be checked against the minimum and maximum values as defined for each parameter. There are no data defined for the control variables because these are usually related to component flow rate or heat flux which are determined by the action of a control law defined in a control loop. When no control loop is to be specified, then the control variable value will be assigned an initial value in the plant network definition file. The additional output parameters are those variables which are necessary for the calculation of the heat transfer inside the component and may be of interest when evaluating the performance of the plant system. For example, by identifying the type of each output, it is possible to analyse the system performance in terms of total energy consumption, system output, heat lost to surroundings and so on. The currently available output types are listed in Table 4.11b.

Table 4.11a Definition of state variable index

Substance	Energy only	Energy+1st phase mass balance	Energy+2 phase mass balances
water	0	10	20
air	1	11	21
solid	9	19	29

Table 4.11b Definition of additional output types

Output type	Description
1	Energy input (W)
2	Energy output (W)
3	Heat lost to surroundings (W)
4	Temperature (C)
5	Flow rate (kg/s)

The final step in the installation procedure is concerned with the addition of the coefficient generator subroutine. The implementation of the theory together with the equations used to generate the component matrix coefficients are coded inside this subroutine. The naming convention of a coefficient generator is "CMPnnC" in which "nn" represents the component code (item 4, Table 4.10, divided by 10). For example, if the component code was assigned a value of 100, then a typical subroutine name for the coefficient generator will be "CMP10C". The reason for this is to enable ESP-r to call the coefficient generator corresponding to a component's type code number. There is another subroutine which must be added to fill in arrays so that the data is organised into coefficient related order. This subroutine also checks that the correct number and fluid type connections were specified. The naming convention for this subroutine is "CMPnnS" where "nn" is the same as that for its related coefficient generator subroutine name (eg. for a component code of 100, subroutine name would be "CMP10S").

4.5.2 TRNSYS type component models

Here it is assumed that the generic matrix coefficient generator for TRNSYS models has already been installed as explained in the previous section. It should be mentioned that the steps followed when installing TRNSYS type models are not the same as installing a single/multiple node model. The following steps are usually followed when TRNSYS type models are to be installed:

1- The number of working fluids in the model is determined in order to decide on whether a single or multi-node generic coefficient generator is required.

2- The TRNSYS type is then described inside the generic coefficient generator component in the plant component database.

3- The subroutine for the TRNSYS model is then added and some statements appended to the generic coefficient generator subroutine to set the appropriate inputs and parameters before a call is made to the TRNSYS model and to utilise the generated output variables for inclusion in the common energy balance equation.

The first step is concerned with how many nodes should be used in order to adequately encapsulate the TRNSYS type model inside the dynamic ESP-r type model. For example, ESP-r component type 90 (see Section 4.4.1.1) was modelled using a one node representation by assuming that the water flow rate can be controlled and is at a fixed temperature. Moreover, it made use of a TRNSYS model (type 32) to evaluate the heat transfer rate to the air. A single node generic coefficient generator in which only the air state is considered in the calculation, is therefore appropriate to use for this component. If it was necessary to take into account the variations in the state of the inlet water, then water inside the coil must also be represented by a node in which case the water state will also be evaluated by its own set of characteristic equations. In this case a two-node, generic coefficient generator would be appropriate. Note that if one TRNSYS model type was represented by a single node model and a control variable was defined, then other TRNSYS types inside the same coefficient generator must also have a control variable specified (even though it is not required) in order to maintain compatibility. This implies that for a generic ESP-r algorithmic type component, the number of control variables specified for it must equal the TRNSYS model type with the highest number of control variables.

The second step involves the description of the selected TRNSYS type model in the plant component database. Another component type was added to define the required format for TRNSYS types as shown in Table 4.12 The table format is similar to that given in Table 4.10 with the exception that one generic coefficient generator component can hold the definitions of a number of TRNSYS type models as long as the component matrix integrity is maintained. Each TRNSYS type model will have its default parameters defined with the option of modifying them when desired. It was decided that this format will give immediate access to all available TRNSYS types defined within this type when using ESP-r's plant definition module and therefore simplifies the selection process considerably.

The third step involves the addition of TRNSYS type component to the ESP-r system. Before this, code must be added to the generic coefficient generator component to call a common routine which in turn calls the appropriate TRNSYS type routine and processes any relevant output variables such as the heat transferred to the air stream so that they can be correctly added to the energy balance equation as was explained in Section 4.4.3.

4.5.3 Meta components

It was stated earlier that when installing meta components, a coefficient generator is not required because existing coefficient generators for the sub-components making up the meta component will be used. Two steps are required for the definition of a meta component:

1- The sub-components and their inter-connection must first be determined and the components at inlet and at outlet must be identified.

2- The meta component description is then entered into the plant component database using the format given in Table 4.13.

The first step involves the determination of the required single components from the plant component database. These will then be referred to by their code number (item 4 Table 4.10). Each connection must then be defined (see section 6.1) to describe component inter-connections. The inlet and outlet external connections will be determined from the identified components at inlet and outlet

Table 4.12 Component data format for TRNSYS type models

Number	Field	Description
1	Generic type	Generic class for component (ie. for different type of boilers this field would contain ’boilers’), maximum of 40 characters allowed.
2	Description	Terse description of component (eg. name and number of nodes), maximum of 80 characters allowed.
3	Type	Component type (eg. TRNSYS component)
4	Component code	This is an integer number which must be divisible by 10 in order to jump to the right coefficient generator subroutine.
5	Number of Nodes	This equals number of control volumes in discretised model.
6	Number of non-zero matrix elements	Total number of coefficients with non-zero value in component matrix (eg. for a two node model, this might be 2).
7	Matrix position	Position of each non-zero coefficient in component matrix (eg. this might be 1,4 for a two node model with diagonal non-zero coefficients).
8	Node connections	Number of external connections to each node.
9	Variable type	An index for each node to identify functionality in terms of supported state variable types and to define nature of a node (see Table 4.11a)
10	Number of available TRNSYS types	This is the number of TRNSYS type models entered so far.
11	TRNSYS type number	This will be a list of TRNSYS types entered so far
	For each TRNSYS type	
12	ADATA items	Number of static manufacturers data items.
13	BDATA items	Number of data items used in model theory and may be expected to be time dependent.
14	CDATA items	Number of variables which may be controlled via a control loop.
15	ADATA data	This includes a description of each item (maximum of 68 characters), default value and valid range (ie. min and max values).
16	BDATA data	This includes a description of each item (maximum of 68 characters), default value and valid range (ie. min and max values).
17	CDATA variables	This includes a description of each variable (maximum of 68 characters).
18	Additional output parameters	This field contains number of additional output parameters to be specified for this component.
19	Output parameters description	This includes a description of each additional output parameter (maximum 20 characters) and the type of each output (1-5).
	repeat for next TRNSYS component...	

Table 4.13 Meta component data format

Number	Field	Description
1	Generic type	Generic class for component (ie. for different type of boilers this field would contain 'boilers'), maximum of 40 characters allowed.
2	Description	Terse description of component (eg. name and number of nodes), maximum of 80 characters allowed.
3	Type	Component type (eg. Meta component)
5	Sub-components code	Code number for each component in plant component database.
6	Inlet and outlet connections	For each sub-component, an index is specified to indicate whether a component is at inlet (index=1) or at outlet (index=2).
7	Number of component inter-connections	This is the total number of component inter-connections.
8	Description of component interconnection	For each component interconnection, the connection type must be described.

respectively. To illustrate this further, consider the example shown in Figure 4.16 for an air-conditioning unit comprising a mixing box, a fan, a cooling and dehumidifying coil and a supply duct.

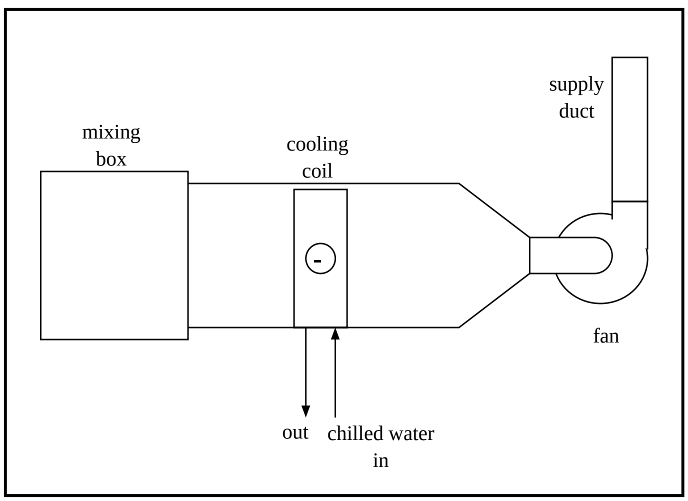

Figure 4.16 Air conditioning unit layout

The component types selected from the plant component database are type 10, 30, 40 and 60 respectively. The mixing box is at the inlet section and the supply duct is at the outlet section. Thus the external connections index for component type 10 is 2 and for component type 60 is 1. There are three component interconnections to be specified: one connecting the fan to the mixing box, one connecting the cooling coil to the fan and one connecting the supply duct to the cooling coil. The air-conditioning unit data description entry will have the format given by Table 4.14.

Table 4.14 Air-conditioning unit example for a meta component.

Field	Data
Generic type	Air conditioner
Description	An air conditioning unit comprising four components.
Type	Meta component
Number of components	4
Sub-components code	10, 30, 40, 60
Inlet and outlet connections	2, 0, 0, 1
Number of inter-connections	3
Component interconnection	2 1 3 1 1 1.0 3 1 3 2 1 1.0 4 1 3 3 1 1.0

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CHAPTER 5
Validation

The aim of simulation modelling is to represent as closely as possible the underlying physical laws and principles of the real world. The steps followed by the model developer in forming a simulation model were defined by Irving (1988) as:

> "Firstly, some aspects of the real world must be chosen and the set of underlying physical laws may be embodied in several mathematical formulations, from which a suitable representation of the mathematical equations is selected. This mathematical formulation of the underlying physical laws must then be rendered into a discrete form and transformed into an algorithmic form using suitable computer languages. The algorithm produced can finally be integrated into the simulation model which will be used on a computer which has a particular architecture and numerical precision."

During the model development process, many assumptions and compromises are inevitably made and as a result the exact replication of reality is not achieved. In order to determine the range of validity and the uncertainty level of building energy simulation programs, some validation methodology must be established. Baker (et al, 1992) defined validation as:

> "The rigorous testing of a program - comprising its mathematical models, software implementation and user interface - under a range of conditions which typify its expected use."

Considering the ESP-r system as an example, it contains hundreds of variables and parameters which makes it virtually impossible to test the effect of changing each parameter in a particular simulation. For this reason the validation methodology outlined by Judkoff (1988), uses three different kinds of tests:

- Comparative, where a building is modelled using two different programs and their predictions compared.
- Analytical verification, in which the predictions of a model are compared with known exact solutions for simple test cases.

- Empirical validation, in which a comparison is made between the model's predictions and measured thermal performance of a real building.

The advantages and disadvantages of these three techniques are shown in table 5.1. The work conducted by the UK consortium (Baker et al, 1992) for the PASSYS project (Passive Solar Components and Systems Testing) and by a Science and Engineering Research Council (SERC) funded team in collaboration with the Building Research Establishment (BRE), has extended the above to include three other topics:

- The examination of individual thermophysical processes that are common in buildings such as solar processes, wall conduction algorithms, convection coefficients and internal longwave exchange.
- The development of a set of standard building specifications as a basis for comparative analysis to help quantify the effects of inaccuracies in models.
- The development of advanced statistical techniques to estimate the accuracy of the numerical solutions produced by models and to conduct sensitivity analysis.

Table 5.1 Advantages and disadvantages of validation techniques (Judkoff 1988)

Technique	Advantages	Disadvantages
Comparative	No input uncertainty; Any level of complexity; Inexpensive; Quick, many comparisons possible	No truth standard
Analytical	No input uncertainty; Exact truth standard given the simplicity of the model; Inexpensive	No test of model; Limited to cases for which analytical solutions can be derived
Empirical	Approximate truth standard within accuracy of data acquisition system; Any level of complexity	Measurement involves some degree of input uncertainty; Detailed measurement of high quality are expensive and time- consuming; A limited number of data sites are economically practical

In order to increase modelling confidence, it is now widely recognised by researchers that this can only be achieved by the repeated application of such validation methodology when the programs are exercised in ways which represent the expected range of application. On the basis of the above validation techniques, the following validation methods were utilised in the research reported here:

- analytical validation
- review of theory
- inter-model comparison
- empirical validation.

These validation methods are applied and discussed in detail in the following sections.

5.1 Analytical techniques.

Analytical techniques can be applied to validate plant component models using three different methods: analytical validation on a single component model; analytical validation on complex networks formed from connecting a number of components of the same type; and analytical validation on a system comprising different component types.

With regards to analytical validation of a single component model, consider the oil filled electric radiator model (type 280) as an example, the following exact solution to the energy balance equation (see appendix A) can be obtained for a pulse function with a duration of $(a - b)$

$$\theta_r = \theta_e + (\theta_r(0) - \theta_e) + \frac{Q_i}{A}\left[(1 - e^{-Z(t-a)})\ u_a(t) - (1 - e^{-Z(t-b)})\ u_b(t)\right] \qquad (5.1)$$

where θ_r is the radiator temperature, θ_e is the environment temperature, $\theta_r(0)$ is the initial radiator temperature, Q_i is the injected energy, and A is defined as:

$$A = \frac{Q_i}{\theta_{nr} - \theta_e} \ .$$

θ_{nr} is the radiator nominal temperature. Z is defined as

$$Z = \frac{A}{\bar{c}M}$$

where $\bar{c}$ is the mass weighted average specific heat capacity and M is the total mass. Figure 5.1 shows the variation of radiator temperature to a pulse input in the electrical energy supplied to the radiator for the parameters listed in table 5.2.

Table 5.2 Parameters defining radiator for the pulse input test

Component total mass (kg)	25.0
Mass weighted average specific heat (J/kgK)	1000.0
Radiator exponent ($-$)	1.0
Nominal heat emission of radiator (W)	1000.0
Nominal radiator temperature (C)	50.0
Nominal environment temperature (C)	20.0

To achieve the effect of a pulse function in ESP-r, plant control law 6 was used with function generator type 1. This type is capable of generating a step or a pulse pattern depending on the start and finish time values for the function. For example, the pulse defined for the radiator example had a start time of 0.5 hours and a finish time of 2.6 hours. Two more values can be specified with this function generator type for the maximum and minimum values of the function. For the example considered here, these were 1000 W and 0 W respectively. The simulation time step was 5 minutes. If the start hour for this pulse function is not reached in the simulation, then the minimum value is used. This is reflected in the radiator surface temperature approaching the nominal environmental temperature as demonstrated by Figure 5.1. At the start of the pulse function (eg. injection of heat energy), the radiator response is influenced by some parameters which affect its time constant such as its mass and specific heat capacity. After some time the radiator temperature reaches its nominal value. At the end of the pulse duration (eg. when no more heat injection takes place), the radiator temperature drops with a similar time delay pattern until it reaches the nominal environmental temperature again.

On the basis of visual comparison, the results show good agreement between ESP-r and the exact solution, indicating that the radiator algorithm implemented in the corresponding coefficient generator is reliable in this situation. Note that in situations where the analytical analysis demonstrated above is possible, it is feasible to conduct a parametric analysis to determine the range of component parameter values (eg. mass and specific heat capacity) for a given time-step which produces reliable results. This means that if the radiator component was to be used with parameter values different than those used in this example, then another comparison should be conducted to ensure that reliable results can be obtained with the selected time-step.

With respect to analytical validation of complex networks formed from connecting a number of components of the same type, this was demonstrated by Hensen (1991) with respect to simulation of air flows. He concluded that good agreement was obtained between exact results and ESP-r simulation

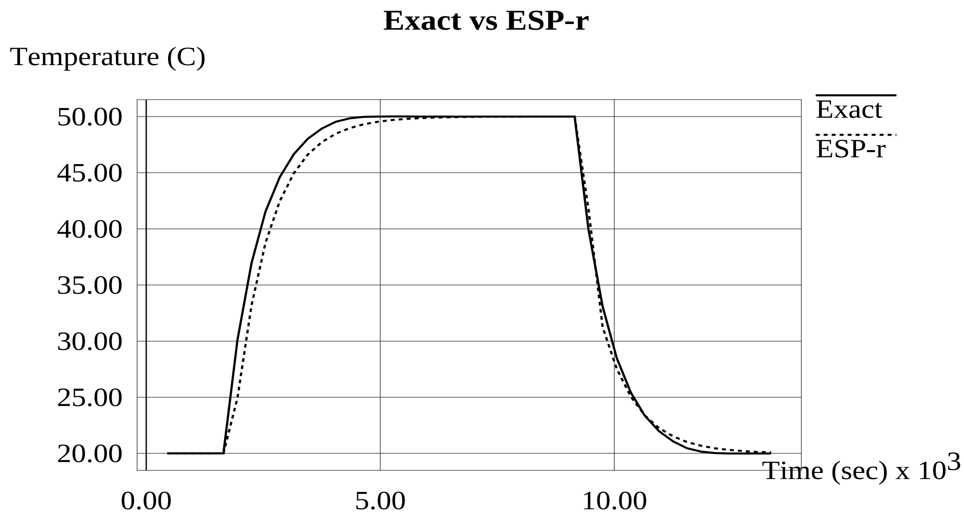

Figure 5.1 Radiator response to a pulse change in heat input.

Figure 5.2 Network of fluid flow components arranged in series and parallel
Hensen (1991)

results from a comparison made on a relatively complex network as shown in Figure 5.2. The air flow network was introduced by Walton (1989) to test his AIRNET air flow network simulator and comprised a number of common orifice flow components (flow component type 40) connected in different serial/parallel arrangements. Using the air flow properties of the parallel and the series arrangement, it was possible to establish a single replacement component for the whole network, for which it is then easy to analytically compute the fluid mass flow rate. ESP-r predicted a mass flow rate of 0.06110 (kg/s) while the exact mass flow rate was evaluated to 0.0611024 (kg/s).

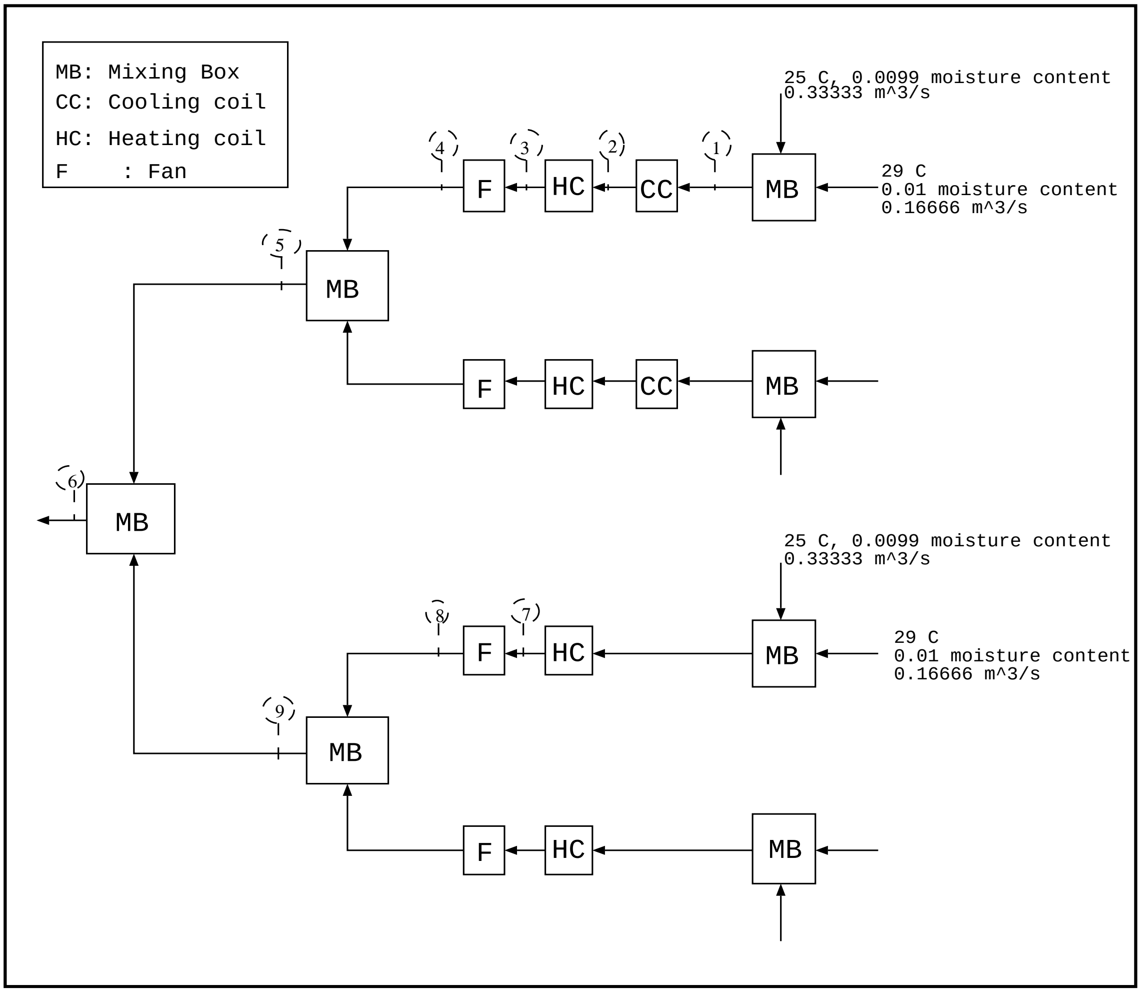

Figure 5.3 Air conditioning system arrangement comprising different components.

With regards to analytical validation of whole systems comprising a number of different components, consider an air conditioning network as shown in Figure 5.3. This comprises a number of different heat flow components such as air mixing boxes, fans, heating coils and cooling coils. Assuming steady state conditions, it is possible to compare the exact solution with ESP-r's solution by first defining the condition of the air (ie. air temperature and specific humidity) at points 2, 3 and 4 to determine analytically the heat addition by the fan and heating coil and heat extraction by the cooling coil. The calculated values for the heat addition and extraction are then defined for the appropriate component in ESP-r together with the air inlet condition to predict the condition of the air at the same points in the network. As shown, the fresh air dry bulb temperature and specific humidity is 29°C and 0.01 respectively. The return air condition is 25°C and 0.0099. The volumetric proportion of return and fresh air is 2 to 1 with a total volumetric flow sum of 0.5 m^3/s. The same inlet conditions apply to the other inlet mixing boxes. Assuming adiabatic mixing and applying the steady flow energy equation to the mixing box, gives

$$\dot{m}_{ar} h_{ar} + \dot{m}_{vr} h_{vr} + \dot{m}_{af} h_{af} + \dot{m}_{vf} h_{vf} = (\dot{m}_{ar} + \dot{m}_{af}) h_{a1} + (\dot{m}_{vr} + \dot{m}_{vf}) h_{v1} \quad (5.2)$$

where $\dot{m}$ is mass flow rate (kg/s), h is enthalpy (J/kg), subscript ar denotes return dry air, subscript af denotes fresh dry air, subscript vr denotes return air vapour and subscript vf denotes fresh air vapour. From equation 5.2 the temperature at point 1 can be calculated. The specific humidity at point 1 ω_1 is calculated from

$$\omega_1 = \frac{\dot{m}_{vr} + \dot{m}_{vf}}{\dot{m}_{ar} + \dot{m}_{af}} \; . \quad (5.3)$$

The heat extracted by the cooling coil Q_c can be calculated from the following steady flow energy equation:

$$Q_c = \dot{m}_a(h_{a1} - h_{a2}) + \dot{m}_{v2}(h_{v1} - h_{v2}) + \dot{m}_c(h_{v1} - h_c) \quad (5.4)$$

where $\dot{m}_c$ is condensate flow rate (kg/s) ($\dot{m}_c = \dot{m}_{v1} - \dot{m}_{v2}$) and h_c is condensate enthalpy (J/kg). The specific humidity at point 2 ω_2 can be calculated from

$$\omega_2 = \frac{\dot{m}_{v2}}{\dot{m}_a} \; .$$

The heat added by the heating coil Q_h, neglecting kinetic energy changes, can be calculated using the following steady flow energy equation

$$Q_h = \dot{m}_a(h_{a3} - h_{a2}) + \dot{m}_v(h_{v3} - h_{v2}) \quad (5.5)$$

The fan power input Q_f can be evaluated from

$$Q_f = \dot{m}_a(h_{a5} - h_{a3}) + \dot{m}_{v3}(h_{v5} - h_{v3}) \quad (5.6)$$

The specific humidity of the air at points 2, 3 and 4 is assumed to be constant (ie. $\omega_3 = \omega_2$ and $\omega_4 = \omega_3$). For the exact values shown in Figures 5.4 and 5.5, the calculated values for Q_c, Q_h and Q_f

were 13680W, 3545W and 1083W respectively.

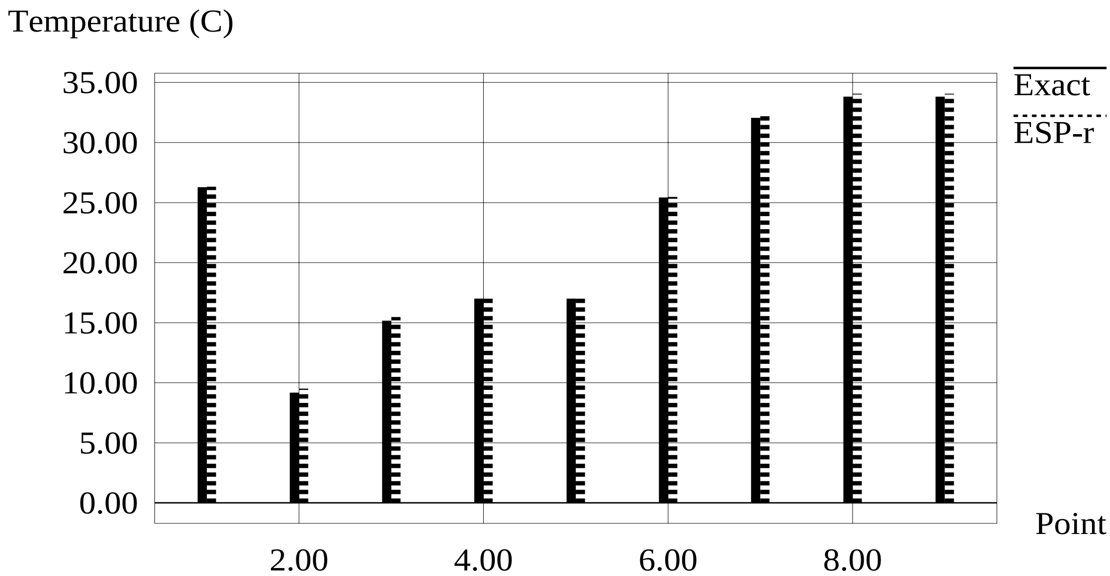

Figure 5.4 Comparison between analytical and ESP-r temperatures.

The components used for the simulation were mixing box type 10; fan type 30; heating coil type 50 and cooling coil type 40 with the parameters specified for each component are listed in Table 5.3.

With reference to Table 5.3, the reason for setting the component's total mass and mass weighted average specific heat to zero is to ensure that the steady-state solution will prevail. In addition to this, in ESP-r a special option was invoked to allow for steady-state calculations. This option sets the implicit/explicit mixing coefficient (see Section 3.1) to unity and the component mass to zero. The heat loss coefficient *UA* was also set to zero to indicate that no heat transfer takes place between a component and its surrounding. The same effect can be achieved if no containment temperature was specified for a component. The plant network was then defined with the indicated inlet boundary condition for the fresh and return air defined as being constant using the appropriate inter-component connection type as explained in Section 6.1. The simulation was carried out for one day with 10 minutes simulation time-steps and the temperature and specific humidity results obtained for this period were averaged to give the values shown in Figures 5.4 and 5.5.

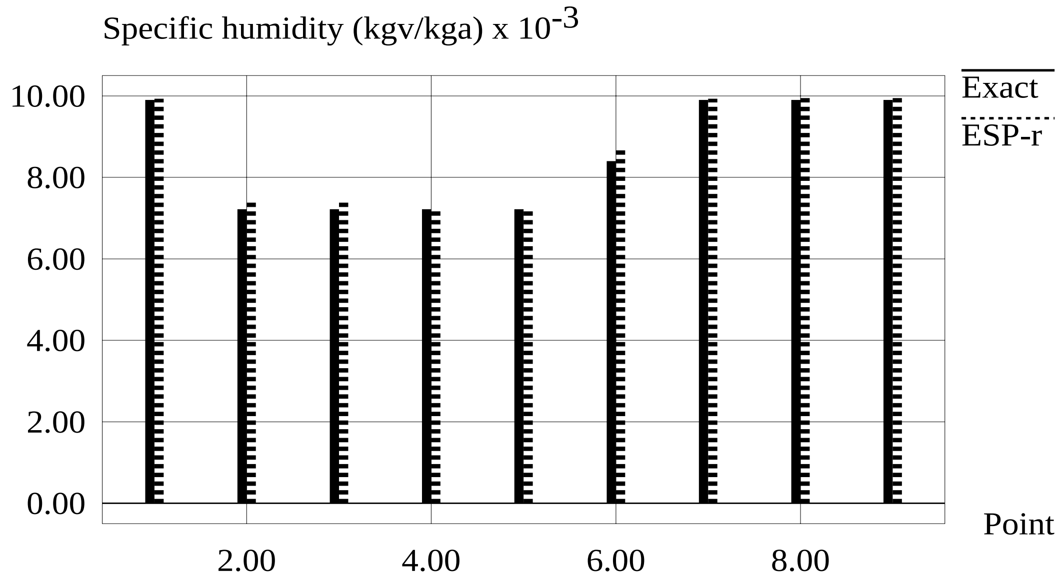

Figure 5.5 Comparison between analytical and ESP-r specific humidity.

Table 5.3 Parameters describing air conditioning system components

Mixing box:	
Component total mass (*kg*)	0.0
Mass weighted average specific heat (*J*/*kgK*)	0.0
UA modulus (*W*/*K*)	0.0
Fan:	
Component total mass (*kg*)	0.0
Mass weighted average specific heat (*J*/*kgK*)	0.0
UA modulus (*W*/*K*)	0.0
Rated total absorbed power (*W*)	1083.0
Rated volume flow rate (*m* 3/*s*)	0.5
Overall efficiency (-)	1.0
Heating coil:	
Component total mass (*kg*)	0.0
Mass weighted average specific heat (*J*/*kgK*)	0.0
UA modulus (*W*/*K*)	0.0
Heating duty (*W*)	3545.0
Cooling coil:	
Component total mass (*kg*)	0.0
Mass weighted average specific heat (*J*/*kgK*)	0.0
UA modulus (*W*/*K*)	0.0
Cooling duty (*W*)	13680.0

In the analytical solution the specific heat of air and the specific heat of vapour were taken from (Rogers and Mayhew, 1987) at atmospheric pressure of 1.01325 bar and ambient temperature of 29°C (temperature of fresh air) and were found to be 1005 J/kgK and 1880 J/kgK respectively. In ESP-r the psychrometric properties of air are calculated based on an atmospheric pressure of 1.01325 bar and the specific heat of air and vapour are calculated based on the fluid temperature. For this reason, specific heat values for air and vapour were fixed inside ESP-r so that the same values as used within the analytical solution are applied. The exact results show that a temperature of 26°C is obtained for point 1 as a result of mixing the fresh air at 29°C and return air at 25°C. The heat extracted by the cooling coil causes a drop in temperature and some condensation to take place and therefore reduces the moisture content as indicated by the condition of the air at point 2. Then at point 3, the heat added by the heating coil causes the air temperature to rise to 15.17°C without any change to the moisture content. Further heat addition takes place at point 4 because of the internal heat generation in the fan so that the air temperature increases to 17°C. The condition of the air at point 5 is identical to that at point 4 because the mixing takes place between fluids at identical temperature and specific humidity. Because no precooling takes place before point 7, the temperature of the air is only affected by the heat addition in the heating coil, which increased the air temperature to 32.06°C. Further heat addition by the fan results in a slight increase in the air temperature at point 8 to 33.82°C. The condition of the mixed air at point 9 is identical to that at point 8 as explained earlier. The condition of the mixed air at point 6 is between that at point 5 and that at point 9, ie. 25.43°C and 0.0084 (kg_v/kg_a). The comparison between ESP-r and the exact solution results shown by Figures 5.4 and 5.5 show that there is good agreement and indicate that the psychrometric routines and the energy equations defined give the expected results for the steady state condition considered. However some routines approximate the specific enthalpy of water condensate, as a function of temperature, based on empirical relationships. In the example considered here, it was not reasonable to fix this value inside the code because the temperature predicted by ESP-r at point 2 is used to determine the water condensate enthalpy. This is the likely cause of the small difference in the results.

5.2 Theory and code examination

Review of theory is usually overlooked by those who only wish to compare a model's results with real results. It serves two important purposes however: to check the code of an algorithm in a model and to determine the area in which the algorithm may be appropriate. ESP-r has been subjected to extensive international validation in which the theories implemented in the algorithms used to predict solar radiation, shading, conduction, convection and many other thermal processes were individually investigated. The report on the second phase of the PASSYS II (Baker et al, 1992) project contains numerous tests and results in this respect. In general the validation involves comparing the results obtained from an algorithm with an exact solution, if possible, of the underlying theory.

Code checking involves the systematic examination of the source code to ensure that the selected algorithms are correctly implemented. The use of structured programming, high level of documentation and Computer Aided Software Engineering (CASE) tools such as code browsers and checkers are good aids in this process. In addition to CASE tools an increasing number of Computer Aided Learning (CAL) tools for solving complex mathematical equations are becoming available and can be used to aid the formulating of solutions for complex dynamic equations as encountered in plant simulation. For example, Maple (Bruce, 1991) was used to find the exact solution of the differential equations describing the two node cooling coil (type 430 as described in section 4.4.2.1) for a negative step change in the inlet water temperature.

Air equation:-

$$\theta_a = 0.6882 - 0.8159\ e^{(-0.43t)}\ sinh(0.363t) - 0.6882\ e^{(-0.43t)}\ cosh(0.363t)\ . \qquad (5.7)$$

Water equation:-

$$\theta_w = 0.94 - 0.918\ e^{(-0.43t)}\ sinh(0.363t) - 0.94\ e^{(-0.43t)}\ cosh(0.363t)\ . \qquad (5.8)$$

The solution given by Equations 5.7 and 5.8 was obtained using the parameters defined in Table 5.4.

Table 5.4 Cooling coil (type 430) parameters used for the negative pulse input test

Mass and specific heat product of solid (J/K)	7500.0
Mass and specific heat product of water (J/K)	58956.4
Specific heat of air (J/kgK)	1008.0
Specific heat of water (J/kgK)	4200.0
Air film thermal resistance (K/W)	0.0001
Water film thermal resistance (K/W)	0.0001
Metal thermal resistance (K/W)	0.0001
Air mass flow rate (kg/s)	0.363
Water mass flow rate (kg/s)	1.0

In ESP-r, the 2-node cooling coil model was incorporated in a small plant network consisting of a temperature source component model (type 900), a fan (type 30) and a water pump (type 240). The simulation was carried out for one day with a one day start-up period and a simulation time-step of one second (because of the small time constant of the cooling coil). The air and water nodes of the temperature source were maintained at 1°C during the simulation start-up period. After the start-up period, control was imposed on the water node such that a negative pulse pattern was generated using control law 6 with function generator type 1. The maximum and minimum values for the water temperature were 1°C and 0°C respectively. The simulation and the exact results are compared in Figure 5.6. As can be seen, good agreement is achieved for the model algorithm for the case considered.

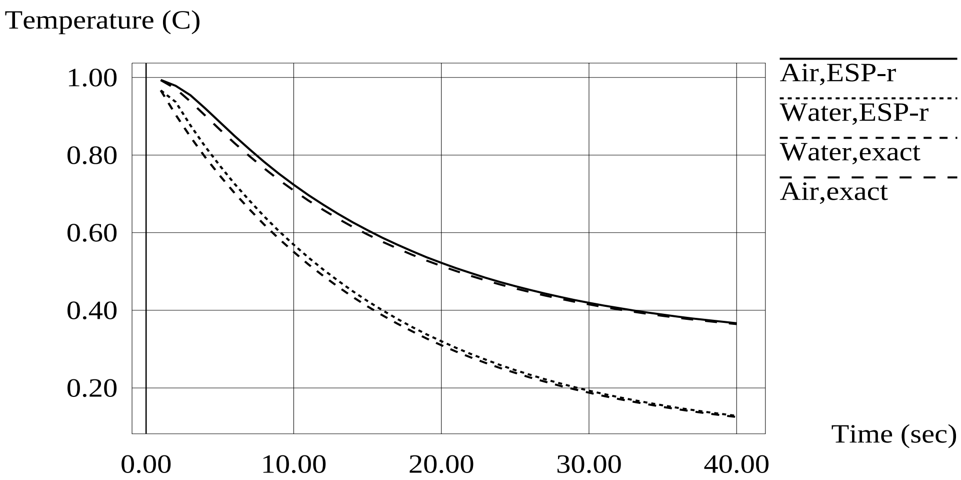

Figure 5.6 Variations in cooling coil air and water temperatures.

5.3 Inter-model comparison

Idealy, inter-model comparison should be conducted against measured data. For plant components this is not always possible because not all simulation programs have the same type of component models. However, it was shown by Hensen (1991) that for some models it is possible to conduct such a comparison as demonstrated for the boiler model (type 260) with aquastat control. In his work, good agreement was obtained between ESP-r's boiler model and TRNSYS version of the boiler model.

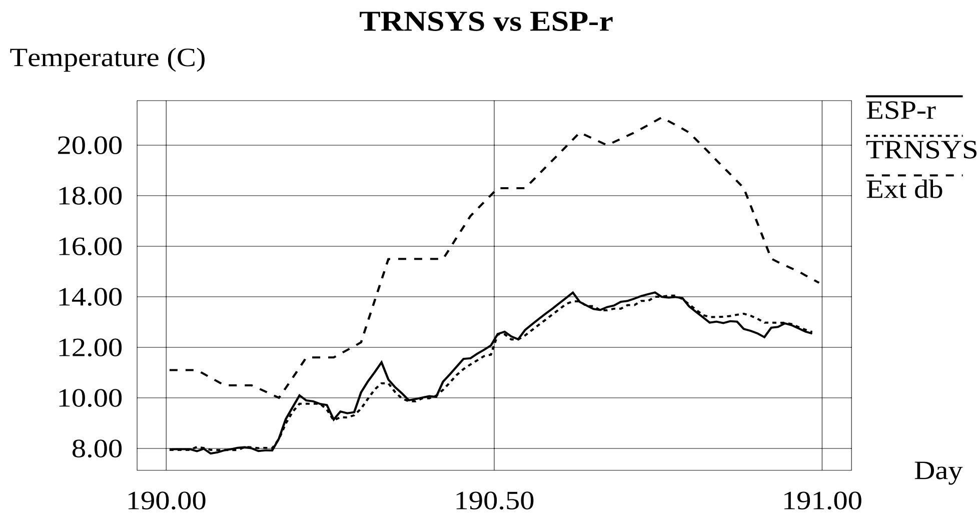

Figure 5.7 Cooling coil air temperature using ESP-r and TRNSYS.

Another ESP-r plant component which can be compared with an equivalent TRNSYS model is the cooling coil component model (type 90). Figure 5.7 shows the results obtained from a simulation run for one day with a time-step of 15 minutes. The plant network which was set up for this exercise consisted of a fan (type 30) and a cooling coil model (type 90) with water mass flow rate control. The parameters defining the cooling coil model are listed in table 5.5. A control loop for the cooling coil inlet mass water flow rate was set to introduce a step change, from $0.1 kg/s$ to $1.0 kg/s$, between time 6 and 12 hours. Again this was achieved using control law 6 with function generator type 1.

Table 5.5 Parameters defining cooling coil (type 90) for step input test

Component total mass (kg)	15.0
Mass weighted average specific heat (J/kgK)	1000.0
UA modulus (W/K)	0.0
Coil face area (m^2)	0.2
Internal tube diameter (m)	0.015
Inlet water temperature (C)	5.0
Number of rows deep (–)	1.0
Number of parallel coil circuits (–)	1.0

The inlet dry and wet bulb temperatures to the cooling coil obtained from ESP-r were used in TRNSYS using the card reader component. The step change in water flow rate was generated using the forcing function component. The results show similar coil response patterns from both models, however there was no experimental data available to compare against.

