THE MODELLING AND SIMULATION
OF
ENERGY MANAGEMENT CONTROL SYSTEMS.

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ABSTRACT

This thesis is concerned with improving the integrity and applicability of building energy management systems (BEMS) simulation tools.

The present work attempts to overcome certain inadequacies of contemporary simulation applications with respect to environmental control systems, by developing novel building control systems modelling schemes. These schemes are then integrated within a state-of-the-art simulation environment so that they can be employed in practice.

After reviewing the existing techniques and various approaches to control systems design and appraisal, a taxonomy of building control system entities grouped in terms of logical, temporal and spatial element, is presented. This taxonomy is subsequently used to identify the models, algorithms, and features comprising a comprehensive modelling environment.

Schemes for improving system integrity and applicability are presented based upon a simulation approach which treats the building fabric and associated plant systems as an integrated dynamic system. These schemes facilitate the modelling of advanced BEMS control structure and strategies, including:

- hierarchical (systems level and zone-level) control systems;
- single input, single output (SISO) and multiple input, multiple output (MIMO) systems;
- advanced BEMS controller algorithms;
- simulated-assisted control strategies based on advanced simulation time-step control techniques.

The installation of the developed schemes within a whole building simulation environment, ESP-r, is also presented. Issues related to verification of the developed schemes are subsequently discussed.

Users of control system simulation programs are identified and categorised. Typical applications of the new control modelling features are demonstrated in terms of these user groups. The applications are based on both research and consultancy projects.

Finally, the future work required to increase the applicability and accuracy of building control simulation tools is elaborated in terms of the required integration with other technical subsystems and related computer-aided design tools.

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Chapter 1

INTRODUCTION.

"Control system modelling is the key ingredient of future simulation systems which will be applied in the pursuit of the so-called 'Intelligent Building.'" [Clarke 1987].

"The accurate modelling of control systems is important if the simulation of the environment inside buildings is to be realistic, and essential if simulation is to play a credible role in the design and comparative assessment of control system behaviour." [Dexter 1988].

1.1 CONTROL SYSTEMS SIMULATION: THE NEED.

The need for energy efficiency, both for economic and environmental reasons, has never been greater. The International Energy Agency [IEA 1994a] predicts that the global demand for primary energy will continue to grow at an average annual rate of 2.1 per cent and that, by 2010, the world will be consuming 48% more energy than it was in 1991. World GDP is also expected to be more than 70% higher in 2010 than in 1991. It is this underlying assumption of economic growth (especially in the developing world) which, more than any other factor, is the reason for the anticipated increase in energy demand. Moreover, excessive use of fossil fuels eventually brings about global problems such as acid rain, the greenhouse effect and thermal pollution as well as a shortage of non-renewable fuels [Masters 1991].

Consideration of energy in relation to the built environment throughout the world's developed countries, reveals that 20-40% of all delivered energy can be directly associated with buildings [IEA 1994a and 1994b] (Figure 1.1). Consequently, technologies suitable for buildings are going to make a significant contribution to reducing energy consumption. More specifically, by raising the efficiency of energy utilisation through improved automatic control techniques, it is possible to reduce the consumption of buildings in the UK by 10-30%, representing a saving of around 3 Mtce† per year, or several hundred million pounds [EEO 1987 and DTI 1994].

Technical progress has been made during recent years in the capabilities of heating, ventilation and air conditioning (HVAC) control equipment and building energy management systems (BEMS). Developments have been made in sensor technology, information transfer, actuators and the controller itself. However, optimisation of such complex technology can be elusive and expensive, and users require information from researchers on the use of BEMS, the performance to be expected and how to assess performance and compare different BEMS equipment. Evaluation will not be relevant, though, unless it takes into account the effect of BEMS functionality upon the managed facility as a whole. Factors as varied as operating cost, comfort, equipment wear, flexibility and behaviour in case of failure, must be integrated into the evaluation.

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† Millions of tonnes of coal equivalent

Hence, both with respect to environmental impact and economics, the ability to make sensible and well based decisions regarding the choice and design of building control systems is of the utmost importance. Simulation offers an means of assessing the performance of alternative building control system strategies so that a desirable comfort level can be achieved with a minimum consumption of energy and optimisation of plant systems [Hanby 1989].

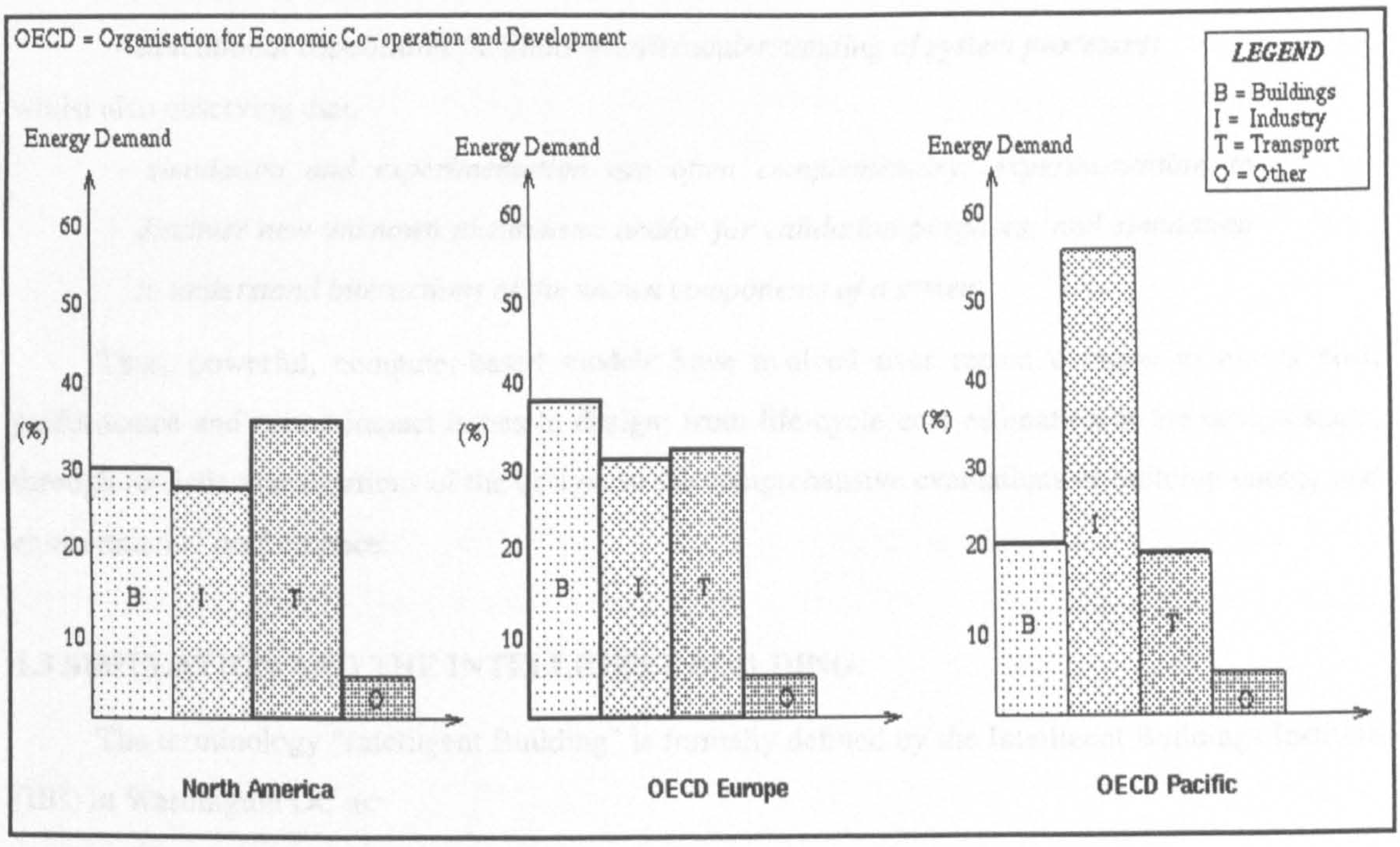

Figure 1.1 Sectoral energy demand 1993 [IEA 1994a].

1.2 SIMULATION: THE GOALS AND BENEFITS.

The terminology "simulation" may be regarded as the art of representing some aspects of the real world by numbers or symbols which may be easily manipulated to facilitate their study. Over the past 60 years, the field of simulation has undergone tremendous growth in its scope and capabilities. When once simulation was employed in the study of relatively simple systems, today hardly an industry or a discipline does not use simulation techniques extensively [Colella *et al* 1974]. The ability to handle complete systems has advanced to the point where global socio-economic systems are being investigated with such portentous variables as population, national resources and quality of life.

Tang [1985] described the goals of simulation as:-

- *predicting system performance under particular operating conditions;*
- *testing and evaluating a system or a particular subsystem;*
- *identifying those portions of the system that require further investigation;*

adding,

- *the activities of modelling, computer implementation and program utilisation may* *be regarded as the most important subprocesses within the overall process of simulation.*

Hensen [1991] described the main reasons as to why modelling and simulation have become indispensable engineering techniques (and in many cases replaced experimentation) as:-

- *economy and speed of analysis;*
- *prediction of systems which do not (at that time) exist;*
- *educational capabilities facilitate greater understanding of system processes;*

whilst also observing that,

- *simulation and experimentation are often complementary; experimentation to discover new unknown phenomena and/or for validation purposes; and simulation to understand interactions of the known components of a system.*

Thus, powerful, computer-based models have evolved over recent decades to assess cost, performance and visual impact issues in design; from life-cycle cost estimation at the design stage, through realistic visualisations of the design, to the comprehensive evaluations of building energy and environmental performance.

1.3 SIMULATION AND THE INTELLIGENT BUILDING.

The terminology "Intelligent Building" is formally defined by the Intelligent Buildings Institute (IBI) in Washington DC as:

> *'... one which integrates various systems (such as lighting, HVAC, voice and data communications and other building functions), to effectively manage resources in a coordinated mode to maximise occupant performance, operating cost-savings and flexibility. Various levels of intelligence are provided through interactive controls and communications devices driven by either central or distributed micro-chip intelligence and employing sensing devices and interactive distribution media.' [McLean 1991].*

As many commercial and industrial buildings today contain one or more of these various systems, they can be considered to have some degree of intelligence. The intelligent building can therefore exist on a broad spectrum of capabilities. Thus, it is not a comparison between 'intelligent' buildings on the one hand and 'moronic' buildings on the other, but rather that all buildings exist on a continuum of capabilities ranging from the least to the most intelligent.

Although modern BEMS *can* be effective and offer considerable improvement in controlling buildings, hyperbolic claims of the capabilities of intelligent buildings based on such technology are often made. BEMS effectiveness is due principally to their data processing capabilities, not to characteristics of intelligence [Haves, 1992]. The building cannot be termed "intelligent" because the control systems are based upon algorithms which do not consider the implications of their actions on the whole building. Energy management is the lowest form of intelligence which can be given to a building and *automated building control* would, perhaps, be a more accurate definition.

Recent experience [Hartman 1988] has shown that there are impediments to increased performance of BEMS-based buildings and to them becoming truly intelligent. Traditionally, building control is based on steady state strategies. However, due to the rapidly changing outdoor and indoor environmental conditions, steady state control is neither effective nor efficient in the utilisation of energy for comfort conditioning. With the advent of direct digital control (DDC) techniques, most present day BEMS application software combines steady state with dynamic control strategies. Unfortunately these control strategies frequently work counter to one another, resulting in a conglomeration of routines that are too complicated to understand and monitor effectively. This provides neither efficiency nor comfort and succeeds only in 'optimising the irrelevant' [Bordass 1993].

Optimisation of energy conservation and comfort levels can best be achieved if the building's thermal performance, HVAC system sizing and control strategy are considered together within the building design process. However, buildings and their environmental control systems are complex (multi-dimensional and highly interactive) making this optimisation task non-trivial [Clarke 1985]. The design and layout of practical control systems varies dramatically owing to the diversity of design conditions which, in turn, are due to variations in climatic conditions, the type of space occupied, occupant behaviour and the relationship between building and plant. Deciding on the best control strategy or the optimum arrangement of design features is thus an extremely complex task and one which does not lend itself to simple paradigms and rules of thumb.

In order to *fully* exploit and optimise BEMS technology it is vital, as argued by Hensen [1991], that tools exist to allow the simulation and assessment of building control systems and that these tools be based on a *fully integrated simulation approach* in which the dynamic thermal interaction between building, plant and control system (under the influence of occupant behaviour and outdoor climate) is assessed. It is desirable that these simulation programs accommodate a large number of accurate, robust models of control system entities housed within a structure which allows flexibility of application. The integrity of the real world must be conserved within the computational medium because, if disregarded, will compromise simulation predictions and the related design decisions.

In addition to optimising BEMS control strategy at the design stage, simulation also has a crucial role in the *on-line optimisation* of future generation intelligent buildings. McLean [1991] *redefined* the intelligent building as comprising three elements which, when integrated together, make the building intelligent.

1. *The controls of all the systems in a building, whilst retaining their own integral intelligence, are linked integrally to all others in the system.*
2. *The building has the ability to respond to any changes in the interior and/or external environment, necessitating the use of new building technologies.*
3. *The most important feature of a truly intelligent building will be the integration of 1 and 2 above by means of a dynamic simulation tool which can supervise the control system whilst coordinating the use of the building's 'dynamic' features to ensure optimum performance in terms of occupant comfort and energy consumption (Figure 1.2). The simulation program simulates the building in real time, being continually updated by sensor information. If some control action is requested, the control supervisor in rapid iterative mode predicts the consequences of various control strategies and selects the most efficient.*

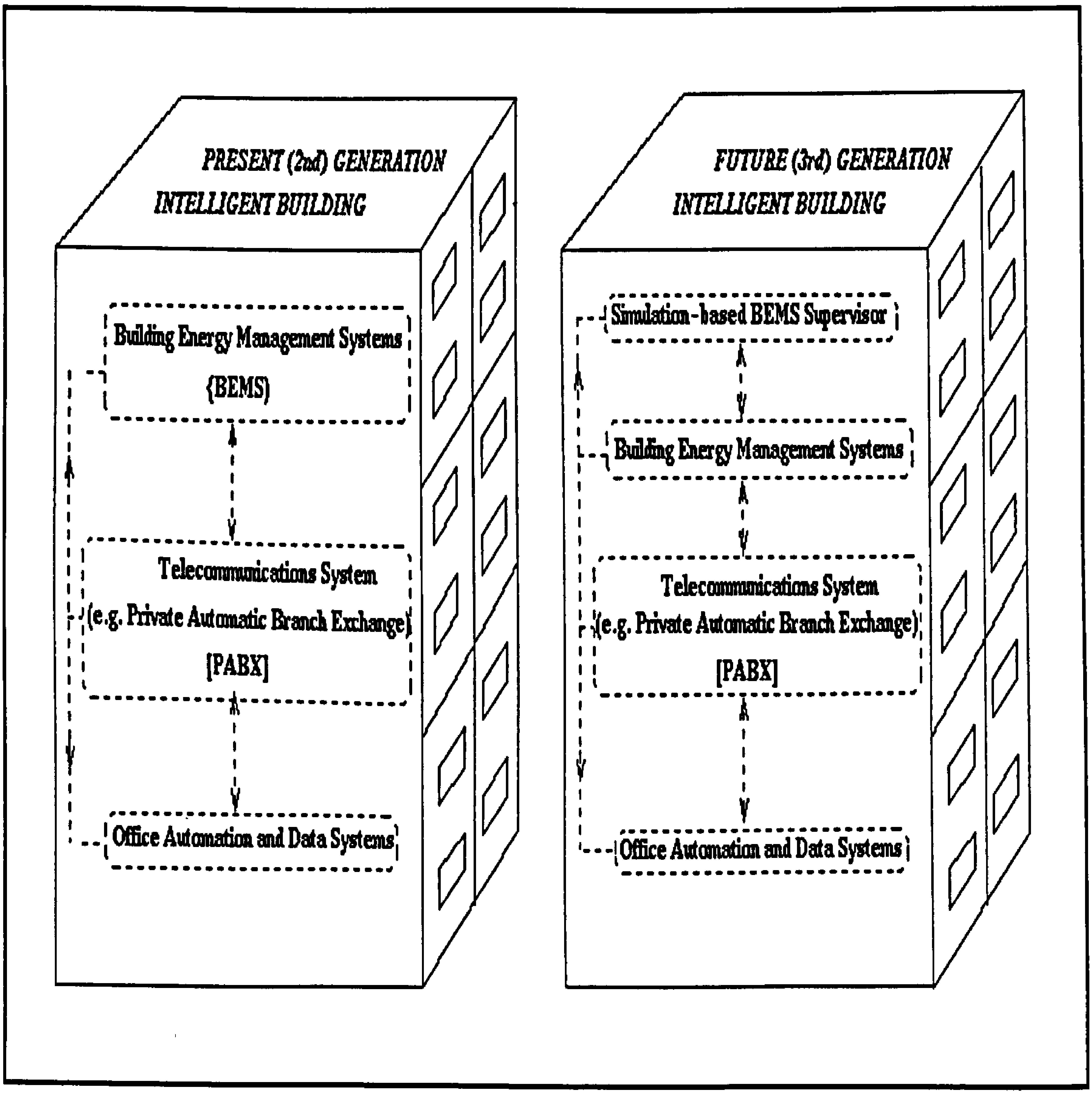

Figure 1.2 The infrastructure of present and future generation intelligent buildings.

1.4 OBJECTIVES AND OUTLINE OF THE PRESENT WORK.

1.4.1 Project objectives.

It was against the background outlined in the previous sections that the present research project commenced in 1992. The following visions of future simulation programs were observed:

- the diversity of real, practical control systems requires a comprehensive library of accurate, robust models of system entities;
- advances in computer technology will eventually allow a radical new approach to building controller design in which simulation will play an integral part. On-line, simulation tools - based on predictive-iterative techniques rather than empirical techniques - will allow control system optimisation and 'orchestration';
- in order to fully utilise an energy simulation model in such applications, a number of existing barriers and deficiencies in contemporary modelling techniques must be overcome so that a practical application to the simulation of combined building and HVAC systems can be attained and the intelligent building can become a reality.

Consequently, this research work has encompassed the following specific objectives:

- to identify and classify the control system entities extant in building control systems;
- to employ the resulting taxonomy of control system entities in the form of a general purpose control system simulation environment in order to improve the applicability and accuracy of the modelling, simulation and appraisal process;
- to implement, validate and verify the above when incorporated within the ESP-r program.

1.4.2 Thesis outline.

Chapter 2 of this thesis contains a review of the commonly occurring building control systems and discusses the theory underlying various approaches to system synthesis and design. Chapter 3 describes the ESP-r simulation environment which was employed as a test bed for assessing control modelling schema. Chapters 4, 5 and 6 identify the essential features and describes the structure and development of a control system taxonomy for systems simulation in terms of spatial, temporal and logical control system elements, respectively. Chapter 7 addresses the issue of validation of building control system modelling programs. Chapter 8 discusses applicability of the developed control modelling schema. Finally, Chapter 9 contains the conclusions drawn from the present project and indicates possible directions for further work.

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Chapter 2

BUILDING ENVIRONMENTAL CONTROL SYSTEMS

The need for environmental control system simulation programs has been established in Chapter 1. The present Chapter details the main types of automatic building control system and reviews the modelling methods commonly adopted for their appraisal. This review highlights some of the disadvantages and shortcomings inherent in these methods, indicating that alternative approaches are required. It is concluded that such an approach should focus on expanding applicability of the system within multi-disciplinary building design environments.

2.1 INTRODUCTION TO ENVIRONMENTAL CONTROL SYSTEMS.

2.1.1 The need.

Environmental control is the control of temperature, moisture content, air quality, air circulation and lighting levels as required by occupants, processes, or equipment in the building space. Properly applied automatic controls ensure that correctly designed heating, ventilating and air conditioning (HVAC) and lighting installations will maintain a comfortable environment and perform economically under a wide range of indoor and outdoor conditions.

Limit controls ensure safe operation of HVAC equipment and prevent injury to building occupants and damage to the system. In the event of a fire, controlled air distribution can provide smoke-free evacuation passages and smoke detection in ducts can close dampers to prevent the spread of smoke and toxic gases.

It was not until the start of the twentieth century that automatic control was introduced. Since then, developments have been rapid with detailed analytical design methods evolving to meet the needs of increasing complexity in building structures, high construction costs and energy shortages.

2.1.2 Types of system.

2.1.2.1 Control system elements.

The premise of this thesis is that *all* building control systems - regardless of their exact make-up, function and operational characteristics - comprise the following elements:

- logical (e.g. controller intent);
- spatial (e.g. sensor location);
- temporal (e.g. time-and-event programs).

It is assumed that all systems can be assessed and categorised in terms of these three elements as depicted in Figure 2.1, thereby supporting the notion of a taxonomy of control system entities - a theme expanded upon in later chapters.