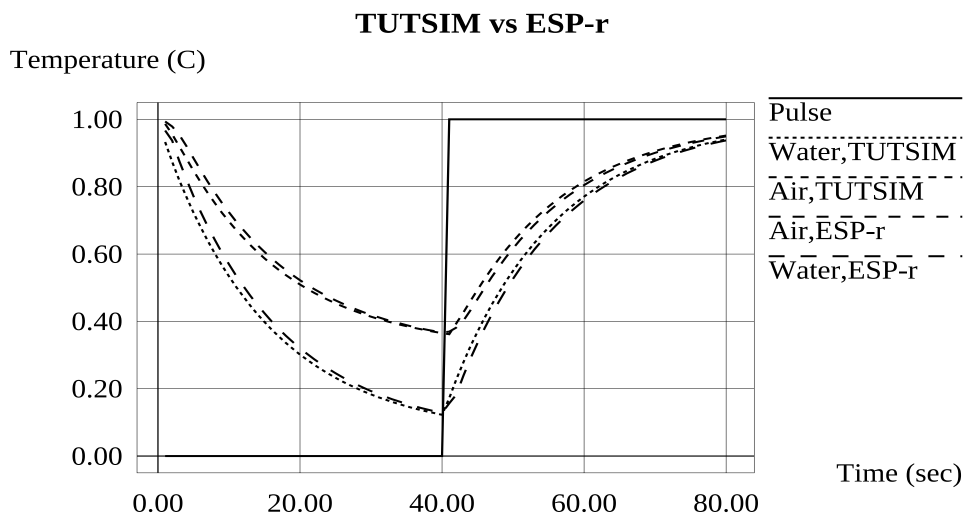

Figure 5.8 Cooling coil air and water temperatures using ESP-r and TUTSIM

Figure 5.8 shows another comparison between the ESP-r cooling coil model (type 430) and an equivalent model constructed using a general purpose simulation program called TUTSIM. For a thorough explanation of TUTSIM, the reader should refer elsewhere (Walter 1990). Briefly stated, TUTSIM is particularly suited for the simulation of continuous dynamic systems. For this reason it was used here since most dynamic systems are represented by differential equations as is the case for ESP-r models. TUTSIM is like a toolbox with a large number of elementary equations preprogrammed. Each elementary function may be represented as a block so that interconnections between blocks will complete the system being modelled. To illustrate how such tool can be used in the context of inter-model validation, the cooling coil air and water differential equations given by Equations 5.7 and 5.8, can be constructed from a number of blocks as shown in Figure 5.9. The initial inlet water temperature initiated by the pulse function was 0°C from time 0 to 40 seconds. A step change from 0°C to 1°C then occurs from time 40 to 80 seconds. In TUTSIM this was achieved by defining the start time, end time and pulse amplitude associated with a pulse source function. Other fixed parameters related to the cooling coil were defined using a constant function. The air and water node temperatures were obtained by adding up the appropriate quantities and parameters and then using an integrator function to find the derivative of the target variable. TUTSIM was then instructed to begin the simulation using a time-step

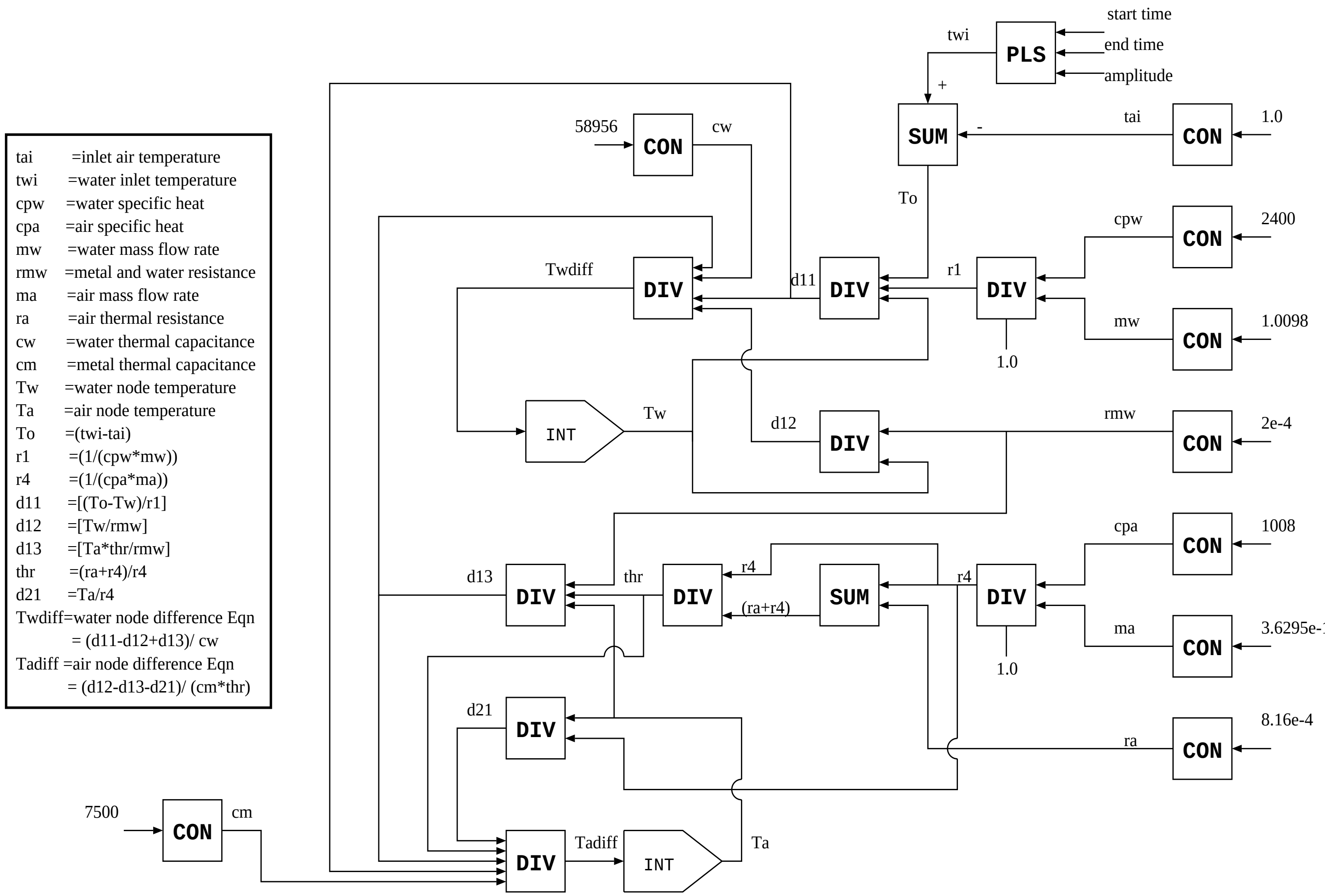

Figure 5.9 Construction of cooling coil model from TUTSIM blocks.

of 0.5 seconds. The reason for chosing such a small time-step value is that the integrator function did not give smooth results at time-steps similar to that used in ESP-r (i.e. 1 second). As clarified by Figure 5.8, good agreement was obtained between ESP-r predictions and TUTSIM simulations indicating that the differential equation coefficients established by the cooling coil model in ESP-r and the solution of the nodal equations is accurate.

It can be concluded that TUTSIM offers useful and powerful tools to model a continuous differential equation of any order. In cases where more complex models of either single or multiple differential equations are required, then one way to verify their solution within ESP-r, is to make use of the TUTSIM functions.

5.4 Empirical validation

This is considered to be the most important stage of the validation methodology because it is considered to be a near conclusive test of whether a program's predictions reflect reality. Figure 5.10 shows the elements of the empirical validation as adopted in the PASSYS II project. The experimental design element is concerned with acquiring an understanding of the principal factors which are involved in the system to be studied and how they effect the control variable. For example, the effect of the solar absorptivity on the air temperature may be investigated by conducting a simulation in order to decide on appropriate measurement scheme. Implementation of the experiment involves the construction and installation of the test component, the calibration and placing of sensors, the measurement of thermophysical properties, measurements of air tightness of the room and finally experiment initiation. The production of high quality data sets require the careful checking, documentation, pre-processing and storage of the experimental data to ensure that the criteria defining high quality data sets have been achieved. Finally the analysis phase is concerned with how good the comparison is between measured and predicted results and investigation of cases where there are large disagreements by the use of parametric and differential sensitivity analysis. In this section, it is assumed that all but the analysis element have been considered.

The author has participated in a ’blind’ validation exercise requested by the IEA as part of Annex 21 which is concerned with improving the usability and credibility of detailed thermal simulation programs of buildings. The term ’blind’ means that the measured data is not available in advance and therefore the simulation results will reflect how close the program resembles the measured data on the basis of practical input parameter assignments. A number of research institutes have participated in this

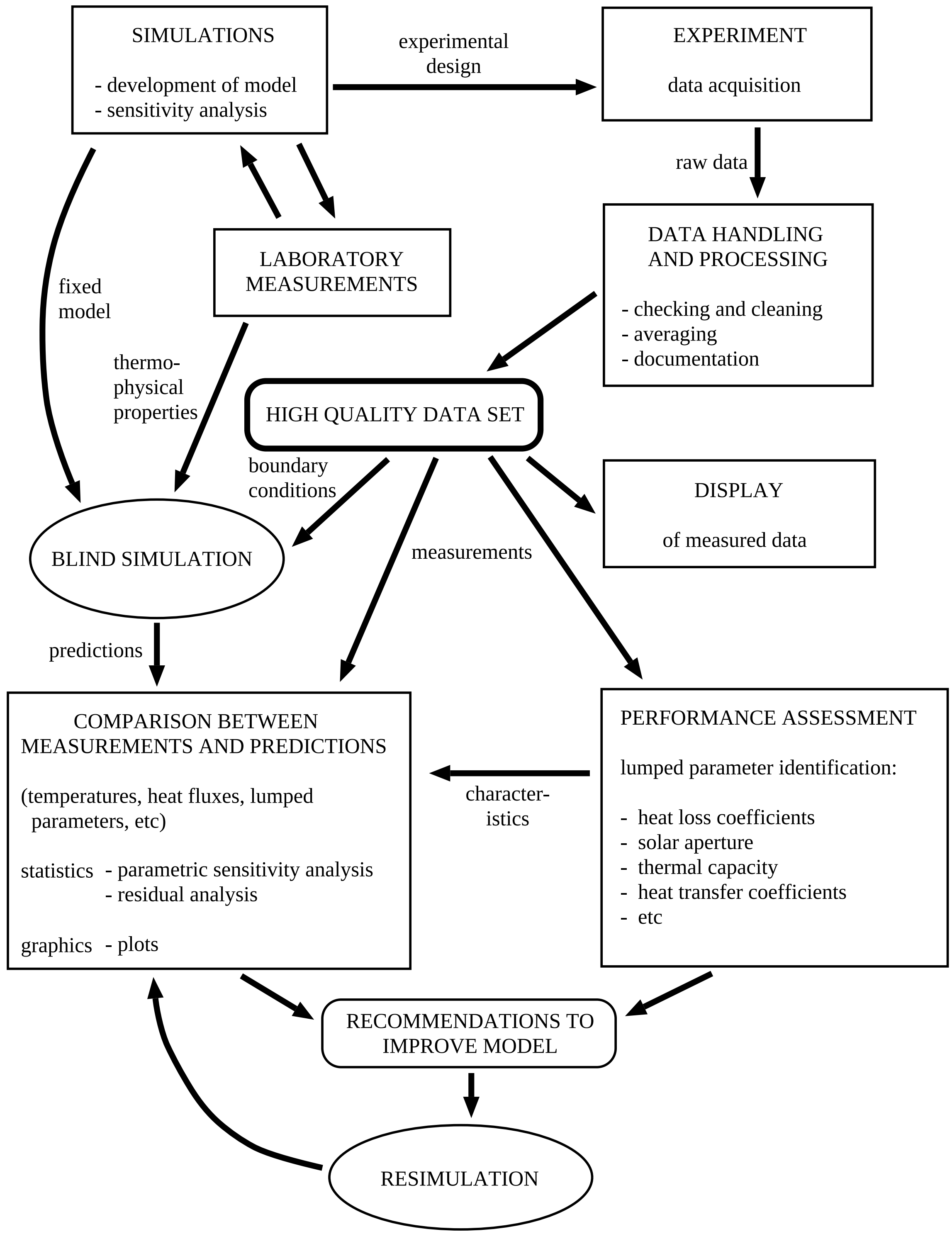

Figure 5.10 The PASSYS methodology for empirical whole model validation

exercise using different energy simulation programs such as BLAST, DOE, ESP-r, TRNSYS and others. However, emphasis will be made here on ESP-r.

5.4.1 Test site details

The outdoor test facility is the property of the Energy Monitoring Company and consists of eight test rooms, in four semi-detached pairs. This facility was established in 1985 and was used to conduct work which may fall under three main headings: testing the performance of specific building elements; investigating thermophysical processes which underlie the thermal performance of buildings; and empirical validation. The main feature of these rooms is that the glazing panels are interchangeable allowing different glazing options to be installed in the test rooms. Table 5.6 summarises the site location details. The glazed surface is installed in a wall facing 9° west of south. For this exercise, only two rooms were considered, one fitted with a double glazed window and the other with no glazing at all.

Table 5.6 Site location details

Latitude	52.07° N
Longitude	0.63° W
Altitude	100 m above msl
Exposure	Rural isolated
Ground reflectivity	0.2
Glazing orientation	9° west of south

Figure 5.11 shows a view of the site with the adjacent building represented as an obstruction block. This indicates that a shading analysis is necessary and indeed this was done prior to the thermal simulation using ESP-r's shading module. Each building consisted of a test room above which there is a roofspace. The thermophysical properties of the wall layers, walls construction and glazing properties are listed in Appendix C. The rooms considered for this exercise may be described as being of lightweight, timber framed construction. Thermal mass in the rooms is provided by the plasterboard lining of the walls and ceiling, and by a concrete slab floor.

5.4.2 Test rooms operational details

The test rooms were designed to be tightly sealed in order to eliminate potentially uncertain air infiltration. For this reason the air change rate within each test room was assumed to approach zero. The roofspaces are ventilated by gaps in the building eaves on the north and south faces. An air change

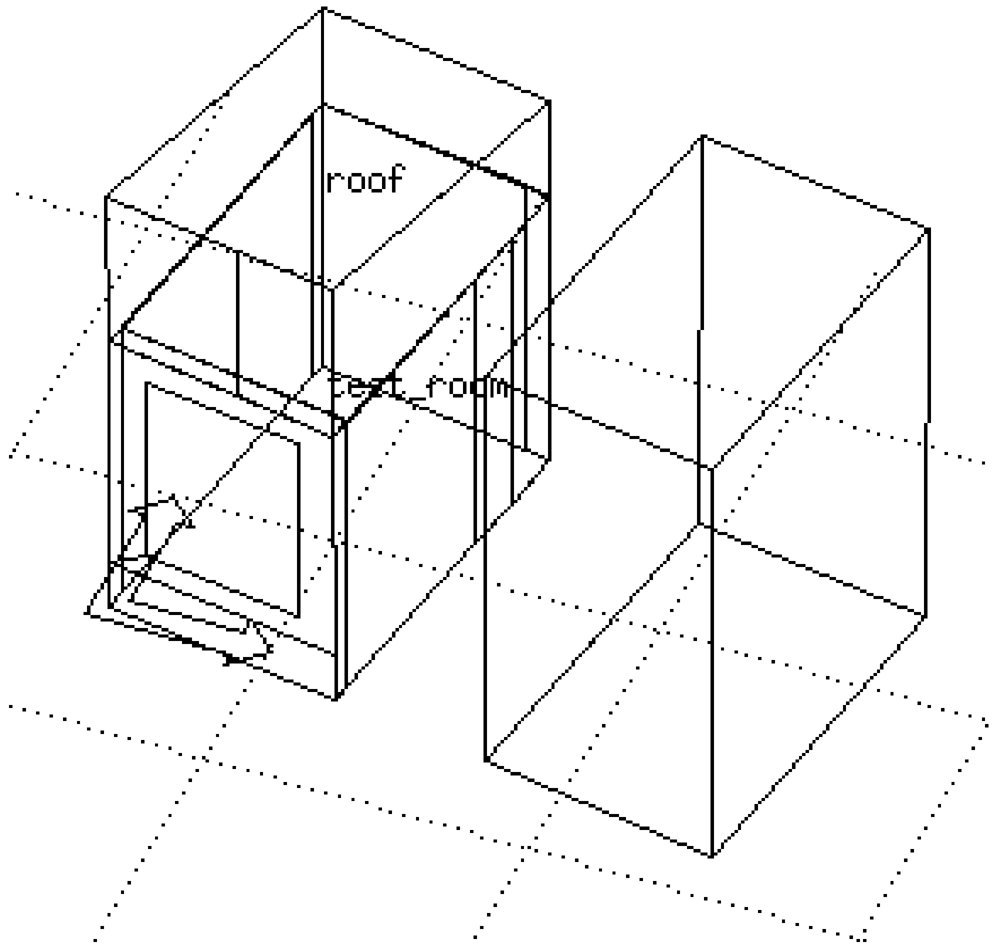

Figure 5.11 A view of the test site from the sun.

rate of 1 ACPH was assumed for each roof space because they were ventilated by gaps in the building eaves on the north and south faces. The test rooms were each heated by an oil-filled electric panel radiator with an average maximum power output of 680 W, with deviations of approximately ± 20 W. Based on standard empirical results for the convective and radiative heat transfer from a vertical heated plate, it was stated that the heat output from the radiator was 60% radiant and 40% convective. It was also stated that the radiator dynamics could be well represented by a first order system with a time constant of 22 minutes. The radiator was controlled by a proportional + integral + derivative control system with a proportional band of 4°C, an integral time of 99 minutes and 59 seconds and a derivative time of 15 minutes. It was stated that the control period is from 6:00 hours to 18:00 hours only.

5.4.3 Simulation considerations

Since the test rooms are semi-detached, it was assumed that the dividing surface may be considered as adiabatic with no heat transfer. Further, since the test rooms were supported approximately 300 mm above the ground, with free air circulating beneath them, it was not necessary to model heat loss to the ground and the floor external surface solar absorptivity was set at 0.01. Although it is possible to build an obstruction block similar in shape to the adjacent building to account for its shading effect, a simple rectangular block was considered since the shading effect on the roof space was assumed to be minimal. The double glazed window was considered to be a transparent multi-layer construction with an air gap of 6 mm and a glass thermal conductivity, density, specific heat and thickness of 1.05 W/K, 2500 kg/m^3, 750 J/kgK and 4 mm respectively. ESP-r heat flow component model type 280 was used to represent the oil-filled electric radiator panel. Table 5.7 lists the values of the parameters describing this component. Note that since not all the data required by this component were provided, it was assumed that the radiator total mass and mass-weighted average specific heat could be set to give a radiator time constant close to the specified value of 22 minutes. A control loop was set for the radiator component using plant control law type 1 with the PI feature enabled by specifying the data associated with the commercial controller mentioned above. Coupling of the radiator component to the building was achieved using a building control function with control law type 6. The control period for this control law was specified to be active over 24 hours. This was necessary because when the radiator is switched off at 18:00 there will still be some heat emission due to the radiator time constant. Actuator location type -2 was chosen because it allows the definition of the convective fraction (C) as a percentage of the radiator power output. The radiative fraction is then evaluated as $(100 - C)$.

It should be mentioned here that even though caution was taken to ensure the data as supplied for the exercise was accurate, some data, such as those describing material properties at the corner sections, had their U-value modified to account for the three dimensional heat flow effects which occur at the room corners. Because these modifications were based on steady state calculations, then this is expected to cause some errors.

Table 5.7 Parameters defining radiator component for empirical validation

Component total mass (kg)	25.0
Mass weighted average specific heat (J/kgK)	1000.0
Radiator exponent ($-$)	1.3
Nominal heat emission of radiator (W)	680.0
Nominal radiator temperature (C)	70.0
Nominal environment temperature (C)	30.0

5.4.4 Results

Figure 5.12 shows a comparison between measured and ESP-r predicted results. Note that the measured data was made available to participants after submission of their predicted results. The figure shows the free floating temperature pattern for the two test rooms (ie. opaque and double glazed). It can be seen that ESP-r underpredicts room temperatures although it follows the same temperature pattern. Figure 5.13 shows another comparison but this time heating is imposed on the room air to bring it to a temperature of 30°C between 06:00 hours and 18:00 hours. The total heating energy calculated for the seven day simulation period was lower than the measured results by 21% for the double glazed case and by 12.5% for the opaque case. The reason for this last discrepancy was traced to a rapid increase in the air temperature as predicted by ESP-r causing the temperature set point to be reached earlier than with the real building where it was observed that the test room air temperature reached the set point after about 50 minutes. In ESP-r this delay was of the order of 20 minutes for the opaque test room. The significance of this time delay is in predicting the power output from the heater. For example, since the predicted test room temperature reached the set point earlier than the actual case, this meant that ESP-r would predict less power output resulting in lower heater power output. Moreover, during the middle of the heating period in the double glazed test room, when the solar gains are high, the room temperature seems to increase rapidly and therefore less heating demand is required. This was also expected to reduce the predicted total heating supplied by the radiator.

The radiator dynamics could have been investigated further if measured data associated with the radiator was available. Unfortunately, this was not the case which explains why the comparison was only limited to the building thermal response. It is important to point out that for this exercise, the data supplied for the radiator was very basic and, unlike the building, there was no standard data sheet. This is a common problem encountered by many energy simulation programs when attempting to simulate plant components and, as a consequence, research is underway to overcome this problem (see Section

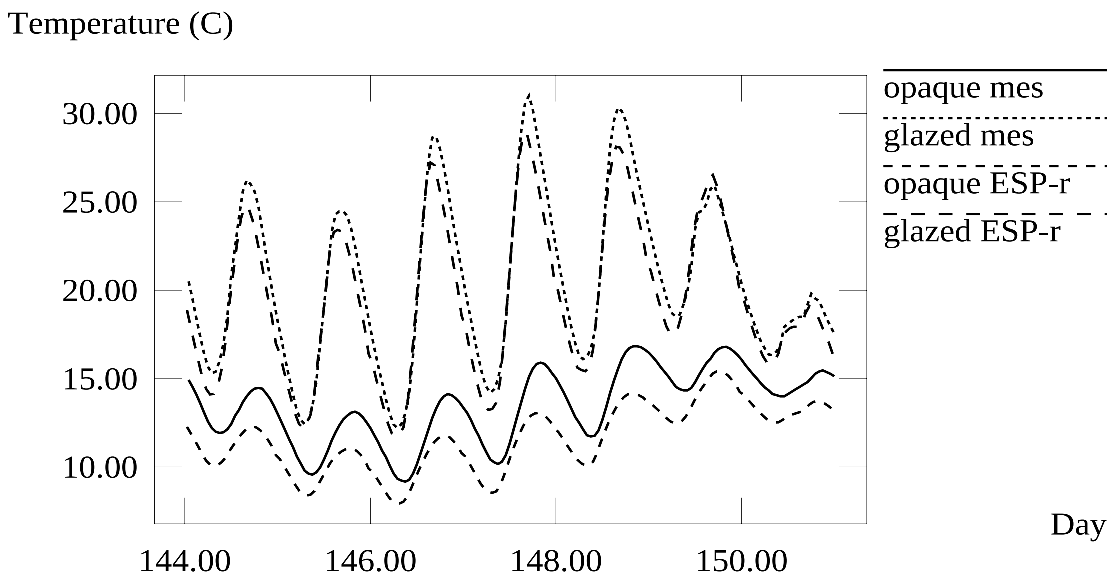

Figure 5.12 Free floating temperature variations of opaque and double glazed test rooms

7.1).

5.5 Sensitivity analysis

Sensitivity analysis is essential in order to determine the uncertainty level associated with a model to, for example, predicting an output variable such as internal air temperature. This entails modifying an input parameter within some expected minimum and maximum values and then conducting simulations to study its effect on the output variable. The comparison is often made with measured data which also has its own uncertainty band. If there is an overlap between the prediction and measured uncertainty bands, and assuming that the bands are acceptably narrow, then confidence can be placed in the predictions. In order to determine which input parameter has the greatest effect on the output variable, a number of input parameters must be considered. Parametric sensitivity analysis is sensitive to the standard deviation of the input parameters, which are based on subjective judgements and experience, and therefore cannot test the dynamic aspects of a program's behaviour. Furthermore, it does not give a clear indication of why a program is performing poorly.

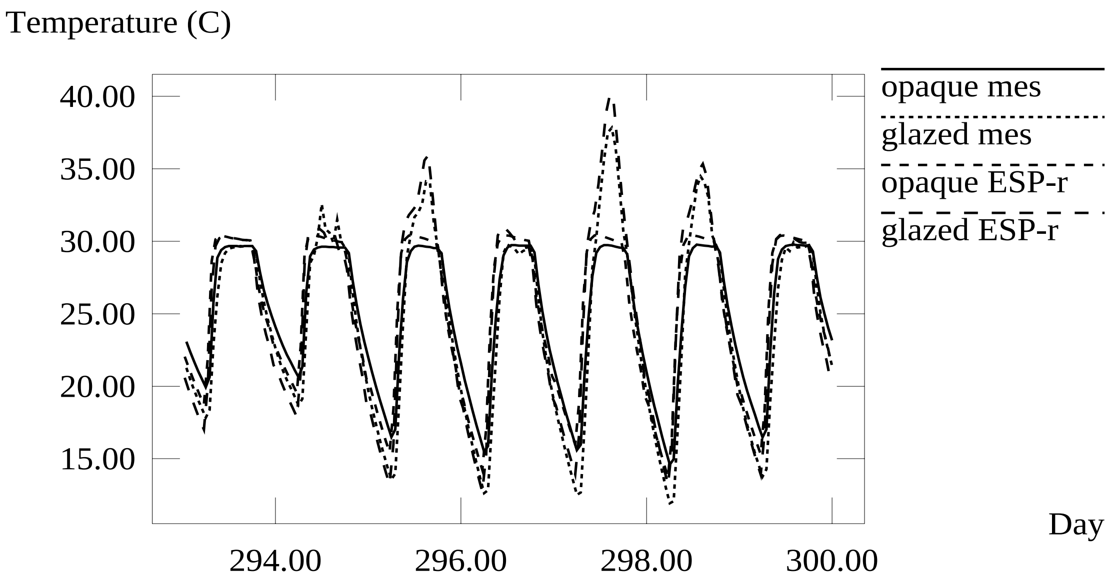

Figure 5.13 Temperature variations of opaque and double glazed test rooms with heating.

To show how this technique can be applied, consider the exercise described in the previous section. To establish a possible cause for the disagreement between predicted and measured free floating air temperature for the opaque room, a series of sensitivity analysis tests were carried out.

Figure 5.14 shows the results of a sensitivity analysis on the effect of varying the external convective heat transfer coefficient. These variations were in the order of ± 50% (estimated by Allen (1987) to be a minimum). It can be seen that this parameter has little effect on the test room air temperature. The reason for this is that because of the absence of a window, only the longwave and shortwave radiation processes on the external surfaces are dominant. Figure 5.15 shows another sensitivity analysis on the effect of external surface solar absorptivity. The values stated by the IEA group were 0.16 for the white painted plywood. This was not measured in situ but was stated according to British Standard BS4800. However according to Chantant (1991), the solar absorptivity of a white-coated plywood, measured in situ, was found to be 0.29. The reason for this difference is that solar absorptivity is highly influenced by the surface condition. As can be seen, this has a significant effect on the indoor air temperature because more heat is being conducted through the opaque walls. Another sensitivity analysis was carried out on the external surfaces view factors. It was stated that the test site is

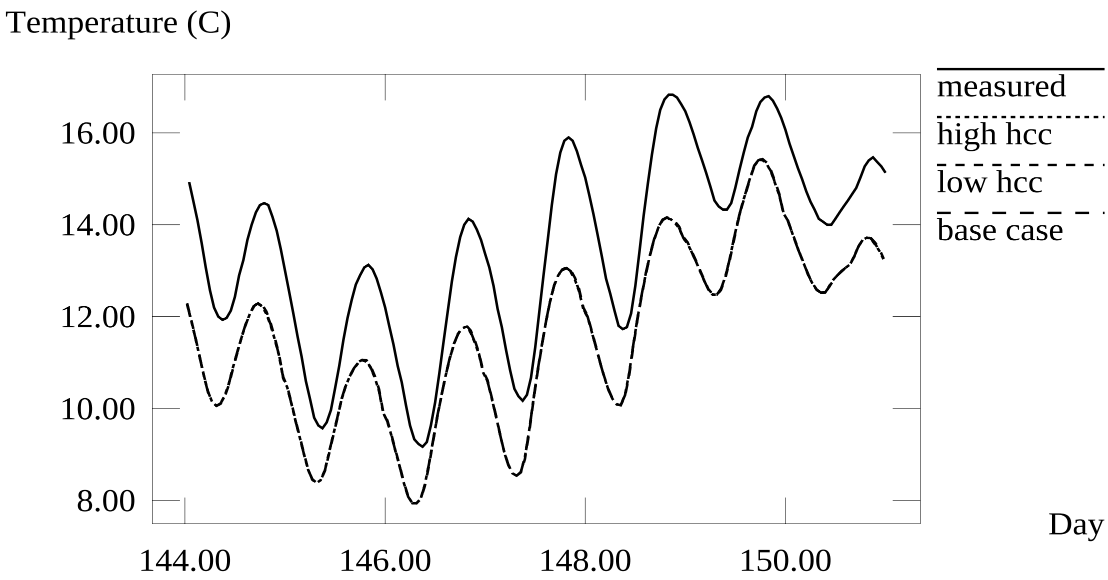

Figure 5.14 Sensitivity analysis on the effect of external convective heat transfer coefficients on opaque room air temperature.

in a rural location and that the south facing wall had an unobstructed view. This implies building, sky and ground view factors of 0, 0.5, 0.5 respectively for the south facing wall. This does not apply to all surfaces because the east wall faces the west wall of the adjacent building and therefore the view factors should be changed accordingly. At present, ESP-r does not offer a way of defining different external view factors for each surface, rather it assumes all surfaces have the same factors. Figure 5.16 shows the effect of modifying these factors to 0.3, 0.35 and 0.35 for the building, sky and ground respectively.

For the case where there was heating in the test rooms, the output variable considered was the radiator total energy consumption for the period considered (i.e 20 October until 26 October). For both rooms, a sensitivity analysis was conducted to study the effect of using different algorithms which calculate the internal surface heat transfer coefficient on the total energy consumption. The algorithms considered were the Alamdari (1983), Khalifa & Marshall (1990) and Halcrow (1987). The first algorithm is the default adopted by ESP-r whereas Khalifa & Marshall make use of a correlation developed from experiments conducted on a test room of different size than the one considered here but was equipped with a radiator located under a window as in the double glazed test room considered here. The Halcrow case assumes a fixed heat transfer coefficient value of 7 W/m^2K for all internal surfaces.

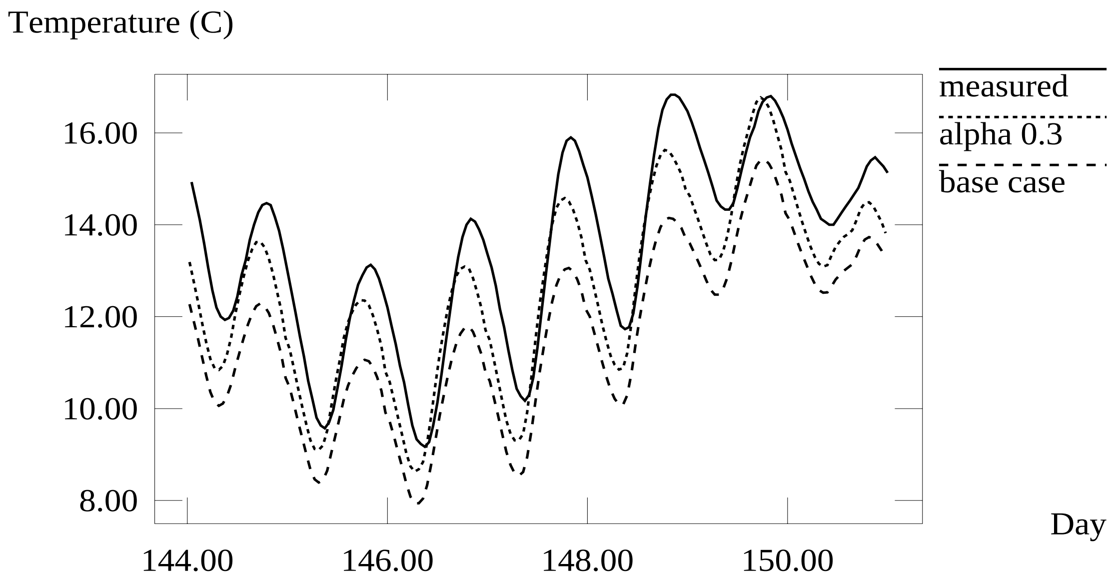

Figure 5.15 Sensitivity analysis on the effect of external solar absorptivity value on opaque room air temperature.

Table 5.8 Total heating energy (MJ)

Measured		ESP-r		
Opaque	Double glazed	Algorithm	Opaque	Double glazed
117	89	Alamdari	102.4	70
117	89	Khalifa	107.5	78.7
117	89	Halcrow	112.96	80.97

It can be seen from Table 5.8 that the inside heat transfer coefficient has a significant effect on the total energy consumption in this particular situation indicating that accurate modelling of this parameter is important. Accurate modelling is possible by conducting an experiment on the test rooms to establish a better correlation for the prediction. Regarding the radiator component, it was stated that the maximum output of the radiator is 680 *W* with deviations of approximately ± 20 *W* for individual units. It was observed that changing the radiator heat output from 680 *W* to 700 *W* caused an increase of 0.2 *MJ* to the total energy consumption which is not significant. It was also found by conducting similar analysis that the effect of changing the radiator time constant has very little effect on the overall energy consumption.

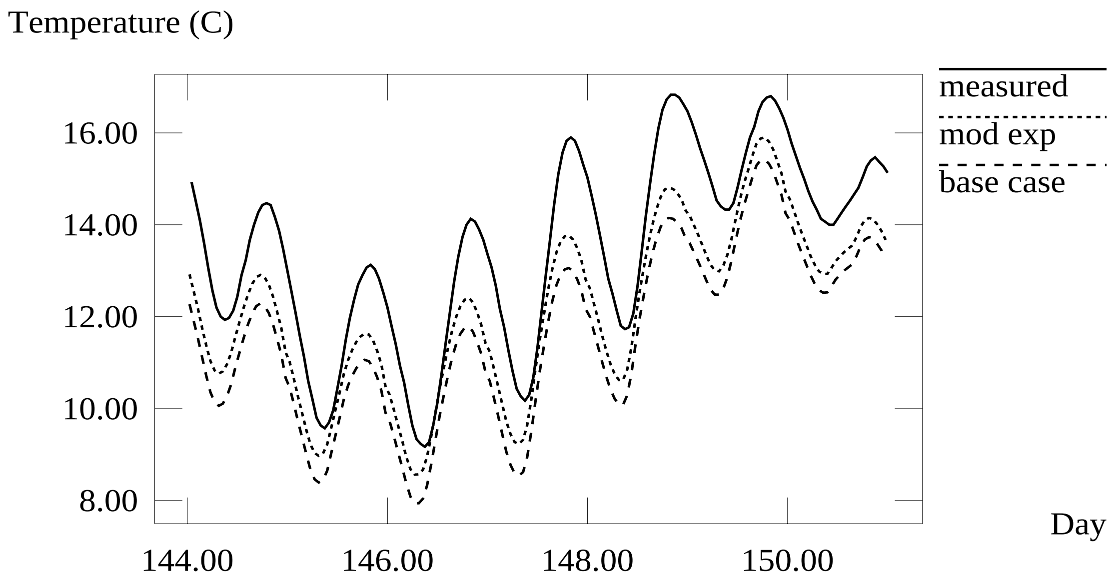

Figure 5.16 Sensitivity analysis on the effect of external surfaces view factor on opaque room air temperature.

From the results reviewed above it is not possible to draw a single conclusion on what input parameter is the main cause for the disagreement between predicted and measured values. It was mentioned earlier that this is one of the main disadvantages of the parametric sensitivity analysis method. However there are other statistical methods, by Palomo and Tellez (1991a and 1991b) for example, which operate on the residuals in an attempt to determine the causal factors. This is outside the scope of the current project and the reader should refer to the PASSYS II final report (PASSYS, 1992) for a thorough discussion. The uncertainty surrounding some input parameters can be minimised by making accurate measurements, where possible, such as in the case of the external solar absorptivity value for the white painted plywood. ESP-r treatment of external viewfactors for the sky, ground and building should be extended to allow for different external viewfactor values to be specified for each external surface. This experiment showed that for accurate assessment of energy requirements, accurate correlations are required for the predictions of the internal heat transfer coefficient.

Further work

In order to validate a building energy simulation program, it is necessary to follow several such as analytical testing, theory checking, inter-model comparison and empirical validation. It is clear that a considerable amount of effort is required to conduct the validation phase successfully. This was experienced especially with the empirical validation stage in which a simple case of plant and building interaction was considered. Other examples which include building, plant and fluid flow, such as in an air conditioning system, must also be considered.

While conducting the empirical validation stage, a number of input errors were discovered. This is always a problem which is encountered when testing energy simulation programs mainly because of the large amount of input data required for the definition of the problem. One way to minimise such errors is to make use of an "intelligent front end" which is discussed in detail in section 7. In terms of plant simulation, some difficulties were encountered when establishing input parameters from published data. Manufacturer's data are usually related to well controlled steady state test conditions resulting in sparse data for the dynamic case. In order to benefit more from a dynamic simulation of plant systems, there has to be a standard form of manufacturer's data to be made available to research institutes concerned with the dynamic simulation of systems.

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CHAPTER 6
Applications

All the new features and plant components which were developed and then installed within the ESP-r system, are applied in this chapter in a form of examples with varying degrees of complexity. Because the data associated with a plant network must be defined in a certain format, the chapter starts with a detailed description of the plant network configuration file and the tools currently available for its generation. The chapter then presents some basic examples of plant systems before gradually progressing to real, complex systems incorporating a large number of components, flows, controls and building-side zones. Finally, case studies are included at the end of the chapter in order to show how the new plant simulation tools and features may be applied in practice.

6.1 Plant network definition

In ESP-r, a system configuration file exists to define a project. From within this file, building and plant definition files may be referenced. For a full description of the system configuration file and building definition file, the reader should refer elsewhere (Aasem et al). In this section, only the plant network file will be described because of its relevance.

The format supported by the ESP-r system for the definition of plant networks is shown in Table 6.1. The plant component data base contains entries for all components currently defined in ESP-r. In problems where component parameters are not the same as those defined in the database (i.e a duct with a different length) then, rather than defining these new parameters in a separate database, an index for specifying different parameters was introduced. This index must be assigned a value of either zero to indicate that default parameters should be used, or a value equal to the number of parameters specified in the data base, in which case the record immediately after it will contain the list of the modified parameters.

The plant matrix type value ranges from 1 to 3 to indicate that energy only, energy plus one phase or energy plus two phase fluid simulation is required respectively. For example, when simulating an oil-filled electric radiator where there are no inter-component fluid flows, then the energy only option would be appropriate. Energy plus one phase fluid simulation is applicable to systems in which the working fluid inter-connecting the components is a single phase fluid (eg. water) as in the case of a wet central heating system.

Table 6.1 Plant network definition file format

• Plant components data base file
• Plant configuration title
• Total number of components in network and plant matrix type
• For each component: - component name (15 characters), and entry number in plant component database - number of control variables - list of values for each control variable - index indicating whether different parameters are required - if different parameters are required then a list of new parameters must be specified
• Total number of inter-component nodal connections
• For each connection; component name (15 characters) and node number of receiving node, connection type, component name (15 characters) and node number of sending node, mass diversion ratio, and up to 2 supplementary data items
• Total number of component containments
• For each containment; component name (15 characters), containment type and up to 3 supplementary data items
• Plant fluid flow simulation index
• If fluid flow simulation is required and if not already defined for the building then: - name of mass flow network description file - name of wind pressure coefficient file - name of file to which mass flow results will be transferred
• If fluid flow simulation is required then; for each plant component inter-connection, a mass flow network connection must be referenced

Energy plus two phase fluid simulation would be appropriate for systems in which the working fluid inter-connecting the components is moist air as in the case of air-conditioning systems. Note that because ESP-r supports the simulation of decoupled systems, then energy only and energy plus one phase are also appropriate options for a two phase fluid simulation. For instance, when simulating a multi-zone building in which a zone temperature might be controlled by an electric radiator and the temperature of another zone might be controlled by an air-conditioning system, then energy plus two phase fluid simulation will be appropriate although some of the components will require one or no phases.

The supported connection types and the supplementary data associated with each are described in Table 6.2. Note that connection type 4 with the first supplementary data item referring to a zone can only be used if a building is defined with the plant system being considered for simulation.

Table 6.2 Inter-component connection types

Type	Description	Supplementary data
1	component receives fluid at a temperature and humidity ratio identical to receiving node.	none
2	component receives fluid at a known and fixed temperature and humidity ratio values.	1- Temperature (°C) 2- Humidity ratio ($\frac{kg_v}{kg_a}$)
3	component receives fluid at a temperature and humidity ratio of sending node	none
4	component receives fluid at a temperature and humidity ratio of ambient air	1- 0
4	component receives fluid at a temperature and humidity ratio of specified zone	1- zone number

The supported component containment types and the supplementary data associated with each are described in Table 6.3. For containment type 2, if the node number item is specified as zero then a default node number of 1 will be assumed. Further, if the component supplementary data is set to 0 then the component containment temperature will be at the node temperature of the same component. For containment type 3, three possibilities exist: containment is at some zone's temperature (ie. supplementary data 2 and 3 are set to 0); containment is at some surface's temperature (ie. supplementary data 3 is set to 0); or containment is at some construction node's temperature.

6.1.1 Generation of plant network configuration files

A plant network definition module was developed to allow the definition of a plant network in a relatively user friendly manner. This tool offers on line help at each stage of data entry as well as direct access to the plant component data base in a menu form as shown in Figure 6.1. Component parameters are described by the text predefined at component entry time in the component database and the user has the option of modifying their values within the allowed range. When using this tool, plant

Table 6.3 Component containment types

Type	Description	Supplementary data
0	containment is ambient air temperature	1) increment or decrement to be added to ambient air temperature (°C) 2) 0 3) 0
1	containment is at a temperature of a specified plant node	1) component name (as defined in configuration file) 2) node number of component 3) increment or decrement to be added to node temperature (°C)
2	containment is at a specified temperature	1) specified temperature (°C) 2) 0 3) 0
3	containment is at construction temperature	1) zone number 2) surface number 3) construction number

component inter-connection definition is greatly simplified because information regarding the number of nodes in receiving and sending components and the fluid type to be specified for a connection can be checked and appropriate warning messages issued for any mismatch detected.

The data entered for a particular plant network is then transferred to a user specified file in a format similar to that given by Table 6.1. The plant configuration file is then ready to be read by ESP-r prior to a simulation.