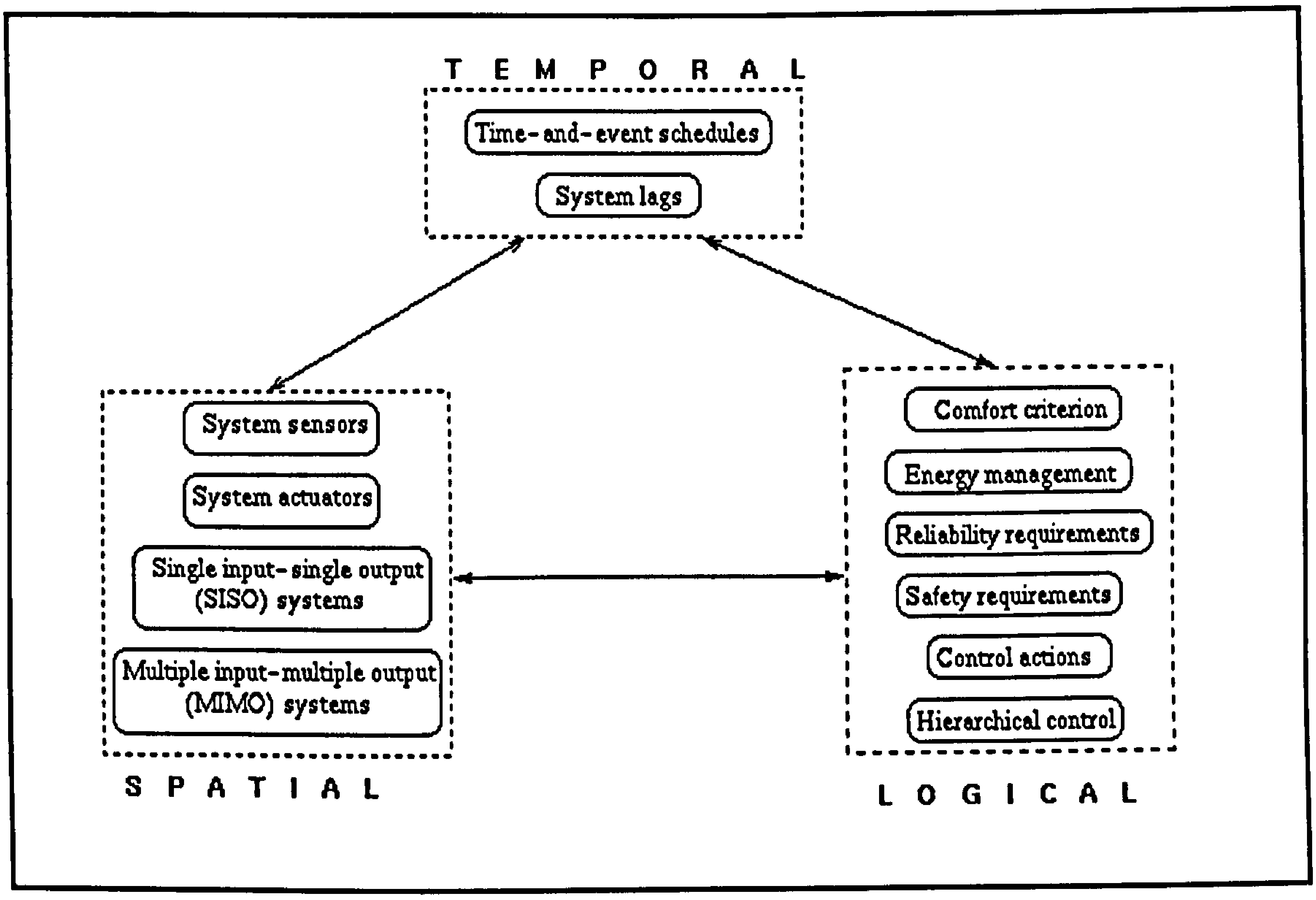


Figure 2.1 Building control systems: the main elements.

2.1.2.2 Automatic feedback control.

The most common type of building control system is that based on the principle of automatic feedback control. Such systems comprise one or more *control loops.* Basically, a control loop comprises three components: a sensor, a controller and an actuator (Figure 2.2). These elements serve the following purposes:

- *sensor:* to monitor the output from a given process;
- *controller:* to determine what action to take to maintain desired condition;
- *actuator:* the means by which corrective action may be initiated to bring about the desired condition.

In feedback control, the controller is error driven, i.e. the controller receives a continuous measurement of the difference between required and actual behaviour, and its output is some function of this error. The feedback principle works well provided that the available control actions do not encounter constraints that limit their magnitudes. For example, in the case of temperature control there will always be some limit on fuel flow rate.

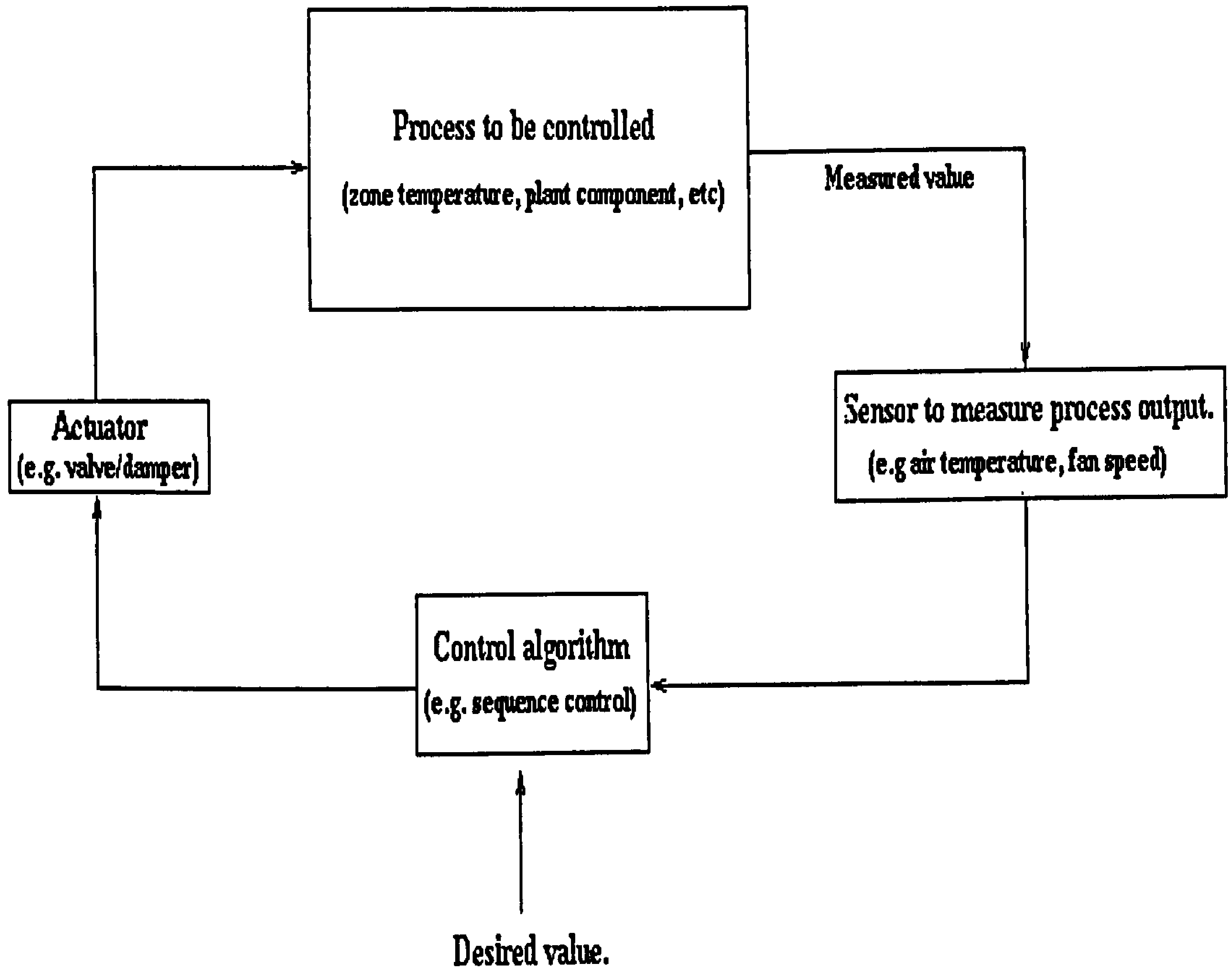


Figure 2.2 Block diagram of a control loop.

2.1.2.3 Alternatives to feedback control.

(1) *Preprogrammed control:* Here a recipe, strategy or sequence of control instructions is calculated in advance and is implemented with no account taken of system output signals.

(2) *Feedforward control:* Where all disturbances are assumed to be measured independently (not as a measure of received disturbances) and assumes control actions are accurately calculable with the aim of eliminating error before it can occur.

(3) *Predictive control:* Future conditions are predicted (using extrapolation algorithms or past records) and are used to allow the best possible positioning of the control system. It is often used in large delay systems where it can take a long time to bring in equipment; e.g, electrical generation systems.

2.1.3 Building energy management systems (BEMS).

In the nineteen fifties, it became apparent that there was a need to centralise the flow of information from increasingly large and complex technical systems in buildings. The first generation of BEMS were characterised by centralisation of information and remote control of technical installations (Figure 2.3(a)). In the nineteen sixties, with the trend of centralisation of company services, a flourishing economy and large-scale building programs in and around the cities, facilities such as air-conditioning, document transport systems, etc. were designed into new buildings. This increased the complexity of the control systems and led to selective data presentation systems which used the switching methods employed by telephone switchboards. The digital signals were no longer wired directly to the control panel but were collected in data gathering panels (DGP's) connected to the central panel. This resulted in reduced cabling requirements, whilst allowing flexible control signalling and selection strategies (Figure 2.3(b)). At the beginning of the nineteen seventies, developments in electronics led to digital switching techniques, facilitating digitalised analogue signals. Subsequently, the central control panel was replaced by a computer system. These systems were characterised by considerably increased processing speed and an increased number of data points.

The energy crisis of 1973 and the urgent need to reduce energy consumption led to a rapid increase in the installation of energy saving equipment controlled using so-called "energy management schemes" [Scheepers 1991]. These include night set-back, optimum start and event-sequenced strategies. Systems which previously used dedicated computer systems were altered so that standard mini-computers could be used as the central system (Figure 2.4(a)).

At this point, microprocessors were introduced into BEMS allowing intelligent substations to carry out some of the work previously done by the central station. As systems grew larger, they incorporated *distributed intelligence* where each zone/floor/building could have its own micro-computer. Since the early nineteen eighties, there has been many developments involving BEMS. Data processing is more widely distributed, resulting in increasingly distributed and autonomous substations. In addition, more functions, such as DDC (direct digital control) and PLC (programmable logic controllers) were added to the substations. Thus, the control functions previously carried out by means of analogue hardware, were now usually included in the substations.