A third party tool (Cheng, 1991) is also available to assist in the definition process of a plant network. This is a two dimensional drawing facility that allows the user to draw and manipulate objects in the X window system. It supports the ’bottom-up’ construction of hierarchical drawings by providing the capability to instantiate a building-block object in a drawing. For instance, in the terminology, a ’symbol file’ specifies a building-block object such as a duct, a number of these building block objects can be instantiated to make up the complete system. A number of these symbol files can be created to represent a number of different components. This utility allows text attributes to be

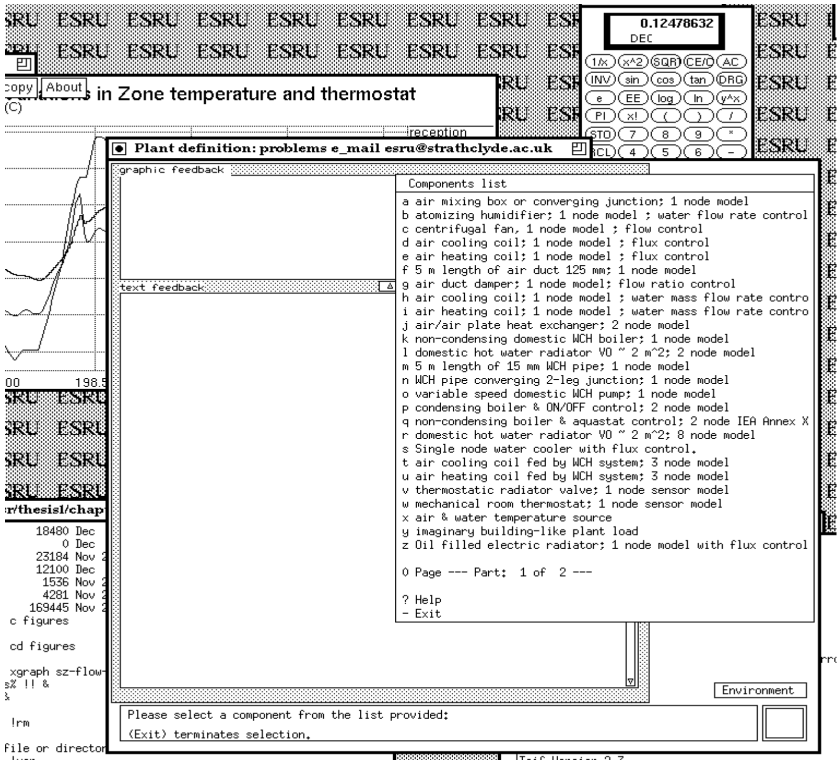


Figure 6.1 Plant component selection from data base

attached to an object so that when a building-block is instantiated, its attributes (eg. component name and parameters) are also inherited. The files for this tool are stored in the form of Prolog facts so that Prolog code can be written to interpret drawings and to generate network files in the desired format. Due to the time limitation for the current research, this task will require future work. Figure 6.2 shows an example of a plant network constructed from predefined building-blocks (eg. components). This graphic utility also includes a facility which allows the user to view the attributes of any object, a very useful feature especially when defining very complex systems made up of a number of components with different parameters. In this case, by activating a component object, its parameters can be viewed instantly.

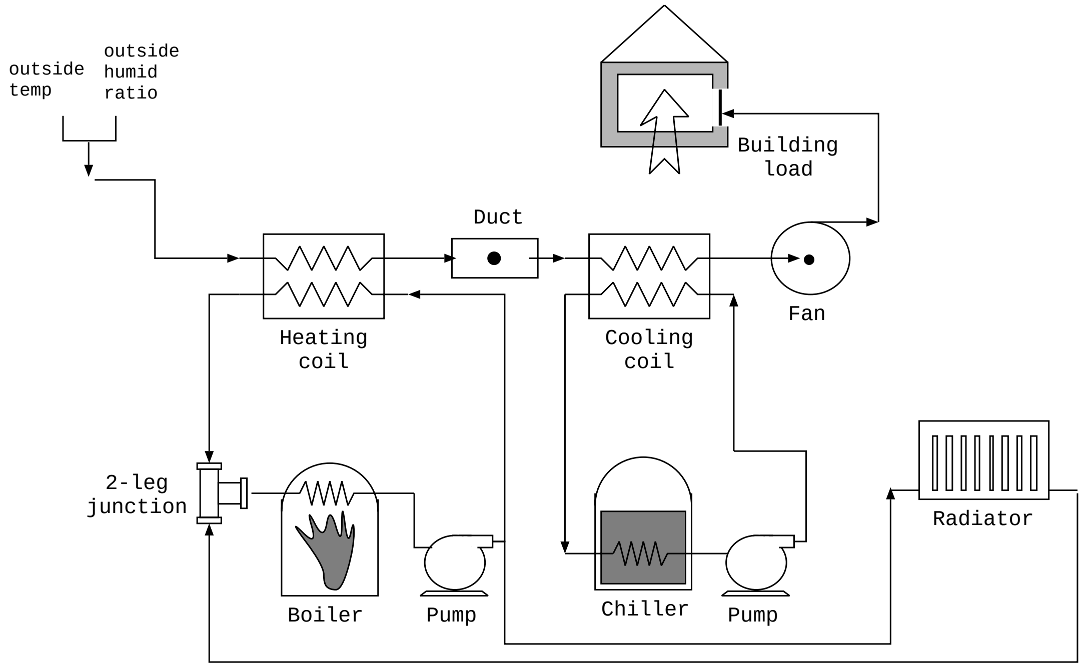


Figure 6.2 A plant network defined using a graphical drawing package

6.2 Results recovery

The simulation results for the plant can be analysed using two different method. In one method the results can be viewed at simulation time using the state monitoring facility of ESP-r’s simulator. This facility was developed to allow the user to monitor not only plant component nodes state variables but also zone variables such as air temperature and energy injections. It was mentioned earlier that the currently supported state variables for the plant are temperature, first phase and second phase flow rates. By use of the monitor facility, these state variables can be monitored for any number of nodes at simulation time as shown in Figure 6.3.

In the other method, ESP-r’s results recovery module can be used to extract the required information from a plant result file. In addition to the three state variables which may be calculated for each component node, some components may also have additional output variables (eg. heat loss to the environment, power consumption, etc.). By using this module, it is possible to obtain tabular output for these additional output variables as well as tabular output for nodal state variables. In addition, plots for the desired variables in a manner similar to that used for the building can also be obtained. The tabular output for the plant can be used directly by third party tools if the user wishes to use different means for

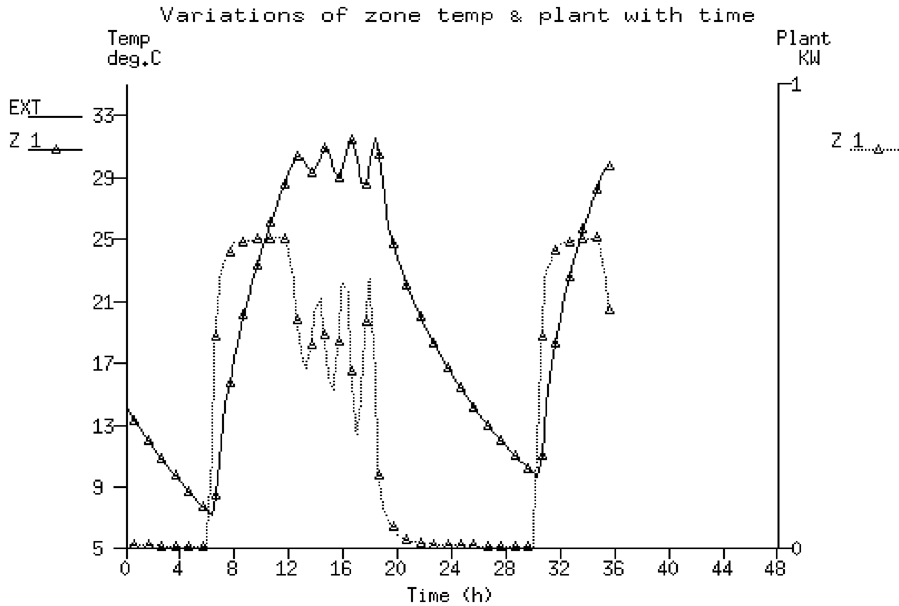


Figure 6.3 A graph being generated at simulation time
using the monitor facility

graph generation and data analysis.

6.3 Simulation of real systems

In this section a number of examples are presented to show how some systems may be modelled using ESP-r. The examples considered are not imaginary in that they are used in practice for different applications ranging from ventilation with heat recovery, to multi-zone air conditioning systems. Only the parameters specified for the different components used in the following systems may be considered hypothetical.

6.3.1 Simple ventilation system

Figure 6.4 shows the general layout for this system (see configuration file listing given in Appendix B, example 1). It comprises of six components with duct components 1, 2, 4 and 6 of type 60, a fan component 5 of type 30 and a mixing box component 3 of type 10. In this system, fresh outside air is mixed with zone return air which is assumed to be at a fixed temperature and humidity ratio of 25°C and 0.005 respectively.

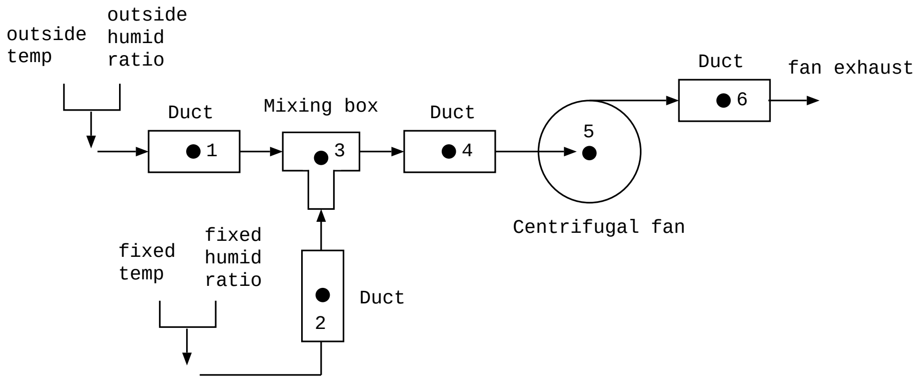


Figure 6.4 Plant layout for a simple ventilation system

The mixed air is then exhausted to some other zone in a building. This is a basic arrangement in that no control, no building and no mass flows are included in the simulation.

The simulation for this example was conducted using an ESP-r test climate file for the period between 9 April and 12 April with a simulation time-step of 15 minutes. The results for some component nodal temperatures are shown in Figure 6.5.

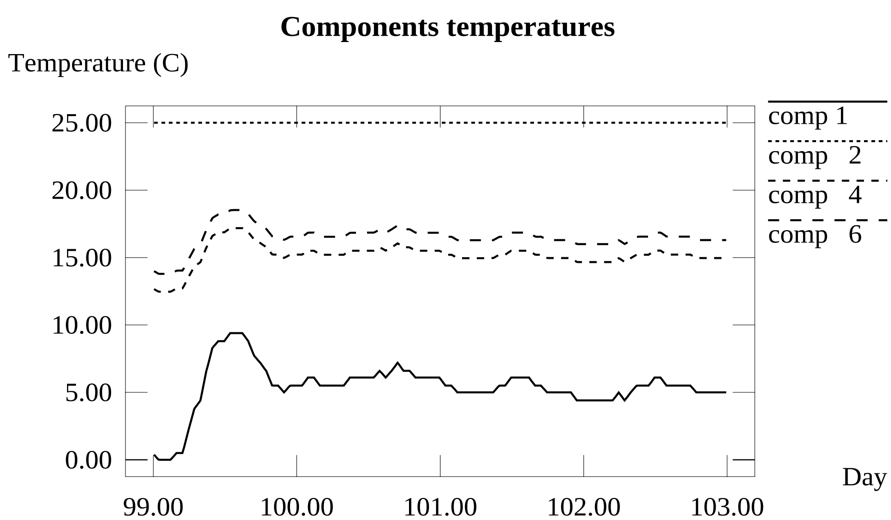


Figure 6.5 Components nodal temperature variations for the simple ventilation plant example.

It can be seen that the mixing of outside cold fresh air with the warm return air results in a substantial increase of outside air temperature. A further temperature rise takes place across the fan due to the internal heat generation in the fan component. According to Hensen (1991), the fan internal heat generation (ϕ_i), in case where a fluid flow network is not active, is calculated from:

$$\phi_i = \left[\frac{\dot{q}}{\dot{q}_r} \right]^3 E_r \tag{6.1}$$

where $\dot{q}$ is the fan volume flow rate (m^3/s), $\dot{q}_r$ is the volume flow rate (m^3/s) and E_r is the total (electric) power consumption at $\dot{q}_r$. It can be seen from Equation 6.1 that care must be taken when specifying values for $\dot{q}$ and $\dot{q}_r$ because their ratio is to the power 3. In situations where this fact was overlooked, a substantial increase in temperature across the fan was experienced.

6.3.2 Detailed ventilation system

The most common ventilation system used in practice is of the mechanical inlet and extract type. This implies that both supply air and exhaust air are handled by mechanical means (eg. using fans). This type can be applied to all manner of spaces and is preferred to other ventilation systems (eg. mechanical inlet and natural extract, natural inlet and mechanical extract). Some applications include smoke control in fire escape routes, kitchens, fume extracts and so on.

In practice, the ratio between the air volume flow rate of the inlet and extract systems are selected to suit the particular application (Faber and Kell, 1979). For instance, in normal living and working spaces where no noxious fumes are generated, the extract volume is usually arranged to be less by 10-20% than that provided by the inlet system. In cases where fumes might be generated in a space, the balance would be reversed so that the inlet volume is less by 10-20% than that handled by the extract system. The former arrangement was applied to the system shown in Figure 6.6. The system comprises a suction fan (component 8), an exhaust fan (component 5), a heating coil (component 9) and some ducting arrangement. The heating coil used is of type 50 which has the heating flux as the control variable. A control loop with control law 1 was defined in proportional control mode to actuate the coil heating flux based on the component 11 air temperature. The heating set point for this controller was set to 20°C with a throttling range of 3°C and the maximum and minimum heating flux was set to be 6000W and 0W respectively.

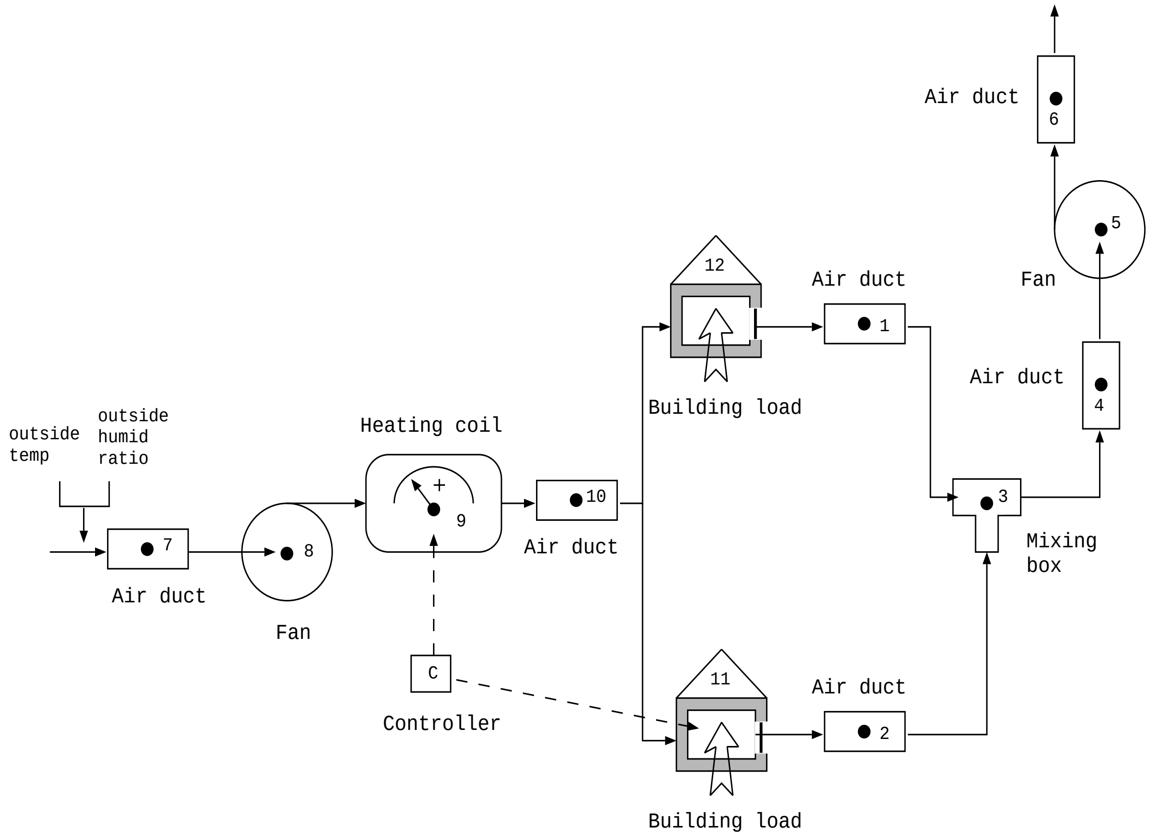


Figure 6.6 Plant layout for the detailed ventilation system.

Components 11 and 12 are used as a building like load generator (type 910) in which a control variable exists to act as the building load. Although the building load can be introduced as time dependent, in this example it was assumed constant with a value of -500 *W* for component 11 and -1000 *W* for component 12, the negative sign indicating a heat loss. The complete listing of the simulation input files for this example are included in Appendix B, example 2. A simulation for the period between 9 Jan and 11 Jan was conducted using ESP-r test climate file with a simulation time-step of 15 minutes. The temperature variation of the nodes of interest are shown in Figure 6.7. The inlet duct temperature is the same as the external dry bulb temperature (not shown here) since the connection type specified for this component was to the outside. The exit duct temperature experiences continuous fluctuations because of the controller action to maintain component 11 temperature within the throttling range specified.

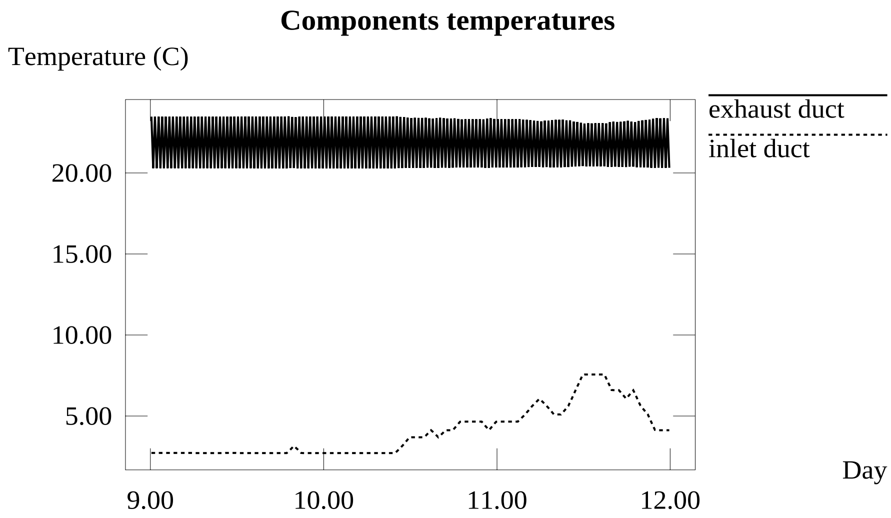


Figure 6.7 Components nodal temperature variations for the detailed ventilation system.

In order to simulate a system as close as possible to a real system, in which building, plant and flows are coupled together, the above network was coupled to the three zone building shown in Figure 6.8 and a fluid flow network was defined for the building/plant problem. This building is one of ESP-r's test cases and consists of a reception zone, an office zone and a roof space zone. Also shown are the obstructions above the south facing window and the west facing door to take into account the resulting shading effect.

Plant components 11 and 12 were removed from the plant configuration file and were replaced by the reception and office zones respectively as shown in Figure 6.9. Two networks are shown in this figure, the one at the top represents the fluid flow network and the one at the bottom is the plant network. The dashed arrows indicate which flow components are mapped to which plant inter-component connections. Note that the flow network also allows the air flows in buildings to be modelled as shown by the window component between the reception zone and the north boundary node. In this example it is assumed that no air flow occurs between the two zones. For this reason, no flow component (door) was specified. The listing of the files used for this example are included in Appendix B, example 3. The coupling of the zones with the fresh air supply duct was achieved by defining a control strategy file and using a building control function with control law 6 specified for each zone. The controller specified for the heater control loop was of the proportional type (plant control law 1) with a heating set point of 20°C and a throttling range of 2°C. The maximum and minimum heating flux

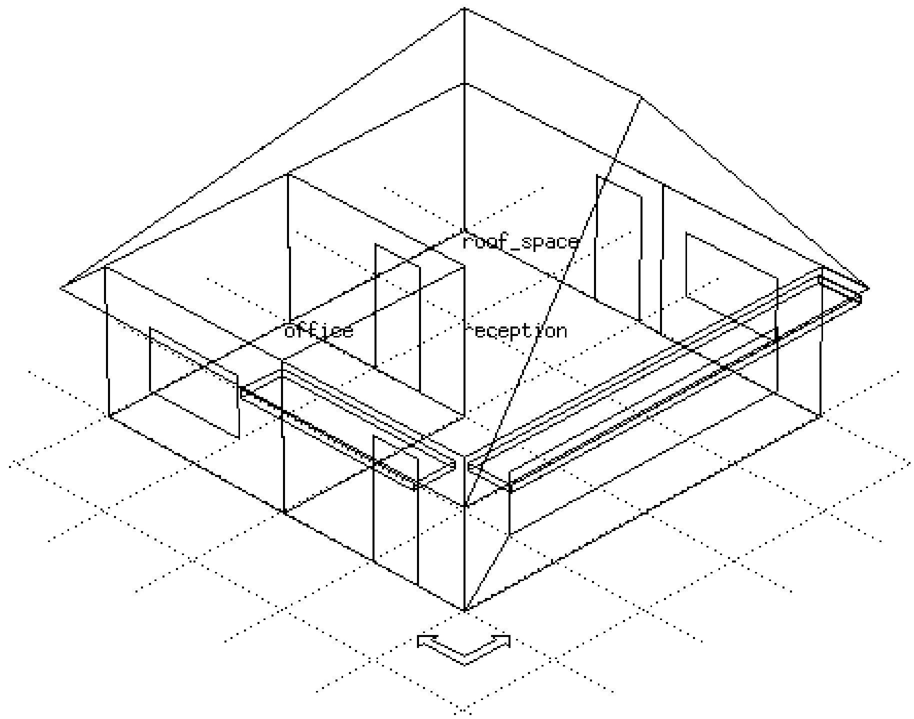
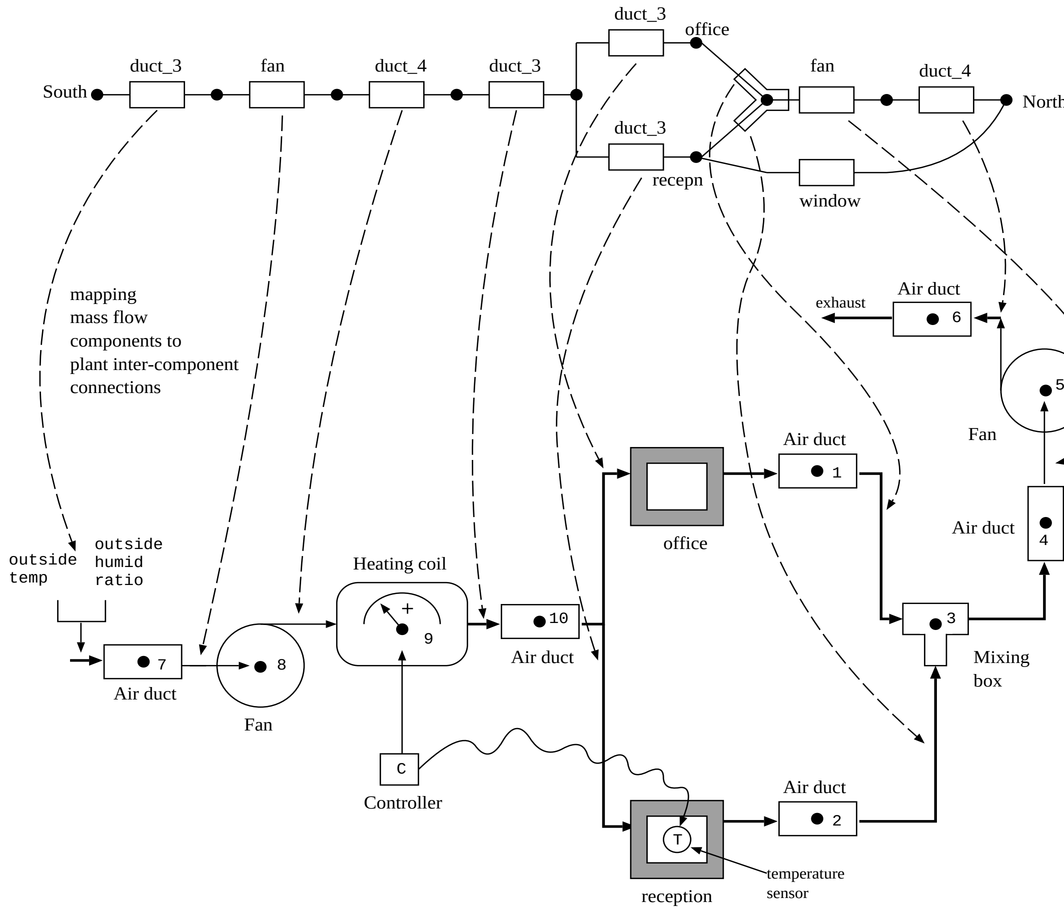


Figure 6.8 Building used in conjunction with the ventilation system.

was 4000W and 0W respectively. An ideal sensor located in the reception zone was also defined so that the heater output flux can be actuated on the basis of that temperature. Figure 6.9 shows the resulting reception zone temperature from the combined building, plant, control and flow simulation for the period from 9th February until 11th February. It can be seen that the temperature variations tend to fluctuate rapidly within the specified controlled temperature range, this is due to the fact that the sensor type used was ideal and does not have any time lag associated with its characteristics. Later, another example will be given to show how to account for sensor time lags by using a plant component.

The example presented here shows how the level of detail within a simulation may be stretched in order to account for the heat and mass transfers that occur in real systems. The mechanical inlet and extract ventilation system considered is not economical in that useful energy is wasted by the extract system. This limitation can be overcome by employing a heat recovery system in which the inlet cold air exchanges heat with the exhaust air and thus reduces the heating load demand provided by the heating coil. Figure 6.10 shows the new ventilation system layout with component 11 being introduced



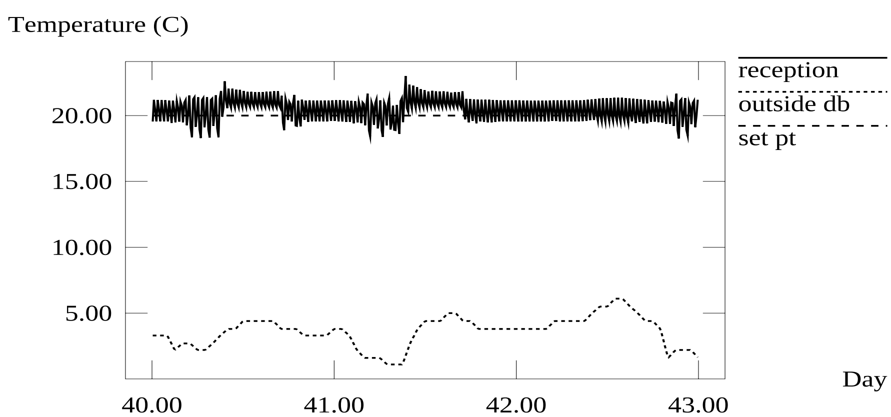


Figure 6.9 Plant and mass flow mapping with resulting air point temperature of the reception area controlled by the detailed ventilation system.

as a heat recovery unit (component type 120). This is a two node component model which expects two external connections having air as the working fluid type. The heat recovery unit has reduced the total heat supplied by the heating coil from 3435.7 *KW* to 2942 *KW*, ie a reduction of 493.7 *KW* for the simulation period considered.

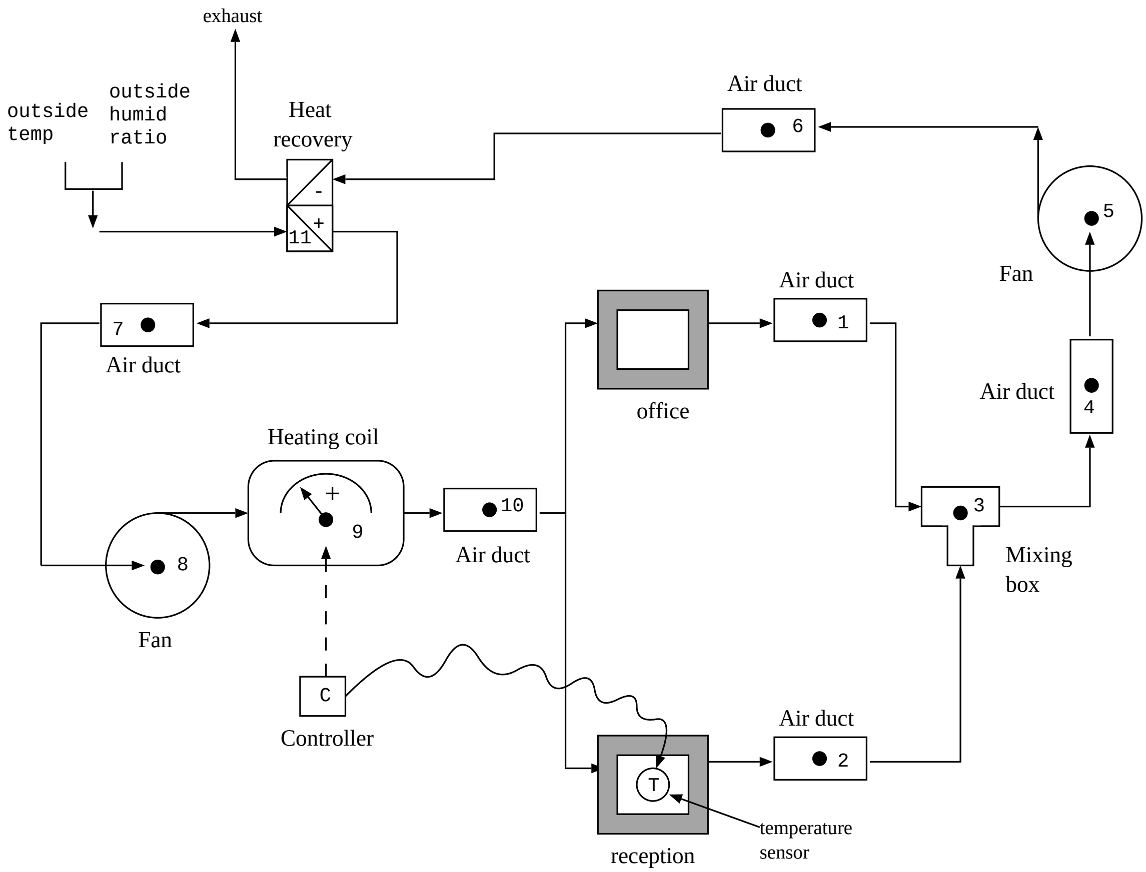


Figure 6.10 Ventilation system with heat recovery

6.3.3 Single zone air-conditioning system

This system is suitable for air-conditioning large single spaces, such as theatres, cinemas, restaurants, exhibition halls or factory spaces where no spatial sub-division exists. The general layout for such systems is as shown in Figure 6.11. As can be seen, it consists of a mixing box, an air filter, a heating coil, a cooling coil, a fan and ducting arrangement.

The heating coil is usually fed by hot water from a boiler whereas the coiling coil could be either fed by chilled water or could be directly connected to a refrigeration plant and so contain the actual refrigerant; this is known as a direct expansion (DX) system. For humidity control, this system can also be fitted with a humidifier so that the relative humidity of the space supply air can be controlled if necessary.

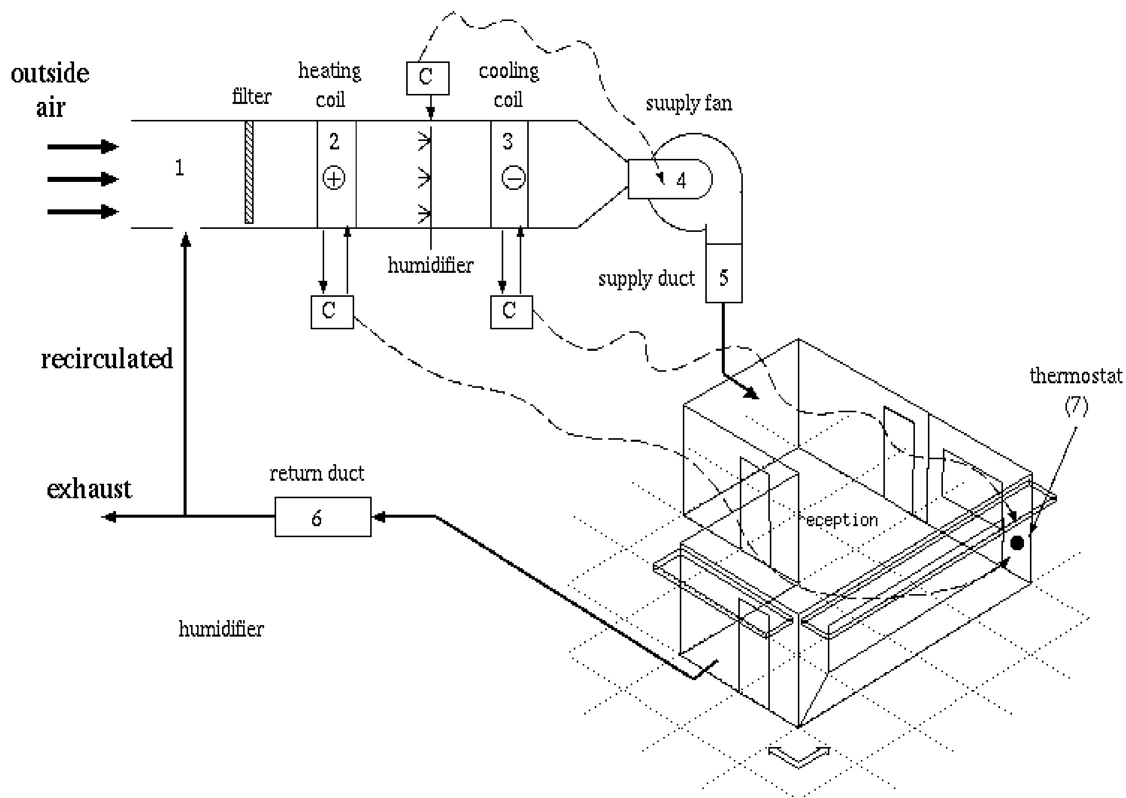


Figure 6.11 Single zone air-conditioning system layout

In order to illustrate how a building air-conditioning system can be simulated, the reception zone of the test building was coupled to the air-conditioning system and a fluid flow network defined for the combined plant/building problem. The associated configuration files for the building, plant, flow and controls are listed in Appendix B, example 4. With the fluid flow network incorporated in the simulation, it is possible to include the air filter by introducing an additional flow resistance in the fluid flow network definition file. A mechanical thermostat component (type 510) was used as a sensor to sense the zone temperature so that the time lags associated with the sensor are taken into account. The thermostat was developed to be used in conjunction with heating systems employing a boiler. This thermostat model also allows for acceleration heating to prevent any overshoot of indoor temperature. For the current example, the acceleration heating feature was disabled since only the sensor time lags are of interest here. The thermostat component was installed on the inside surface of the south facing wall and two sensors were attached to it, one is used to actuate the heating coil flux and the other to actuate the cooling coil flux. The cooling set point was chosen to be 23°C with a throttling range of 1°C while the heating set point was chosen to be 20°C with a throttling range of 1°C. An additional sensor was defined to sense the relative humidity of the air in the fan and a controller (plant control law 2) was defined to actuate the water spray flow rate between 0.02 *kg/s* and 0.003 *kg/s* for a relative humidity of 40% and 60% respectively. An alternative to this is to sense the relative humidity of the zone air if more strict humidity control is required. This was not considered here because moisture transfer from a plant component to the building zone has not yet been implemented to ESP-r.

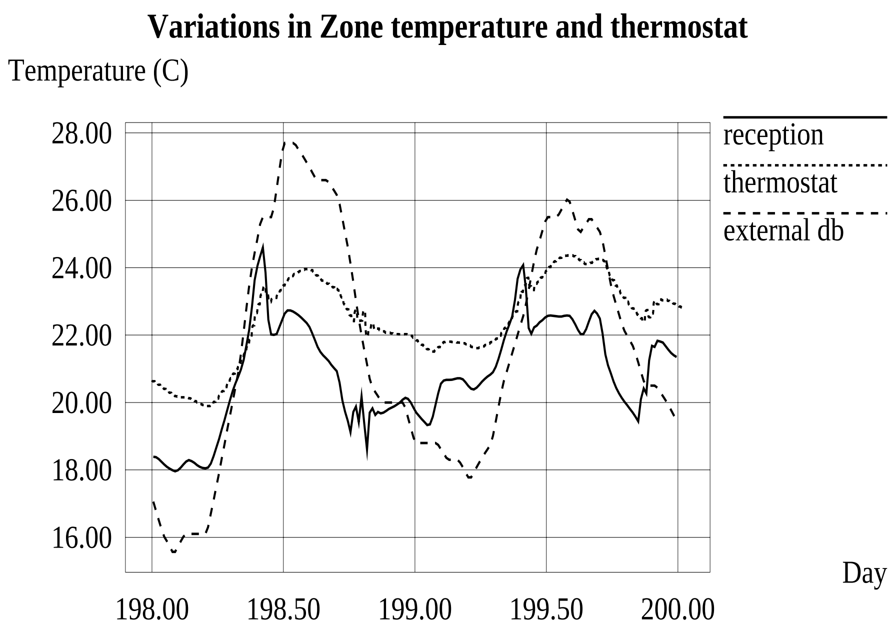


Figure 6.12 Zone air temperature influenced by sensor component characteristics.

A summer simulation was then conducted during the period from the 17th July until 18th July using an ESP-r test climate file. Figure 6.12 shows the temperature variations in the reception zone air and in the sensor component. The sensor temperature is also affected by the surface temperature on which it is mounted and by other parameters such as the convective conductance to the zone air and radiative conductance to the wall. It can be seen that because the thermostat temperature is being sensed and not the zone air, there is overshooting at the start of the day. Once the sensor temperature is within the cooling control range, the zone air temperature decreases. The sensor temperature indicates that heat is injected to the zone air at the early hours of the first day since its temperature is within the heating control band defined for the controller. However the heating load is not sufficient to increase the zone air temperature to the desired level. It can be concluded from this simulation that considering a temperature sensor as a component is important for the determination of correct heating and cooling set points when more strict temperature control is required.

One variation to this system is to modulate the fan flow rate based on the zone air temperature. This is possible to simulate because the fan volume flow rate was defined as a control variable and therefore may be actuated based on some sensed property. A control loop can be defined in the control strategy file in which the sensor of the previous example can be used to actuate the volume flow rate by a proportional controller (plant control law 2). A control function will be required to couple the building zone with the zone supply duct. Another variation to the system is to include a reheater or a recooler to heat/cool the supply air before it enters the zone. In this case the heating/cooling load is actuated on the bais of zone sensed temperature. Such systems are more suited for multi-zone buildings as will be shown in the following section.

6.3.4 Multi zone air-conditioning systems

The system discussed in the previous section can be modified to work in conjunction with multi zone buildings. The main objective of such systems is to have the air-conditioning system serve two or more zones of approximately equal size from a single plant. One extension to the basic system is to divide the supply fan outlet into the appropriate number of ducts and fitting a separate reheater to each as shown in Figure 6.13. The output of the central plant cooling coil must be arranged to meet the demand of whichever zone requires the maximum cooling. For this reason a substantial amount of reheat will be required leading to uneconomic running costs. In order to simulate this system, the reheat sections of the plant were coupled to the reception and office zones of the building shown in Figure 6.8. A control loop was defined for each reheater so that the heating coil flux could be actuated on the basis of the appropriate zone air temperature. For the central plant cooling coil, an ideal control strategy would be to incorporate a multi sensor and to actuate the cooling required by the central plant cooling coil based on the maximum sensed temperature. However, because of the time constraint of this research, the multi sensor concept was left for future work. This problem was overcome for this particular example by sensing the fan air temperature and actuating the flux for the central plant heating and cooling coils to control that temperature within cooling and heating set points of 23°C and 20°C respectively. Example 5 in Appendix B, contains the listing for the plant configuration and control strategy files.