The trend towards further distribution of tasks is not limited to substations in BEMS. The central station is also subject to the same evolution [Honeywell 1989]. The arrival of the personal computer and communications network systems have resulted in an increase in networked, less hierarchical BEMS. Such systems do not require a central computer as each operator station is itself a micro-computer. Combined hierarchical and network systems with the BEMS, included in an organisation's total buildings facilities management system, are also commonplace (Figure 2.4(b)).

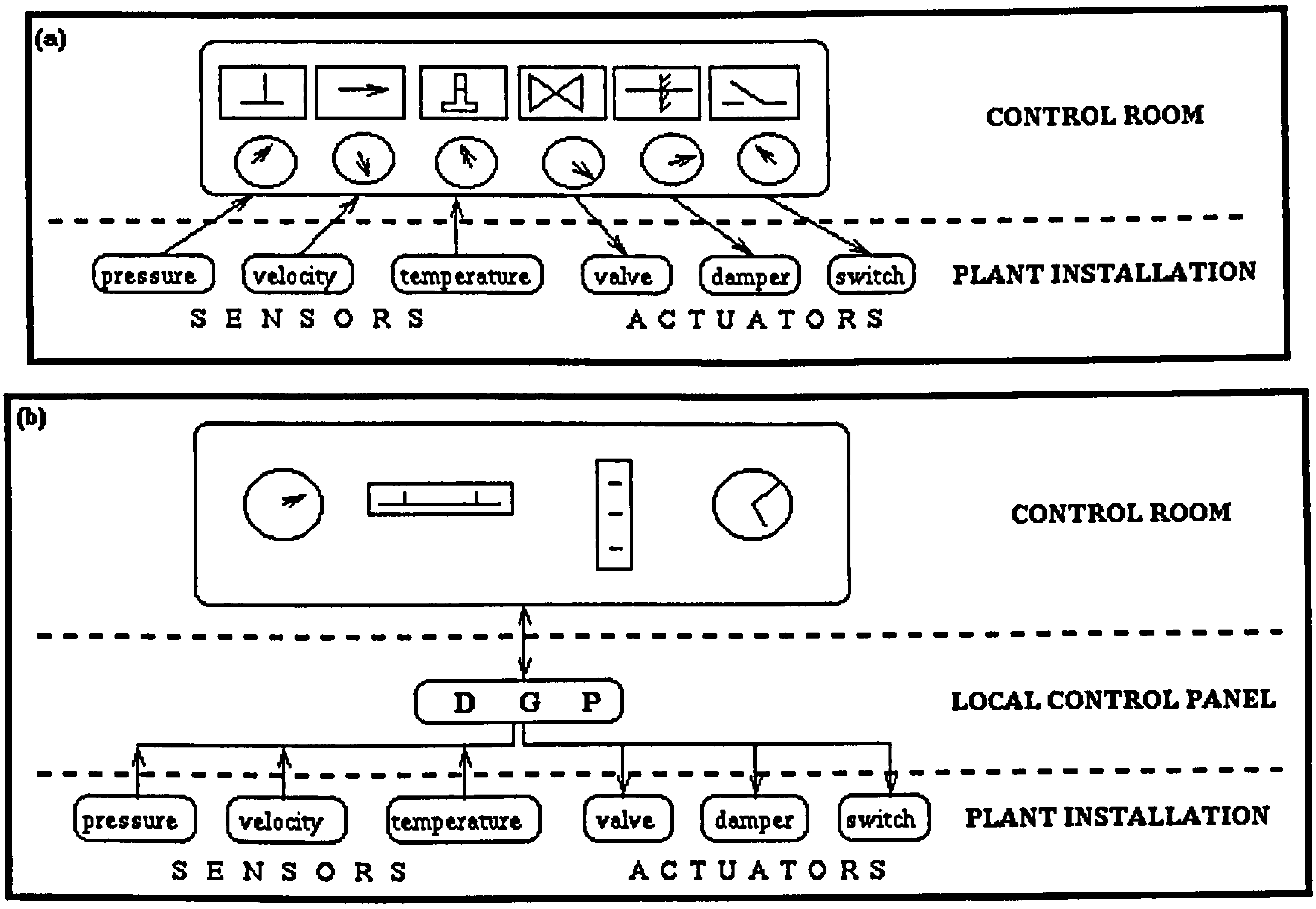


Figure 2.3 (a) Central control panel: (b) data gathering panels

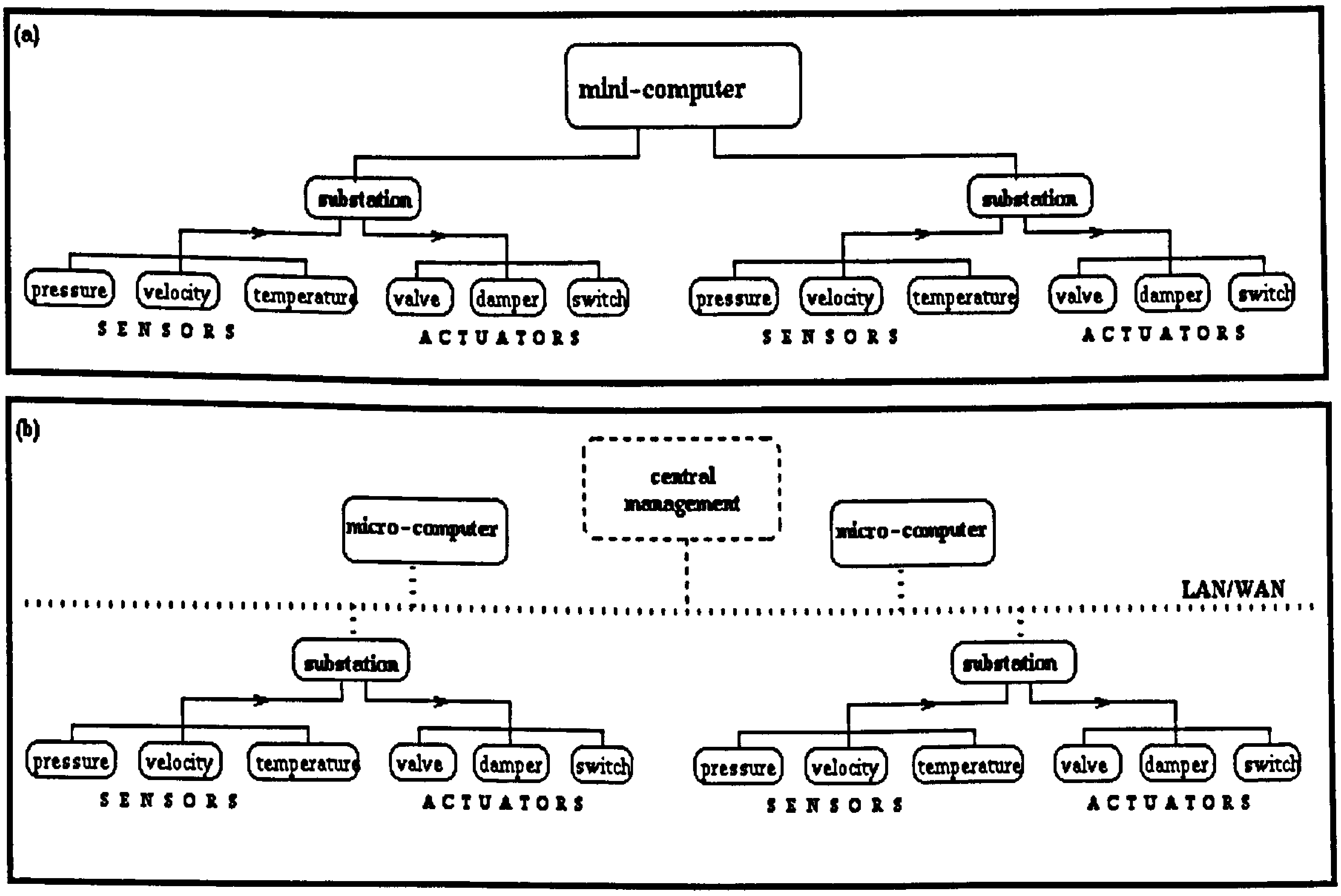


Figure 2.4 (a) Central computer system: (b) peer-to-peer network system

2.2 REVIEW OF CONTROL SYSTEMS MODELLING METHODS.

2.2.1 Classical linear feedback control theory.

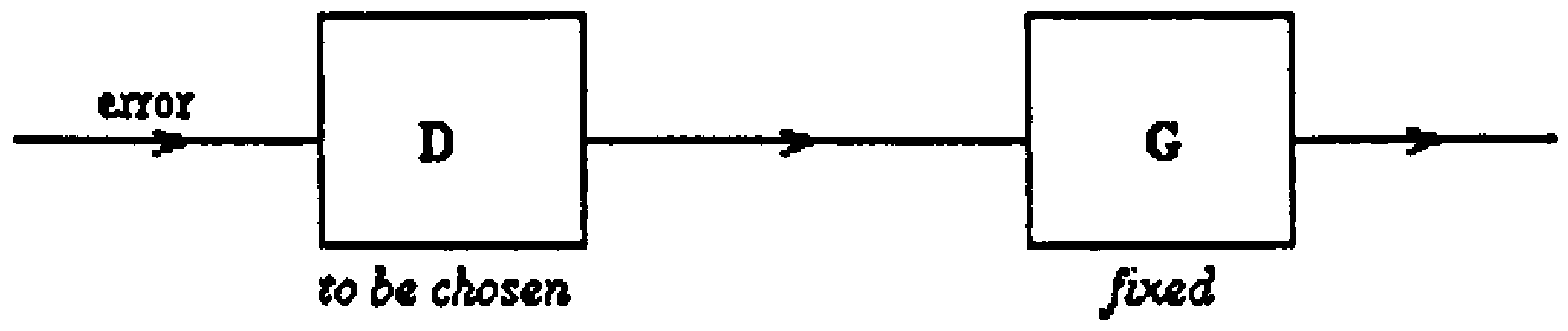
2.2.1.1 Introduction.