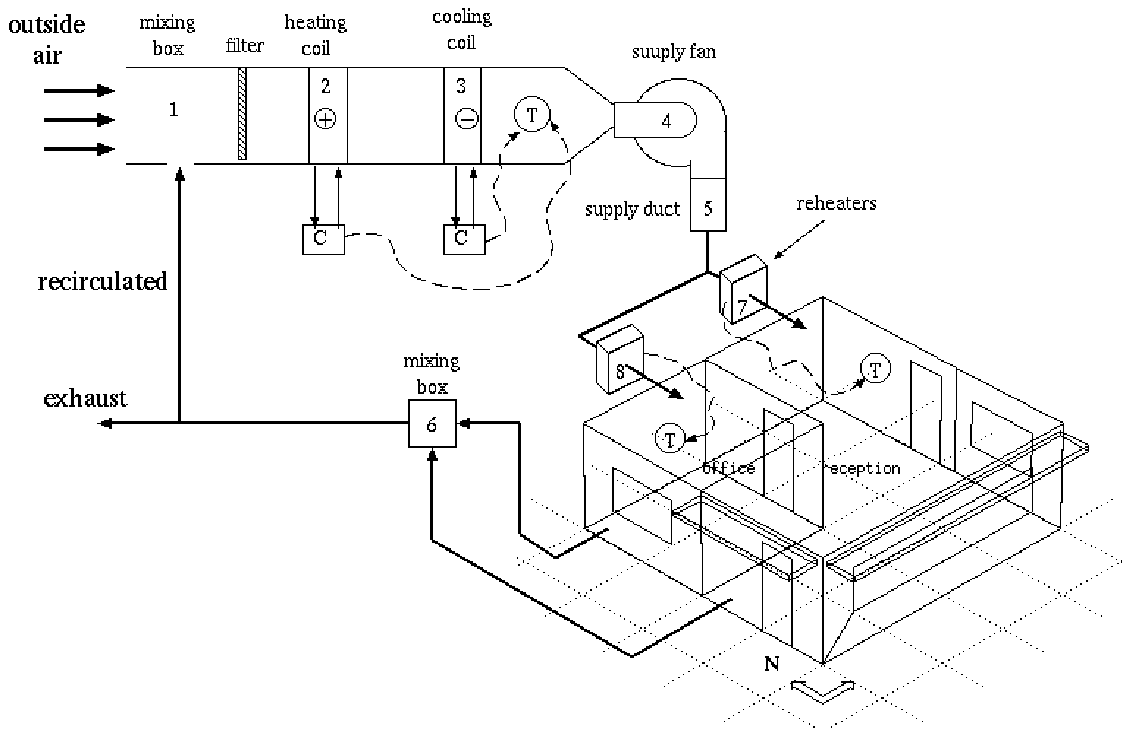
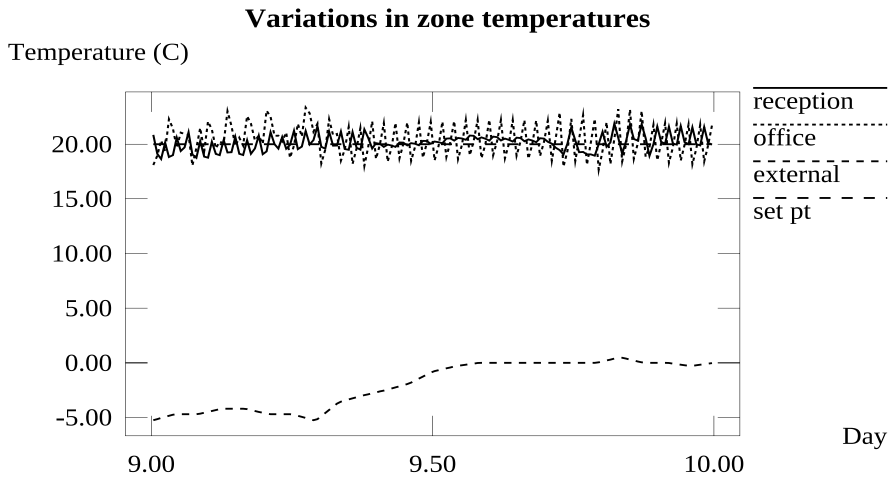


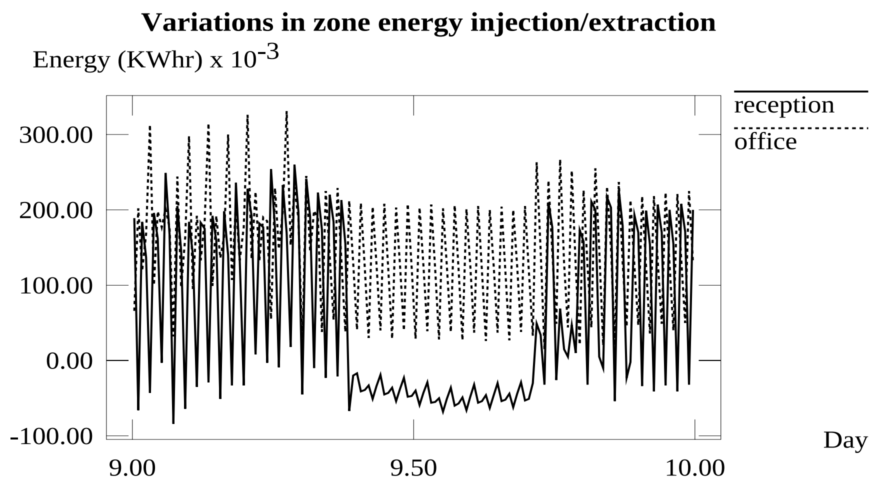
Figure 6.13 Multi zone air-conditioning system layout with reheat

A winter simulation was carried out for the combined building/plant model. Although it is possible to include a fluid flow network in the simulation, it was not considered for this example but was included in a multi-zone air conditioning system with VAV terminals as shown in the following example. The simulation period considered was for the 9th January using ESP-r test climate file. Initially, the simulation was conducted for a building time-step of 10 minutes and a plant time-step of 2 minutes. For this setup, the iterative/direct solution method for the plant did not converge because the amount of heat injected/extracted by the central plant heating/cooling coils in each iteration, to maintain the fan air temperature at the specified level, was too large for the selected time-step. The solution converged however with plant simulation time-steps in the order of seconds. It is suspected that the use of temperature sensors with no time lag characteristics are the main source for this problem. This was certainly the case in this example because the problem was alleviated when the sensor was modelled as a component inhibiting mass and time constant properties. It was found that the maximum heating energy specified for the central plant heating coil control loop was insufficient for the specified heating set point. When this parameter was increased from $3000W$ to $6000W$, the problem encountered earlier with the convergence of the plant solution occurred again. It was concluded therefore that for situations where there is heating and cooling taking place on the same working fluid, some other means should be adopted for the iterative solution. One way to overcome this problem is to process the control loops only once and then to proceed with the iteration as before. As a result, a new feature was added to ESP-r to disable iterations on the control loops if the need arises. The results for the reception and office zones air temperatures and the corresponding heat injection/extraction are shown in Figures 6.14a and 6.14b respectively. It can be concluded from the results that the reheat system is capable of responding to load requirements of individual zones when the correct heating and cooling energy for the central plant is sufficient to maintain the reheaters supply air at a desired level.

Another variant of the above system is to replace the reheaters by variable air volume terminals, known as VAV terminals. A system with variable air volume can cope with changes in local load conditions by adjustment of the volume at constant temperature. Such systems consist of a main central plant, which provides conditioned air at constant temperature and flow rate, and an appropriate number of VAV terminals to cater for the local load changes of each zone. Control of the air flow is usually achieved by means of a thermostat sensing the controlled zone air temperature and a controller acts to modify the flow rate in the VAV terminals. A plant network of this type was set up by replacing the reheaters in the previous example with air dampers and was coupled to the same zones (ie. reception and office). The input file listings are included in Appendix B, example 6. In order to allow for air flow rate control in the dampers, a fluid flow network was also set up and included two general flow corrector components (type 410). The control on the dampers allowed them to be fully open if the zones temperature falls below 19°C and 10% open if the temperature is above 24°C. This control strategy was selected for winter conditions. Figures 6.15a and 6.15b show the building zones response to the operation of the VAV system. It can be seen that each zone is catered for by the appropriate VAV terminal according to the load requirements of that zone.



(a)



(b)

Figure 6.14 Thermal response of building zones to the action of the multi-zone reheat system. (a) zones control temperatures. (b) resulting heat injection/extraction.

It is also common to have reheat included in the VAV terminal so that in addition to volume flow control there is also temperature control on the zone supply air. The advantage of incorporating the fluid flow solver in the simulation is that information regarding pressures will be available in the network for more sophisticated control if a study of economics in overall energy consumption is to be carried out.

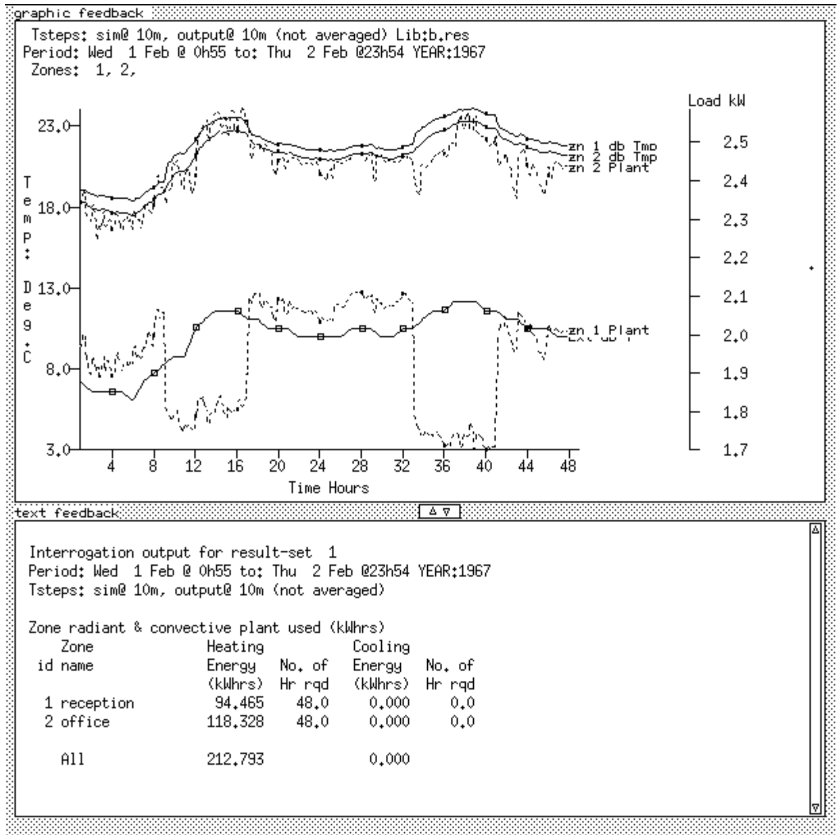


Figure 6.15 Thermal response of building zones to the action of the multi-zone VAV system.

For example, some pressure sensors can be positioned at appropriate points, at VAV terminal units say, so that a central pressure controller can reduce the volume flow rate at the central plant. This requires the use of a multi sensor controller so that the central plant volume output is actuated on the basis of the feedback from all pressure sensors. This entails the addition of new sensors in the fluid flow network which is beyond the scope of the present study.

6.3.5 Dual duct air-conditioning system

The multi-zone systems previously described are arranged to mix, at the central plant, supplies of hot and cold air in such proportions as to meet load variations in building zones. In the dual-duct system, the mixing is transferred from the central plant to either individual rooms or small groups of rooms having similar characteristics with respect to load variations. The system makes use of two ducts, one conveying warm air and the other conveying cold air. A mixing box at each room contains air dampers so that cool, warm or a mixture of both can be delivered into the room. A typical dual-duct system is shown in Figure 6.16 providing conditioned air to two zones. The air dampers at the mixing boxes are controlled such that a constant quantity of air is supplied to each room and at the desired temperature. The application of this system is demonstrated in detail in the case study example of Section 6.4.

6.3.6 Simulation of solar systems

In order to demonstrate the fitness of dynamic simulation for multi-domain problems such as solar systems (Hand et al. 1993), a building which includes several active and passive solar design strategies was considered as shown in Figure 6.17 A model was created for the building, plant, flows and controls. As can be seen, the building was divided into four distinct regions in order to cater for the different schemes implemented in this example. The first scheme "a direct gain room" uses direct solar gain as much as possible with an oil filled electric radiator as a backup heating source. The middle two zones, *rad_test* and *heatexch*, were used for the next two schemes and were heated via a solar sourced wet central heating system, while for the last scheme, the zone "air collector room" was heated by an air solar collector.

The wet central heating system is composed of a $10m^2$ liquid solar collector feeding a nominal 1kW radiator in *rad_test*, a fan-coil unit in *heatexch*, a variable speed pump (sensing collector temperature) and then back to the collector. Input files listing are included in Appendix B, example 7.

Since the passive solar design element is introduced in this example, the temporal interaction with the sun is of interest, particularly in the direct gain room. By using a facility which allows the viewing of the building model from the sun's position at different times of the day, it was decided that an hour by hour shading and internal insolation distribution analysis was required in all south facing rooms and that subdivision of the floor and partitions is justified in the direct gain room. Since there was no measured data available for infiltration, an air flow network should be introduced to allow the calculation of infiltration based on some realistic values specified for cracks at the windows and soffit vents in the roof. To take into account grills in the doors between zones, inter-zone flow-paths were also introduced. Because there is no air conditioning in the model it was specified that occupants would choose to open windows if the room temperature rises above 23°C. This was achieved by representing a window as a common orifice flow component with a built-in, on/off controller to define a window opening scheme. In addition to the window opening strategy, the zones *heatexch* and *mixed_test* also

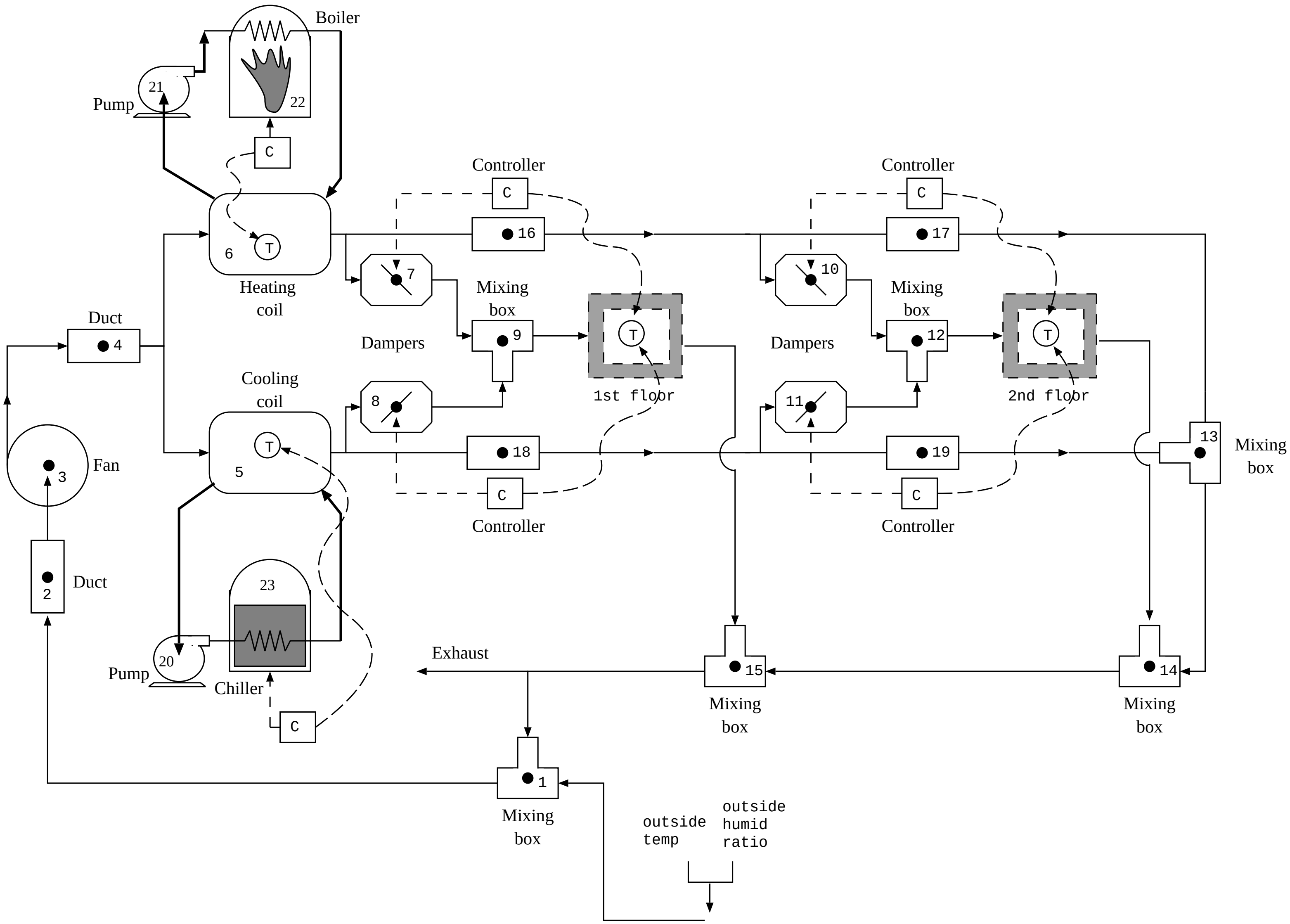


Figure 6.16 A dual duct system coupled to building zones.

have an extract fan which switches on if the room temperature rises above 22°C. 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 option to describe the fan as a flow inducer with a pressure flow curve or approximate it as a volume flow component (for initial sizing).

Two variants of the air solar collector are represented in this example. In the first case, an explicit representation is assumed in which all of the internal and external shortwave and longwave radiation and thermal mass is modelled. The temperature gradient in the collector is accounted for by using three contiguous zones. To operate the collector three nodes have been established within a fluid flow network, linked, along with a fan, to the air node of *mixed_test*. while this level of resolution will provide a reasonable indication of how such a system will perform, higher resolution can be achieved by further subdivision of the collector.

In the second case, a single node plant model, based on the flat plate solar collector algorithm described in the TRNSYS manual (TRNSYS, 1983), was used. 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 the nodal temperature which represents the average component state. 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 connection. An eight node model is also available but since this example is focused on the thermal interaction between plant and building zones, rather than on the accuracy of the individual models, 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 700 W. While an ideal control could have been used, the choice of a plant component means that the time lags associated with the heater are accounted for in full. 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 0.055 kg/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 0.06 m^3/s when the air temperature in the heating coil exceeds 18°C. The period selected for the simulation is from 25th April until 26th April with boundary conditions from the 1967 ESP-r test climate file. The building time-step selected was 15 minutes while the time-step for the plant was taken as 3 minutes.

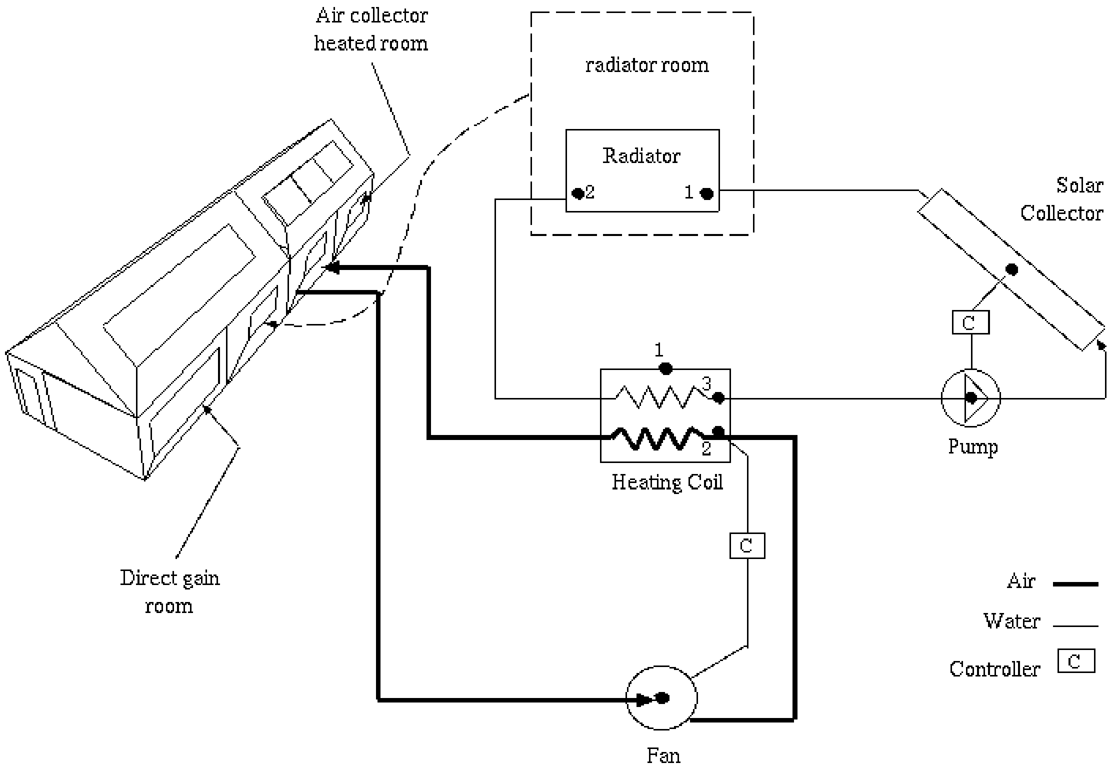


Figure 6.17 Building an plant details for solar model

Figure 6.18 shows the variation of the solar system 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 rejected to *rad_test* during the day, and through the heating coil in *heatexch* where more heat is rejected to the incoming air.

Figure 6.19 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.

Figure 6.20 shows zone temperatures which are directly affected by the solar system performance. The first day of the simulation is cloudy and no heat addition to the zones takes place apart from the zone fitted with the electric oil-filled radiator. Because of the higher collector water temperature during the second day, more heating takes place to bring the zone temperatures to a

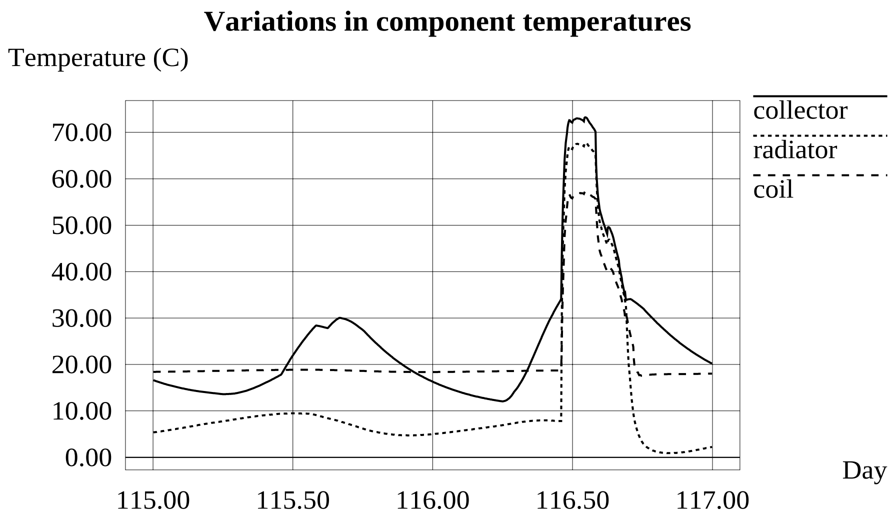


Figure 6.18 Variation of component temperatures.

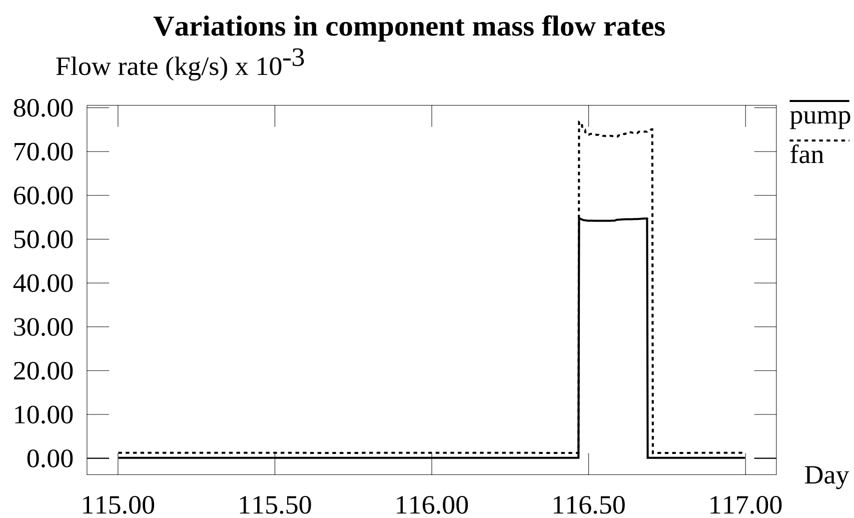


Figure 6.19 Variation of component flows.

maximum of 27°C for the zone served by the heating coil. The zone fitted with the electric oil-filled radiator is maintained at the desired temperature during the two day simulation indicating that the radiator power is sufficient.

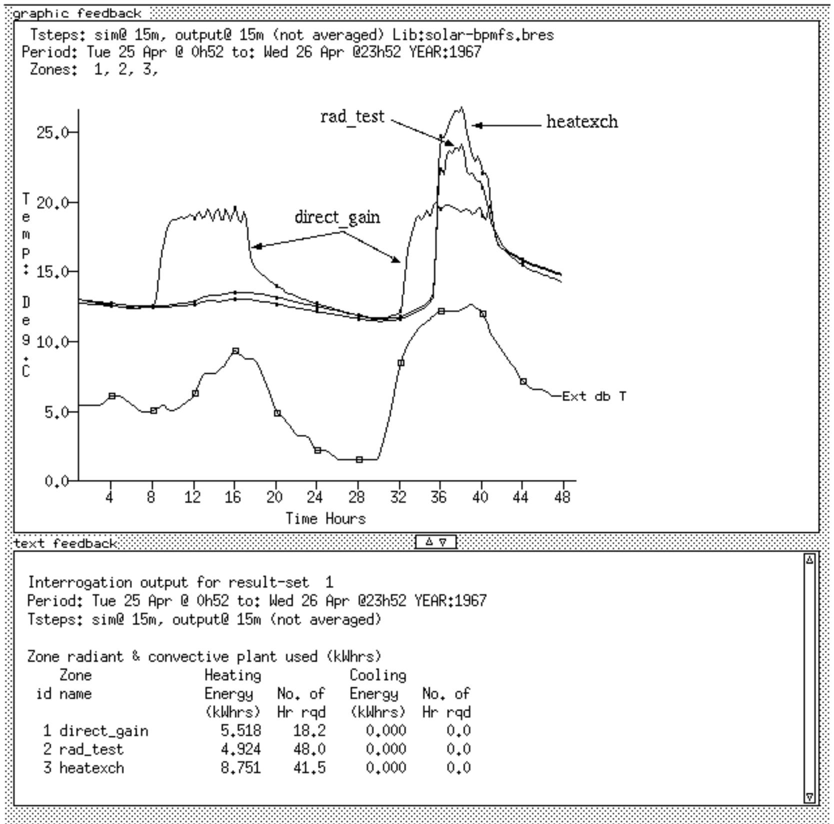


Figure 6.20 Room temperatures.

The fluid flow network defined for this problem did not account for flows in the plant network. The plant system considered for this example contains two networks with two different working fluid types (eg. air and water). The fluid flow network does allow for such decoupled systems to be defined in case where detailed flow simulation is required for all fluid types. Obviously, manufacturer's data should be available in order to specify realistic values for some flow components, such as the coefficients used to evaluate pressure drops across heat exchangers, solar collectors and ducts. However, arbitrary data was selected in order to demonstrate how a flow simulation can be conducted for such a plant system. For the water circuit, power law flow components (type 15) were specified to represent flows inside the heating coil and radiator. The solar collector was represented by a flow conduit mass flow component (type 210) with a length of 10 metres. A fixed flow rates component (type 460) was specified to represent the pump because it allows for different flow rates to be specified based on a sensed property, solar collector temperature in this case.

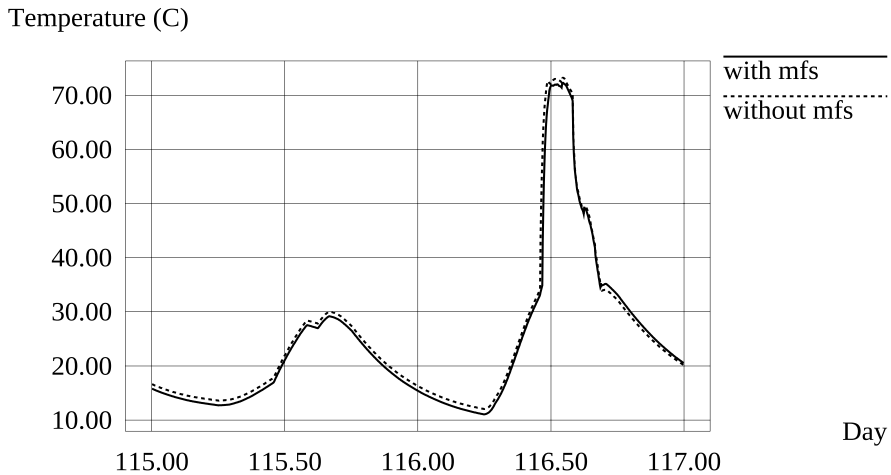


Figure 6.21 Solar system response with the mass flow solver active.

Note that since the fluid flow network controls the flow rates in the water circuit, no control loop was specified for the pump in the control strategy file. These fluid flow components together with their associated data were added to the same fluid flow network definition file specified for the whole building. In this way the mapping between the building zones and the flow network is by referencing air nodes to appropriate zones, whereas for the plant, mapping is achieved by referencing fluid flow connections to the plant component's inter-nodal connections. Another fluid flow network was established for the fan and heating coil. A fixed flow rate component (type 460) was also specified for the fan in order to control the air flow to the zone when the air temperature in the coil exceeds 20°C. The air flow inside the heating coil was modelled using a power law flow component (type 15). The flow network for the fan and the air-side of the heating coil was coupled to node "exch" in the heating coil room. The resulting difference between the initial plant model and the new model incorporating the fluid flow network is shown in Figure 6.21 in terms of collector temperatures. It is clear that the addition of explicit fluid flow simulation influences the system's performance because the fluid flow rates in the network are calculated as a function of the pressure drops. The effect of this is reflected in a lower collector temperatures. For the case when the fluid flow network is incorporated in the simulation, the zone temperature patterns are similar to that shown in Figure 6.20.

If the thermal performance of the solar system considered was to be improved, then one way to achieve this would be to improve the response of the collector so that more solar radiation can be converted to useful heat energy. This can be achieved through the application of the sun tracking mechanism built into the collector model. Sun tracking can be implemented using a fixed collector slope angle or it can be implemented using a slope angle which gives the maximum solar radiation intensity on the collector. The effect of the sun tracking mechanism with a fixed collector slope is shown in Figure 6.22. It is obvious that for the second day, more heat is injected to the zones served by the solar system.

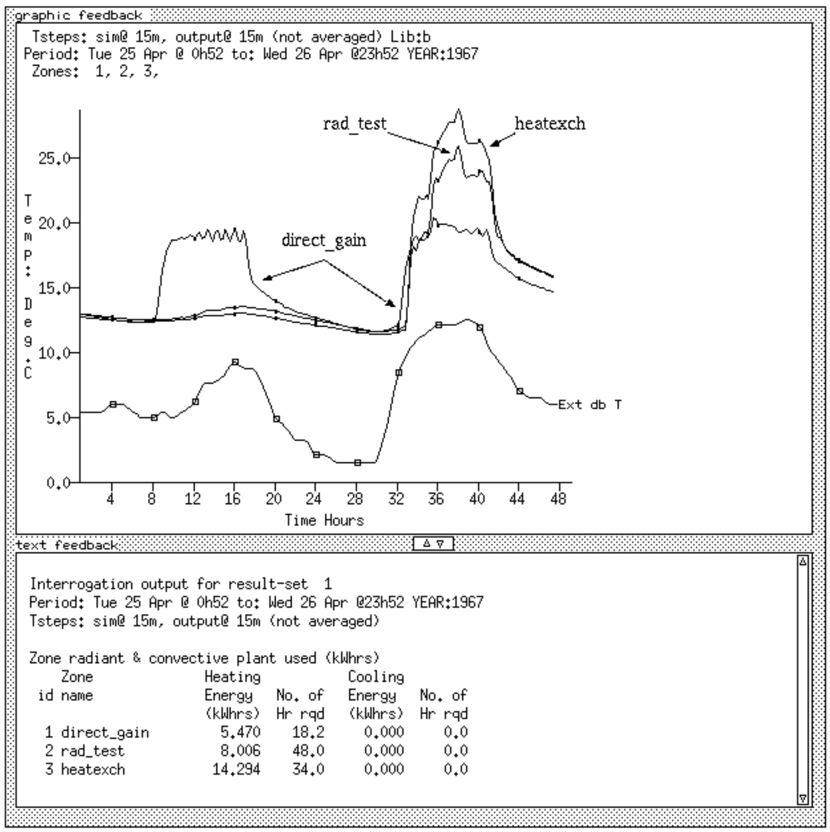


Figure 6.22 Improving system thermal response with the sun tracking facility

This example illustrated the flexibility and capability of the ESP-r system in extending the building, plant and flows model to account for their mutual interaction. The ability to encapsulate algorithmic models, such as the TRNSYS solar collector model, inside ESP-r’s equation type models, means that more existing models can be utilised within an overall, integrative framework in which all aspects of the building energy sub-system are processed in tandem.

6.4 Case studies

In the following sections, the use of ESP-r in a building performance evaluation context is demonstrated to show the system's suitability to real world applications. Two case studies, which were conducted as part of a consultancy project, are presented. In the first case, a problem with coupled air flow and heat transfer in a building incorporating heating plant is considered. The objective is to assess the environmental condition within hospital spaces, such as dayrooms and conservatories, in which substantial solar gain can be expected. In the second case, a new-building project is considered which contain a large atria requiring simultaneous building and plant simulation.

6.4.1 Thermal analysis of hospital spaces

As reported elsewhere (Hand and Aasem 1990), an environmental assessment of the Invernairn Ward dayroom of Erskine Hospital in Scotland was carried out. As shown in Figure 6.23, the problem consists of a dining room area and a dayroom. The dayroom consists of windows with large glazing area which give rise to high temperatures during summer. The occupants of the dayroom are elderly patients who are not always capable of judging thermal stress and so would be unlikely to leave the dayroom when overheating occurs or take corrective action by, for example, opening a window. The objective of this study was to advise on possible modifications to the hospital ward in order to better control its radiation and temperature environment.

A base case test was conducted for a typical Glasgow summer weather pattern for the period of Wednesday July 7 to Thursday 8 July. In this test it was assumed that all the blinds are open in the dayroom and that a fixed infiltration rate of one air change per hour prevails. Shading analysis was performed in order to take into account any obstructions and overhangs. The resulting temperatures are shown in Figure 6.24. As can be seen, the thermal stresses in the dayroom are significant. In reality, it is unlikely that fixed infiltration will occur since this will depend on many factors such as the magnitude of open windows, cracks, vents and so on and changes in pressures and temperatures across the building envelope. For this reason, an air flow network was set up in which the dayroom was represented by nodes on two vertical levels to account for temperature stratification, and other air nodes were added to represent wind induced pressures on the various facades. The air flow network nodes were then

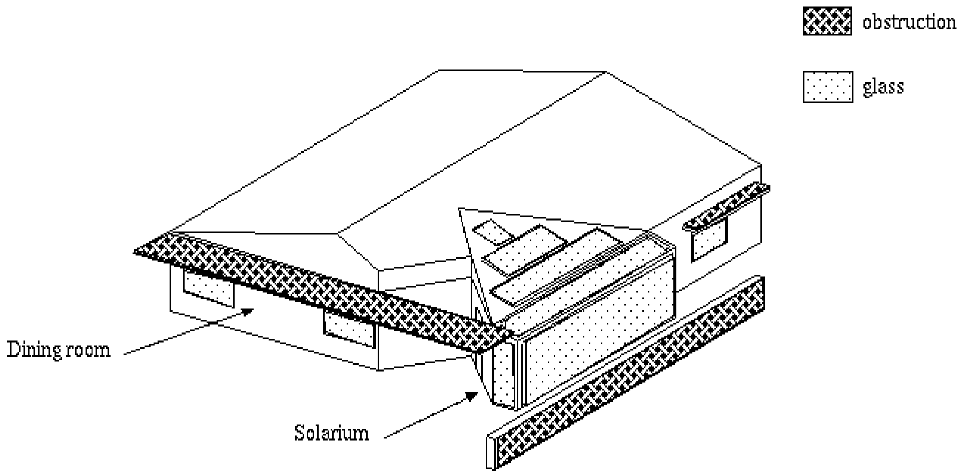


Figure 6.23 General layout of Erskine hospital Invernairn Ward.

connected by flow components to represent cracks, windows and doors. Initially, it was assumed that windows in the dayroom would remain open at all times. However, the effect of opening and closing of windows in the dining room was subsequently considered by the addition of components to represent flow control (eg type 450 frictionless fluid flow component). The control action taken was to open a window when the adjacent indoor air node temperature exceeded 20°C. This was applied to the dining room. An extract fan component was also defined and was set to be thermostatically controlled so that air is extracted from the dayroom upper point (hottest level) if the upper level temperature exceeds 25°C and exhausts the hot air through the west wall.

A plant was also set up (Appendix B, example 8) to represent the heating system which is expected to be operating when room temperatures are below the desired heating set point temperature of 21°C. The drop in temperature below the heating set point occurs because it was assumed that dayroom windows are open all the time and thus ambient air free cooling takes place. The plant consisted of oil filled electric radiators located at the appropriate zones. Each zone has a radiator with a heating capacity sufficient to bring the zone temperature to the heating set point, for example the dayroom was fitted with a 3000 *W* electric radiator whereas the dining room was fitted with a 5000 *W* unit. Note that these capacities were arrived at by conducting an initial simulation using an ideal controller instead of the plant. The heating output was split into 40% convective and 60% radiative. It should be noted that the building, plant and fluid flow arrangement was arrived at after a number of runs using different control

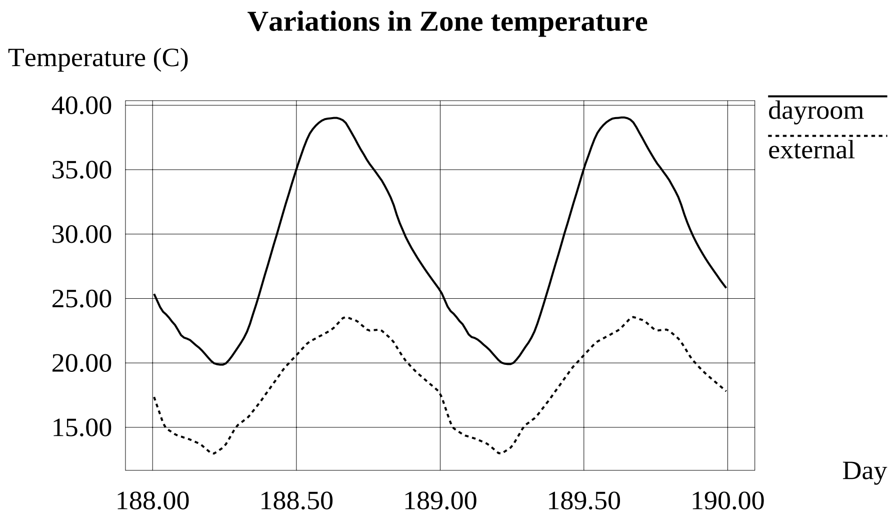


Figure 6.24 Base case with no blinds and 1 ACPH

schemes. The results for the predicted room temperature is shown in Figure 6.25.

From Figure 6.25 it can be seen that the dayroom temperature is lower than the dining room temperature when there is no solar radiation. The temperature increases during the day to a level slightly higher than the dining room temperature. Heating takes place when the dayroom and dining room temperatures fall below 21C°. A drop in the dayroom upper level temperature occurs in mid-morning because that is when the extraction fan is activated by the thermostatic controller. With this building, plant and flows arrangement it was possible to decrease the dayroom temperature with respect to the base case. It is possible also to reduce the amount of heating required by the heating system if control is also imposed on the dayroom windows so that they remain closed if the dayroom temperature falls below a certain level. To achieve this, an additional flow component was considered to represent flow control (eg type 450 frictionless fluid flow component) so that the window is closed if the dayroom temperature falls below 20°C. The predicted temperatures are shown in Figure 6.26.

The total heating required in the case where the dayroom windows are left open was 102.2 KWhrs compared to 39.5 KWhrs for the window control case. It can be concluded from this case that the detailed analysis and rigorous simulation carried out was only possible because of the ability of the ESP-r system to handle multi-domain problems using a simultaneous approach.

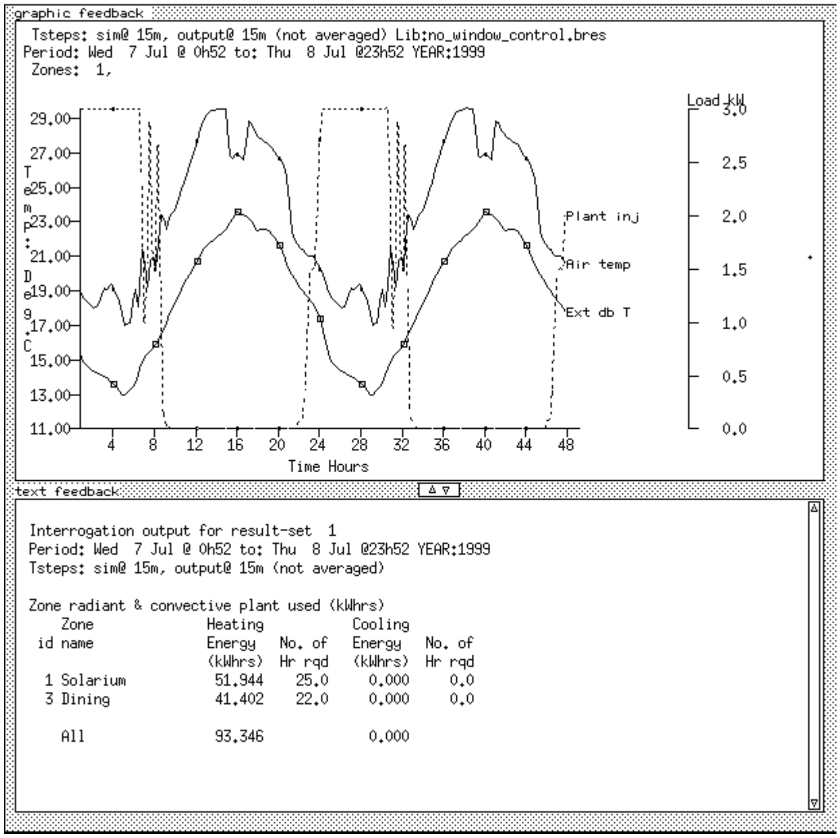


Figure 6.25 Predicted dayroom air temperature with plant and mass flow network with no control on dayroom windows.