Traditionally the approach to control system modelling is to establish a model of the process and then to combine this with a controller model to give some *overall* characteristic for the system (Figure 2.5). In feedback controller design the task is to establish a controller model D, so that when it is connected to process model G, a suitable overall characteristic for the system will be obtained. In this way, the controller artificially enhances the process characteristics in ways chosen by the designer in order to achieve some desired system performance. The following relationships are obtained:

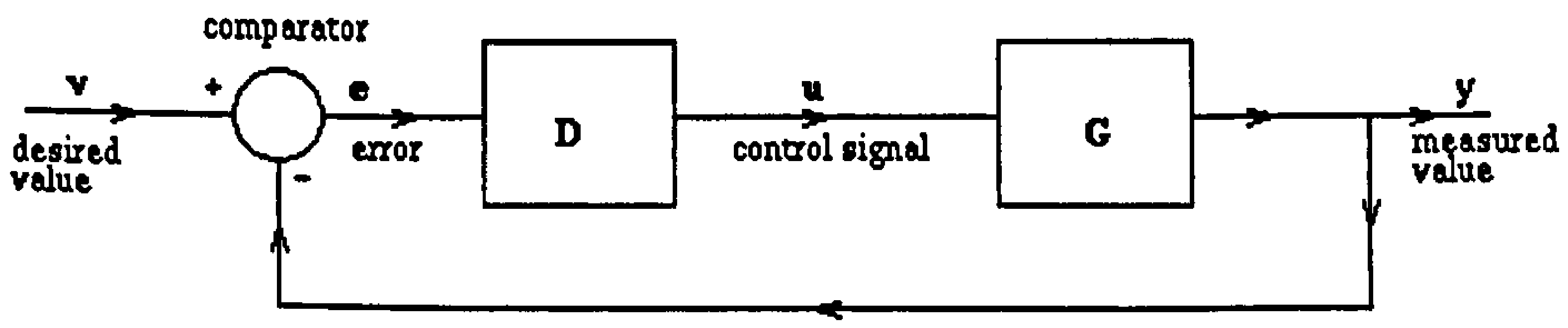
$$\text{system output} = Gu, \tag{2.1}$$

$$\text{controller input} = e = v - y, \tag{2.2}$$

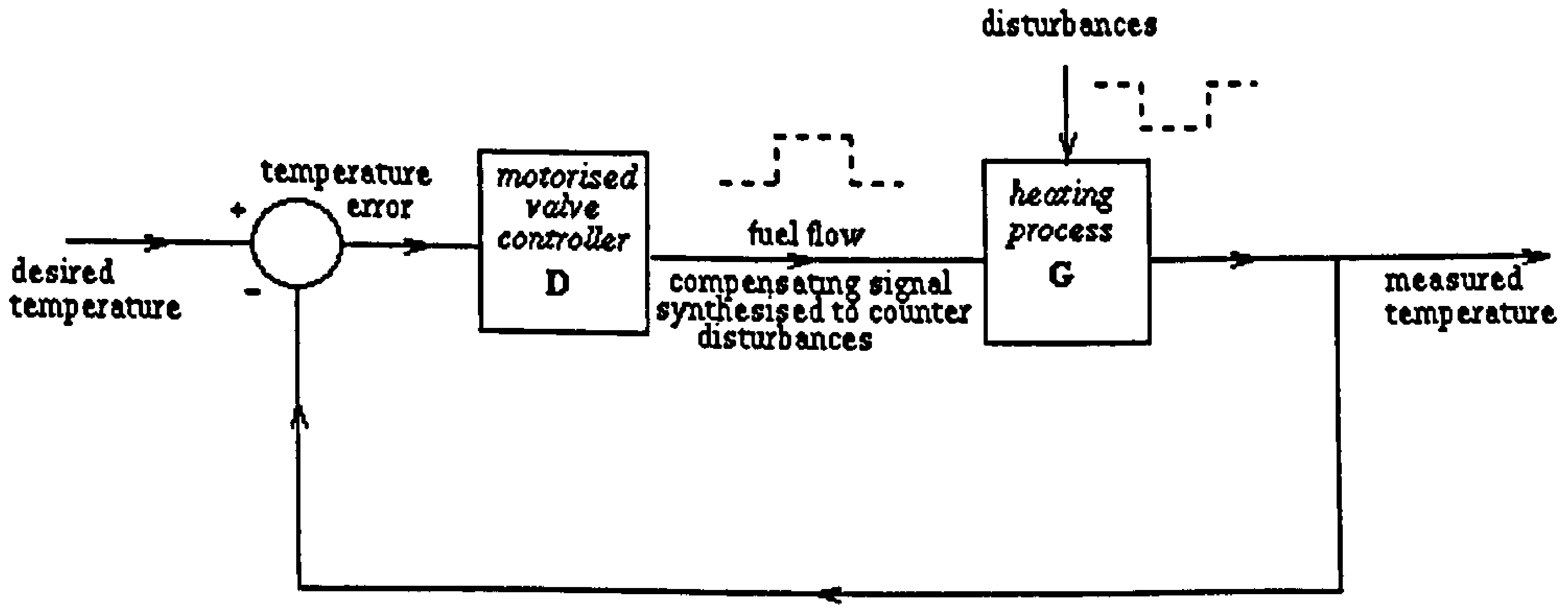
$$\text{controller output} = De. \tag{2.3}$$



(a) A controller-process combination.



(b) A feedback loop with the system to be controlled G and the controller D.



(c) An (ideal) feedback controller will synthesise an equal and opposite signal to counter the effect a disturbance.

Figure 2.5 Feedback controller modelling.

If it is possible to synthesise the best possible actions continuously by some algorithm, then there is fully *automatic feedback control.* The success of the scheme depends on the disturbances being measurable and on the existence of an accurate quantitative understanding of the system to be controlled.

In order to determine whether or not the control action taken at the input will be successful, and to what extent it should be taken, control engineers must have some mathematical means of modelling the process under consideration. Typically, this is done by writing energy-balance differential equations for the components and applying the Laplace transform which converts the differential equation into an algebraic form so that a *transfer function* can be extracted [Liptak 1995]. Block diagram algebra is often deployed to help determine the overall transfer function for two or more coupled subsystems [Westphal 1995].

The transfer function of a dynamic system with input $u(t)$ and output $y(t)$ is defined to be the Laplace transform of $y(t)$ under the condition that $u(t)$ is a unit impulse applied at time $t = 0$; or more generally applicable in practice,

$$G(s) = y(s)/u(s) \tag{2.4}$$

where the complex variable $s = \sigma + j\omega$.

If $G(s)$ can be expressed as $G(s) = P(s)/Q(s)$ then the zeros are the roots of the equation $P(s) = 0$ while the poles are the roots of the equation $Q(s) = 0$. $Q(s)$ governs the nature of the system's response to initial conditions and hence also its stability; conversely, $P(s)$ affects the manner in which the system responds to external inputs.

2.2.1.2 Controller algorithm design.

There are two main approaches to controller algorithm design. The first approach is synthesis of D(s) in order to achieve a specified closed loop transfer function $H(s)$. The second approach is to use a gain plus compensator scheme.

It is assumed that there exists a desired hypothetical process with overall performance $H(s)$. From equations (2.1 to 2.4):

$$y(s) = G(s)D(s)[v(s) - y(s)] \tag{2.5}$$

and

$$y(s)/v(s) = \frac{G(s)D(s)}{1 + G(s)D(s)}. \tag{2.6}$$

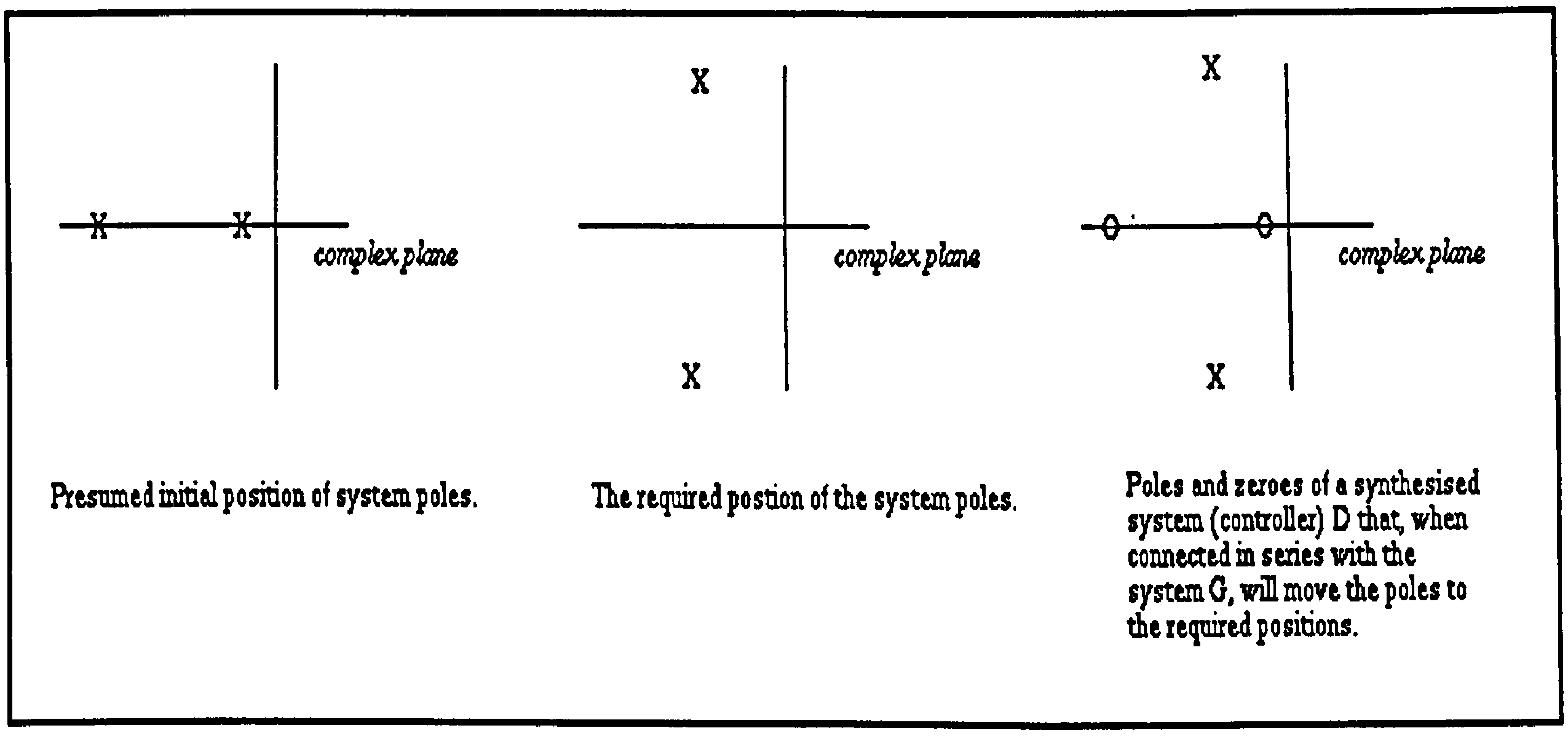
Thus

$$D(s) = \frac{H(s)}{G(s)(1 - H(s))} \tag{2.7}$$

will set $y(s)/v(s)$ equal to $H(s)$, i.e. the specification of the overall system is converted into a closed loop transfer function $H(s)$ with $D(s)$ selected to make the synthesised configuration behave like the chosen hypothetical process $H(s)$.

However, as Leigh [1992] argues, not every $D(s)$ is synthesisable in practice, and even then care must be taken in defining $H(s)$ so as to avoid instability and over-sensitivity. There are usually difficulties encountered when specifying $H(s)$, since limits on attainable performance are set by the constraints in the process (e.g. system lags and plant capacity limits); constraints not all modelled by the (linear) operator $G(s)$, as elaborated later in this chapter.

An alternative strategy is to design a controller with element $D(s)$ having a pole-zero diagram of Figure 2.6 which will cancel the poles of $G(s)$ and produce the required pole positions. This technique is called *pole-placement*, and is elaborated by Towill [1970].



Presumed initial position of system poles.

The required postion of the system poles.

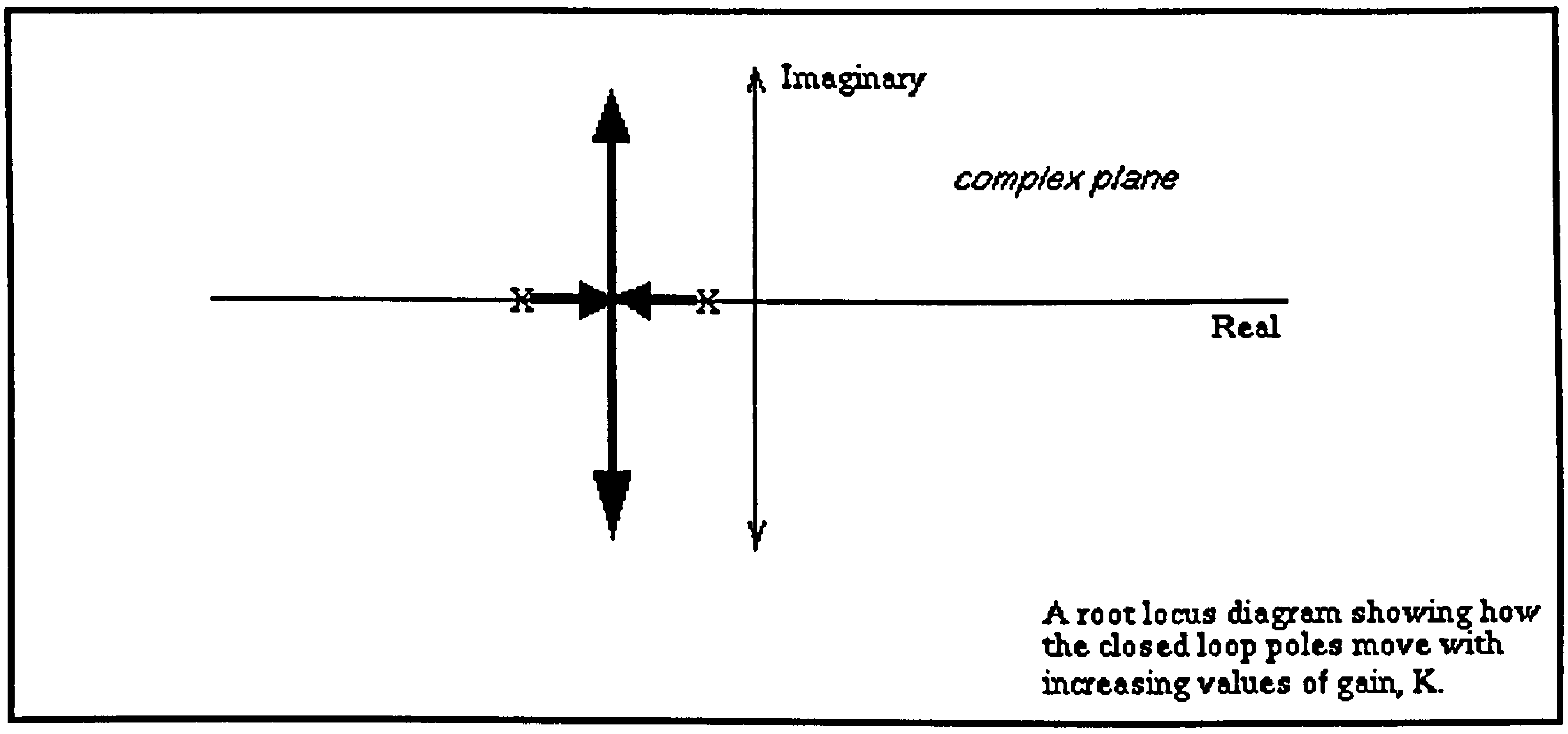
Poles and zeroes of a synthesised system (controller) D that, when connected in series with the system G, will move the poles to the required positions.

Figure 2.6 Pole-placement controller design technique.

2.2.1.3 Stability and performance appraisal.

The feedback control loop provides a means of close control; however, the existence of the loop brings the possibility of the potentially destructive phenomenon of instability. Usually performance is quoted in terms of the highest frequency that the control system can follow, when required to do so. All control loops tend to become unstable as higher and higher performance is sought. A system is stable so long as the output quantity can be controlled by the reference signal, i.e. a change in the reference signal results in a controlled change in the system output. Most systems become unstable as gains are increased in order to achieve high performance.

One commonly adopted approach to the determination of system stability is the Routh-Hurwitz procedure in which the poles are assessed to determine whether or not any lie in the right half plane thus indicating instability [Healey 1967]. It is possible, however, for a system equation to be on the borderline between stability and instability, a fact which does not emerge from the Routh-Hurwitz analysis. To have a method which indicates how near a system is to instability and which permits some assessment of the performance of a stable system, requires the observation of the movement of the characteristic equation roots as some parameter such as controller gain is varied - this is possible using the *Root Locus* method.



A root locus diagram showing how the closed loop poles move with increasing values of gain, K.

Figure 2.7 Root Locus plot.

For a polynomial equation with real coefficients, the roots will always be either real or occur in complex conjugate pairs. The Root Locus plot is the plot in the complex plane of the paths followed (loci) by the roots as a parameter of the equation varies, usually over the range zero to positive infinity (Figure 2.7). The parameter varied is usually the controller gain, *K*. With the aid of the Root Locus diagram, the value of *K* can be selected so that the closed loop poles are in desirable positions in the complex plane. In general, for a negative feedback control system with an overall forward-path transfer function *G(s)* and an overall feedback path function *H(s)*, the characteristic equation is:

$$G(s).H(s) + 1 = 0 \tag{2.8}$$

hence

$$G(s).H(s) = -1 \tag{2.9}$$

giving the two relations:-

Magnitude condition

$$|G(s).H(s)| = 1 \tag{2.10}$$

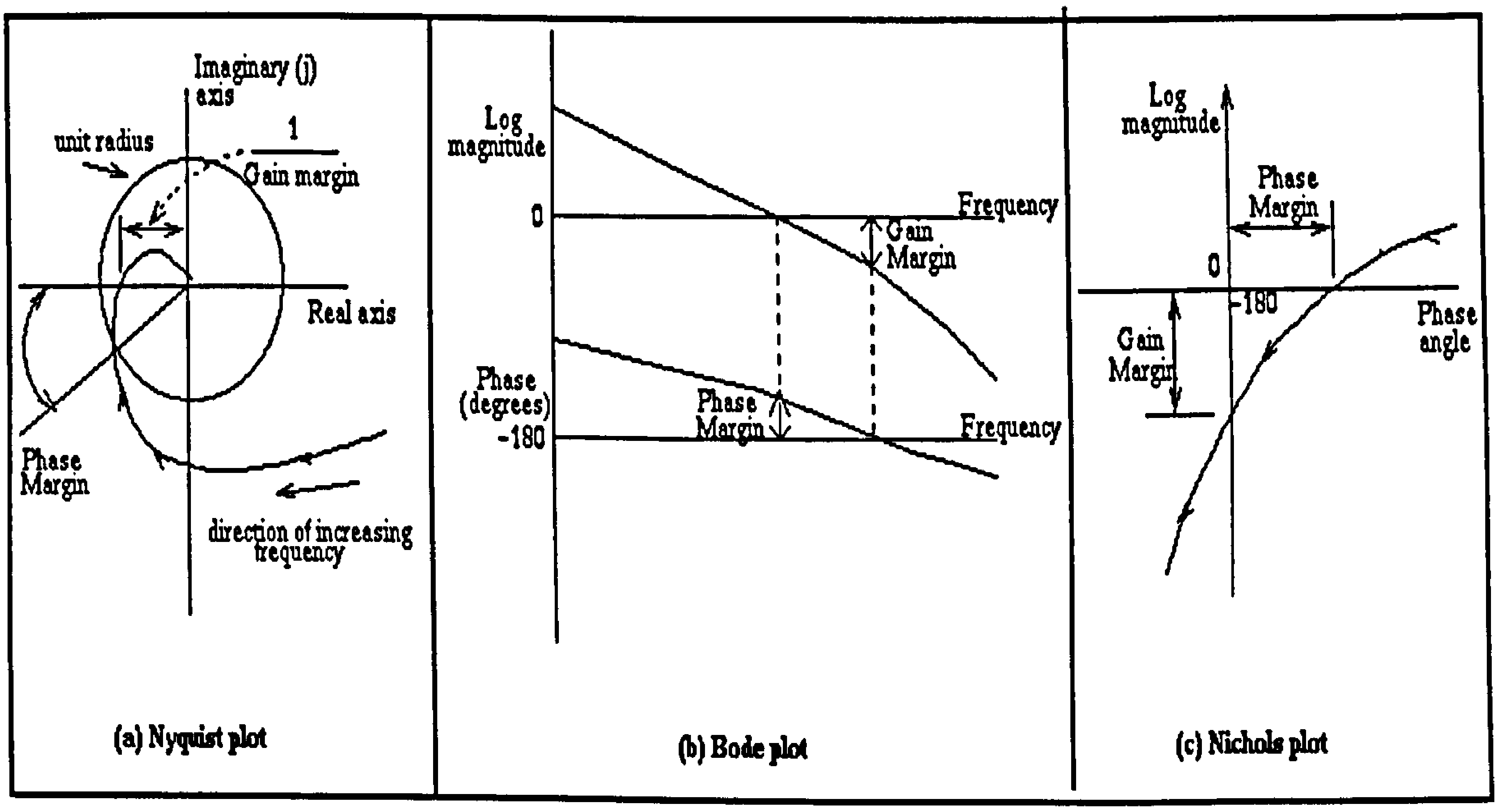
and *Angle condition*

$$arg[G(S).H(s)] = +/- 180^o \tag{2.11}$$

if *G(s)* is regarded as a complex function whose value is determined by the value of the complex variable, *s*.

From these two conditions a number of simple construction rules can be derived for sketching the loci of roots of a given equation [Westphal 1995].