6.4.2 Environmental assessment of large buildings with atrium

This case study was reported by Hand and Aasem (1990) and involved an environmental analysis of a new large office building for the Royal Bank of Scotland prior to its construction. The building consisted of a south section, a middle section and a north section. Each section comprised a number of offices surrounding a central atrium. In this study a comprehensive environmental assessment was carried out on the thermal comfort of persons located at the base of the atrium and on the air flow movement within the atrium for winter and summer weather patterns. For this reason two models with different geometric complexity were constructed to represent each section in turn. In the first model, the atrium was considered as a simple ’box’ shape to allow for a mean radiant temperature analysis based on surfaces view factors. In the second model, a more detailed description was created in which the atrium was constructed from a number of sub-zones to allow for a detailed modelling of air flow movement within the atrium, for example for the south section as shown in Figure 6.27 which

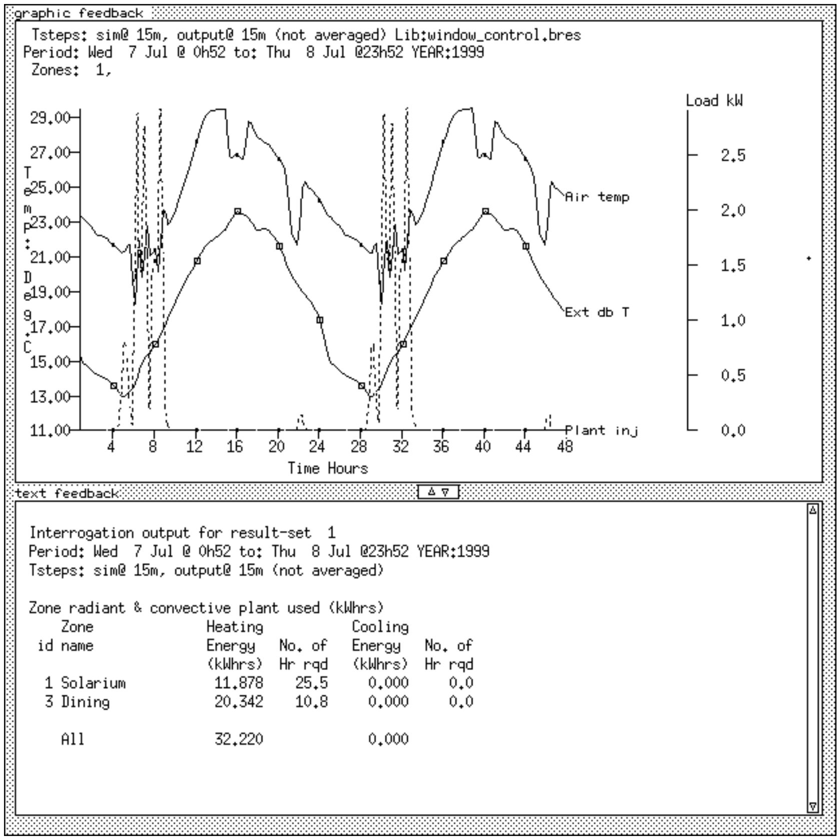


Figure 6.26 Predicted dayroom air temperature with plant and mass flow network and control on dayroom windows.

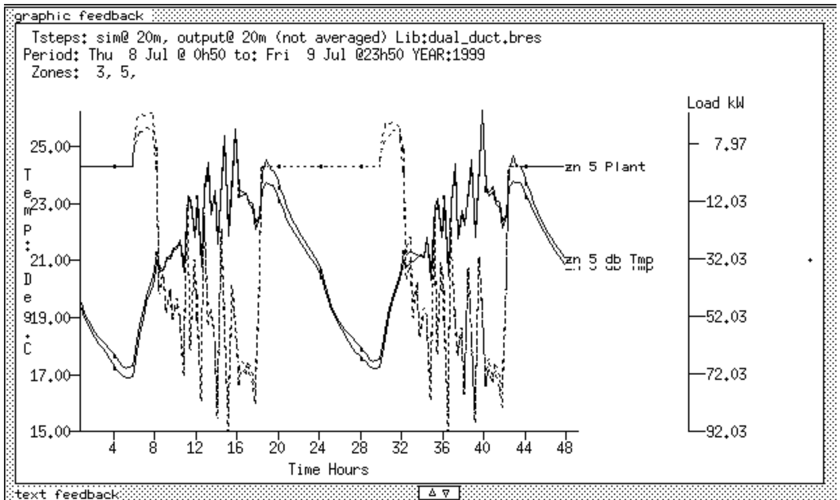
comprised a total number of twelve zones.

When the work was carried out on this project, temperature control of the zones air was achieved using an ideal controller installed in the appropriate zones. The ideal controller maintained the air temperature within a specified minimum and maximum of 21°C and 22°C respectively. In the real world, ideal control is difficult to achieve (if not impossible) because of the continuously changing boundary conditions and the dynamic effects of the building, flows, plant and controls. To further investigate these effects on the overall performance of this building, the dual duct plant network shown in Figure 6.16 (input files listing in Appendix B, example 9), was coupled to two zones of the south section. These zones were the first and second floors of the building (ie. zones 3 and 5 respectively). The dual duct system is suitable in this case because it can be used for both winter and summer conditions. The temperature of each zone can be controlled by actuating the cold and warm damper positions so that the correct cold and warm air quantities can be mixed in the mixing box and delivered at a constant flow rate. In this way each zone temperature can be controlled separately. The ratio of the cold damper (serving the first floor) mass flow rate to that leaving the cooling coil was assumed to be 0.4 whereas the ratio of the mass flow rate through the cold duct (component 18) to that of the cooling coil was taken as 0.6. This means that when the damper is fully open, only 40% of the air flow leaving the cooling coil is allowed through the damper. The same applies to the warm damper and the heating coil. As for the dampers serving the second floor (zone 5), the ratio of the damper mass flow to that leaving the warm/cold duct was chosen such that when the zone 3 cold damper was fully open, the same flow rate will be delivered to the second floor cold damper. This resulted in a ratio of 0.667.

Because of the large space volume of these zones (4039 m^3 for zone 3 and 3511.3 m^3 for zone 5), the volume flow rate supplied by the fan was chosen to be 80 m^3/s. The control period was set to be from 6 hours in the morning until 18 hours in the evening. The upper and lower limit for the sensed temperature was 22°C and 21°C respectively. The maximum and minimum damper position values corresponding to the upper and lower sensed values were 1 (fully open) and 0.05 for the cold dampers and 0.05 and 1 for the warm dampers. Air temperature sensors were defined for the heating coil and the cooling coil. These sensors were used to actuate the heating and cooling fluxes for the boiler and the chiller respectively so that the air temperature in the cooling coil is controlled at 10°C and the air temperature in the heating coil is controlled at 30°C. To achieve this type of control, plant control law 1 was used in proportional control mode with a throttling range for the controlled temperature set to 2°C for both coils. The control on the dampers was achieved using plant control law 5 which was defined for each damper so that their mass diversion ratios are actuated based on proportional control.

The resulting zone temperatures and energy injections/extractions for a summer simulation is shown in Figure 6.28. The weather conditions assumed were based on synthetic Glasgow weather patterns. The simulation results were obtained from a two day run from the 8th until the 9th of July using 20 minutes time-step for the building and 2 minute time-step for the plant. As can be seen, large fluctuations in the zone air temperatures result from the control action on the dampers. At the start of the control period, heat is injected to the zone air to bring the air temperature up to the required level. During the day when the dry bulb temperature and the solar radiation are high, energy is extracted from the zones using the maximum capacity of the coil. It is obvious that a cooling coil with a larger cooling capacity is required to bring the temperature down to the desired level. In order to obtain more reliable results, smaller time-steps should be used for the building and the plant, however, it is not possible to

Figure 6.27 South section of office block.



text feedback

Interrogation output for result-set 1
Period: Thu 8 Jul @ 0h50 to: Fri 9 Jul @23h50 YEAR:1999
Tsteps: sim@ 20m, output@ 20m (not averaged)

Zone radiant & convective plant used (kWhrs)

Zone id	Zone name	Heating Energy (kWhrs)	Heating No. of Hr rqd	Cooling Energy (kWhrs)	Cooling No. of Hr rqd
3	Zone-3	66.149	4.7	-1101.830	20.0
5	Zone-5	45.050	4.0	-1092.998	20.7
	All	111.199		-2194.828	

Figure 6.28 Predicted air temperatures and energy injection/extraction for the controlled zones.

predict a suitable time-step value before commencing the simulation. It is instead possible to invoke a time-step controller to reduce the simulation time-step based on some user specified tolerance value for the zone temperature and energy injection/extraction. For this, building time-step controller type 2 was defined to be active through the whole simulation period with a tolerance value of 0.5°C for the zone air temperature and 100 W for the zone energy injection/extraction were specified. The maximum number of iterations allowed for the time-step reduction was specified to be 4.

The results of Figure 6.29 indicate that the time-step controller was able to reduce the fluctuations in temperature resulting in better control of zone air temperature. The penalty from use of a time-step controller is the increase in simulation time because of its iterative, time-step reduction mechanism. For example, the simulation time when the time-step controller was active using a SUN SPARC 1+ workstation was 42 minutes which is an increase of 35 minutes on the simulation time without the time-step controller.

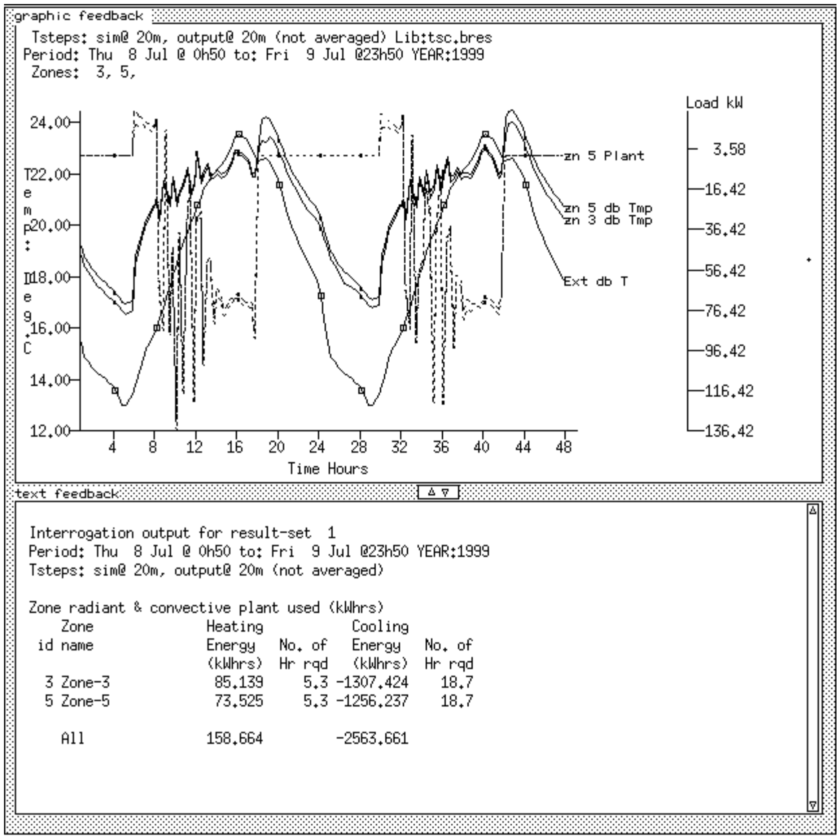
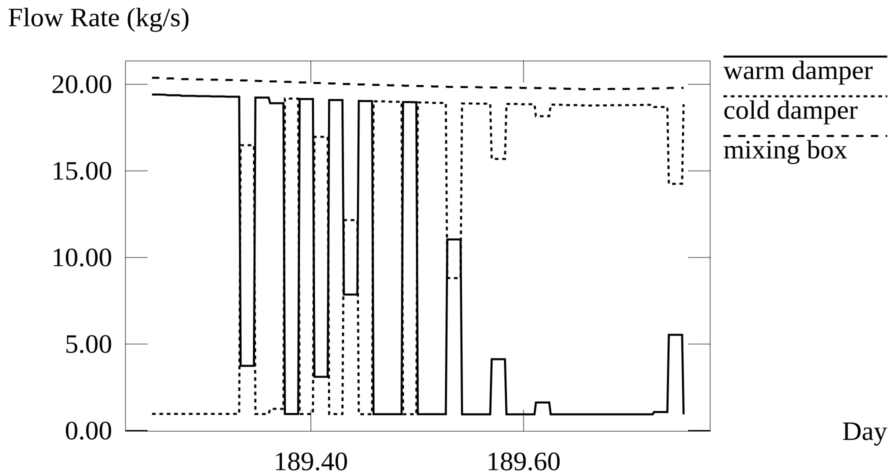
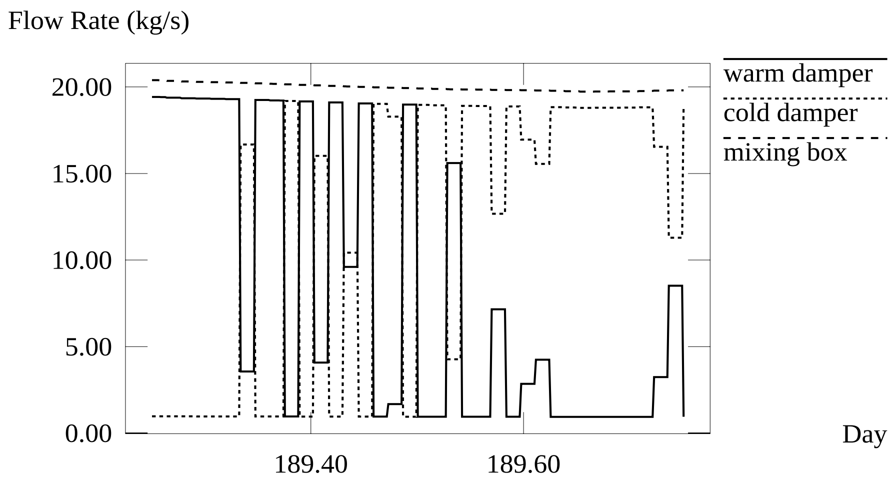


Figure 6.29 Predicted air temperatures and energy injection/extraction for
the controlled zones with time-step controller active.

With respect to the mass flow rates delivered by the zone mixing boxes (ie. components 9 and 12), the flow rates during the control period for the 8th of July through the dampers and the mixing boxes are shown in Figures 6.30a and 6.30b for the first and second floors respectively. It can be seen that the flow rates through both the first floor and second floor mixing boxes are almost constant because the dampers have the same temperature control range and the flow rates from the heating and the cooling coils are assumed to be constant. Note that the mass flow pattern through the cold and warm dampers serving the first floor are not identical to those serving the second floor. This indicates that the dual duct system function was achieved in that it can respond to each zone's load requirement by continuously modifying the damper positions for correct mixing of the warm and cold air. Figure 6.31 shows a comparison between energy injection/extraction for the case where an ideal controller is used and for the case where the dual duct system was coupled to the building. It can be seen that when an ideal controller is used, no account is taken of the plant characteristics. The decision between choosing



(a)



(b)

Figure 6.30 Predicted mass flow rates through dampers and mixing boxes of first floor (a) and second floor (b) zones.

such an ideal controller and an actual plant system to perform the control function depends on many factors. If the plant performance, in terms of energy consumption, is not important then an ideal controller may prove adequate. For this example, the sensitive nature of the air dampers make the ideal control choice unsuitable. In situations, where a plant system is not so sensitive, such as the case when using electric radiators, the choice for an ideal control may be more suitable.

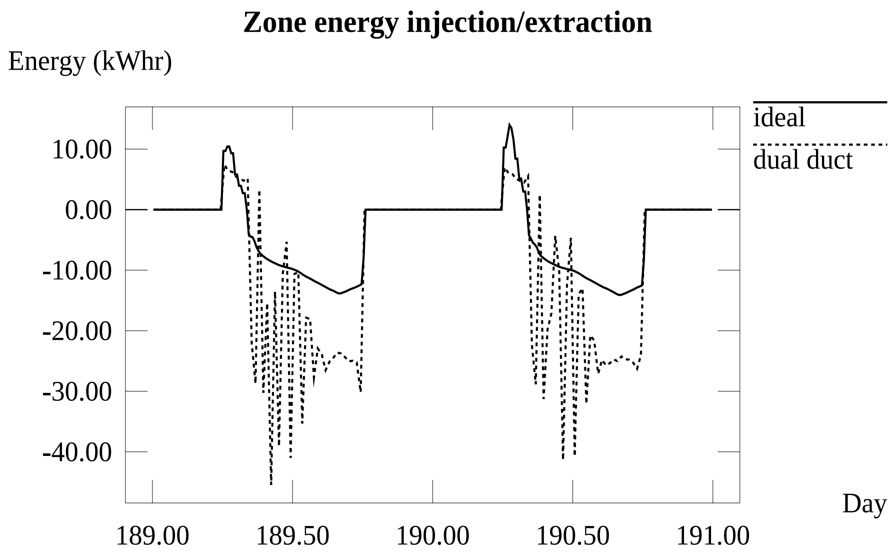


Figure 6.31 Zone energy injection/extraction comparison between ideal controller and control by the dual duct system on the first floor.

As a result of the complexity of this exercise, a utility program was developed to help in the generation of a connectivity list for inter-connected building surfaces. The procedure adopted in generating such a list was to consider a surface in a zone and to then scan all other surfaces in all zones in order to locate a connection when two surfaces have matching vertices. This tool was found to be useful especially when working with multi-zone problems because it saves a great deal of time and effort and most importantly reduces the input errors. In addition, it will also allow for more complex buildings to be modelled. Another feature which was added to the plant configuration files, is the ability to designate meaningful names for the plant components used in a network instead of referring to a component by a number. This was found to be useful in large, complex plant networks, such as the dual duct system considered in this example.

The case study has shown how far a simulation can be extended in order to account for variations in flows, building, plant and control dynamics in an interacting environment. As a result of the enhancements and developments carried out, the plant simulation capabilities have increased substantially. Further enhancements to the dual duct system considered is to add a fluid flow network so that the dampers and flows resulting can be modelled more accurately and to make use of static pressure sensors to modify the fan flow rate if economical operation of the system was to be investigated.

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CHAPTER 7
Future Trends in Building Energy Modelling

This chapter addresses current research issues related to building energy modelling. These issues although strongly related, are targeted on different objectives. For instance, in a neutral model format approach in the context of plant simulation, the main objective is to eliminate the problem concerned with a comprehensive library of component models; the objective of a modular approach to model construction is to permit the rapid prototyping of any programme architecture to facilitate a coherent approach to development, validation and maintenance; the objective of a knowledge based approach to simulation is to provide an intelligent user interface to assist designers in the problem description phase, recognise their performance appraisal wishes, commission computer simulations and report back on performance. The following sections discuss each issue in turn.

7.1 Neutral components.

In order to overcome many of the obstacles encountered in systems modelling (such as lack of component models, availability of manufacturer's data and model validation), a neutral component model can be described in which the equations describing the model are defined together with the parameters attached to it in a standard format. These neutral models could then be accessed by most common energy simulation environments. Sahlin (et al 1992a) have worked out the specifications of a neutral model format NMF. The basic objective of the NMF is to provide a common format of model expression for a number of existing and emerging simulation environments such as ESP-r, TRNSYS, HVACSIM+, CLIM2000, SPARK, IDA and ZOOM. Another objective is to provide a natural form of model expression, i.e. a form which makes it easy and fast to express new models for any environment and appeals to engineers as well as to well trained simulation experts. The main advantages of the approach are threefold:

- The usefulness of an energy simulation environment may be enhanced by the existence of a common single model libraries.
- Users of different simulation environments are encouraged to communicate more frequently resulting in better model quality and usage.

- Repeated environment comparisons will occur as a result of enhanced model and user mobility providing more accurate information about environment performance simulation.

A number of the energy simulation environments mentioned above make use of developer-defined mathematical models of components that are expressed in separate modules which a user can interconnect to define the system model. Such component models are usually defined with an input-output relationship which the modeller defines when the model type is written. The pre-selection of given variables leads in some cases to limitations in the actual use of the models. Frequently a system modeller, using available types, would like to connect the inputs of one component with the inputs of another and similarly for the outputs. This, of course, is impossible and one of the component models has to be rewritten, with a different input-output selection. The system modeller is forced to become a component modeller and write, debug and compile code. These difficulties are overcome in some of the more recently proposed environments (e.g SPARK and IDA) by leaving the input- output designation to the environment which will substantially increase the versatility of each component model.

In general a system's behaviour is determined from a set of variables which carry information between individual components. For example in an HVAC system such variables may be enthalpy, dry air mass flow rate and vapour mass flow rate. In other system the variables might be pressure and fluid flow rate. In a NMF environment, these set of variables are defined globally and the modeller can then make use of those already defined variable types. A link type can then be defined for a particular system which is made up of a group of variable types. For instance in an HVAC system the link type would be enthalpy, dry air mass flow rate and vapour mass flow rate. Other link types can be defined in a similar manner for other systems. The main advantage of the link concept is to allow the user to connect component models at interface level rather than variable by variable as is the case with TRNSYS and HVACSIM+. The other advantage is that link types can be used to check whether a user is making realistic connections.

The NMF concept also supports a single inheritance mechanism to allow models of the same physical component but with increasing level of complexity to inherit properties from less complicated ancestors. For example, a collector model with massflow- enthalpy-relative humidity links would inherit most of its properties from a massflow-enthalpy collector. Hierarchical decomposition in which one sub model is within another in multiple levels are also supported. The benefits of this is to enable incremental modelling and a more rational approach to validation. For instance a model for a compressor may be developed, validated and then used to define a heat pump comprising a compressor, evaporator and condenser (both evaporator and condenser. The other advantage of hierarchical decomposition is to encourage the development of good graphical interfaces which can be constructed for a corresponding hierarchical presentation of a model.

In order that the existing energy simulation environments to have access to any future library of components expressed in NMF, some means must be provided to allow these environments to make use of such components. The method suggested is to develop translators which will convert a model defined in NMF to a format known to the targeted environment. The task involved in developing such translators will depend a great deal on the component modelling theory and structure of the targeted environment. For example, an environment supporting link types and equation type models might require less time and effort than that which supports algorithmic type models and variable type inter-component connection.

The idea of having a common library of components encourages the inclusion of component specific information such as theory description, the parameter ranges within which a component has been validated and documented. It is clear that having a common format to describe a component model together, with a common library of components, will increase the worthiness and confidence level in using many of the existing building energy simulation programes. However, some obstacles have been highlighted, (Sahlin et al. 1992b) including the fact that some developers might be reluctant to have one of their component models included in a public domain library because the model is a strong selling point. Other problems are encountered with expressing algorithmic models in NMF equation type models.

The current state of NMF is that a stable model format exists and more work and effort is required to develop models and translators. In the following section, a discussion is presented on the issues surrounding the use of NMF within an environment such as ESP-r.

7.1.1 NMF with the ESP-r system

ESP-r already contains some of the NMF features, such as equation type models, systems described by link types and hierarchical decomposition. However, since the emphasis here is on how ESP-r can access component models expressed in NMF rather than how they are expressed under ESP-r environment, an example will be considered to show how this may be achieved. In a sense, what follows is a specification of an NMF translator for ESP-r.

For a thorough understanding of the NMF structure, the reader should refer elsewhere (Sahlin 1992c). Consider the ESP-r heating coil component model type (50) with flux control. This component is represented in NMF as shown in Figure 7.1. The assumption here is that there is no control imposed on the heating flux and so it is assumed constant.

```
CONTINUOUS_MODEL heating_coil

ABSTRACT
"Heating coil.
 No pressure calculations.
 No environmental heat loss.
 One node model with constant heating flux.
 Dry air and vapour mass flow rates are also calculated"

EQUATIONS

    IF ISTATS==1 THEN
        cM * T' = C * ( Ti - T ) + Qi
    ELSE_IF ISTATS==2 THEN
        mfa := R * mfai
    ELSE_IF ISTATS==3 THEN
        mfv := R * mfvi
    END_IF ;

LINKS

moist_air    inlet    POS_IN     mfai,Ti,Pi,wi
moist_air    outlet   POS_OUT    mfa,T,Pi,w

VARIABLES

temp       Ti    IN   0   -273.  BIG  "Inlet air temperature"
temp       T     OUT  0   -273.  BIG  "Outlet air temperature"
hum_ratio  wi    IN   0     0.   1.0  "Inlet humidity ratio"
hum_ratio  w     OUT  0     0.   1.0  "Outlet humidity ratio"
massflow   mfai  IN   0     0.   BIG  "Inlet dry air flow rate"
massflow   mfa   OUT  0     0.   BIG  "Outlet dry air flow rate"
massflow   mfvi  IN   0     0.   BIG  "Inlet vapour flow rate"
massflow   mfv   OUT  0     0.   BIG  "Outlet vapour flow rate"
pressure   pi    IN   0     0.   BIG  "Inlet pressure"
GENERIC    R     IN   1     0.   1.0  "Mass diversion ratio"

MODEL_PARAMETERS
INT     ISTATS    2    1   3   "Variable state"
```

```
PARAMETERS
thermal_mass  cM              "Mass*specific heat"
GENERIC    M               "Component total mass"
heat_capacity cp             "Mass weighted specific heat"
heat_capacity cpa            "Air specific heat capacity"
heat_capacity cpv            "Vapour specific heat capacity"
power     Qi              "Heating flux"

PARAMETER_PROCESSING
cM := M * cp
C  := mfai * SHTFLD(1,Ti) * R + mfvi * SHTFLD(2,Ti) * R

END_MODEL

FUNCTION
FLOAT SHTFLD (iftype, ftemp) ;
LANGUAGE F77

INPUT
INTEGER iftype;
FLOAT  ftemp;

CODE
C SHTFLD is a real function which returns the specific heat (J/kgK)
C of dry air (IFLD=1), water vapour (IFLD=2), or water (IFLD=3)
C as a function of (TEMP) the fluid temperature (C)

    FUNCTION SHTFLD(IFLD,TEMP)

    IF(IFLD.EQ.1) THEN
      SHTFLD=1006.+(TEMP/200.)+(TEMP*TEMP/7500.)
    ELSE IF(IFLD.EQ.2) THEN
      SHTFLD=1858.4+(.10875*TEMP)+(3.083E-4*TEMP*TEMP)
    ELSE IF(IFLD.EQ.3) THEN
      SHTFLD=4244.-(22.65*SQRT(TEMP))+(1.95*TEMP)
    END IF
    RETURN
    END
END_CODE
```

Figure 7.1 Heating coil model in neutral model format.

The equations used to define the heating coil model under the ESP-r system are listed in Appendix A. It can be seen from Figure 7.1 that the model defined is a continuous model which can be expressed by an equation. For example, the temperature is expressed in terms of a differential equation with the temperature derivative being T'. The mass flow equations are assumed to be linear and can be expressed in terms of a simple algebraic equation. Because in the ESP-r system, the equations are solved by a modular simultaneous approach, i.e dry air mass flow rates are solved first, then vapour mass flow rate and then nodal temperatures, a condition is defined based on the value of ISTATS to decide which state variable to solve for. Moreover, ESP-r requires that a plant component model must be discretised into finite difference form. It may be possible to define equations for the discretised form within the model format, but the disadvantage of this is that this will limit the use of a model to be restricted to environments which support model discretisation and therefore the advantage of having a common model format diminishes. For this reason it was decided that the translator should be made capable of performing this task on the equations defined for each state. The link type specified is a built-in type and includes the following group of variable types: dry air mass flow rate, temperature, pressure, humidity ratio. Note that the pressure variable had to be specified even though it is not used in the model. This is necessary in order to use the moist_air link type. In ESP-r, a moist_air link exists but without the pressure variable which is not used in this model in any event. It is possible to specify a GENERIC link in which only the used variables may be defined (i.e same variables as in moist_air link, but without pressure).

The variable types used were defined globally as

Type name	unit	kind
temp	"Deg-C"	CROSS
hum_ratio	"kg/kg"	CROSS
massflow	"kg/s"	THRU
pressure	"kpa"	CROSS

The terms under the ’kind’ column signify that variables can be categorised as being of either direction dependent flow-type (THRU), or direction independent potential type (CROSS). Model parameters allow the user to adapt a model structurally as shown in the above example. Model parameters must be declared as integers which may also be used to dimension arrays and matrices. Model parameter ISTATS was declared as integer with initial value of 2 to process mass flows first and a minimum and maximum values of 1 and 3 respectively. The parameters used are globally defined as

Type name	unit
thermal_mass	"J/kg"
heat_capacity	"J/(kg K)"
power	"W"

In the parameter processing section, the various named coefficients of the equation model which may be expressed in terms of a user specified parameter or are a function of some variable, are defined. Note that it is also possible to call an external function or a subroutine to calculate some property (specific heat in the current example). The modeller can also chose the programming high level language implemented for the function definition. These functions may also be declared as global to other models in the common library.

It was stated by the authors of NMF that the translation software should be partitioned into two portions. One portion which should be the same regardless of the target simulation environment, called the *interpreter*, and the other portion which generates the models in the format of a particular environment, called the *generator*. The *interpreter* knows the NMF syntax and library format while the *generator* knows the syntax and format of the target environment. In addition, the *interpreter* is expected to be made available with the library of component models. This implies that only the *generator* needs to be customised for the target environment. In the ESP-r system, the *generator* will produce an equivalent coefficient generator from a model in neutral format. Thus the main task of the generator will be to construct the equations for each coefficient from the set of equations representing the continuous model and also to encompass any parameter processing. The user may still have to define the component matrix structure and parameters in the plant component database, but in addition to having access to a large common library of components, the time it will take to install a model will be reduced substantially.

7.2 Modular approach to model construction.

The fundamental elements comprising the mathematical model of the building (such as walls and spaces) are permanently in existence. The absence of other elements participating in the system, e.g. an occupant gain or the variation of solar gain at an external wall, etc., changes only the magnitude of certain parameters contributed to the boundary conditions, the topological structure of the system remains the same. As a result, the topological model structures of the building enclosures are usually pre-structured as part of the simulation program and the solution of the system mathematical model can be optimised.

For plant, the components used usually vary from system to system. The connections which couple the components within the system may also be different even when the same components are used. This requires an arbitrary selection of components and their connections to allow the definition of the run-time system equation-set topology. To this end, most of the plant simulation models adopt a modular approach by which each component comprising the system can be considered as an internally pre-defined model while the complete system topology can only become definitively known when the components and connections are selected and defined at run-time. To satisfy various requirements, a plant system program has to accommodate a large number of component modules within its code. As a result, many component modules of the program will not be used for a particular simulation. For instance, if the requirement is just to be able to simulate wet central heating systems, then other components concerning cooling coils, chillers, ducts will not be utilised. However, these redundant components (e.g. in form of subroutines) are memory resident as part of the program executable and are carried along the whole simulation.

The current state-of-the-art methodologies for plant system modelling have evolved by adopting two different methods in term of system architecture, the sequential approach and the simultaneous approach as discussed in chapter 3.

7.2.1 The Object-Oriented implementation

The advance in Object Oriented (OO) technologies offers a new dimension in system modelling within the building context. A number of systems have emerged in recent years including the US SPARK (Sowell, 1991); the Swedish MODSIM, (Sahlin, 1988); and the UK Energy Kernel System (Charlesworth et al. 1991).

The SPARK system, for example, was developed primarily for plant and control simulation and concentrated on a novel solver which optimises the solution sequences using graph theory techniques. The aim of the IDA system was to develop a generalised solver for plant and control problems, removing input-output connotations from the problem (Sahlin et al., 1992a). The EKS system, in contrast, concentrated on the development of an OO platform for the creation, maintenance and validation of all simulation models (Clarke et al., 1992).

Within the EKS development, an important aspect has been addressed concerning the provision of a modular, dynamic topological modelling capability for plant and control system. This work focuses on:

- A generic software structure which allows the creation of state-of-the-art plant system simulation models;
- The elimination of the burden of redundant components by allowing a simulation program to be built with only the components required for the simulation.

The development of plant modelling facilities within the EKS inherits the software utilities provided by the environment. These include: the computational support classes which encapsulates a spectrum of analytical, numerical or statistical solution methods; the intrinsic classes for data transport, generic list and network classes for dynamic data structures, meta-classes and template classes for automatic class creation. On top of these, the development of plant modelling focuses on the particular issues which dominates the domain. These include:

- Knowledge identification and representation
- Data encapsulation
- Automatic model construction

7.2.2 Knowledge Representation

Under the object orientated approach, a program can be composed of independent objects communicating via messages. To achieve this, the physical system has to be decomposed, in a certain way, into objects which represent the knowledge of the physical world in the OO design space. It was appreciated that in the OO research and application field there was still no commonly accepted definition of the OO approach. For this reason, the EKS has adopted the methodology of functional/data decomposition and the result of this is a taxonomy of parts (Clarke et al. 1992).

For the development of functional/data decomposition of the plant system within the EKS, two approaches were envisaged (Tang and Clarke 1993); the *atomic* approach and the *component based* approach.

In the atomic approach a number of fundamental processes (e.g. thermal conduction, surface convection, etc.) are identified that can be used to construct any component. The system should be able to handle the creation of the intra-component topology, usually predefined, and the inter-component topology created at run-time. In contrast to the atomic approach, the component based approach treats each component as a pre-defined topological structure with the program being responsible for the creation and maintenance of the dynamic inter-component topology. In this approach, the mathematical complexity of each individual component will be irrelevant to the dynamic topology of the system network.

Within the EKS at the present time the component based approach was adopted for the creation of simulation models incorporating the sequential and equation-based architectures. Program codes available from existing systems, e.g. TRNSYS, ESP-r, etc. can be directly imported for the implementation of component classes. The concept of the atomic approach is being investigated within current research being undertaken by Chow (1993). In his work, a number of primitive parts are identified to represent the mass and energy flow in various air-handling equipments. These primitive parts, which are summarised in Table 7.1, can then form the atoms from which the intra-component topology is created. For example, a tube section of a cooling coil can be modelled by a combination of part numbers 4, 1 and 10 each, representing the external surface, tube metal, and the internal surface respectively. Then the single component 'cooling coil' can be built up by a network of the tube sections connected in the same configuration as in the actual physical arrangements, i.e. single pass, serpentine or double serpentine arrangements.

Table 7.1 List of primitive parts (Chow 1993)

Part No.	Description
1	Thermal conduction
2	Surface convection
3	Surface radiation
4	Flow (moist air) upon surface
5	Flow (moist air) upon water spray
6	Flow (moist air) diverger
7	Flow (moist air) converger
8	Flow (moist air) leakage in-to-out
9	Flow (moist air) leakage out-to-in
10	Flow (single-phase fluid) upon surface
11	Flow (single-phase fluid) diverger
12	Flow (single-phase fluid) converger
13	Flow (single-phase fluid) accumulator
14	Water injector
15	Flow (2-phase fluid) upon surface
16	Flow (2-phase fluid) diverger
17	Flow (2-phase fluid) converger
18	Steam injector
19	Heater (moving fluid)
20	Heater (vapour generating)

A top-down approach is adopted to further develop the representation scheme for plant systems. Figure 7.2 summarises the classes identified and the associated paths of inheritance. Here, the instantiation controls are shown only to the base classes. It should be equally applied to the class cluster at each corresponding level.

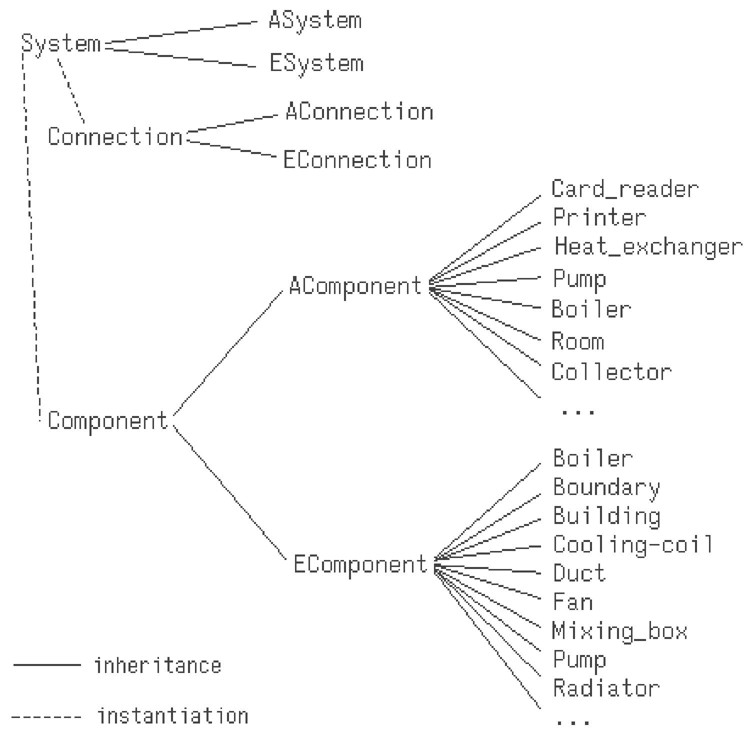

Figure 7.2 Inheritance of the plant classes

7.2.3 Data Encapsulation

Within the EKS plant classes are created for the encapsulation of data and functional implementations based on the class hierarchy.

Two levels of alternative implementations are provided. In the first level, it facilitates the creation of model architectures, i.e. the sequential and equation-based approaches. In the second level, it allows the arbitrary incorporation of component modules to be built into the system model.

The implementation of this is achieved by applying the technique of explicit polymorphism which means that the same operation may apply to many different classes and can take on different forms in different classes. For example, in C++ this is implemented using the constructs of derived class and virtual function (Rumbaugh et al., 1991).

In doing so, the base class of the component holds a virtual function table built into its private data, with the entry of the function pointer resolved at run time. C++ guarantees that the virtual function entry of the base class can be substituted by any implementation of the function in the classes derived from the base component. Therefore, at program construction time, any type of component object can be coupled to the dynamic list held by the system as part of the program. At program run-time, these components can be instantiated or duplicated and connected arbitrarily to the system network as defined by the program run-time topology.

To implement the alternative model architectures, two sets of classes are derived in parallel from the generic base class.

As an example, the following codes show the implementation of the generic base classes of System, Component and Connection.

```
class System : public EKSObject {
protected:
  Network(Connection,Component) system;
  Component*     findnode(char* component_name);
public:
  System(Metaclass* meta, System_def* def);
  ~System();
  List(Component)& components();
  List(Connection)& connections();
  List(Connection)& in_connection_for(Component* cmp);
  List(Connection)& out_connection_for(Component* cmp);
  List(Component)& up_stream_node_for(Component* cmp);
  List(Component)& down_stream_node_for(Component* cmp);
  Matrix&       connectivity();
  Matrix&       adjacency();
  virtual void    execute();
};
class Component : public EKSObject {
public:
  Component(Metaclass* meta, Component_def* def);
  ~Component();
};
```

```
class Connection : public EKSObject {
private:
friend class System;
  Component*  the_source;
  Component*  the_target;
  void     assign_source(Component* src);
  void     assign_target(Component* tgt);
protected:
  char*     the_source_name;
  char*     the_target_name;
public:
  Connection(Metaclass* meta, Connection_def* def);
  ~Connection();
  Connection& operator=(Connection& conns);
  Component*  source() { return the_source; };
  Component*  target() { return the_target; };
  char*    source_name() { return the_source_name; };
  char*    target_name() { return the_target_name; };
  char*    my_name() { return name(); };
};
```

Here, the generic base class System implements the system topology by creating an object of Network class which accommodates the actual components and connections to be created at program run-time.

To further implement the functionality of arbitrary component module selection, two sets of classes are created for the implementation of the actual components each of which is derived from its parent class, i.e. AComponent for algorithmic components and EComponent for equation-based components, respectively.

In a sequential system, each Component possesses a pair of heterogeneous vectors as an i/o interface. The Connection receives data from the source component and sends it to the target component. The solution sequence of the system is based on an over-relaxation scheme by which the system executes the connection stack of the network while each connection object activates the source and target components. This is done to ensure that:

- only those components which are connected will be executed.
- and that the target component always receives the latest information available.

In the equation-based system, each component is represented by a set of equations with potential nodes pointing outwards to its boundary to be resolved by connection at run-time. The construction of the complete system matrix is connection based. The system executes the connection stack of the network to allocate the source and target component matrices as diagonal blocks in the system matrix and creates the coupling sub-matrices between each pair of diagonal blocks. At the same time a pointer reference component list is created to ensure that no component matrix is duplicated in the system. This treatment also ensures that at run-time, only those components connected in the system network will be allocated into the diagonal block of the system matrix.

In both sequential and equation-based systems, the actual components are implemented as classes derived from the generic components, i.e. class AComponent and EComponent. The inheritance mechanism ensures that the actual components can be substituted into the entries created initially for the generic component objects and therefore allows the arbitrary selection of component modules to be built into the system model.

7.2.4 Automatic Model Construction

The configuration of the system architecture is supported by the problem's context classes which is equivalent to the creation of a main program in conventional programming.

The following code shows one examples of the problem context classes. Here, class Context is the EKS principal class which coordinates the whole taxonomy; Context_base_plant coordinates the creation of the plant network dynamic topology; Context_a_plant and Context_e_plant coordinate the creation of different system architectures, i.e. the sequential and equation-based systems, respectively.

```
class Context_base_plant : public Context {
protected:
    EKSObject*    the_system;
public:
    Context_base_plant(Metaclass* meta, Context_base_plant_def* def);
    ~Context_base_plant();
    System* get_system();
virtual void  simulate();
static void  description(Metaclass* meta, ostream& s);
};
```

```
class Context_a_plant : public Context_base_plant {
public:
    Context_a_plant(Metaclass* meta, Context_a_plant_def* def);
    ~Context_a_plant();
    ASystem*    get_system();
virtual void  simulate();
static void  description(Metaclass* meta, ostream& s);
};

class Context_e_plant : public Context_base_plant {
protected:
    Solver*    the_solver;
public:
    Context_e_plant(Metaclass* meta, Context_e_plant_def* def);
    ~Context_e_plant();
    ESystem*    get_system();
virtual void  simulate();
static void  description(Metaclass* meta, ostream& s);
};
```

The automatic construction of the simulation program is supported by the 'shell' utility programs provided by the EKS (Clarke et al. 1992). The following utility programs are used:

EKS_cb: the context builder which allows the creation of user specified program context.

EKS_tb: the template builder allows the selection of class variants to be built into the program.

EKS_mb: the model builder which allows the program construction by which the OODB-installed "Template" is consulted and correct class use is guaranteed.

The execution of the programs to result are similar to the conventional simulation programs by which any component class can be instantiated to create multiple objects of the same type and be connected to other component objects.

To demonstrate the plant model construction process under the EKS, a heating plant system, as shown in Figure 7.3, is used as an example.

Two system templates are created for the sequential (Table 7.2) and equation-based (Table 7.3) system architectures, with selected component classes built into the templates.

Figure 7.4 shows the run-time model created by the instantiation of component and connection classes defined in the template of Table 7.2 The execution of the program is similar to the sequential/iterative solution scheme found in the TRNSYS program.

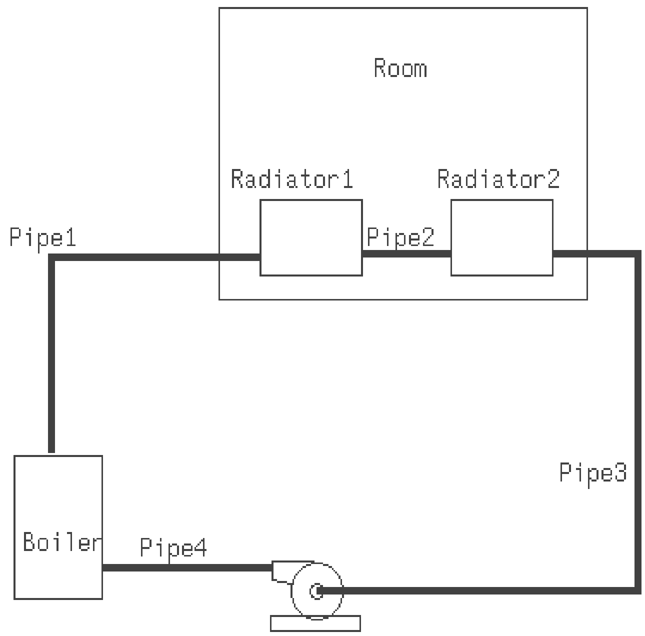

Figure 7.3 The heating plant system

Table 7.2 Template for Sequential plant system

Base class	Class offered	Class selected
Context	Context	Context_a_plant
System	ASystem	ASystem
Component	AComponent	ACard_reader
Component	AComponent	ABoiler
Component	AComponent	ARadiator
Component	AComponent	APump
Component	AComponent	ARoom
Component	AComponent	APipe
Component	AComponent	AHeat_exchanger
Component	AComponent	APrinter
Connection	AConnection	AConnection

Figure 7.5 shows the run-time system matrix, created by the instantiation of component and connection classes defined by the template of Table 7.3. The result is similar to the mathematical model structure of the ESP-r program.

Table 7.3 Template for equation-based plant system

Base class	Class offered	Class selected
Context	Context	Context_e_plant
System	ESystem	ESystem
Component	EComponent	EBuilding
Component	EComponent	ERadiator
Component	EComponent	EPipe
Component	EComponent	EPump
Component	EComponent	EBoundary
Connection	EConnection	EConnection
Solver	Solver	Gauss_column_pivot

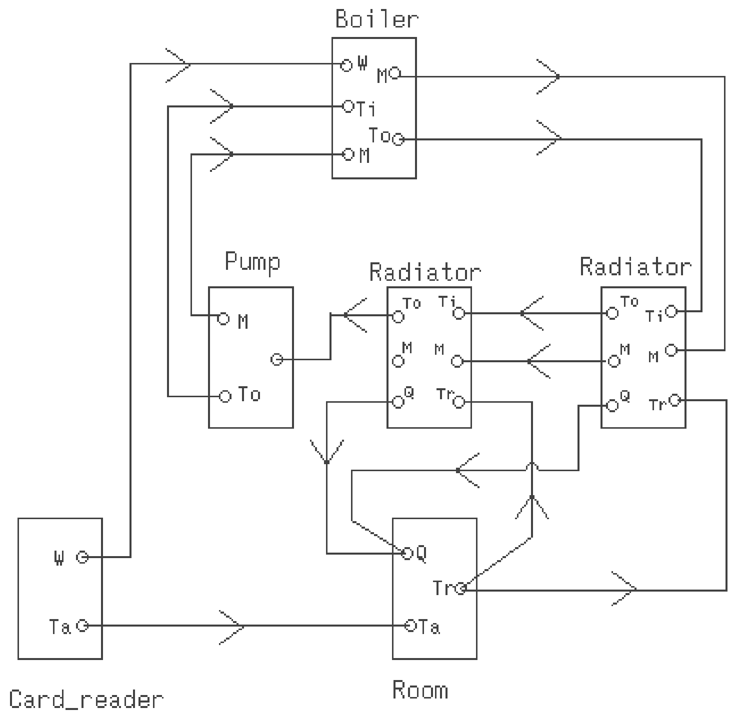

Figure 7.4 The sequential plant system

7.3 Knowledge based approach to simulation.

The EKS, as discussed in the previous section, is a support environment for the construction of the technical component of future program for building energy and environmental prediction. In order to construct program efficiently, some user interface must be used in conjunction with the EKS. Moreover, the main barrier to the appraisal of environmental systems (whether using existing simulation environments or using those produced by the EKS) is the problem of problem description and data preparation in the face of uncertainty. One approach to deal with such problems is the design

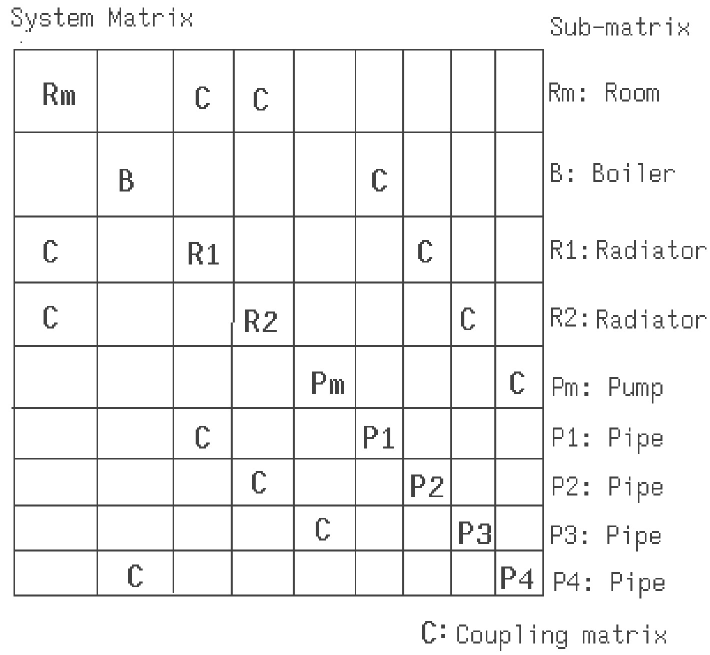

Figure 7.5 The state-space plant system

of an intelligent knowledge base system which offers an intelligent front end (IFe) (Clarke and Mac Randal, 1989).

In the context of building energy simulation, the IFe acts as an expert consultant, recognising the user's plan, commissioning simulations and reporting back on overall performance. The IFe system architecture is as shown in Figure 7.6 and comprises the following modules.

A *blackboard* (or communications centre) exists to manage information. Each module of the system can examine this blackboard for relevant information, posting back results where appropriate. The *knowledge base* and *knowledge handler*, implemented in Prolog, address long term knowledge concerning energy in buildings, the data knowledge concerning appropriate defaults, modelling knowledge defining simulation strategy and user knowledge concerning user stereotypes. The *dialogue handler* is the user communication mechanism. It controls the consultation session, allowing a user to volunteer information, to redirect the systems line of inquiry, or to make 'Why do you want to know' type responses to the system's prompts. The IFe can also cater for several user types - architect, engineer, energy modeller, student, etc. - at one of two levels, naive and proficient. The *data handler* assembles the data structure required by ESP-r from the available data. These data can come directly

Figure 7.6 The IFe system architecture

from a user or from the knowledge base in the form of dynamic defaults which may depend on the user dialogue. Users can select a building/plant from existing models; the building and system data will then become the focus in the blackboard. It is then possible to activate the ESP-r system to conduct an energy simulation on the combined building and system problem to study a certain aspect of the design process, such as comfort. The user is therefore able to study the relationship between design performance and design alteration. The system models may be either whole systems already defined or they may be constructed from existing individual component. The benefit of being able to define a system under the IFe environment is that a knowledge base can be constructed to aid the user in the problem definition process. For example, a plant component may have default parameters and for each parameter maximum and minimum values may be specified, the meaning of each parameter can be explained in detail in case the user wishes to alter any of the default parameters etc. The use of the IFe to prototype a new interface is a four stage process as follows:

1 Definition of the Human Computer Interface (HCI) in terms of concepts (such as location, boiler type, time-step and so on) and meta-concepts (such as system layout, controls and so on) acceptable to the targeted user type. This is done by the creation of a set of forms, each containing the entities comprising a single meta-concept.

2 Development of a related knowledge base to validate user entries against each of these concepts and make any meaningful inferences. The IFe offers standard built-in predicates to establish a related knowledge base in Prolog. These predicates are related to dialogue coordination (in terms of loading and unloading), user entry validation, inferencing, the assertion of facts within the knowledge base and storage of the evolving problem on the IFe Blackboard.

3 Definition of the data requirements of the targeted application(s) to allow the IFe to prepare data-sets in the required format. This involves transforming the Blackboard information into the format of the targeted application. This may be done by using the Data Handler to extract the Blackboard data, formatting it as required, or by requesting a dump of a particular area of the Blackboard. If the former case was pursued, a Data Definition Script must be established.

4 Installation of appraisal scripts to control the applications to which the IFe will be front ended. This can be done in one of two ways. Either an application can be attached to the Blackboard in the same manner as is done for the Dialogue, Knowledge, User, Appraisal, Data and Application Handlers or, more typically, an appraisal Shell Script is established and made known to the Appraisal Handler.

In terms of results recovery, particularly for the plant, the IFe is an ideal tool which can be implemented to overcome current deficiencies. The results requirements for the novice differ from those for the expert. For instance, the expert might wish to detect patterns in, and relationships between, the different plant parameters, in an attempt to isolate the dominant causal factors. This can be achieved by having all data generated by the simulation made available. Whereas the novice requires a concise summary of performance in terms of those parameters which are most meaningful to the design team (such as total energy consumption of a system, system efficiency, running cost and so on).

7.4 Further work

The future issues discussed in this chapter such as the NMF, EKS and IFe could be expanded further particularly in the field of systems simulation. For example, more work should be directed towards developing the generator part of the NMF translator so that a component model in the common library can be quickly converted to a format which is acceptable to ESP-r. In addition, more existing ESP-r dynamic models should be written using the NMF so that other institutes can have access to these models to increase model reliability and to unify model validation. With respect to the EKS, more component models are required in both equation type and algorithmic type components such as ESP-r and TRNSYS types respectively. However, it is more efficient to develop another generator which is capable of generating either TRNSYS (AComponent) or ESP-r (EComponent) classes from existing components in the common library of NMF models. It is envisaged that such generators for the EKS will allow component models from other simulation environments to be easily imported. Finally, some effort is required to improve data input preparation and results recovery and analysis; the existing IFe is a practical tool which could be deployed to this end.

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CHAPTER 8
Conclusions and Future Work

8.1 Conclusions

It was shown that energy simulation tools can play an important role in the development of energy conservation measures to existing and new buildings. In order to increase our knowledge and understanding of the thermal behaviour of buildings and their interacting plant systems, an energy simulation environment which allows a rigorous analysis of the energy and mass transfer regimes is of paramount importance. From this perspective, the main objective of this thesis was to investigate the capabilities and deficiencies of one state-of-the-art energy simulation environment, ESP-r, when applied to complex building and air-conditioning systems, and then to develop new tools and refine existing features in order to eliminate these deficiencies.

The plant simulation capabilities and robustness of the ESP-r system have been substantially improved. The system has been restructured on the plant-side to handle the practical simulation of combined building and plant systems more efficiently. Plant networks comprising a large number of multiple-node components can now be handled in an efficient manner allowing for more ‘real world’ systems, which are often complex, to be investigated. A structure has been put in place to allow other component models (such as those in TRNSYS) to be installed within ESP-r. The benefit of this is not only to increase the number of available component models but also to use such models under the integrated framework of ESP-r. Further modifications have been carried out on the plant component data base to enable the establishment of a more user friendly problem definition process. This is reflected in the development of new tools which utilise the new structure in order to reduce the burden on the user during the problem description phase.

The new plant solver developed to cope with the sparse nature of the overall plant system matrix, proved to be effective in terms of computational speed and memory storage requirement. Because real world plant systems are complex in nature, in most simulation cases this necessitates the use of small time-steps, even smaller than one second in some situations, for the plant system simulation with the building being defined as multi-zone, complex geometrical spaces interacting with the installed plant system. In addition to this, there is also the simulation of fluid flow in building/plant systems which increases the computational time requirement when simulating the whole building/plant and flows configuration. It is in such situations that the benefit of having a fast and efficient solver will be appreciated.

The result transfer structure for the plant simulation was changed to allow for a variable number of records of data to be transferred for a particular component. This means that a component model of any number of control volumes (nodes) can be installed in ESP-r. With these changes, detailed and perhaps more accurate models can be tested and validated against a specific performance criteria. The developed system demonstrated its capability and flexibility in handling components models with different nodal schemes. With this feature, simple models can be used in situations where, for example, a detailed analysis of the temperature distribution of a fluid is not of interest, such as in a converging junction where only the quantity of the mixed fluids is of interest. At the same time, detailed models can be used where the temperature distribution is of interest, such as a fluid temperature as it passes through heat exchanger tube bundles or the temperature distribution of a tube fin. The system is also capable of simulating the building, plant, controls and multiple fluid type flows simultaneously and at an equal level of detail as was demonstrated by a number of the application examples.

With respect to validation techniques, four validation methods were implemented to demonstrate the robustness of the developed component models. The use and application of general purpose simulation tools, such as TUTSIM, was also demonstrated as part of the inter-model validation exercise. The new control law developed for validation purposes proved to be useful for the cases considered. An empirical validation was also carried out on a combined building/plant IEA exercise followed by a sensitivity analysis in an attempt to determine the effect of different parameters on the simulation results. The validation methodology adopted in this thesis increases reliability and confidence in using the developed component models. In addition, in all the validation methods suggested, the new plant solver developed was also being tested and validated indirectly.

The plant component data base was modified to allow for new component models structures such as ‘meta components’ and ‘generic TRNSYS type components’ to be installed in the data base. In addition, parameter description is now part of the component data entry which allows other programs to have access to such data; for example, the utility program developed to assist in plant network definition. Another module which also makes use of such data is the result recovery program which was enhanced to allow plant simulation results analysis. Additional information regarding fluid flow components can also be added to the component data entry in the data base so that it can be used if a fluid flow network is to be generated from a previously defined plant network. These features proved to be essential.

The system's capability to handle real air-conditioning systems, and real world multi-domain problems has been demonstrated through the application examples considered. These examples varied in complexity from simple to complex problems comprising plant, building, flows and control interaction. Case studies which were also presented and proved to be useful in enhancing the system's capabilities further as they provided a real world testing component. Through these application examples, more component models and controllers were developed and more enhancements were carried out on existing system features, so that the system robustness and simulation capabilities were substantially increased.

Control features on the simulation time-step were developed and tested on building/plant problems. A number of time-step controller types were added to allow for time-step reduction based on some user defined criterion. The type which implements iteration as well as time-step reduction eliminated the burden on the user to select appropriate time-step reduction trigger variables offered by the other types. This type was found to be suitable for applications where a small building time-step is required, such as in buildings of light construction with small time constant characteristics. Another indirect use of time-step control, is when carrying out a simulation for a large multi-zone problem and the maximum number of output variables are required to be saved for later result recovery, which is impossible if the storage requirements are too great for the available resources. In this case an initial, and reasonably large time-step value can be specified and a time-step controller invoked which allows for a different time-step to be used in the simulation with the results transferred at the initial time-step value. This in effect reduces the amount of storage space required for the simulation results.

8.2 Future work

With respect to the input of a plant network definition, effort is required in order to make the data input more user-friendly and more intuitive. Improvements and enhancements can be made on the utility "pdf" developed in this thesis and can also be made on existing Intelligent Front end packages such as the IFe. Because of the modular feature of components, they may be best represented by graphical objects to which some attributes (eg. component parameters and nodal scheme description) may be attached for further editing to suit a particular application. A graphical tool "Network" supporting this application is currently under development and requires refinements. In addition, extensive work and effort is required to further develop and enhance the capabilities of the plant simulation results analyser. Again, this may also be investigated using sophisticated packages allowing for more intelligent features, such as the IFe. It was found that a useful way to present simulation results for an air-conditioning system is to display the air condition at certain points in the network on a pshycrometric chart using the existing result recovery module currently available. Such results presentation is of great value on both the research and design levels.

The plant solver developed for the solution of highly sparse matrices proved to be very promising and the iteration techniques adopted for plant simulation can overcome most problems associated with non-linearities and equation coupling. However, solution methods allowing for direct non-linear solution of systems should be further considered. For example, the conjugate gradient method, used for the solution of linear algebraic equations and very suitable for matrices of a sparse nature, can be generalised to the minimisation of non-linear functions. The description of this method is available in many text books and it deserves consideration if the effect of system non-linearities is to be investigated. Current research activities at the Energy Systems Research Unit (ESRU) are concerned with future issues such as the coupling of CFD's with building energy simulators, the effects of two and three dimensional heat conduction on environmental and energy performance, and on the implementation of sophisticated energy management control systems allowing for multi-sensors and hierarchical control. These issues are currently being investigated in conjunction with ESP-r. In order to allow for the implementation of such issues to ESP-r, the solver for the building side of the simulation is expected to be further refined.

The induced type air-conditioning system was not simulated in the present thesis because there was no fluid flow component at present which can be used as an air jet nozzle. Induced air occurs as a result of a pressure difference existing between the zone air and the nozzle outlet jet. Such a component should be developed. In other air-conditioning systems, in which a number of VAV terminals are used to service a number of zones, it is desirable for economical purposes to reduce the primary air flow rate by reducing the fan speed based on information sent via multiple sensors measuring the pressure drop across each VAV terminal. Sensors of this type should be made available to allow the simulation of real systems as close as possible.

In order to encourage the future development for a centralised library of plant components, the Neutral Model Format (NMF) of representing plant component models should be addressed for other more complex multi-node components. The development of a translator for NMF component models to be imported into the ESP-r environment, is a step forward and promises an improvement in the quantity and reliability of component models supported by ESP-r. The EKS at present seems suitable for use to generate a plant simulation environment for both algorithmic type and equation based component models. However, the generalisation of mass and energy flow in various air-conditioning systems into a well defined number of primitive parts (atoms), would allow the EKS to generate the required component models for a particular energy simulation model.

With respect to time-step controllers, the types considered in this thesis attempt to reduce the time-step based on some criterion. The effect of increasing the time-step should also be considered. Further enhancements could be carried out so that real time simulation is enabled.

Modelling of plant components with refrigerants as the working fluid should be considered. The heat exchanger model developed in this thesis could be extended to be used as an evaporator or a condenser in a refrigeration plant. However, this implies significant changes to the structure of the fluid flow solver since at present it is only capable of solving incompressible fluids.

Simulation of solar systems can be further enhanced by the addition of other TRNSYS type solar models as was demonstrated in this thesis. ESP-r's solar processor should be extended to allow plant component models to have access to its features. Moreover, multi-node models for solar components should also be considered to allow for true dynamic simulation of solar systems.

With the continuous advances in information technology transfer and increasing computer processing power, the prospect for energy simulation is promising. The technology is now available to overcome major barriers to practical application of plant simulation such as data availability for components and advanced human computer interface to cater for the practical need of the profession.

APPENDIX A
Templates of available plant components

Table of Contents

Air mixing box; 1 node model (type 10)

Characterisitic balance equation		
State space variable	Node	Equation
Temperature (C)	1	$C_{1,j}(\theta_j - \theta_1) + C_{1,k}(\theta_k - \theta_1) + UA(\theta_e - \theta_1) = \frac{\overline{c} M \delta\theta_1}{\delta t}$
First phase mass flow rate (kg/s)	1	$\dot{m}_{a,1} - R_{1,j}\dot{m}_{a,j} - R_{1,k}\dot{m}_{a,k} = 0$
Second phase mass flow rate (kg/s)	1	$\dot{m}_{v,1} - R_{1,j}\dot{m}_{v,j} - R_{1,k}\dot{m}_{v,k} = 0$

Generated coefficients		
State space variable	Coefficient	Equation
Temperature	1	$= \alpha(-C_{1,j,t+\Delta t} - C_{1,k,t+\Delta t} - UA_{t+\Delta t}) - \frac{\overline{c}M}{\Delta t}$
	2	$= \alpha\, C_{1,j,t+\Delta t}$
	3	$= \alpha\, C_{1,k,t+\Delta t}$
	4	$= \left\{ (1-\alpha)\left[C_{1,j,t} + C_{1,k,t} + UA_t \right] - \frac{\overline{c}M}{\Delta t} \right\} \theta_{1,t} + (1-\alpha)(-C_{1,j,t})\,\theta_{j,t} + (1-\alpha)(-C_{1,k,t})\,\theta_{k,t} - \alpha\, UA_{t+\Delta t}\,\theta_{e,t+\Delta t} - (1-\alpha)UA_t\theta_{e,t}$
First phase mass flow rate	1	$= 1.0$
	2	$= -R_{1,j}$
	3	$= -R_{1,k}$
	4	$= 0.0$
Second phase mass flow rate	1	$= 1.0$
	2	$= -R_{1,j}$
	3	$= -R_{1,k}$
	4	$= 0.0$

Component default parameters		
M	Component total mass (kg)	1.0
$\overline{c}$	Mass weighted average specific heat (J/kgK)	500
UA	Overall heat loss coefficient (W/K)	3.5

ESP-r coefficient generator name "CMP01C", plant component database reference number 1.

Atomizing humidifier; 1 node model; water vapour flow rate control (type 20)

Characterisitic balance equation		
State space variable	Node	Equation
Temperature (C)	1	$C_{1,j}(\theta_j - \theta_1) + UA(\theta_e - \theta_1) + \dot{m}_w^v H_{w=} \dfrac{\overline{c} M \delta\theta_1}{\delta t}$
First phase mass flow rate (kg/s)	1	$\dot{m}_{a,1} - R_{1,j}\dot{m}_{a,j} = 0$
Second phase mass flow rate (kg/s)	1	$\dot{m}_{v,1} - R_{1,j}\dot{m}_{v,j} = \dot{m}_w^v$

Generated coefficients		
State space variable	Coefficient	Equation
Temperature	1 2 3	$= \alpha\,(-C_{1,j,t+\Delta t} - UA_{t+\Delta t}) - \dfrac{\overline{c}M}{\Delta t}$ $= \alpha\, C_{1,j,t+\Delta t}$ $= \left\{ (1-\alpha)\left[C_{1,j,t} + UA_t \right] - \dfrac{\overline{c}M}{\Delta t} \right\} \theta_{1,t}$ $+ (1-\alpha)(-C_{1,j,t})\,\theta_{j,t}$ $- \alpha\, UA_{t+\Delta t}\,\theta_{e,t+\Delta t} - (1-\alpha) UA_t \theta_{e,t}$ $+ \alpha\,(\dot{m}_w^v H_w)_{t+\Delta t} + (1-\alpha)(\dot{m}_w^v H_w)_t$
First phase mass flow rate	1 2 3	$= 1.0$ $= -R_{1,j}$ $= 0.0$
Second phase mass flow rate	1 2 3	$= 1.0$ $= -R_{1,j}$ $= \dot{m}_w^v$

Component default parameters		
M	Component total mass (kg)	25
$\overline{c}$	Mass weighted average specific heat (J/kgK)	1000
UA	Overall heat loss coefficient (W/K)	3.5
E_r	Rated effectiveness (-)	0.85
v_r	Rated face velocity (m/s)	1.0
A_f	Face area ($m\,2$)	0.15

Control data variables
Water vapour supply rate $\dot{m}_w^v(kg/s)$

ESP-r coefficient generator name "CMP02C", plant component database reference number 2.

Centrifugal fan, 1 node model ; flow control (type 30)

Characterisitic balance equation		
State space variable	Node	Equation
Temperature (C)	1	$C_{1,j}(\theta_j - \theta_1) + UA(\theta_e - \theta_1) + q_i = \frac{\bar{c}M\delta\theta_1}{\delta t}$
First phase mass flow rate (kg/s)	1	$\dot{m}_{a,1} = \Gamma$
Second phase mass flow rate (kg/s)	1	$\dot{m}_{v,1} - R_{1,j}\dot{m}_{v,j} = 0$

Generated coefficients		
State space variable	Coefficient	Equation
Temperature	1 2 3	$= \alpha\,(-C_{1,j,t+\Delta t} - UA_{t+\Delta t}) - \frac{\bar{c}M}{\Delta t}$ $= \alpha\, C_{1,j,t+\Delta t}$ $= \left\{ (1-\alpha)\left[C_{1,j,t} + UA_t \right] - \frac{\bar{c}M}{\Delta t} \right\} \theta_{1,t}$ $+ (1-\alpha)(-C_{1,j,t})\,\theta_{j,t}$ $- \alpha\, UA_{t+\Delta t}\,\theta_{e,t+\Delta t} - (1-\alpha)UA_t\theta_{e,t}$ $- \alpha\, q_{i,t+\Delta t} - (1-\alpha)\, q_{i,t}$
First phase mass flow rate	1 2 3	$= 1.0$ $= 0.0, \quad = -R_{1,j}$ (if mfs active) $= \Gamma, \; = 0.0$ (if mfs active)
Second phase mass flow rate	1 2 3	$= 1.0$ $= -R_{1,j}$ $= 0.0$

Component default parameters		
M	Component total mass (kg)	10.0
$\bar{c}$	Mass weighted average specific heat (J/kgK)	500.0
UA	Overall heat loss coefficient (W/K)	7.0
q_r	Rated total absorbed power (W)	200.0
Γ_r	Rated volume flow rate (m^3/s)	0.1
η	Overall efficiency (-)	0.7

Control data variables
Volume flow rate $\Gamma(m^3/s)$

ESP-r coefficient generator name "CMP03C", plant component database reference number 3.

Air cooling coil; 1 node model; flux control (type 40)

Characterisitic balance equation		
State space variable	Node	Equation
Temperature (C)	1	$C_{1,j}(\theta_j - \theta_1) + UA(\theta_e - \theta_1) + q_i + \dot{m}_w^v H_{w=} \frac{\overline{c} M \delta \theta_1}{\delta t}$
First phase mass flow rate (kg/s)	1	$\dot{m}_{a,1} - R_{j,1} \dot{m}_{a,j} = 0$
Second phase mass flow rate (kg/s)	1	$\dot{m}_{v,1} - R_{1,j} \dot{m}_{v,j} = \dot{m}_w^v$

Generated coefficients		
State space variable	Coefficient	Equation
Temperature	1	$= \alpha\, (- C_{1,j,t+\Delta t} - UA_{t+\Delta t}) - \frac{\overline{c} M}{\Delta t}$
	2	$= \alpha\, C_{1,j,t+\Delta t}$
	3	$= \left\{ (1-\alpha) \left[C_{1,j,t} + UA_t \right] - \frac{\overline{c} M}{\Delta t} \right\} \theta_{1,t}$ $+ (1-\alpha)\,(-C_{1,j,t})\,\theta_{j,t}$ $- \alpha\, UA_{t+\Delta t}\, \theta_{e,t+\Delta t} - (1-\alpha) UA_t \theta_{e,t}$ $- \alpha\, q_{i,t+\Delta t} - (1-\alpha)\, q_{i,t}$ $- \alpha\, (\dot{m}_w^v H_w)_{t+\Delta t} - (1-\alpha)\, (\dot{m}_w^v H_w)_t$
First phase mass flow rate	1	$= 1.0$
	2	$= - R_{1,j}$
	3	$= 0.0$
Second phase mass flow rate	1	$= 1.0$
	2	$= - R_{1,j}$ for $T_{air} \geq T_{dew}$ else $= 0.0$
	3	$= 0.0$ for $T_{air} \geq T_{dew}$ else $= \dot{m}_w^v$

Component default parameters		
M	Component total mass (kg)	15.0
$\overline{c}$	Mass weighted average specific heat (J/kgK)	1000.0
UA	Overall heat loss coefficient (W/K)	3.5

Control data variables
Cooling duty $q_i(W)$

ESP-r coefficient generator name "CMP04C", plant component database reference number 4.

Air heating coil; 1 node model ; flux control (type 50)

Characterisitic balance equation		
State space variable	Node	Equation
Temperature (C)	1	$C_{1,j}(\theta_j - \theta_1) + UA(\theta_e - \theta_1) + q = \frac{\bar{c}M\delta\theta_1}{\delta t}$
First phase mass flow rate (kg/s)	1	$\dot{m}_{a,1} - R_{1,j}\dot{m}_{a,j} = 0$
Second phase mass flow rate (kg/s)	1	$\dot{m}_{v,1} - R_{1,j}\dot{m}_{v,j} = 0$

Generated coefficients		
State space variable	Coefficient	Equation
Temperature	1	$= \alpha\,(-C_{1,j,t+\Delta t} - UA_{t+\Delta t}) - \frac{\bar{c}M}{\Delta t}$
	2	$= \alpha\, C_{1,j,t+\Delta t}$
	3	$= \left\{ (1-\alpha)\left[C_{1,j,t} + UA_t \right] - \frac{\bar{c}M}{\Delta t} \right\} \theta_{1,t}$ $+ (1-\alpha)(-C_{1,j,t})\,\theta_{j,t}$ $-\alpha\, UA_{t+\Delta t}\,\theta_{e,t+\Delta t} - (1-\alpha)UA_t\theta_{e,t}$ $-\alpha\, q_{t+\Delta t} - (1-\alpha)\, q_t$
First phase mass flow rate	1	$= 1.0$
	2	$= -R_{1,j}$
	3	$= 0.0$
Second phase mass flow rate	1	$= 1.0$
	2	$= -R_{1,j}$
	3	$= 0.0$

Component default parameters		
M	Component total mass (kg)	15.0
$\bar{c}$	Mass weighted average specific heat (J/kgK)	1000.0
UA	Overall heat loss coefficient (W/K)	3.5

Control data variables
Heating duty $q(W)$

ESP-r coefficient generator name "CMP05C", plant component database reference number 5.

Air duct; 1 node model (type 60)

Characterisitic balance equation		
State space variable	Node	Equation
Temperature (C)	1	$C_{1,j}(\theta_j - \theta_1) + UA(\theta_e - \theta_1) = \frac{\bar{c}M\delta\theta_1}{\delta t}$
First phase mass flow rate (kg/s)	1	$\dot{m}_{a,1} - R_{1,j}\dot{m}_{a,j} = 0$
Second phase mass flow rate (kg/s)	1	$\dot{m}_{v,1} - R_{1,j}\dot{m}_{v,j} = 0$

Generated coefficients		
State space variable	Coefficient	Equation
Temperature	1	$= \alpha\,(-C_{1,j,t+\Delta t} - UA_{t+\Delta t}) - \frac{\bar{c}M}{\Delta t}$
	2	$= \alpha\, C_{1,j,t+\Delta t}$
	3	$= \left\{ (1-\alpha)\left[C_{1,j,t} + UA_t \right] - \frac{\bar{c}M}{\Delta t} \right\} \theta_{1,t}$ $+ (1-\alpha)(-C_{1,j,t})\,\theta_{j,t}$ $- \alpha\, UA_{t+\Delta t}\,\theta_{e,t+\Delta t} - (1-\alpha)UA_t\theta_{e,t}$
First phase mass flow rate	1	$= 1.0$
	2	$= -R_{1,j}$
	3	$= 0.0$
Second phase mass flow rate	1	$= 1.0$
	2	$= -R_{1,j}$
	3	$= 0.0$

Component default parameters		
M	Component total mass (kg)	9.25
$\bar{c}$	Mass weighted average specific heat (J/kgK)	500.0
UA	Overall heat loss coefficient (W/K)	14.0
d_h	Hydraulic diameter of duct (m)	0.125
L	Length of duct section (m)	5.0
A_f	Cross sectional face area (m^2)	0.01227

ESP-r coefficient generator name "CMP06C", plant component database reference number 6.

Air damper; 1 node model; flow ratio control (type 70)

Characterisitic balance equation		
State space variable	Node	Equation
Temperature (C)	1	$C_{1,j}(\theta_j - \theta_1) + UA(\theta_e - \theta_1) = \frac{\overline{c}M\delta\theta_1}{\delta t}$
First phase mass flow rate (kg/s)	1	$\dot{m}_{a,1} - f_r R_{1,j} \dot{m}_{a,j} = 0$
Second phase mass flow rate (kg/s)	1	$\dot{m}_{v,1} - f_r R_{1,j} \dot{m}_{v,j} = 0$

Generated coefficients		
State space variable	Coefficient	Equation
Temperature	1	$= \alpha\,(-C_{1,j,t+\Delta t} - UA_{t+\Delta t}) - \frac{\overline{c}M}{\Delta t}$
	2	$= \alpha\, C_{1,j,t+\Delta t}$
	3	$= \left\{ (1-\alpha)\left[C_{1,j,t} + UA_t \right] - \frac{\overline{c}M}{\Delta t} \right\} \theta_{1,t}$ $+ (1-\alpha)(-C_{1,j,t})\,\theta_{j,t}$ $- \alpha\, UA_{t+\Delta t}\,\theta_{e,t+\Delta t} - (1-\alpha) UA_t \theta_{e,t}$
First phase mass flow rate	1	$= 1.0$
	2	$= -(f_r R_{1,j})$
	3	$= 0.0$
Second phase mass flow rate	1	$= 1.0$
	2	$= -(f_r R_{1,j})$
	3	$= 0.0$

Component default parameters		
M	Component total mass (kg)	1.0
$\overline{c}$	Mass weighted average specific heat (J/kgK)	500.0
UA	Overall heat loss coefficient (W/K)	3.5

Control data variables
Flow ratio $f_r(-)$

ESP-r coefficient generator name "CMP07C", plant component database reference number 7.

Air cooling coil; 1 node model; water mass flow rate control (type 100)

Characterisitic balance equation		
State space variable	Node	Equation
Temperature (C)	1	$C_{1,j}(\ \theta_j - \theta_1) + UA\ (\ \theta_e - \theta_1) + q_i + \dot{m}^v_w H_{w=}\ \dfrac{\overline{c} M \delta \theta_1}{\delta t}$
First phase mass flow rate (kg/s)	1	$\dot{m}_{a,1} - R_{j,1} \dot{m}_{a,j} = 0$
Second phase mass flow rate (kg/s)	1	$\dot{m}_{v,1} - R_{1,j} \dot{m}_{v,j} = \dot{m}^v_w$

Generated coefficients		
State space variable	Coefficient	Equation
Temperature	1	$= \alpha\ (-\ C_{1,j,t+\Delta t} - UA_{t+\Delta t}\ ) - \dfrac{\overline{c} M}{\Delta t}$
	2	$= \alpha\ C_{1,j,t+\Delta t}$
	3	$= \left\{ (1-\alpha) \left[\ C_{1,j,t} + UA_t \right] - \dfrac{\overline{c} M}{\Delta t} \right\} \theta_{1,t}$
		$+ (1-\alpha)\ (\ -C_{1,j,t})\ \theta_{j,t}$
		$-\ \alpha\ UA_{t+\Delta t}\ \theta_{e,t+\Delta t} - (\ 1-\alpha\ ) UA_t \theta_{e,t}$
		$-\ \alpha\ q_{i,t+\Delta t} - (\ 1-\alpha\ )\ q_{i,t}$
		$-\ \alpha\ (\dot{m}^v_w H_w)_{t+\Delta t} - (\ 1-\alpha\ )\ (\dot{m}^v_w H_w)_t$
First phase mass flow rate	1	$= 1.0$
	2	$= -\ R_{1,j}$
	3	$= 0.0$
Second phase mass flow rate	1	$= 1.0$
	2	$= -\ R_{1,j}$ for $T_{air} \geq T_{dew}$ else $= 0.0$
	3	$= 0.0$ for $T_{air} \geq T_{dew}$ else $= \dot{m}^v_w$

Component default parameters		
M	Component total mass (kg)	15.0
$\overline{c}$	Mass weighted average specific heat (J/kgK)	1000.0
UA	Overall heat loss coefficient (W/K)	3.5
A_a	Coil air side heat transfer area (m^2)	15.0
A_w	Coil water side heat transfer area (m^2)	0.33
A_f	Coil face area (m^2)	0.25
R_m	Coil metal thermal resistance ($m^2 K/W$)	$0.1\ 10^{-2}$
d_i	Internal tube diameter (m)	0.015
θ_{wi}	Inlet water temperature (C)	10.0

Control data variables
Water flow rate (kg/s)

ESP-r coefficient generator name "CMP10C", plant component database reference number 8.

Air heating coil; 1 node model; water mass flow rate control (type 110)

Characterisitic balance equation		
State space variable	Node	Equation
Temperature (C)	1	$C_{1,j}(\theta_j - \theta_1) + UA(\theta_e - \theta_1) + q_i = \frac{\bar{c}M\delta\theta_1}{\delta t}$
First phase mass flow rate (kg/s)	1	$\dot{m}_{a,1} - R_{j,1}\dot{m}_{a,j} = 0$
Second phase mass flow rate (kg/s)	1	$\dot{m}_{v,1} - R_{1,j}\dot{m}_{v,j} = 0$

Generated coefficients		
State space variable	Coefficient	Equation
Temperature	1 2 3	$= \alpha(-C_{1,j,t+\Delta t} - UA_{t+\Delta t}) - \frac{\bar{c}M}{\Delta t}$ $= \alpha\, C_{1,j,t+\Delta t}$ $= \left\{ (1-\alpha)\left[C_{1,j,t} + UA_t \right] - \frac{\bar{c}M}{\Delta t} \right\} \theta_{1,t}$ $+ (1-\alpha)(-C_{1,j,t})\,\theta_{j,t}$ $- \alpha\, UA_{t+\Delta t}\,\theta_{e,t+\Delta t} - (1-\alpha)UA_t\theta_{e,t}$ $- \alpha\, q_{i,t+\Delta t} - (1-\alpha)\,q_{i,t}$
First phase mass flow rate	1 2 3	$= 1.0$ $= -R_{1,j}$ $= 0.0$
Second phase mass flow rate	1 2 3	$= 1.0$ $= -R_{1,j}$ $= 0.0$

Component default parameters		
M	Component total mass (kg)	15.0
$\bar{c}$	Mass weighted average specific heat (J/kgK)	1000.0
UA	Overall heat loss coefficient (W/K)	3.5
A_a	Coil air side heat transfer area (m^2)	15.0
A_w	Coil water side heat transfer area (m^2)	0.33
A_f	Coil face area (m^2)	0.25
R_m	Coil metal thermal resistance (m^2K/W)	$0.1\ 10^{-2}$
d_i	Internal tube diameter (m)	0.015
θ_{wi}	Inlet water temperature (C)	80.0

Control data variables
Water flow rate (kg/s)

ESP-r coefficient generator name "CMP11C", plant component database reference number 9.

Air to air plate heat exchanger; 2 node model (type 120)

Characterisitic balance equations		
State space variable	Node	Equation
Temperature (C)	1	$C_{1,j}(\theta_j - \theta_1) + \frac{UA}{2}(\theta_e - \theta_1) + q = \frac{\bar{c}M\delta\theta_1}{\delta t}$
	2	$C_{2,k}(\theta_k - \theta_2) + \frac{UA}{2}(\theta_e - \theta_2) - q = \frac{\bar{c}M\delta\theta_1}{\delta t}$
First phase mass flow rate (kg/s)	1	$\dot{m}_{a,1} - R_{j,1}\dot{m}_{a,j} = 0$
	2	$\dot{m}_{a,2} - R_{k,2}\dot{m}_{a,k} = 0$
Second phase mass flow rate (kg/s)	1	$\dot{m}_{v,1} - R_{1,j}\dot{m}_{v,j} = 0$
	2	$\dot{m}_{v,2} - R_{2,k}\dot{m}_{v,k} = 0$

Generated coefficients		
State space variable	Coefficient	Equation
Temperature	1	$= \alpha\,(- C_{1,j,t+\Delta t} - \frac{UA_{t+\Delta t}}{2}) - \frac{\bar{c}M}{\Delta t}$
	2	$= \alpha\,(- C_{2,k,t+\Delta t} - \frac{UA_{t+\Delta t}}{2}) - \frac{\bar{c}M}{\Delta t}$
	3	$= \alpha\, C_{1,j,t+\Delta t}$
	4	$= \alpha\, C_{2,k,t+\Delta t}$
	5	$= \left\{ (1-\alpha)\left[C_{1,j,t} + \frac{UA_t}{2} \right] - \frac{\bar{c}M}{\Delta t} \right\} \theta_{1,t}$ $+ (1-\alpha)(-C_{1,j,t})\,\theta_{j,t}$ $- \alpha\, \frac{UA_{t+\Delta t}}{2}\,\theta_{e,t+\Delta t} - (1-\alpha)\,\frac{UA_t}{2}\,\theta_{e,t}$ $- \alpha\, q_{t+\Delta t} - (1-\alpha)\, q_t$
	6	$= \left\{ (1-\alpha)\left[C_{2,k,t} + \frac{UA_t}{2} \right] - \frac{\bar{c}M}{\Delta t} \right\} \theta_{2,t}$ $+ (1-\alpha)(-C_{2,k,t})\,\theta_{k,t}$ $- \alpha\, \frac{UA_{t+\Delta t}}{2}\,\theta_{e,t+\Delta t} - (1-\alpha)\,\frac{UA_t}{2}\,\theta_{e,t}$ $+ \alpha\, q_{t+\Delta t} + (1-\alpha)\, q_t$
First phase mass flow rate	1	$= 1.0$
	2	$= 1.0$
	3	$= -R_{1,j}$
	4	$= -R_{2,k}$
	5	$= 0.0$
	6	$= 0.0$
Second phase mass flow rate	1	$= 1.0$
	2	$= 1.0$
	3	$= -R_{1,j}$
	4	$= -R_{2,k}$
	5	$= 0.0$

Generated coefficients		
State space variable	Coefficient	Equation
	6	$= 0.0$

Component default parameters		
M	Component total mass (kg)	10.0
$\bar{c}$	Mass weighted average specific heat (J/kgK)	1000.0
UA	Overall heat loss coefficient (W/K)	7.0
A_p	Total plate heat transfer area (m^2)	15.0
A_f	Heat exchanger net face area (m^2)	0.25

ESP-r coefficient generator name "CMP12C", plant component database reference number 10.