As an alternative to the Routh-Hurwitz and Root Locus methods of analysis, it is possible to predict a control system's stability behaviour by examining its *open-loop sinusoidal frequency response* in terms of the relationship between the gain, phase shift and frequency. A number of sinusoidal changes are applied to the input with a constant amplitude but with an increasing frequency. The dynamic process gain and the phase shift are measured for each frequency and expressed in a graph (assuming all transient effects have died away - i.e. steady state response). Three ways of showing this relationship graphically are: the Nyquist plot, the Bode plot and the Nichols plot [Morris 1983] (Figure 2.8). The Nyquist Criterion is then used to draw conclusions about the significance of a given type of frequency response. The Nyquist Criterion states: if the magnitude of the frequency response of the open-loop transfer function is greater than unity when the phase lag is 180° then the system is unstable. The Nyquist Criterion shares with the Root Locus method the ability to indicate how near the system is to being unstable. This can be quantified by the use of Phase Margin and Gain Margin. These are defined as follows for a stable system: *Phase Margin* is the difference between -180° and the open-loop transfer function phase lag when the open-loop transfer function magnitude is unity; *Gain Margin* is the number of decibels to be added to the log-magnitude when the phase is -180° to make the log-magnitude equal to zero. As a rough guide for building systems, a 5 dB Gain Margin *and* 40° Phase Margin will generally be acceptable [Letherman 1981].



(a) Nyquist plot (b) Bode plot (c) Nichols plot

Figure 2.8 Phase and Gain Margins in Nyquist, Bode and Nichols plots.

Control design in the frequency domain typically consists of choosing a suitable compensator *D(s)*, and a gain *K* to obtain a closed loop system having high bandwidth. *D(s)* (containing frequency sensitive elements) is usually designed so that *G(s)* and *D(s)* taken together have a phase characteristic that reaches -180^0 at a much higher frequency than was the case for $G(s)$ alone. The gain K (which affects only amplitude - it has no effect on the phase shift) is then chosen so that the necessary stability margin is obtained whilst allowing for variations in the real system. In this way, $D(s)$ is being used to modify the phase characteristics of $G(s)$ in such a way that a high gain K can be used without incurring stability problems.

The Nyquist, Bode and Nichols plots clearly show at which frequencies actions taken can still be effective. If the frequency of the input value is so great that the process gain becomes small and the phases shift approaches 180^0, the process cannot be controlled by taking corrective actions at the input. Thus other courses of action will have to be taken in order to stabilise the output. These may be control methods such as feed-forward control, but usually it will be necessary to change the process itself in order to obtain a different dynamic process gain. Thus, by using these plots, it can be determined at which frequency of changes at the input the process will be self-stabilising, can be stabilised, or cannot be stabilised.

2.2.2 Modern control theory.

2.2.2.1 Optimal control.

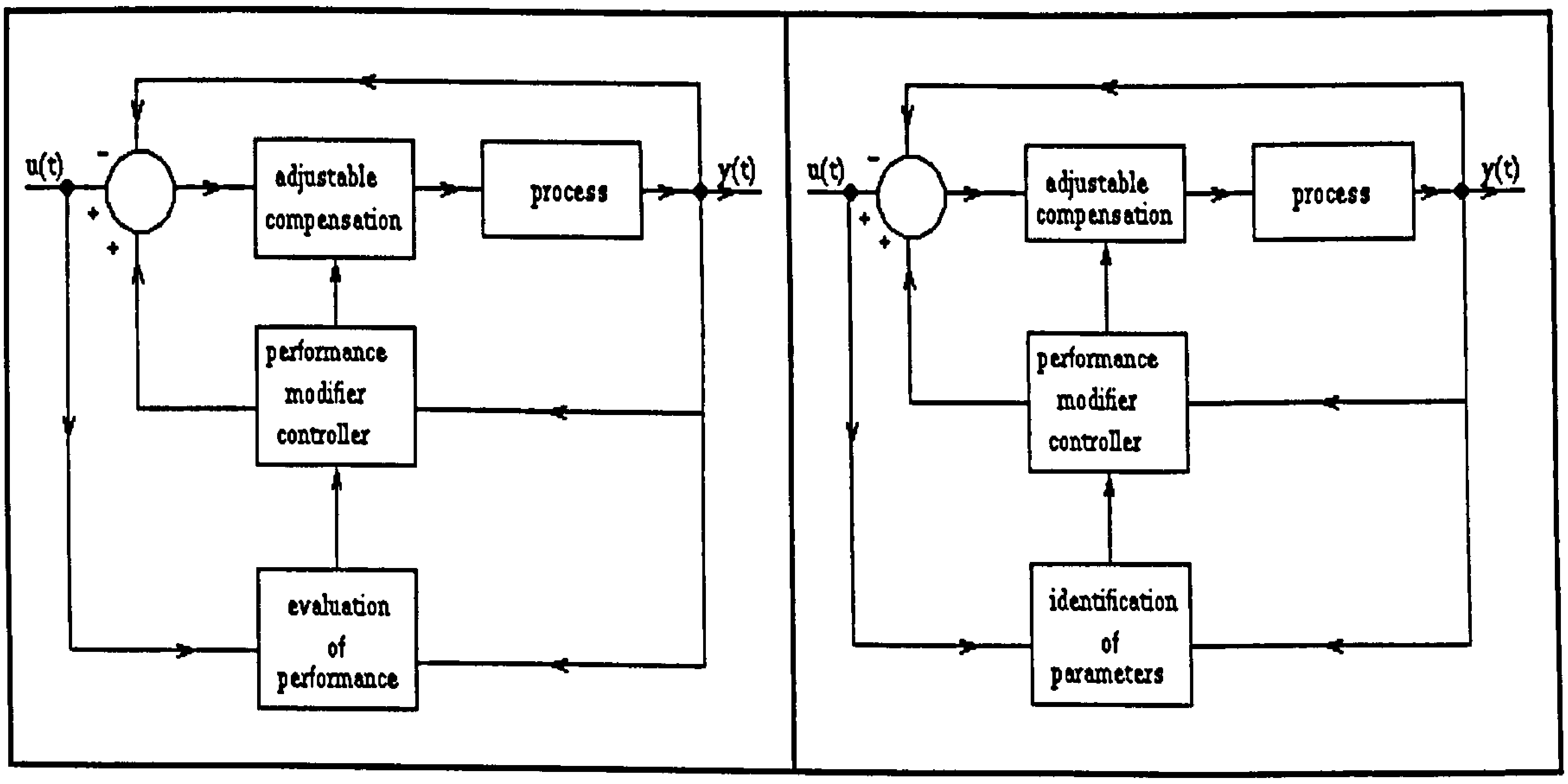
So far, the techniques described have used simple optimisation techniques, such as obtaining maximum phase margin from a system by adjusting compensating network parameters. It is, however, possible to consider the introduction of a performance index directly involving system error, (i.e. the difference between system input and system output) which is often what is really required to be kept small and perhaps even be minimised in a mathematical sense. The concept of a performance index, or *cost function,* as the integral of some function of the system error, is then used to determine either system parameters or control inputs, or both, to minimise this error. Even the simplest optimal control design of a control system for some (building) process Σ requires a scalar-valued cost function $J(x,u,..)$ that realistically quantifies all the building process factors of importance. (For example, in a building heating process, J might map variables such as deviation from a set point, a comfort index and energy loss into a single number which, when minimised, ensures optimal control profitability of the process). Given the equations (model) of the process, Σ, and the cost function, J, optimal control theory then attempts to establish a control policy $u(k)$, $k = 0,\ldots\ldots n$ which will achieve given control objectives and simultaneously minimise (and, in some cases, maximise) the cost function J.

The classical mathematical tool for solution of optimisation problems is the *calculus of variations.* However, this method cannot deal with discontinuities and thus cannot be applied in many practical control situations [Sagan 1969]. *Pontryagin's Maximum Principle* or *Bellman's dynamic programming method* then need to be used [Bryson and Ho 1975]. These methods all yield open-loop optimisation strategies since they all specify $u_{optimal}$ for all t in the time interval of interest. Since, pragmatically, it is more usual to implement closed-loop optimisation, these strategies need to be converted to a closed loop algorithm. Provided that a quadratic cost function (i.e. with J restricted to be simply a weighted sum of squares of its arguments) is adopted and the process equations are linear, the conversion is always possible by solution of the *Riccati equation.* Since the performance of the design is judged with respect to *J*, nothing else matters in the optimisation and so it is important to formulate the objectives correctly. In practice the choice of *J* is always an extremely difficult one - a compromise always has to be reached between relevance and mathematical tractability in the search for a well-specified cost function. Also, implementation often requires massive real-time computation.

2.2.2.2 Adaptive, learning and self-organising control systems.

Often, control systems must be designed to operate in an environment such that the dynamics of the system or the inputs to the system are either incompletely known and/or change characteristics in an unpredictable way. Thus the design of a control system which will perform well in the face of many uncertainties is an attractive possibility. The primary objective of *adaptive, learning* or *self organising control* is to reduce uncertainties concerning knowledge of the environment and systems dynamics, and to alter controller performance in an on-line or real time fashion in order to continually ensure satisfactory system operation and further seek better performance.

Most adaptive systems can be classified as either *performance adaptive*, in which observations of the input and output of the controller are made and the parameters of the controller adjusted by composing the input-output performance of the system with a reference standard; or *parameter adaptive*, in which control system parameters are identified by observing control system input-output relations, and control system compensators modified in an on-line fashion in accordance with these changes (Figure 2.9). These topics are reviewed by Sage [1978].



(a) Performance adaptive control system.

(b) Parameter adaptive control system.

Figure 2.9 Approaches to adaptive control.

2.2.2.3 Non-linear systems.

The mathematical description of a dynamic system can be embodied in a differential equation such as:

$$a\ddot{\theta}(t) + b\dot{\theta}(t) + c\theta(t) = f(t) \qquad (2.12)$$

and such a system would be described as linear if the coefficients a, b and c are not affected by the values of the dependent variable θ(t) or of the independent variable f(t). Most of the control systems design and analysis tools operate only on linear models: matrix and vector methods, transform methods, block diagram algebra, frequency response methods, poles and zeros and root loci are inapplicable [Leigh 1992]. Thus efforts are usually made to replace a non-linear system with a corresponding linear system model.