Non-condensing domestic WCH boiler; 1 node model (type 200)

Characterisitic balance equation		
State space variable	Node	Equation
Temperature (C)	1	$C_{1,j}(\theta_j - \theta_1) + UA(\theta_e - \theta_1) + q = \frac{\bar{c}M\delta\theta_1}{\delta t}$
First phase mass flow rate (kg/s)	1	$\dot{m}_{w,1} - R_{1,j}\dot{m}_{w,j} = 0$
Second phase mass flow rate (kg/s)	1	Not applicable

Generated coefficients		
State space variable	Coefficient	Equation
Temperature	1	$= \alpha\,(-C_{1,j,t+\Delta t} - UA_{t+\Delta t}) - \frac{\bar{c}M}{\Delta t}$
	2	$= \alpha\, C_{1,j,t+\Delta t}$
	3	$= \left\{ (1-\alpha)\left[C_{1,j,t} + UA_t \right] - \frac{\bar{c}M}{\Delta t} \right\} \theta_{1,t}$ $+ (1-\alpha)(-C_{1,j,t})\,\theta_{j,t}$ $-\alpha\, UA_{t+\Delta t}\,\theta_{e,t+\Delta t} - (1-\alpha)UA_t\theta_{e,t}$ $-\alpha\, q_{t+\Delta t} - (1-\alpha)\, q_t$
First phase mass flow rate	1	$= 1.0$
	2	$= -R_{1,j}$
	3	$= 0.0$
Second phase mass flow rate	1	$= 1.0$
	2	$= 0.0$
	3	$= 0.0$

Component default parameters		
M	Component total mass (kg)	50.0
$\bar{c}$	Mass weighted average specific heat (J/kgK)	600.0
UA	Overall heat loss coefficient (W/K)	20.0

Control data variables
Energy supplied $q(W)$

ESP-r coefficient generator name "CMP20C", plant component database reference number 11.

Characterisitic balance equations		
State space variable	Node	Equation
Temperature (C)	1	$C_{1,j}(\theta_j - \theta_1) = \frac{\bar{c}M\delta\theta_1}{2\delta t}$
	2	$\dot{m}_{w,1}c_{pw}(\theta_1 - \theta_2) - q_1 = \frac{\bar{c}M\delta\theta_2}{2\delta t}$
First phase mass flow rate (kg/s)	1	$\dot{m}_{w,1} - R_{j,1}\dot{m}_{w,j} = 0$
	2	$\dot{m}_{w,2} - \dot{m}_{w,1} = 0$
Second phase mass flow rate (kg/s)	1	Not applicable
	2	Not applicable

Generated coefficients		
State space variable	Coefficient	Equation
Temperature	1	$= \alpha(-C_{1,j,t+\Delta t}) - \frac{\bar{c}M}{2\Delta t}$
	2	$= \alpha\, \dot{m}_{w,1,t+\Delta t}c_{pw}$
	3	$= \alpha(-\dot{m}_{w,1,t+\Delta t}c_{pw}) - \frac{\bar{c}M}{2\Delta t}$
	4	$= \alpha\, C_{1,j,t+\Delta t}$
	5	$= \left\{(1-\alpha)\,C_{1,j,t} - \frac{\bar{c}M}{2\Delta t}\right\}\theta_{1,t}$ $+ (1-\alpha)(-C_{1,j,t})\,\theta_{j,t}$
	6	$= \left\{(1-\alpha)(\dot{m}_{w,1,t}c_{pw})\right\}\theta_{2,t}$ $+ (1-\alpha)\left[-\dot{m}_{w,1,t}c_{pw} - \frac{\bar{c}M}{2\Delta t}\right]\theta_{2,t}$ $+ \alpha\, q_{1,t+\Delta t} + (1-\alpha)\, q_{1,t}$
First phase mass flow rate	1	$= 1.0$
	2	$= -1.0$
	3	$= 1.0$
	4	$= -R_{1,j}$
	5	$= 0.0$
	6	$= 0.0$
Second phase mass flow rate	1	$= 1.0$
	2	$= 0.0$
	3	$= 1.0$
	4	$= 0.0$
	5	$= 0.0$
	6	$= 0.0$

Component default parameters		
M	Component total mass (kg)	25.0
$\overline{c}$	Mass weighted average specific heat (J/kgK)	600.0
n	Radiator exponent (–)	1.3
q_0	Nominal heat emission of radiator (W)	1005.0
$\theta_{s,0}$	Nominal supply temperature (C)	90.0
$\theta_{x,0}$	Nominal exit temperature (C)	70.0
$\theta_{e,0}$	Nominal environment temperature (C)	20.0
I_Z	Index of coupled building zone (–)	0.0
N_w	Number of walls used for defining environment temperature (–)	0.0
$I_{w,1}$	Index of first wall (–)	0.0
$a_{w,1}$	Weighting factor of first wall (–)	0.0
$I_{w,2}$	Index of second wall (–)	0.0
$a_{w,2}$	Weighting factor of second wall (–)	0.0
	etc.	

ESP-r coefficient generator name "CMP21C", plant component database reference number 12.

WCH pipe; 1 node model (type 220)

Characterisitic balance equation		
State space variable	Node	Equation
Temperature (C)	1	$C_{1,j}(\theta_j - \theta_1) + UA_{x(}\ \theta_e - \theta_1) = \frac{\bar{c}M\delta\theta_1}{\delta t}$
First phase mass flow rate (kg/s)	1	$\dot{m}_{w,1} - R_{1,j}\dot{m}_{w,j} = 0$
Second phase mass flow rate (kg/s)	1	Not applicable

Generated coefficients		
State space variable	Coefficient	Equation
Temperature	1	$= \alpha\ (- C_{1,j,t+\Delta t} - UA_{x,t+\Delta t}\ ) - \frac{\bar{c}M}{\Delta t}$
	2	$= \alpha\ C_{1,j,t+\Delta t}$
	3	$= \left\{ (1-\alpha) \left[C_{1,j,t} + UA_{x,t} \right] - \frac{\bar{c}M}{\Delta t} \right\} \theta_{1,t} + (1-\alpha)\ (-C_{1,j,t})\ \theta_{j,t} - \alpha\ UA_{x,t+\Delta t}\ \theta_{e,t+\Delta t} - (1-\alpha)UA_{x,t}\theta_{e,t}$
First phase mass flow rate	1	$= 1.0$
	2	$= -R_{1,j}$
	3	$= 0.0$
Second phase mass flow rate	1	$= 1.0$
	2	$= 0.0$
	3	$= 0.0$

Component default parameters		
M	Component total mass (kg)	2.0
$\bar{c}$	Mass weighted average specific heat (J/kgK)	2250.0
UA	Overall heat loss coefficient (W/K)	2.0
d_h	Hydraulic diameter of pipe (m)	0.015
L	Length of pipe section (m)	5.0
A_f	Cross sectional face area (m^2)	$0.1767\ 10^{-3}$

ESP-r coefficient generator name "CMP22C", plant component database reference number 13.

WCH pipe converging 2-leg junction; 1 node model (type 230)

Characterisitic balance equation		
State space variable	Node	Equation
Temperature (C)	1	$C_{1,j}(\theta_j - \theta_1) + C_{1,k}(\theta_k - \theta_1) + UA(\theta_e - \theta_1) = \frac{\overline{c}M\delta\theta_1}{\delta t}$
First phase mass flow rate (kg/s)	1	$\dot{m}_{w,1} - R_{1,j}\dot{m}_{w,j} - R_{1,k}\dot{m}_{w,k} = 0$
Second phase mass flow rate (kg/s)	1	Not applicable

Generated coefficients		
State space variable	Coefficient	Equation
Temperature	1	$= \alpha(- C_{1,j,t+\Delta t} - C_{1,k,t+\Delta t} - UA_{t+\Delta t}) - \frac{\overline{c}M}{\Delta t}$
	2	$= \alpha\, C_{1,j,t+\Delta t}$
	3	$= \alpha\, C_{1,k,t+\Delta t}$
	4	$= \left\{ (1-\alpha)\left[C_{1,j,t} + C_{1,k,t} + UA_t \right] - \frac{\overline{c}M}{\Delta t} \right\} \theta_{1,t}$ $+ (1-\alpha)(- C_{1,j,t})\,\theta_{j,t} + (1-\alpha)(- C_{1,k,t})\,\theta_{k,t}$ $- \alpha\, UA_{t+\Delta t}\, \theta_{e,t+\Delta t} - (1-\alpha) UA_t \theta_{e,t}$
First phase mass flow rate	1	$= 1.0$
	2	$= - R_{1,j}$
	3	$= - R_{1,k}$
	4	$= 0.0$
Second phase mass flow rate	1	$= 1.0$
	2	$= 0.0$
	3	$= 0.0$
	4	$= 0.0$

Component default parameters		
M	Component total mass (kg)	0.1
$\overline{c}$	Mass weighted average specific heat (J/kgK)	2250
UA	Overall heat loss coefficient (W/K)	0.02

ESP-r coefficient generator name "CMP23C", plant component database reference number 14.

Variable speed domestic WCH pump; 1 node mode (type 240)

Characterisitic balance equation		
State space variable	Node	Equation
Temperature (C)	1	$C_{1,j}(\theta_j - \theta_1) + UA\,(\theta_e - \theta_1) + q = \frac{\bar{c}M\delta\theta_1}{\delta t}$
First phase mass flow rate (kg/s)	1	$\dot{m}_{w,1} = \Gamma$
First phase mass flow rate (kg/s) with mfs active	1	$\dot{m}_{w,1} - R_{1,j}\dot{m}_{w,j} = 0$
Second phase mass flow rate (kg/s)	1	Not applicable

Generated coefficients		
State space variable	Coefficient	Equation
Temperature	1	$= \alpha\,(-C_{1,j,t+\Delta t} - UA_{t+\Delta t}) - \frac{\bar{c}M}{\Delta t}$
	2	$= \alpha\, C_{1,j,t+\Delta t}$
	3	$= \left\{ (1-\alpha)\left[C_{1,j,t} + UA_t \right] - \frac{\bar{c}M}{\Delta t} \right\} \theta_{1,t} + (1-\alpha)\,(-C_{1,j,t})\,\theta_{j,t} - \alpha\, UA_{t+\Delta t}\,\theta_{e,t+\Delta t} - (1-\alpha) UA_t \theta_{e,t} - \alpha\, q_{t+\Delta t} - (1-\alpha)\, q_t$
First phase mass flow rate	1	$= 1.0$
	2	$= 0.0$, $= -R_{1,j}$ (if mfs active)
	3	$= \Gamma$, $= 0.0$ (if mfs active)
Second phase mass flow rate	1	$= 1.0$
	2	$= 0.0$
	3	$= 0.0$

Component default parameters		
M	Component total mass (kg)	5.0
$\bar{c}$	Mass weighted average specific heat (J/kgK)	2250.0
UA	Overall heat loss coefficient (W/K)	0.2
q_r	Rated total absorbed power (W)	150.0
Γ_r	Rated volume flow rate ($m\,3/s$)	0.0003
η	Overall efficiency (-)	0.7

Control data variables
Volume flow rate $\Gamma(m^{3/s})$

ESP-r coefficient generator name "CMP24C", plant component database reference number 15.

Characterisitic balance equations		
State space variable	Node	Equation
Temperature (C)	1	$C_{1,j}(\theta_j - \theta_1) = \frac{\overline{c}M\delta\theta_1}{2\delta t}$
	2	$\dot{m}_{w,j}c_{pw}(\theta_1 - \theta_2) + q_w - q_{sb} = \frac{\overline{c}M\delta\theta_2}{2\delta t}$
First phase mass flow rate (kg/s)	1	$\dot{m}_{w,1} - R_{j,1}\dot{m}_{w,j} = 0$
	2	$\dot{m}_{w,2} - \dot{m}_{w,1} = 0$
Second phase mass flow rate (kg/s)	1	Not applicable
	2	Not applicable

Generated coefficients		
State space variable	Coefficient	Equation
Temperature	1	$= \alpha\,(-C_{1,j,t+\Delta t}) - \frac{\overline{c}M}{2\Delta t}$
	2	$= \alpha\,\dot{m}_{w,1,t+\Delta t}c_{pw}$
	3	$= \alpha\,(-\dot{m}_{w,1,t+\Delta t}c_{pw}) - \frac{\overline{c}M}{2\Delta t}$
	4	$= \alpha\,C_{1,j,t+\Delta t}$
	5	$= \left\{(1-\alpha)\,C_{1,j,t} - \frac{\overline{c}M}{2\Delta t}\right\}\theta_{1,t} + (1-\alpha)(-C_{1,j,t})\,\theta_{j,t}$
	6	$= \left\{(1-\alpha)(\dot{m}_{w,1,t}c_{pw})\right\}\theta_{2,t} + (1-\alpha)\left[-\dot{m}_{w,1,t}c_{pw} - \frac{\overline{c}M}{2\Delta t}\right]\theta_{2,t} + \alpha\,(q_{w,t+\Delta t} - q_{sb,t+\Delta t}) + (1-\alpha)(q_{w,t} - q_{sb,t})$
First phase mass flow rate	1	$= 1.0$
	2	$= -1.0$
	3	$= 1.0$
	4	$= -R_{1,j}$
	5	$= 0.0$
	6	$= 0.0$
Second phase mass flow rate	1	$= 1.0$
	2	$= 0.0$
	3	$= 1.0$
	4	$= 0.0$
	5	$= 0.0$
	6	$= 0.0$

Component default parameters		
M	Component total mass (kg)	50.0
$\overline{c}$	Mass weighted average specific heat (J/kgK)	1000.0
F_{ON}	Full load gas firing rate if boiler on (m^3/s)	0.0003
F_{sb}	Stand-by gas consumption relative to 1 (-)	0.01
H	Gas heating value at STP (J/m^3)	$0.35\ 10^8$
η_c	Full load water sided efficiency at θ_c (-)	0.86
$tg(\alpha_1)$	Tangent of efficiency curve for $\theta_j < \theta_c (1/K)$	0.0025
$tg(\alpha_2)$	Tangent of efficiency curve for $\theta_j > T_c (1/K)$	0.00025
$L_{sb,0}$	Stand-by loss at $\theta_j = \theta_e$ relative to 1 (-)	0.008
$tg(\beta)$	Tangent of stand-by loss curve ($1/K$)	0.00041
t_0	Normalized start-stop loss (s)	1.0
$\theta_{\max}$	Upper boiler temperature limit (C)	95.000

Control data variables
ON/OFF control signal (-)

ESP-r coefficient generator name "CMP25C", plant component database reference number 16.

Characterisitic balance equations		
State space variable	Node	Equation
Temperature (C)	1	$C_{1,j}(\ \theta_j - \theta_1) = \frac{\overline{c}M\delta\theta_1}{2\delta t}$
	2	$\dot{m}_{w,1}c_{pw}\ (\ \theta_1 - \theta_2) + q_w = \frac{\overline{c}M\delta\theta_2}{2\delta t}$
First phase mass flow rate (kg/s)	1	$\dot{m}_{w,1} - R_{j,1}\dot{m}_{w,j} = 0$
	2	$\dot{m}_{w,2} - \dot{m}_{w,1} = 0$
Second phase mass flow rate (kg/s)	1	Not applicable
	2	Not applicable

Generated coefficients		
State space variable	Coefficient	Equation
Temperature	1	$= \alpha\ (-\ C_{1,j,t+\Delta t}) - \frac{\overline{c}M}{2\Delta t}$
	2	$= \alpha\ \dot{m}_{w,1,t+\Delta t}c_{pw}$
	3	$= \alpha\ (-\dot{m}_{w,1,t+\Delta t}c_{pw}) - \frac{\overline{c}M}{2\Delta t}$
	4	$= \alpha\ C_{1,j,t+\Delta t}$
	5	$= \left\{\ (1-\alpha)\ C_{1,j,t} - \frac{\overline{c}M}{2\Delta t}\right\}\theta_{1,t}$ $+ (1-\alpha)\ (-\ C_{1,j,t})\ \theta_{j,t}$
	6	$= \left\{\ (1-\alpha)\ (\dot{m}_{w,1,t}c_{pw})\ \right\}\theta_{2,t}$ $+ (1-\alpha)\left[\ -\ \dot{m}_{w,1,t}c_{pw} - \frac{\overline{c}M}{2\Delta t}\right]\theta_{2,t}$ $+ \alpha\ q_{w,t+\Delta t} + (\ 1-\alpha\ )\ q_{w,t}$
First phase mass flow rate	1	$= 1.0$
	2	$= -1.0$
	3	$= 1.0$
	4	$= -\ R_{1,j}$
	5	$= 0.0$
	6	$= 0.0$
Second phase mass flow rate	1	$= 1.0$
	2	$= 0.0$
	3	$= 1.0$
	4	$= 0.0$
	5	$= 0.0$
	6	$= 0.0$

Component default parameters		
M	Component total mass (kg)	225.0
$\overline{c}$	Mass weighted average specific heat (J/kgK)	951.0
$\dot{m}_f$	Fuel mass flow rate (kg/s)	$0.6303\ 10^{-3}$
CO_2	Volumetric ratio of CO_2 in flue gases during operation (-)	0.136
$(AU)_0$	Heat exchange coefficient water/flue gases in nominal conditions (W/K)	34.28
K_1	Sensitivity coefficient for AU (-)	0.5
K_2	Sensitivity coefficient for AU (-)	0.005
Y_w	Heat loss to the environment if OFF (W/K)	4.208
DY_w	Heat loss increase to environment if ON (W/K)	9.792
K_w	weighting factor for defining mean water temperature (-)	0.5
$\dot{m}_{f,0}$	fuel nominal mass flow rate (kg/s)	$0.6303\ 10^{-3}$
$\dot{m}_{w,0}$	water nominal mass flow rate (kg/s)	1.624
$(CO_2)_0$	nominal ratio of CO_2 in flue gases (-)	0.136
C_1	coefficient for defining specific heat flue gases (J/kgK)	3294.0
C_2	coefficient for defining specific heat flue gases (J/kgK)	2105.0
c_{pf}	Fuel specific heat (J/kgK)	1880.0
H	Fuel heating value (J/kg)	$0.42875\ 10^{8}$

Control data variables
Aquastat set point (C)
ON/OFF control signal (-)

ESP-r coefficient generator name "CMP26C", plant component database reference number 17.

Domestic hot water radiator; 8 node model (type 270)

Characterisitic balance equations		
State space variable	Node	Equation
Temperature (C)	1 n=2,8	$C_{1,j}(\theta_j - \theta_1) = \frac{\overline{c}M\delta\theta_1}{2\delta t}$ $\dot{m}_{w,1}c_{pw}(\theta_{n-1} - \theta_n) - q_{n-1} = \frac{\overline{c}M\delta\theta_n}{8\delta t}$
First phase mass flow rate (kg/s)	1 n=2..8	$\dot{m}_{w,1} - R_{j,1}\dot{m}_{w,j} = 0$ $\dot{m}_{w,n} - \dot{m}_{w,n-1} = 0$
Second phase mass flow rate (kg/s)	n=1,8	Not applicable

Generated coefficients		
State space variable	Coefficient	Equation
Temperature	1 k=2,4..14 k=3,5..15 16 17 k=18..24	$= \alpha\,(-C_{1,j,t+\Delta t}) - \frac{\overline{c}M}{8\Delta t}$ $= \alpha\,\dot{m}_{w,1,t+\Delta t}c_{pw}$ $= \alpha\,(-\dot{m}_{w,1,t+\Delta t}c_{pw}) - \frac{\overline{c}M}{8\Delta t}$ $= \alpha\,C_{1,j,t+\Delta t}$ $= \left\{(1-\alpha)\,C_{1,j,t} - \frac{\overline{c}M}{8\Delta t}\right\}\theta_{1,t}$ $+ (1-\alpha)\,(-C_{1,j,t})\,\theta_{j,t}$ $= \left\{(1-\alpha)\,(-\dot{m}_{w,1,t}c_{pw})\right\}\theta_{n,t}$ $+ (1-\alpha)\left[\dot{m}_{w,1,t}c_{pw} - \frac{\overline{c}M}{8\Delta t}\right]\theta_{n,t}$ $+ \alpha\,q_{n,t+\Delta t} + (1-\alpha)\,q_{n,t} \quad n = 2..8$
First phase mass flow rate	1 k=2,4..14 k=3,5..15 16 k=17..24 6	$= 1.0$ $= -1.0$ $= 1.0$ $= -R_{1,j}$ $= 0.0$ $= 0.0$
Second phase mass flow rate	1 k=2,4..14 k=3,5..15 k=16..24	$= 1.0$ $= 0.0$ $= 1.0$ $= 0.0$

Component default parameters		
M	Component total mass (kg)	25.0
$\bar{c}$	Mass weighted average specific heat (J/kgK)	600.0
n	Radiator exponent (–)	1.3
q_0	Nominal heat emission of radiator (W)	1005.0
$\theta_{s,0}$	Nominal supply temperature (C)	90.0
$\theta_{x,0}$	Nominal exit temperature (C)	70.0
$\theta_{e,0}$	Nominal environment temperature (C)	20.0
I_Z	Index of coupled building zone (–)	0.0
N_W	Number of walls used for defining environment temperature (–)	0.0
$I_{W,1}$	Index of first wall (–)	0.0
$a_{W,1}$	Weighting factor of first wall (–)	0.0
$I_{W,2}$	Index of second wall (–)	0.0
$a_{W,2}$	Weighting factor of second wall (–)	0.0
	etc.	

ESP-r coefficient generator name "CMP27C", plant component database reference number 18.

Single node water cooler with flux control (type 300)

Characterisitic balance equation		
State space variable	Node	Equation
Temperature (C)	1	$C_{1,j}(\theta_j - \theta_1) + UA(\theta_e - \theta_1) + q = \frac{\bar{c}M\delta\theta_1}{\delta t}$
First phase mass flow rate (kg/s)	1	$\dot{m}_{w,1} - R_{1,j}\dot{m}_{w,j} = 0$
Second phase mass flow rate (kg/s)	1	Not applicable

Generated coefficients		
State space variable	Coefficient	Equation
Temperature	1	$= \alpha\,(-C_{1,j,t+\Delta t} - UA_{t+\Delta t}) - \frac{\bar{c}M}{\Delta t}$
	2	$= \alpha\, C_{1,j,t+\Delta t}$
	3	$= \left\{(1-\alpha)\left[C_{1,j,t} + UA_t\right] - \frac{\bar{c}M}{\Delta t}\right\}\theta_{1,t}$ $+ (1-\alpha)(-C_{1,j,t})\,\theta_{j,t}$ $-\alpha\, UA_{t+\Delta t}\,\theta_{e,t+\Delta t} - (1-\alpha)UA_t\theta_{e,t}$ $-\alpha\, q_{t+\Delta t} - (1-\alpha)\, q_t$
First phase mass flow rate	1	$= 1.0$
	2	$= -R_{1,j}$
	3	$= 0.0$
Second phase mass flow rate	1	$= 1.0$
	2	$= 0.0$
	3	$= 0.0$

Component default parameters		
M	Component total mass (kg)	20.0
$\bar{c}$	Mass weighted average specific heat (J/kgK)	1000.0
UA	Overall heat loss coefficient (W/K)	15.0

Control data variables
Cooling duty $q(W)$

ESP-r coefficient generator name "CMP30C", plant component database reference number 19.

Air cooling coil fed by WCH system; 3 node model (type 400)

Characterisitic balance equation		
State space variable	Node	Equation
Temperature (C)	1 (solid)	$k_a(\theta_a - \theta_s) + k_w(\theta_w - \theta_s) + UA(\theta_e - \theta_s) = \frac{\overline{c}_s M_s \delta\theta_s}{\delta t}$
	2 (air)	$C_{a,j}(\theta_j - \theta_a) + k_a(\theta_e - \theta_a) + q_a = 0$
	3 (water)	$C_{w,k}(\theta_k - \theta_{w)} + k_w(\theta_s - \theta_{w)} + q_w = \frac{\overline{c}_w M_w \delta\theta_w}{\delta t}$
First phase mass flow rate (kg/s)	1 (solid)	Not applicable
	2 (air)	$\dot{m}_a - R_{a,j}\dot{m}_{a,j} = 0$
	3 (water)	$\dot{m}_w - R_{w,k}\dot{m}_{w,k} = 0$
Second phase mass flow rate (kg/s)	1 (solid)	Not applicable
	2 (air)	$\dot{m}_v - R_{a,j}\dot{m}_{v,j} = 0$
	3 (water)	Not applicable

Generated coefficients		
State space variable	Coefficient	Equation
Temperature	1	$= \alpha(-k_{a,t+\Delta t} - k_{w,t+\Delta t} - UA_{t+\Delta t}) - \frac{\overline{c}M}{\Delta t}$
	2	$= \alpha\, k_{a,t+\Delta t}$
	3	$= \alpha\, k_{w,t+\Delta t}$
	4	$= k_{a,t+\Delta t}$
	5	$= -C_{a,j} - k_{a,t+\Delta t}$
	6	$= \alpha\, k_{w,t+\Delta t}$
	7	$= \alpha(k_{w,t+\Delta t} - C_{w,k,t+\Delta t}) - \frac{\overline{c}_w M_w}{\Delta t}$
	8	$= C_{a,j,t+\Delta t}$
	9	$= \alpha\, C_{w,k,t+\Delta t}$
	10	$= \left\{(1-\alpha)\left[k_{a,t} + k_{w,t} + UA_t\right] - \frac{\overline{c}_a M_a}{\Delta t}\right\}\theta_{s,t}$ $+ (1-\alpha)(-k_{a,t})\,\theta_{a,t}$ $+ (1-\alpha)(-k_{w,t})\,\theta_{w,t}$ $- \alpha\, UA_{t+\Delta t}\,\theta_{e,t+\Delta t} - (1-\alpha)UA_t\theta_{e,t}$
	11	$= -q_{a-}\,\dot{m}_{vc,t+\Delta t}h_c$
	12	$= (1-\alpha)(-k_{w,t})\,\theta_{s,t}$ $+ \left\{(1-\alpha)(C_{w,k,t} + k_{w,t}) - \frac{\overline{c}_w M_w}{\Delta t}\right\}\theta_{w,t}$ $+ (1-\alpha)(-C_{w,k,t})\,\theta_{k,t}$ $- \alpha\, q_{w,t+\Delta t} - (1-\alpha)\,q_{w,t}$
First phase mass flow rate	1	$= 1.0$
	2	$= 0.0$
	3	$= 0.0$

Generated coefficients		
State space variable	Coefficient	Equation
	4	$= 0.0$
	5	$= 1.0$
	6	$= 0.0$
	7	$= 1.0$
	8	$= - R_{a,j}$
	9	$= - R_{w,k}$
	10	$= 0.0$
	11	$= 0.0$
	12	$= 0.0$
Second phase mass flow rate	1	$= 1.0$
	2	$= 0.0$
	3	$= 0.0$
	4	$= 0.0$
	5	$= 1.0$
	6	$= 0.0$
	7	$= 1.0$
	8	$= - R_{a,j}$ for $\theta_{air} \geq \theta_{dew},$ $else$ $= 0.0$
	9	$= 0.0$
	10	$= 0.0$
	11	$= 0.0$ for $\theta_{air} \geq \theta_{dew},$ $else$ $= \dot{m}_{v,max}$
	12	$= 0.0$

Component default parameters		
M	Component total mass (kg)	15.0
$\bar{c}$	Mass weighted average specific heat (J/kgK)	500.0
UA	Overall heat loss coefficient (W/K)	3.5
M_w	Mass of water encapsulated in component (kg)	2.0
A_o	Coil outside (air) heat transfer area (m^2)	15.0
A_i	Coil inside (water) heat transfer area (m^2)	0.33
A_f	Coil face area (m^2)	0.25
R_m	Metal thermal resistance ($m^2 K/W$)	0.001
d_i	Internal tube diameter (m)	0.015

ESP-r coefficient generator name "CMP40C", plant component database reference number 20.

Air Heating coil fed by WCH system; 3 node model (type 410)

Characterisitic balance equation		
State space variable	Node	Equation
Temperature (C)	1 (solid)	$k_a(\ \theta_a - \theta_s) + k_w(\ \theta_w - \theta_s) + UA\ (\ \theta_e - \theta_s) = \dfrac{\overline{c}_s M_s \delta\theta_s}{\delta t}$
	2 (air)	$C_{a,j}(\ \theta_j - \theta_a) + k_a\ (\ \theta_e - \theta_a) + q_a = 0$
	3 (water)	$C_{w,k}(\ \theta_k - \theta_{w)} + k_w(\ \theta_s - \theta_{w)} + q_w = \dfrac{\overline{c}_w M_w \delta\theta_w}{\delta t}$
First phase mass flow rate (kg/s)	1 (solid)	Not applicable
	2 (air)	$\dot{m}_a - R_{a,j}\dot{m}_{a,j} = 0$
	3 (water)	$\dot{m}_w - R_{w,k}\dot{m}_{w,k} = 0$
Second phase mass flow rate (kg/s)	1 (solid)	Not applicable
	2 (air)	$\dot{m}_v - R_{a,j}\dot{m}_{v,j} = 0$
	3 (water)	Not applicable

Generated coefficients		
State space variable	Coefficient	Equation
Temperature	1	$= \alpha\ (-\ k_{a,t+\Delta t} - k_{w,t+\Delta t} - UA_{t+\Delta t}\ ) - \dfrac{\overline{c}M}{\Delta t}$
	2	$= \alpha\ k_{a,t+\Delta t}$
	3	$= \alpha\ k_{w,t+\Delta t}$
	4	$= k_{a,t+\Delta t}$
	5	$= -\ C_{a,j} - k_{a,t+\Delta t}$
	6	$= \alpha\ k_{w,t+\Delta t}$
	7	$= \alpha\ (\ k_{w,t+\Delta t} - C_{w,k,t+\Delta t}) - \dfrac{\overline{c}_w M_w}{\Delta t}$
	8	$= C_{a,j,t+\Delta t}$
	9	$= \alpha\ C_{w,k,t+\Delta t}$
	10	$= \left\{ (1-\alpha)\left[\ k_{a,t} + k_{w,t} + UA_t \right] - \dfrac{\overline{c}_a M_a}{\Delta t} \right\} \theta_{s,t}$
		$+ (1-\alpha)\ (-\ k_{a,t})\ \theta_{a,t}$
		$+ (1-\alpha)\ (-\ k_{w,t})\ \theta_{w,t}$
		$-\ \alpha\ UA_{t+\Delta t}\ \theta_{e,t+\Delta t} - (\ 1-\alpha\ )UA_t\theta_{e,t}$
	11	$= -\ q_a$
	12	$= (1-\alpha)\ (-\ k_{w,t})\ \theta_{s,t}$
		$+ \left\{ (1-\alpha)\ (\ C_{w,k,t} + k_{w,t}) - \dfrac{\overline{c}_w M_w}{\Delta t} \right\} \theta_{w,t}$
		$+ (1-\alpha)\ (-C_{w,k,t})\ \theta_{k,t}$
		$-\ \alpha\ q_{w,t+\Delta t} - (1-\alpha)\ q_{w,t}$
First phase mass flow rate	1	$= 1.0$
	2	$= 0.0$
	3	$= 0.0$

Generated coefficients		
State space variable	Coefficient	Equation
	4	$= 0.0$
	5	$= 1.0$
	6	$= 0.0$
	7	$= 1.0$
	8	$= - R_{a,j}$
	9	$= - R_{w,k}$
	10	$= 0.0$
	11	$= 0.0$
	12	$= 0.0$
Second phase mass flow rate	1	$= 1.0$
	2	$= 0.0$
	3	$= 0.0$
	4	$= 0.0$
	5	$= 1.0$
	6	$= 0.0$
	7	$= 1.0$
	8	$= - R_{a,j}$
	9	$= 0.0$
	10	$= 0.0$
	11	$= 0.0$
	12	$= 0.0$

Component default parameters		
M	Component total mass (kg)	15.0
$\overline{c}$	Mass weighted average specific heat (J/kgK)	500.0
UA	Overall heat loss coefficient (W/K)	3.5
M_w	Mass of water encapsulated in component (kg)	2.0
A_o	Coil outside (air) heat transfer area (m^2)	15.0
A_i	Coil inside (water) heat transfer area (m^2)	0.33
A_f	Coil face area (m^2)	0.25
R_m	Metal thermal resistance ($m^2 K/W$)	0.001
d_i	Internal tube diameter (m)	0.015

ESP-r coefficient generator name "CMP41C", plant component database reference number 21.

Thermostatic radiator valve; 1 node sensor model (type 500)

Characterisitic balance equation		
State space variable	Node	Equation
Temperature (C)	1	$k_w(\theta_w - \theta_1) + k_a(\theta_a - \theta_1) + k_W(\theta_W - \theta_1) + k_r(\theta_r - \theta_1) = \frac{\overline{c} M \delta \theta_1}{\delta t}$
First phase mass flow rate (kg/s)	1	Not applicable
Second phase mass flow rate (kg/s)	1	Not applicable

Generated coefficients		
State space variable	Coefficient	Equation
Temperature	1	$= \alpha\, (-k_{w,t+\Delta t} - k_{a,t+\Delta t} - k_{W,t+\Delta t} - k_{r,t+\Delta t}) - \frac{\overline{c} M}{\Delta t}$
	2	$= \alpha\, k_{w,t+\Delta t}$
	3	$= \alpha\, k_{r,t+\Delta t}$
	4	$= \left\{ (1-\alpha) \left[k_{w,t} + k_{a,t} + k_{W,t} + k_{r,t} \right] - \frac{\overline{c} M}{\Delta t} \right\} \theta_{1,t} + (1-\alpha)\,(-k_{w,t})\,\theta_{w,j,t} + (1-\alpha)\,(-k_{r,t})\,\theta_{r,k,t} - \alpha\, k_{a,t+\Delta t}\theta_{a,t+\Delta t} - (1-\alpha) k_{a,t}\theta_{a,t} - \alpha\, k_{W,t+\Delta t}\theta_{W,t+\Delta t} - (1-\alpha) k_{W,t}\theta_{W,t}$
First phase mass flow rate	1	$= 1.0$
	2	$= 0.0$
	3	$= 0.0$
	4	$= 0.0$
Second phase mass flow rate	1	$= 1.0$
	2	$= 0.0$
	3	$= 0.0$
	4	$= 0.0$

Component default parameters		
M	Component total mass (kg)	0.1
$\overline{c}$	Mass weighted average specific heat (J/kgK)	1000.0
I_Z	Index of coupled building zone (-)	0.0
I_W	Index of coupled wall in that zone (-)	0.0
k_w	Thermal conductance water to sensor (W/K)	0.007
k_a	Equiv. convective conductance to air (W/K)	0.12
k_W	Equiv. radiative conductance to wall (W/K)	0.06
k_r	Equivalent radiative heat transfer conductance to radiator (W/K)	0.006

ESP-r coefficient generator name "CMP50C", plant component database reference number 22.

Mechanical room thermostat; 1 node sensor model (type 510)

Characterisitic balance equation		
State space variable	Node	Equation
Temperature (C)	1	$k_a(\theta_a - \theta_1) + k_{W,1}(\theta_{W,1} - \theta_1) + k_{W,2}(\theta_{W,2} - \theta_1) + q = \frac{\overline{c}M\delta\theta_1}{\delta t}$
First phase mass flow rate (kg/s)	1	Not applicable
Second phase mass flow rate (kg/s)	1	Not applicable

Generated coefficients		
State space variable	Coefficient	Equation
Temperature	1	$= \alpha\,(-k_a - k_{W,1} - k_{W,2}) - \frac{\overline{c}M}{\Delta t}$
	2	$= \left\{ (1-\alpha)\left[k_a + k_{W,1} + k_{W,2}\right] - \frac{\overline{c}M}{\Delta t} \right\} \theta_{1,t}$ $- \alpha\, k_a\theta_{a,t} - (1-\alpha)k_a\theta_{a,t}$ $- \alpha\, k_{W,1}\theta_{W,1,t} - (1-\alpha)k_{W,1}\theta_{W,1,t}$ $- \alpha\, k_{W,2}\theta_{W,2,t} - (1-\alpha)k_{W,1}\theta_{W,2,t}$ $- \alpha\, q_t - (1-\alpha)\, q_t$
First phase mass flow rate	1	= 1.0
	2	= 0.0
Second phase mass flow rate	1	= 1.0
	2	= 0.0

Component default parameters		
M	Component total mass (kg)	0.1
$\overline{c}$	Mass weighted average specific heat (J/kgK)	1000.0
I_Z	Index of coupled building zone (-)	0.0
$I_{W,1}$	Index of viewed wall in that zone (-)	0.0
$I_{W,2}$	Index of wall on which device is mounted (-)	0.0
k_a	Equiv. convective conductance to air (W/K)	0.2
$k_{W,1}$	Equiv. radiative conductance to wall 1 (W/K)	0.1
$k_{W,2}$	Equiv. radiative conductance to wall 2 (W/K)	0.5

ESP-r coefficient generator name "CMP51C", plant component database reference number 23.

Characterisitic balance equations		
State space variable	Node	Equation
Temperature (C)	1 2	$\theta_1 = \theta_a$ $\theta_2 = \theta_w$
First phase mass flow rate (kg/s)	1 2	$\dot{m}_{a,1} - R_{j,1}\dot{m}_{a,j} = 0$ $\dot{m}_{w,2} - R_{k,2}\dot{m}_{w,k} = 0$
Second phase mass flow rate (kg/s)	1 2	$\dot{m}_{v,1} - R_{1,j}\dot{m}_{v,j} = \dot{m}_w^v$ Not applicable

Generated coefficients		
State space variable	Coefficient	Equation
Temperature	1 2 3 4 5 6	1.0 1.0 0.0 0.0 θ_a θ_w
First phase mass flow rate	1 2 3 4 5 6	= 1. 0 = 1. 0 $= - R_{1,j}$ $= -R_{2,k}$ = 0. 0 = 0. 0
Second phase mass flow rate	1 2 3 4 5 6	= 1. 0 = 1. 0 $= - R_{1,j}$ = 0. 0 0. 0 = 0. 0

Control data variables
Air temperature θ_a (C) Water temperature θ_w (C)

ESP-r coefficient generator name "CMP90C", plant component database reference number 24.

Imaginary building-like plant load; 2 node model (type 910)

Characterisitic balance equation		
State space variable	Node	Equation
Temperature (C)	1 (wall)	$k_a(\theta_a - \theta_w) + k_e(\theta_e - \theta_w) + UA(\theta_e - \theta_s) = \frac{\bar{c}_w M_w \delta\theta_w}{\delta t}$
	2 (air)	$C_{a,j}(\theta_j - \theta_a) + k_a(\theta_w - \theta_a) + \dot{m}_l c_p(\theta_e - \theta_a) + q_g = 0$
First phase mass flow rate (kg/s)	1 (wall)	Not applicable
	2 (air)	$\dot{m}_a - R_{a,j}\dot{m}_{a,j} = \dot{m}_l$
Second phase mass flow rate (kg/s)	1 (wall)	Not applicable
	2 (air)	$\dot{m}_v - R_{a,j}\dot{m}_{v,j} = \dot{m}_{vl}$

Generated coefficients		
State space variable	Coefficient	Equation
Temperature	1	$= \alpha(-k_a - k_e) - \frac{\bar{c}M}{\Delta t}$
	2	$= \alpha k_a$
	3	$= k_a$
	4	$= C_{a,j} - k_a - \dot{m}_l c_p$
	5	$= C_{a,j}$
	6	$= \left\{ (1-\alpha)\left[k_a + k_e \right] - \frac{\bar{c}M}{\Delta t} \right\} \theta_{w,t}$ $+ (1-\alpha)(-k_a)\theta_{a,t}$ $- \alpha k_e \theta_{e,t+\Delta t} - (1-\alpha) k_e \theta_{e,t}$
	7	$= -q_g - \dot{m}_l c_p \theta_{e,t}$
First phase mass flow rate	1	$= 1.0$
	2	$= 0.0$
	3	$= 0.0$
	4	$= 1.0$
	5	$= -R_{a,j}$
	6	$= 0.0$
	7	$= \dot{m}_l$
Second phase mass flow rate	1	$= 1.0$
	2	$= 0.0$
	3	$= 0.0$
	4	$= 1.0$
	5	$= -R_{a,j}$
	6	$= 0.0$
	7	$= \dot{m}_{vl}$

Component default parameters		
M	Component total mass (kg)	2500.0
$\overline{c}$	Mass weighted average specific heat (J/kgK)	840.0
U_w	Wall U value (W/m^2K)	0.4
A_w	Total surface area of walls ($m^{2)}$	54.0
V_Z	Zone space volume ($m^{3)}$	27.0
h_i	Inside heat transfer coefficient (W/m^2K)	7.5
h_o	Outside heat transfer coefficient (W/m^2K)	25.0
$ACPH$	Air infiltration	1.0

Control data variables
Building heat gain q_g (W)

ESP-r coefficient generator name "CMP91C", plant component database reference number 25.

Oil filled electric radiator; 1 node model; flux control (type 280)

Characterisitic balance equation		
State space variable	Node	Equation
Temperature (C)	1	$q_i - q_r = \frac{\overline{c} M \delta \theta_1}{\delta t}$
First phase mass flow rate (kg/s)	1	Not applicable
Second phase mass flow rate (kg/s)	1	Not applicable

Generated coefficients		
State space variable	Coefficient	Equation
Temperature	1	$= - \frac{\overline{c} M}{\Delta t}$
	2	$= - \frac{\overline{c} M}{\Delta t} \theta_{1,t} + \alpha\ q_{r,t+\Delta t} + (1 - \alpha)\ q_{r,t} - \alpha\ q_{i,t+\Delta t} - (1 - \alpha)\ q_{i,t}$
First phase mass flow rate	1	$= 1.0$
	2	$= 0.0$
Second phase mass flow rate	1	$= 1.0$
	2	$= 0.0$

Component default parameters		
M	Component total mass (kg)	25.0
$\overline{c}$	Mass weighted average specific heat (J/kgK)	1000.0
n	Radiator exponent (–)	1.3
q_0	Nominal heat emission of radiator (W)	680.0
$\theta_{s,0}$	Nominal radiator temperature (C)	70.0
$\theta_{e,0}$	Nominal environment temperature (C)	20.0
I_Z	Index of coupled building zone (–)	0.0
N_W	Number of walls used for defining environment temperature (–)	0.0
$I_{W,1}$	Index of first wall (–)	0.0
$a_{W,1}$	Weighting factor of first wall (–)	0.0
$I_{W,2}$	Index of second wall (–)	0.0
$a_{W,2}$	Weighting factor of second wall (–)	0.0
	etc.	

Control data variables
Supplied electrical energy q_i (W)

ESP-r coefficient generator name "CMP28C", plant component database reference number 26.

Fictitious boundary component; 1 node model (type 920)

Characterisitic balance equation		
State space variable	Node	Equation
Temperature (C)	1	$\theta_1 = \theta_j$
First phase mass flow rate (kg/s)	1	$\dot{m}_1 - R_{1,j}\dot{m}_{1,j} = 0$
Second phase mass flow rate (kg/s)	1	$\dot{m}_v - R_{1,j}\dot{m}_{v,j} = 0$

Generated coefficients		
State space variable	Coefficient	Equation
Temperature	1 2 3	$= 1.0$ $= 0.0$ $= \theta_j$
First phase mass flow rate	1 2 3	$= 1.0$ $= - R_{1,j}$ $= 0.0$
Second phase mass flow rate	1 2 3	$= 1.0$ $= - R_{1,j}$ $= 0.0$

ESP-r coefficient generator name "CMP92C", plant component database reference number 29.

Air heat exchanger; 10 node model; hot fluid temperature control (type 930)

Characterisitic balance equations		
State space variable	Node	Equation
Temperature (C)	1	$C_{1,j}(\theta_j - \theta_{c,1}) + \frac{1}{R_c}(\theta_{s,6} - \theta_{c,1}) = \frac{\overline{c}_c M_c \delta\theta_{c,1}}{5\delta t}$
	2-5	$\frac{1}{R_c}(\theta_{s,n} - \theta_{c,k}) = \frac{\overline{c}_c M_c \delta\theta_{c,k}}{5\delta t} + \frac{\overline{c}_c M_c \dot{m}_1 \rho}{5A} \frac{\delta\theta_{c,k}}{\delta x}$ $k = 2..5\ ,\ \ n = 7..10$
	6-10	$\frac{1}{R_h}(\theta_h(t) - \theta_{s,n}) + \frac{1}{R_c}(\theta_{c,k} - \theta_{s,n}) + UA(\theta_e - \theta_{s,n})$ $= \frac{\overline{c}_s M_s \delta\theta_{s,n}}{5\delta t}\quad , k = 1..5\ ,\ \ n = 6..10$
First phase mass flow rate (kg/s)	1	$\dot{m}_1 - R_{j,1}\dot{m}_j = 0$
	n=2..5	$\dot{m}_n - \dot{m}_{n-1} = 0$
	n=6..10	Not applicable
Second phase mass flow rate (kg/s)	1	$\dot{m}_{v,1} - R_{j,1}\dot{m}_{v,j} = 0$
	n=2..5	$\dot{m}_{v,n} - \dot{m}_{v,n-1} = 0$
	n=6..10	Not applicable

Generated coefficients		
State space variable	Coefficient	Equation
Temperature	1	$= \alpha\left(-C_{1,j,t+\Delta t} - \frac{1}{R_{c,t+\Delta t}}\right) - \frac{\overline{c}_c M_c}{5\Delta t}$
	k=2,5..14	$= \frac{\alpha}{R_{c,t+\Delta t}}$
	k=3,6..12	$= \frac{\alpha \dot{m}_1 \rho \overline{c}_c M_c}{5A\Delta x}$
	k=4,7..13	$= \alpha\left(-\frac{1}{R_{c,t+\Delta t}} - \frac{\dot{m}_1 \rho \overline{c}_c M_c}{5A\Delta x}\right) - \frac{\overline{c}_c M_c}{5\Delta t}$
	15,17..23	$= \frac{\alpha}{R_{c,t+\Delta t}}$
	16,18..24	$= \alpha\left\{-\frac{1}{R_{h,t+\Delta t}} - \frac{1}{R_{c,t+\Delta t}} - \frac{UA_{t+\Delta t}}{5}\right\} - \frac{\overline{c}_s M_s}{5\Delta t}$
	25	$= \alpha C_{1,j,t+\Delta t}$
	26	$= \left\{(1-\alpha)\left[C_{1,j,t} + \frac{1}{R_{c,t}}\right] - \frac{\overline{c}_c M_c}{5\Delta t}\right\}\theta_{c,1,t}$ $+ (1-\alpha)\left(-\frac{1}{R_{c,t}}\ \theta_{s,6,t} + (1-\alpha)(-C_{1,j,t})\ \theta_{j,t}\right.$

Generated coefficients		
State space variable	Coefficient	Equation
	27..30	$= \left\{ (1-\alpha)\left[\frac{1}{R_{c,t}} + \frac{\dot{m}_1 \rho \overline{c}_c M_c}{5A\Delta x} \right] - \frac{\overline{c}_c M_c}{5\Delta t} \right\} \theta_{c,k,t}$ $+ (1-\alpha)\left[- \frac{\dot{m}_1 \rho \overline{c}_c M_c}{5A\Delta x} \right] \theta_{c,k-1,t} + (1-\alpha)\left[- \frac{1}{R_c} \right] \theta_{s,n,t}$ $k = 2..5\ ,\ \ n = 7..10$
	30..35	$= \left\{ (1-\alpha)\left[\frac{1}{R_h} + \frac{1}{R_c} + \frac{UA_t}{5} \right] - \frac{\overline{c}_s M_s}{5\Delta t} \right\} \theta_{s,n,t}$ $+ (1-\alpha)\ (- \frac{1}{R_{c,t}})\ \theta_{c,k,t}$ $+ (1-\alpha)\ (- \frac{1}{R_{h,t}})\ \theta_{h,t} - \frac{\alpha}{R_{h,t+\Delta t}}\ \theta_{h,t+\Delta t}$ $+ (1-\alpha)\ (- UA_t\ )\ \theta_{e,t} - \alpha UA_{t+\Delta t} \theta_{e,t+\Delta t}$ $k = 1..5\ ,\ \ n = 6..10$
First phase mass flow rate	1	$= 1.0$
	2	$= 0.0$
	3,6..12	$= 1.0$
	4,7..13	$= -1.0$
	5,8..14	$= 0.0$
	15,17..23	$= 0.0$
	16,18..24	$= 1.0$
	25	$= - R_{j,1}$
	26..35	$= 0.0$
Second phase mass flow rate	1	$= 1.0$
	2	$= 0.0$
	3,6..12	$= 1.0$
	4,7..13	$= -1.0$
	5,8..14	$= 0.0$
	15,17..23	$= 0.0$
	16,18..24	$= 1.0$
	25	$= - R_{j,1}$
	26..35	$= 0.0$

Component default parameters		
M_c	Total mass of cold fluid(kg)	4.0
$\overline{c}_c$	Cold fluid specific heat (J/kgK)	1000.0
M_s	Total mass of solid material (kg)	10.0
$\overline{c}_s$	Solid wall specific heat (J/kgK)	2000.0
UA	Overall heat loss coefficient (W/K)	10.0
A	Cold fluid flow area (m^2)	0.05
L	Cold fluid flow length (m)	5.0
R_c	Cold fluid heat transfer resistance (K/W)	0.05
R_h	Hot fluid thermal resistance (K/W)	0.05

Control data variables
Hot fluid temperature $\theta_h(t)$ (C)

ESP-r coefficient generator name "CMP93C", plant component database reference number 30.

Cooling and dehumidifying coil; 2 node model (type 430)

Characterisitic balance equations		
State space variable	Node	Equation
Temperature (C)	1	$\frac{\theta_1 - \theta}{R_{mw}} - \frac{\theta}{R_a + R_4} - UA\ (\ \theta_{i,1} - \theta_e) + \dot{m}_w^v H_w = \frac{\overline{c}_{i,1} M_{i,1} \delta\theta}{\delta t}$
	2	$\frac{1}{R_1}\ (\ \theta_o - \theta_1) - \frac{1}{R_{mw}}\ (\theta_1 - \theta) = \frac{\overline{c}_{i,2} M_{i,2} \delta\theta_1}{\delta t}$
First phase mass flow rate (kg/s)	1	$\dot{m}_{a,1} - R_{j,1}\dot{m}_{a,j} = 0$
	2	$\dot{m}_{w,2} - R_{k,2}\dot{m}_{w,k} = 0$
Second phase mass flow rate (kg/s)	1	$\dot{m}_{v,1} - R_{1,j}\dot{m}_{v,j} = \dot{m}_w^v$
	2	Not applicable

Generated coefficients		
State space variable	Coefficient	Equation
Temperature	1	$= \alpha\ (- \frac{1}{R_{mw,t+\Delta t}}\ R_{r,t+\Delta t} - \frac{1}{R_{4,t+\Delta t}} - UA\ ) - \frac{\overline{c}_{i,1} M_{i,1}}{\Delta t}\ R_{r,t+\Delta t}$
	2	$= \frac{\alpha}{R_{mw,t+\Delta t}}$
	3	$= \alpha\ R_{r,t+\Delta t}$
	4	$= \alpha\ (\ - \frac{1}{R_{1,t+\Delta t}} - \frac{1}{R_{mw,t+\Delta t}}\ ) - \frac{\overline{c}_{i,2} M_{i,2}}{\delta t}$
	5	$= \alpha\ (\ \frac{1}{R_{mw,t+\Delta t}}\ R_{r,t+\Delta t} + \frac{1}{R_{4,t+\Delta t}} - \frac{1}{R_{mw,t+\Delta t}})$ $+ \frac{\overline{c}_{i,1} M_{i,1}}{\Delta t}\ R_{r,t+\Delta t}$
	6	$= \frac{\alpha}{R_{1,t+\Delta t}}$
	7	$= \left\{ (1-\alpha) \left[\left(\frac{R_r}{R_{mw}} \right)_{r,t} + \frac{1}{R_{4,t}} - UA_t \right] - \frac{\overline{c}_{i,1} M_{i,1}}{\Delta t}\ R_{r,t} \right\} \theta_{i,1,t}$ $- \frac{(1-\alpha)}{R_{mw,t}}\ \theta_{i,2,t}$ $+ \left\{ (1-\alpha) \left[-\left(\frac{R_r}{R_{mw}} \right)_{r,t} - \frac{1}{R_{4,t}} + \frac{1}{R_{mw,t}} \right] + \frac{\overline{c}_{i,1} M_{i,1}}{\Delta t}\ R_{r,t} \right\} \theta_{j,t}$ $- \alpha\ UA_{t+\Delta t}\ \theta_{e,t+\Delta t} - (\ 1 - \alpha\ ) UA_t\ \theta_{e,t}$ $- \alpha\ (H_w \dot{m}_w^v)_{t+\Delta t} - (\ 1 - \alpha\ )\ (H_w \dot{m}_w^v)_t$

Generated coefficients		
	8	$= (1-\alpha)\left(\frac{R_r}{R_{mw}}\right)_{r,t} \theta_{i,1,t} + \left\{ (1-\alpha)\left[\frac{1}{R_{1,t}} + \frac{1}{R_{mw,t}}\right] - \frac{\overline{c}_{i,2} M_{i,2}}{\Delta t} \right\} \theta_{i,2,t} - \frac{(1-\alpha)}{R_{4,t}} \theta_{k,t} + \left\{ \frac{(1-\alpha)}{R_{mw,t}} (-1 + R_{r,t}) + \frac{\overline{c}_{i,2} M_{i,2}}{\Delta t} \right\} \theta_{j,t} + \left\{ \frac{\alpha}{R_{mw,t+\Delta t}} (-1 + R_{r,t+\Delta t}) + \frac{\overline{c}_{i,2} M_{i,2}}{\Delta t} \right\} \theta_{j,t+\Delta t}$
First phase mass flow rate	1	$= 1.0$
	2	$= 0.0$
	3	$= 0.0$
	4	$= 1.0$
	5	$= -R_{1,j}$
	6	$= -R_{2,k}$
	7	$= 0.0$
	8	$= 0.0$
Second phase mass flow rate	1	$= 1.0$
	2	$= 0.0$
	3	$= 0.0$
	4	$= 1.0$
	5	$= -R_{1,j}$ for $\theta_{air} \geq \theta_{dew} else = 0.0$
	6	$= 0.0$
	7	$= 0.0$ for $\theta_{air} \geq \theta_{dewelse} = \dot{m}_v$
	8	$= 0.0$

Component default parameters		
M	Component total mass (kg)	15.0
$\overline{c}$	Mass weighted average specific heat (J/kgK)	500.0
UA	Overall heat loss coefficient (W/K)	3.5
N_{rows}	Number of rows (-)	2.0
N_{fins}	Number of fins per metre (-)	316
f_t	Fin thickness (m)	0.00042
η_f	Fin efficiency (-)	0.77
K_f	Thermal conductivity of fin material (W/mK)	350.0
x_t	Tube spacing (m)	0.0375
d_i	Tube inside diameter (m)	0.0136
d_o	Tube outside diameter (m)	0.015
w_f	Coil face width (m)	1.5
h_f	Coil face height (m)	1.2

ESP-r coefficient generator name "CMP43C", plant component database reference number 32.

Flat-plate collector; 1 node model (type 700, TRNSYS type 1)

Characterisitic balance equation		
State space variable	Node	Equation
Temperature (C)	1	$C_{1,j}(\theta_j - \theta_1) + q = \frac{\bar{c}M\delta\theta_1}{\delta t}$
First phase mass flow rate (kg/s)	1	$\dot{m}_{a,1} - R_{1,j}\dot{m}_{a,j} = 0$
Second phase mass flow rate (kg/s)	1	Not applicable

Generated coefficients		
State space variable	Coefficient	Equation
Temperature	1	$= \alpha\,(-C_{1,j,t+\Delta t} -) - \frac{\bar{c}M}{\Delta t}$
	2	$= \alpha\, C_{1,j,t+\Delta t}$
	3	$= \left\{ (1-\alpha)\left[C_{1,j,t} \right] - \frac{\bar{c}M}{\Delta t} \right\} \theta_{1,t}$ $+ (1-\alpha)\,(-C_{1,j,t})\,\theta_{j,t}$ $-\alpha\, q_{t+\Delta t} - (1-\alpha)\, q_t$
First phase mass flow rate	1	$= 1.0$
	2	$= -R_{1,j}$
	3	$= 0.0$
Second phase mass flow rate	1	$= 1.0$
	2	$= 0.0$
	3	$= 0.0$

Component default parameters		
M	Component total mass (kg)	15.0
$\bar{c}$	Mass weighted average specific heat (J/kgK)	1000.0
I_{rm}	Radiation mode (-)	1.0
I_{tm}	Tracking mode (-)	1.0
Lat	Latitude (degrees)	56.0
S_c	Solar Constant (W/mˆ2)	1353.00
$SHFT$	Shift in solar time hour angle (degrees)	0.0
N_s	Number of collectors in series (-)	1.0
A	Total collector area (mˆ2)	10.0
F'	Collector fin efficiency factor (-)	0.884
U_{be}	Loss coefficient per unit aperture area (W/mˆ2 K)	0.14
ε_p	Absorber plate emittance (-)	0.90
α	Absorbtance of absorber plate (-)	0.95
N_G	number of glass covers (-)	1.0
η_R	Index of refraction of cover material (-)	1.56
KL	Product of extinction coefficient and thickness of each cover plate (-)	0.037
ρ_g	Ground reflectance (-)	0.2
β_i	Slope of surface or tracking axis (degrees)	50.0

Component default parameters		
γ_i	Azimuth of surface or tracking axis (degrees)	0.0

ESP-r coefficient generator name "CMP70C", plant component database reference number 31.

Air cooling coil; 1 node model (type 90, TRNSYS type 32)

Characterisitic balance equation		
State space variable	Node	Equation
Temperature (C)	1	$C_{1,j}(\theta_j - \theta_1) + UA(\theta_e - \theta_1) + q_i + \dot{m}_w^v R_{w=} \dfrac{\bar{c}M\delta\theta_1}{\delta t}$
First phase mass flow rate (kg/s)	1	$\dot{m}_{a,1} - R_{j,1}\dot{m}_{a,j} = 0$
Second phase mass flow rate (kg/s)	1	$\dot{m}_{v,1} - R_{1,j}\dot{m}_{v,j} = \dot{m}_w^v$

Generated coefficients		
State space variable	Coefficient	Equation
Temperature	1	$= \alpha\,(-C_{1,j,t+\Delta t} - UA_{t+\Delta t}) - \dfrac{\bar{c}M}{\Delta t}$
	2	$= \alpha\, C_{1,j,t+\Delta t}$
	3	$= \left\{ (1-\alpha)\left[C_{1,j,t} + UA_t \right] - \dfrac{\bar{c}M}{\Delta t} \right\} \theta_{1,t}$ $+ (1-\alpha)(-C_{1,j,t})\,\theta_{j,t}$ $- \alpha\, UA_{t+\Delta t}\,\theta_{e,t+\Delta t} - (1-\alpha)UA_t\theta_{e,t}$ $- \alpha\, q_{i,t+\Delta t} - (1-\alpha)\, q_{i,t}$ $- \alpha\, \dot{m}^v_{w,t+\Delta t} R_{w-}\,(1-\alpha)\,\dot{m}^v_{w,t} R_w$
First phase mass flow rate	1	$= 1.0$
	2	$= -R_{1,j}$
	3	$= 0.0$
Second phase mass flow rate	1	$= 1.0$
	2	$= -R_{1,j}$ for $T_{air} \ge T_{dew}$ else $= 0.0$
	3	$= 0.0$ for $T_{air} \ge T_{dew}$ else $= \dot{m}_v$

Component default parameters		
M	Component total mass (kg)	15.0
$\bar{c}$	Mass weighted average specific heat (J/kgK)	1000.0
UA	Overall heat loss coefficient (W/K)	3.5
A_f	Coil face area (m^2)	0.25
d_i	Internal tube diameter (m)	0.015
θ_{wi}	Inlet water temperature (C)	10.0
N_{row}	Number of rows deep (-)	2.0
N_{coil}	Number of parallel coil circuits (-)	3.0

Control data variables
Water flow rate $\dot{m}_w$ (kg/s)

ESP-r coefficient generator name "CMP09C", plant component database reference number 27.

APPENDIX B
File listing of application examples

The examples discussed in Chapter 6 are available as on line exemplars within the ESP-r system.

The following listings are for the dual duct application example discussed in Chapter 6. These files are for the plant network description and control strategy definition. The user input to ESP-r's simulator is also appended. The building and fluid flow network files can be obtained from ESRU.

Example 9: Dual duct system for the Royal Bank of Scotland building.

Plant configuration file

```
plantc.db1
Dual duct systemwith dampers.
  23   3
#-> air mixing box or converging junction; 1 node model
 in_mix_box      1
  0      # Component has  0 control variable(s).
  0
#-> air duct; 1 node model
 in_duct         6
  0      # Component has  0 control variable(s).
  6
  1.85000   500.000   2.80000  0.125000   1.00000   1.22700E-02
#-> centrifugal fan, 1 node model ; flow control
 in_fan          3
  1      # Component has  1 control variable(s).
  80.0000
  6
 10.00000   500.000   7.00000   150.000   85.0000  0.700000
#-> air duct; 1 node model
 main_s_duct     6
  0      # Component has  0 control variable(s).
  6
  9.25000   500.000   14.0000  0.125000   5.00000   1.22700E-02
#-> air cooling coil fed byWCH system; 2 node model
 cooling_coil    32
  0      # Component has  0 control variable(s).
 13
  30.0000   900.000   3.50000   4.00000   316.000   4.20000E-04  0.800000
  350.000   3.75000E-02   1.36000E-02   1.50000E-02   2.00000   3.00000
#-> air heating coil fed byWCH system; 3 node model
 heating_coil    21
  0      # Component has  0 control variable(s).
  9
  30.0000   900.000   3.50000   5.00000   30.0000   2.00000   6.00000
  1.00000E-03   1.50000E-02
#-> air duct damper; 1 node model; flow ratio control
 1stflr_hdmpr    7
  1      # Component has  1 control variable(s).
  1.00000
  0
#-> air duct damper; 1 node model; flow ratio control
 1stflr_cdmpr    7
  1      # Component has  1 control variable(s).
  1.00000
  0
#-> air mixing box or converging junction; 1 node model
 1stflr_mbox     1
  0      # Component has  0 control variable(s).
  0
```

```
#-> air duct damper; 1 node model; flow ratio control
 2ndflr_hdmpr      7
  1      # Component has   1 control variable(s).
  1.00000
  0
#-> air duct damper; 1 node model; flow ratio control
 2ndflr_cdmpr      7
  1      # Component has   1 control variable(s).
  1.00000
  0
#-> air mixing box or converging junction; 1 node model
 2ndflr_mbox       1
  0      # Component has   0 control variable(s).
  0
#-> air mixing box or converging junction; 1 node model
 ex1_mbox          1
  0      # Component has   0 control variable(s).
  0
#-> air mixing box or converging junction; 1 node model
 ex2_mbox          1
  0      # Component has   0 control variable(s).
  0
#-> air mixing box or converging junction; 1 node model
 ex3_mbox          1
  0      # Component has   0 control variable(s).
  0
#-> air duct; 1 node model
 hot_duct1         6
  0      # Component has   0 control variable(s).
  0
#-> air duct; 1 node model
 hot_duct2         6
  0      # Component has   0 control variable(s).
  0
#-> air duct; 1 node model
 cold_duct1        6
  0      # Component has   0 control variable(s).
  0
#-> air duct; 1 node model
 cold_duct2        6
  0      # Component has   0 control variable(s).
  0
#-> variable speed domestic WCH pump; 1 node model
 chill_pump        15
  1      # Component has   1 control variable(s).
  8.00000E-03
  6
  5.00000   2250.00   0.200000   150.000   5.00000E-02   0.700000
#-> variable speed domestic WCH pump; 1 node model
 boiler_pump       15
  1      # Component has   1 control variable(s).
  4.00000E-03
  6
  5.00000   2250.00   0.200000   150.000   5.00000E-02   0.700000
#-> non-condensing domestic WCH boiler; 1 node model
 boiler            11
  1      # Component has   1 control variable(s).
 0.
  0
```

```
#-> Single node water cooler with flux control.
 chiller        19
  1      # Component has  1 control variable(s).
 0.
  0
# The following is a list of component connections.
 31       # Total number of connections
# receiving     node  conncn sending       node  diversion  suppl1  suppl2
# component            type  component           ratio
 in_mix_box      1    4    in_fan         1    0.990    0.0000
 in_mix_box      1    3    ex3_mbox       1    0.010
 in_duct         1    3    in_mix_box     1    1.000
 in_fan          1    3    in_duct        1    1.000
 main_s_duct     1    3    in_fan         1    1.000
 cooling_coil    1    3    main_s_duct    1    0.500
 cooling_coil    2    3    chiller        1    1.000
 heating_coil    2    3    main_s_duct    1    0.500
 heating_coil    3    3    boiler         1    1.000
 1stflr_hdmpr    1    3    heating_coil   2    0.400
 1stflr_cdmpr    1    3    cooling_coil   1    0.400
 1stflr_mbox     1    3    1stflr_hdmpr   1    1.000
 1stflr_mbox     1    3    1stflr_cdmpr   1    1.000
 2ndflr_hdmpr    1    3    hot_duct1      1    0.667
 2ndflr_cdmpr    1    3    cold_duct1     1    0.667
 2ndflr_mbox     1    3    2ndflr_hdmpr   1    1.000
 2ndflr_mbox     1    3    2ndflr_cdmpr   1    1.000
 ex1_mbox        1    3    hot_duct2      1    1.000
 ex1_mbox        1    3    cold_duct2     1    1.000
 ex2_mbox        1    3    ex1_mbox       1    1.000
 ex2_mbox        1    4    2ndflr_mbox    1    0.100    5.0000
 ex3_mbox        1    3    ex2_mbox       1    1.000
 ex3_mbox        1    4    1stflr_mbox    1    0.100    3.0000
 hot_duct1       1    3    heating_coil   2    0.600
 hot_duct2       1    3    hot_duct1      1    0.333
 cold_duct1      1    3    cooling_coil   1    0.600
 cold_duct2      1    3    cold_duct1     1    0.333
 chill_pump      1    3    cooling_coil   2    1.000
 boiler_pump     1    3    heating_coil   3    1.000
 boiler          1    3    boiler_pump    1    1.000
 chiller         1    3    chill_pump     1    1.000
# No containment temperatures defined
# No mass flow network defined.
  0
```

```
blith control
*Building
Dual duct system
  2
*Control function
   3   0   0   0
   3   0   0
    0
   1  364
    3
   0   2   0.000
    0.0
   0   6   6.000
    7.0
 9   1   1  400000  400000   0   0
   0   2   18.000
    0.0
   1  364
    3
   0   2   0.000
    0.0
   0   6   6.000
    7.0
 9   1   1  400000  400000   0   0
   0   2   18.000
    0.0
   1  364
    3
   0   2   0.000
    0.0
   0   6   6.000
    7.0
 9   1   1  400000  400000   0   0
   0   2   18.000
    0.0
*Control function
   5   0   0   0
   5   0   0
    0
   1  364
    3
   0   2   0.000
    0.0
   0   6   6.000
    7.0
 9   1   1  400000  400000   0   0
   0   2   18.000
    0.0
   1  364
    3
   0   2   0.000
    0.0
   0   6   6.000
    7.0
 9   1   1  400000  400000   0   0
   0   2   18.000
    0.0
   1  364
    3
   0   2   0.000
    0.0
   0   6   6.000
```

```
    7.0
 9   1   1  400000  400000   0   0
   0   2  18.000
    0.0
 0 0 1 0 2 0 0 0 0 0 0 0
*Plant
dual duct control loops.
  6
*Control loops
   3    0   0   0
  -1    7   1
    1
   1 365
    1
   18   5  0.000
    6
0.05 1.0 22.0 21.0 0  0
*Control loops
   3    0   0   0
  -1    8   1
    1
   1 365
    1
   18   5  0.000
    6
1.0 0.05  22.0 21.0 0 0
*Control loops
   5    0   0   0
  -1   10   1
    1
   1 365
    1
   18   5  0.000
    6
0.05 1.0 22.0 21.0 0 0
*Control loops
   5    0   0   0
  -1   11   1
    1
   1 365
    1
   18   5  0.000
    6
1.0 0.05  22.0 21.0 0 0
*Control loops
  -1    6   2
  -1    22   1
    1
   1 365
    1
   0   1  0.000
    9
1.0 300000.0   0 30.0 2.0 0.0 0.0 0.0 0.0
*Control loops
  -1    5   1
  -1    23   1
    1
   1 365
    1
   0   1  0.000
    9
-1.0 300000.0 00000 10.0 2.0 0.0 0.0 0.0 0.0
```

ESP-r user input for the above problem

```
1
y
3
gla99
2
b
dual_duct.bres
b
dual_duct.fres
b
dual_duct.pres
8 7
9 7
3
10
g
101
n
1
100
1
0.01
1
10
0.0005
-
s
y
dual_duct.ctl
y
y
-
f
y
```

APPENDIX C
Construction details of test site

The examples discussed in Chapter 6 are available as on line exemplars within the ESP-r system.

The following listings are for the dual duct application example discussed in Chapter 6. These files are for the plant network description and control strategy definition. The user input to ESP-r's simulator is also appended. The building and fluid flow network files can be obtained from ESRU.

Example 9: Dual duct system for the Royal Bank of Scotland building.

Plant configuration file

```
plantc.db1
Dual duct systemwith dampers.
  23   3
#-> air mixing box or converging junction; 1 node model
  in_mix_box      1
   0      # Component has  0 control variable(s).
   0
#-> air duct; 1 node model
  in_duct         6
   0      # Component has  0 control variable(s).
   6
   1.85000   500.000   2.80000  0.125000   1.00000   1.22700E-02
#-> centrifugal fan, 1 node model ; flow control
  in_fan          3
   1      # Component has  1 control variable(s).
   80.0000
   6
  10.00000   500.000   7.00000   150.000   85.0000  0.700000
#-> air duct; 1 node model
 main_s_duct      6
   0      # Component has  0 control variable(s).
   6
   9.25000   500.000   14.0000  0.125000   5.00000   1.22700E-02
#-> air cooling coil fed byWCH system; 2 node model
  cooling_coil    32
   0      # Component has  0 control variable(s).
  13
   30.0000   900.000   3.50000   4.00000   316.000   4.20000E-04  0.800000
   350.000   3.75000E-02   1.36000E-02   1.50000E-02   2.00000   3.00000
#-> air heating coil fed byWCH system; 3 node model
  heating_coil    21
   0      # Component has  0 control variable(s).
   9
   30.0000   900.000   3.50000   5.00000   30.0000   2.00000   6.00000
   1.00000E-03   1.50000E-02
#-> air duct damper; 1 node model; flow ratio control
  1stflr_hdmpr     7
   1      # Component has  1 control variable(s).
   1.00000
   0
#-> air duct damper; 1 node model; flow ratio control
  1stflr_cdmpr     7
   1      # Component has  1 control variable(s).
   1.00000
   0
#-> air mixing box or converging junction; 1 node model
  1stflr_mbox      1
   0      # Component has  0 control variable(s).
   0
```

```
#-> air duct damper; 1 node model; flow ratio control
 2ndflr_hdmpr      7
  1      # Component has   1 control variable(s).
  1.00000
  0
#-> air duct damper; 1 node model; flow ratio control
 2ndflr_cdmpr      7
  1      # Component has   1 control variable(s).
  1.00000
  0
#-> air mixing box or converging junction; 1 node model
 2ndflr_mbox       1
  0      # Component has   0 control variable(s).
  0
#-> air mixing box or converging junction; 1 node model
 ex1_mbox          1
  0      # Component has   0 control variable(s).
  0
#-> air mixing box or converging junction; 1 node model
 ex2_mbox          1
  0      # Component has   0 control variable(s).
  0
#-> air mixing box or converging junction; 1 node model
 ex3_mbox          1
  0      # Component has   0 control variable(s).
  0
#-> air duct; 1 node model
 hot_duct1         6
  0      # Component has   0 control variable(s).
  0
#-> air duct; 1 node model
 hot_duct2         6
  0      # Component has   0 control variable(s).
  0
#-> air duct; 1 node model
 cold_duct1        6
  0      # Component has   0 control variable(s).
  0
#-> air duct; 1 node model
 cold_duct2        6
  0      # Component has   0 control variable(s).
  0
#-> variable speed domestic WCH pump; 1 node model
 chill_pump       15
  1      # Component has   1 control variable(s).
  8.00000E-03
  6
  5.00000   2250.00  0.200000   150.000   5.00000E-02  0.700000
#-> variable speed domestic WCH pump; 1 node model
 boiler_pump      15
  1      # Component has   1 control variable(s).
  4.00000E-03
  6
  5.00000   2250.00  0.200000   150.000   5.00000E-02  0.700000
#-> non-condensing domestic WCH boiler; 1 node model
 boiler           11
  1      # Component has   1 control variable(s).
 0.
  0
```

```
#-> Single node water cooler with flux control.
 chiller       19
  1     # Component has  1 control variable(s).
 0.
  0
# The following is a list of component connections.
 31      # Total number of connections
# receiving     node  conncn sending       node  diversion  suppl1   suppl2
# component          type  component             ratio
 in_mix_box      1    4    in_fan         1    0.990    0.0000
 in_mix_box      1    3    ex3_mbox        1    0.010
 in_duct         1    3    in_mix_box      1    1.000
 in_fan          1    3    in_duct         1    1.000
main_s_duct      1    3    in_fan          1    1.000
 cooling_coil    1    3    main_s_duct     1    0.500
 cooling_coil    2    3    chiller         1    1.000
 heating_coil    2    3    main_s_duct     1    0.500
 heating_coil    3    3    boiler          1    1.000
 1stflr_hdmpr    1    3    heating_coil    2    0.400
 1stflr_cdmpr    1    3    cooling_coil    1    0.400
 1stflr_mbox     1    3    1stflr_hdmpr    1    1.000
 1stflr_mbox     1    3    1stflr_cdmpr    1    1.000
 2ndflr_hdmpr    1    3    hot_duct1       1    0.667
 2ndflr_cdmpr    1    3    cold_duct1      1    0.667
 2ndflr_mbox     1    3    2ndflr_hdmpr    1    1.000
 2ndflr_mbox     1    3    2ndflr_cdmpr    1    1.000
 ex1_mbox        1    3    hot_duct2       1    1.000
 ex1_mbox        1    3    cold_duct2      1    1.000
 ex2_mbox        1    3    ex1_mbox        1    1.000
 ex2_mbox        1    4    2ndflr_mbox     1    0.100    5.0000
 ex3_mbox        1    3    ex2_mbox        1    1.000
 ex3_mbox        1    4    1stflr_mbox     1    0.100    3.0000
 hot_duct1       1    3    heating_coil    2    0.600
 hot_duct2       1    3    hot_duct1       1    0.333
 cold_duct1      1    3    cooling_coil    1    0.600
 cold_duct2      1    3    cold_duct1      1    0.333
 chill_pump      1    3    cooling_coil    2    1.000
 boiler_pump     1    3    heating_coil    3    1.000
 boiler          1    3    boiler_pump     1    1.000
 chiller         1    3    chill_pump      1    1.000
# No containment temperatures defined
# No mass flow network defined.
  0
```

```
blith control
*Building
Dual duct system
  2
*Control function
   3   0   0   0
   3   0   0
    0
   1  364
    3
   0   2  0.000
    0.0
   0   6  6.000
    7.0
 9   1   1  400000  400000  0  0
   0   2  18.000
    0.0
   1  364
    3
   0   2  0.000
    0.0
   0   6  6.000
    7.0
 9   1   1  400000  400000  0  0
   0   2  18.000
    0.0
   1  364
    3
   0   2  0.000
    0.0
   0   6  6.000
    7.0
 9   1   1  400000  400000  0  0
   0   2  18.000
    0.0
*Control function
   5   0   0   0
   5   0   0
    0
   1  364
    3
   0   2  0.000
    0.0
   0   6  6.000
    7.0
 9   1   1  400000  400000  0  0
   0   2  18.000
    0.0
   1  364
    3
   0   2  0.000
    0.0
   0   6  6.000
    7.0
 9   1   1  400000  400000  0  0
   0   2  18.000
    0.0
   1  364
    3
   0   2  0.000
    0.0
   0   6  6.000
```

```
   7.0
 9   1   1  400000  400000   0   0
  0   2  18.000
   0.0
 0 0 1 0 2 0 0 0 0 0 0 0
*Plant
dual duct control loops.
  6
*Control loops
  3    0   0   0
  -1    7   1
   1
  1 365
   1
  18   5  0.000
   6
0.05 1.0 22.0 21.0 0  0
*Control loops
  3    0   0   0
  -1    8   1
   1
  1 365
   1
  18   5  0.000
   6
1.0 0.05  22.0 21.0 0 0
*Control loops
  5    0   0   0
  -1   10   1
   1
  1 365
   1
  18   5  0.000
   6
0.05 1.0 22.0 21.0 0 0
*Control loops
  5    0   0   0
  -1   11   1
   1
  1 365
   1
  18   5  0.000
   6
1.0 0.05  22.0 21.0 0 0
*Control loops
  -1    6   2
  -1    22   1
   1
  1 365
   1
  0   1  0.000
   9
1.0 300000.0   0 30.0 2.0 0.0 0.0 0.0 0.0
*Control loops
  -1    5   1
  -1    23   1
   1
  1 365
   1
  0   1  0.000
   9
-1.0 300000.0 00000 10.0 2.0 0.0 0.0 0.0 0.0
```

ESP-r user input for the above problem

```
1
y
3
gla99
2
b
dual_duct.bres
b
dual_duct.fres
b
dual_duct.pres
8 7
9 7
3
10
g
101
n
1
100
1
0.01
1
10
0.0005
-
s
y
dual_duct.ctl
y
y
-
f
y
```

APPENDIX C
Construction details of test site

Test room West wall construction

Code	Area m^2	Material	Conductivity W/mK	Density kg/m^3	Specific heat J/kgK	Thickness m
C22	0.221	R-999				
		Foam	0.027	34	1404	0.045
		Wood	0.125	610	1380[4]	0.053
		Plasterboard	0.150	860	1090[4]	0.013
C25	0.385	R-999				
		Wood	0.125	610	1380[4]	0.073
		Airgap				0.025
		Plasterboard	0.150	860	1090[4]	0.013
C27	4.750	R-999				
		Rockwool	0.043	12	840[4]	0.073
		Airgap				0.025
		Plasterboard	0.150	860	1090[4]	0.013

Test room Ceiling construction

Code	Area m^2	Material	Conductivity W/mK	Density kg/m^3	Specific heat J/kgK	Thickness m
C10	0.230	Wood	0.125	610	1380[4]	0.075
		Plasterboard	0.150	860	1090[4]	0.013
C11	3.310	Rockwool	0.043	12	840[4]	0.100
		Plasterboard	0.150	860	1090[4]	0.013

Test room South wall construction

Code	Area m^2	Material	Conductivity W/mK	Density kg/m^3	Specific heat J/kgK	Thickness m
C02A	0.578	WoodA[A]	0.205	610	1380	0.110
C45	1.352	Plywood	0.181	576	1210[4]	0.010
		Rockwool	0.043	12	840[4]	0.070

Test room East wall construction

Code	Area m²	Material	Conductivity W/mK	Density kg/m³	Specific heat J/kgK	Thickness m
C15B	0.918	Plywood	0.181	576	1210[4]	0.013
		WoodB[A]	0.253	610	1380	0.095
		Airgap				0.025
		Plasterboard	0.150	860	1090[4]	0.013
C16	3.217	Plywood	0.181	576	1210[4]	0.013
		Rockwool	0.043	12	840[4]	0.100
		Airgap				0.020
		Plasterboard	0.150	860	1090[4]	0.013
C17	0.262	Plywood	0.181	576	1210[4]	0.013
		Airgap				0.095
		Wood	0.125	610	1380[4]	0.025
		Plasterboard	0.150	860	1090[4]	0.013
C21	0.959	Plywood	0.181	576	1210[4]	0.013
		Rockwool	0.043	12	840[4]	0.076
		Plasterboard	0.150	860	1090[4]	0.013

Test room Floor construction

Code	Area m²	Material	Conductivity W/mK	Density kg/m³	Specific heat J/kgK	Thickness m
C37	3.541	Chipboard	0.140	720	1300[4]	0.018
		Styrofoam	0.027	34	1404	0.050
		Concrete	1.280	2000	920	0.038

Test room North wall construction

Code	Area m²	Material	Conductivity W/mK	Density kg/m³	Specific heat J/kgK	Thickness m
C15A	0.367	Plywood	0.181	576	1210[4]	0.013
		WoodA[A]	0.629	610	1380	0.095
		Airgap				0.025
		Plasterboard	0.150	860	1090[4]	0.013
C16	3.064	Plywood	0.181	576	1210[4]	0.013
		Rockwool	0.043	12	840[4]	0.100
		Airgap				0.020
		Plasterboard	0.150	860	1090[4]	0.013

Roofspace East wall construction

Code	Area m^2	Material	Conductivity W/mK	Density kg/m^3	Specific heat J/kgK	Thickness m
C50	2.445	Plywood	0.181	576	1210[4]	0.013

Roofspace South wall construction

Code	Area m^2	Material	Conductivity W/mK	Density kg/m^3	Specific heat J/kgK	Thickness m
C50	1.073	Plywood	0.181	576	1210[4]	0.010
C51	0.810	Plyonstud	0.125	610	1380[4]	0.088

Roofspace West wall construction

Code	Area m^2	Material	Conductivity W/mK	Density kg/m^3	Specific heat J/kgK	Thickness m
C27	2.445	R-999				
		Rockwool	0.043	12	840[4]	0.073
		Airgap				0.025
		Plasterboard	0.150	860	1090[4]	0.013

Roofspace Ceiling construction

Code	Area m^2	Material	Conductivity W/mK	Density kg/m^3	Specific heat J/kgK	Thickness m
C50	3.596	Plywood	0.181	576	1210[4]	0.013

Roofspace Floor construction

Code	Area m^2	Material	Conductivity W/mK	Density kg/m^3	Specific heat J/kgK	Thickness m
C10R	0.230	Plasterboard	0.150	860	1090[4]	0.013
		Wood	0.125	610	~~840~~[4] 1380	0.075
C11R	3.310	Plasterboard	0.150	860	1090[4]	0.013
		Rockwool	0.043	12	840[4]	0.100

Roofspace North wall construction

Code	Area m²	Material	Conductivity W/mK	Density kg/m³	Specific heat J/kgK	Thickness m
C50	1.250	Plywood	0.181	576	1210[4]	0.013

Test room alternative South facing glazing options

Code	Area m²	Material	Conductivity W/mK	Density kg/m³	Specific heat J/kgK	Thickness m	
Room 1: Double glazed							
DG	1.500	Glass	1.050[5]	2500[5]	750	0.004	
		Airgap				0.006	
		Glass	1.050[5]	2500[5]	750	0.004	
Room 3: Opaque infil panel							
C45	1.335	Rockwool	0.043	12	840[4]	0.070	inside
		Ply	0.181	576	1210[4]	0.010	outside
C48	0.165	Wood	0.125	610	1380[4]	0.069	inside
		Plywood	0.181	576	1210[4]	0.010	outside
Room 5: Single glazed							
SG	1.500	Glass	1.050[5]	2500[5]	750	0.004	

Transmission properties of glass

Refractive index	1.526
Extinction coefficient (/mm)	0.030
Thickness (mm)	4.00