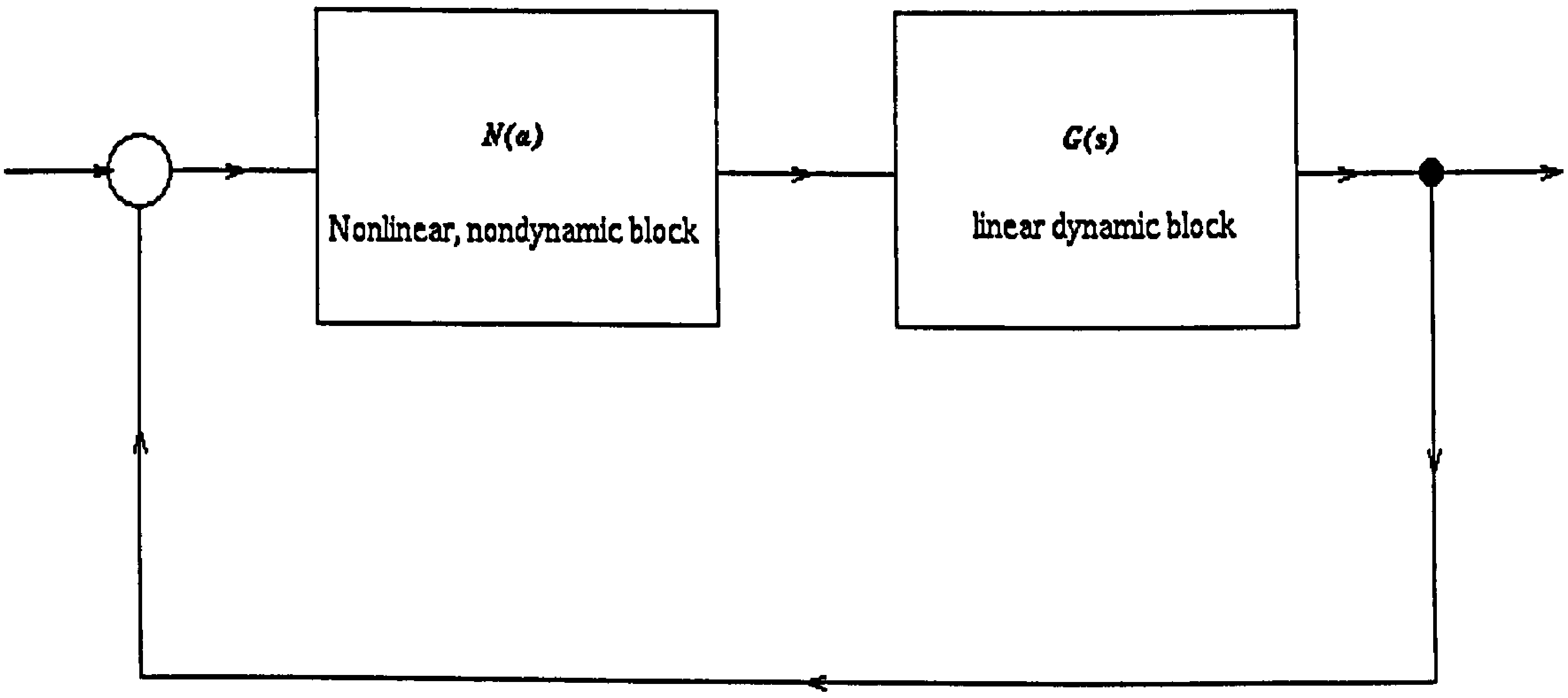


Figure 2.10 Control loop structure for Describing Function method.

This can be considered as an attempt to extend the concept of the linear transfer function to use in non-linear systems. For a linear transfer function with a sinusoidal input of unit amplitude sin(ωt) the output will be a sine wave A(ω) sin(ωt + ϕ). The transfer function introduces an amplification A(ω) and phase shift ϕ(t) both of which may in general be dependent on frequency ω but not on the amplitude. The difficulty in extending this concept to the non-linear systems is that the output waveform for such systems are not in general sinusoidal, and in certain cases may not be of the same frequency as the input wave.

There is an extensive literature on the topic of the control of non-linear systems [Letherman 1981]. Methods commonly adopted in the analysis of such systems include: the Step Response method, the Describing Function method and Tsypkin's method. The Describing Function method, for example, is a linearisation method in which sinusoidal analysis proceeds by the expedient of neglecting harmonics generated by non-linearities. Thus the approximation consists in working only with the fundamental of any waveform generated. The method assumes a system in which the linear and non-linear components can be separated, as shown in Figure 2.10 where *G(s)* is the Laplace transfer function of the linear part of the system, and *N* represents the non-linear part. For example, *N* could be the input/output characteristic of the relay or thermostat. The method consists of deriving two loci in the complex plane, one for the non-linear element *N(a)* and one for the dynamic element *G(s)*. The first locus is a function of amplitude only and the second is a function of frequency only. The describing function method then indicates whether stable oscillations will occur at the intersection of loci.

2.2.2.4 State space approach.

The classical transfer function based techniques described earlier can only permit the design and analysis of the complete input/output description. The advantages of the state space approach over the classical methods are that greater insight into the internal behaviour of the system is possible, as well as the ability to analyse individual sections of the overall system.

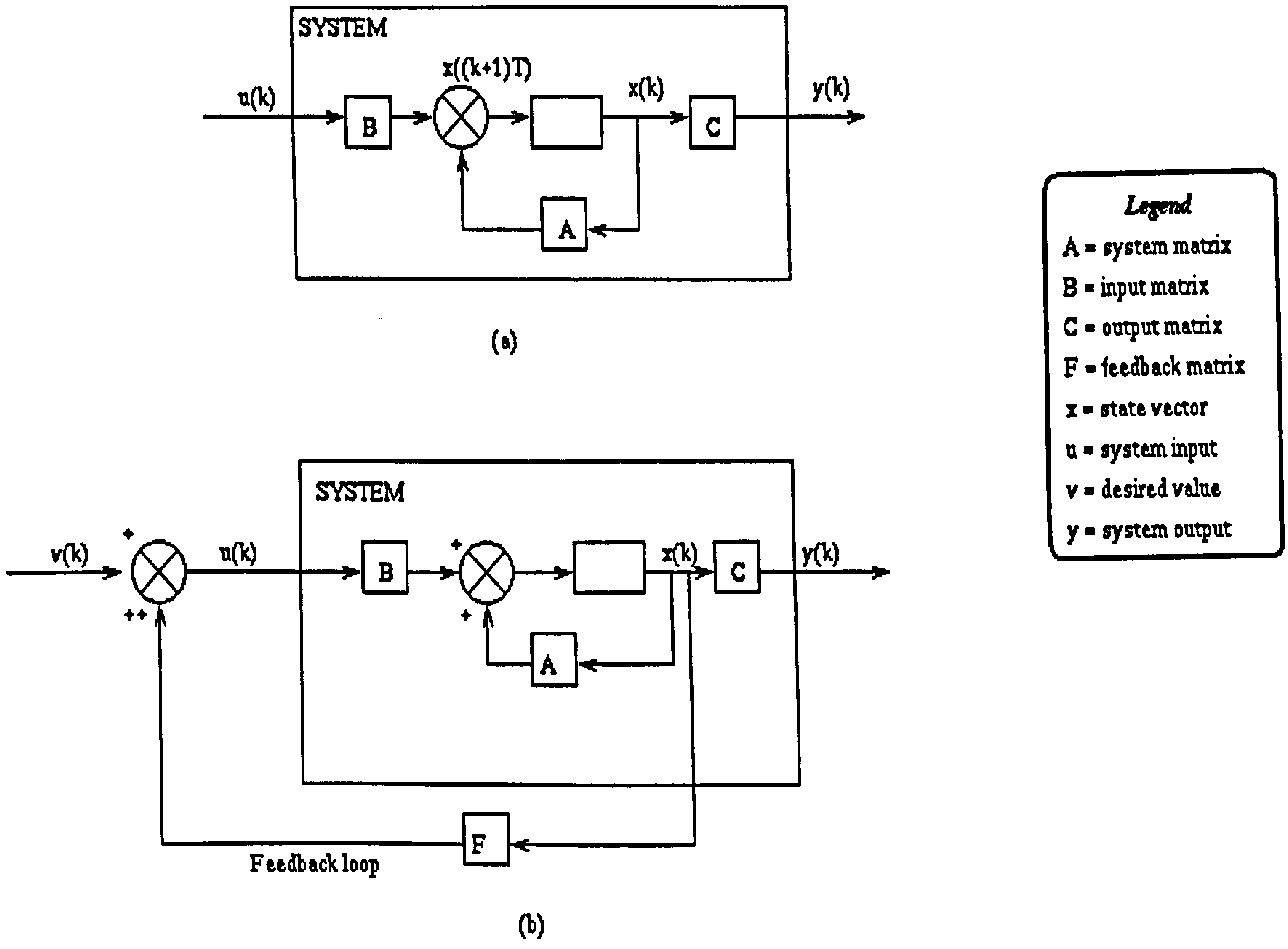


Figure 2.11 State-space modelling.

A state space is defined as a *N* dimensional space with axes of state variables. Therefore, any state can be represented by a point in the state vector of dimension equal to the order of the system. The selection of state variables is not unique, i.e. those considered as a ***minimum set of variables determining the state of the dynamic systems***. For the solution of the state equations, many tools such as linear algebra, vector matrix and numerical methods can be used to analyse the dynamics of the system and optimal control problems. The transfer function may be transformed into an equivalent state space form by the use of classical programming techniques (e.g. the so-called *direct programming* technique [Virk 1991]).

Compensation in state space design.

The system is typically described by a system vector differentiation of the form:

$$\dot{x} = Ax + Bu$$

$$y = Cx \tag{2.13}$$

where x(t) (the *state* vector) is $n \times 1$, u(t) (the *input* vector) is $m \times 1$, y(t) (the *output* vector) is $r \times 1$, A (the *system* matrix) is $n \times n$, B (the *input* matrix) is $n \times m$ and C (the *output* matrix) is $r \times n$.

The A matrix gives rise to the eigenvalues (poles) of the system which define the dynamic behaviour. The classical feedback compensation techniques can be extended to the state-space by the introduction of control loops that generate the input by a linear combination of the state x (Figure 2.11). If the systems is *controllable*, a feedback matrix, F can be designed such that the closed-loop poles are at any desired position. The state-space design methods rely on the complete state vector being available for feedback purposes, which in practice is not the case. This problem is overcome by employing a *state observer (estimator)* that is constructed (assuming the system is *observable)* using knowledge of the A, B, C system matrices. A whole armoury of estimation techniques, under the generic name *Kalman filter*, are available for this purpose [Kalman *et al* 1969]. Using the principle of separation, this state estimate can be used as if it were the real state vector in the design process.

2.2.2.5 Digital control systems.

So far, the discussion has focused on the use of Laplace transforms to solve *differential equations*, where the functions are analogue and continuous in time. However, the ubiquity of the digital computer both as a systems analysis and design tool as well as a component in control systems has led to the need for alternative mathematical approaches. Many other modern control systems, including BEMS, use microprocessors which operate on information obtained at discrete time points, denoted sampling points, sampled data systems or digital control systems (Figure 2.12).

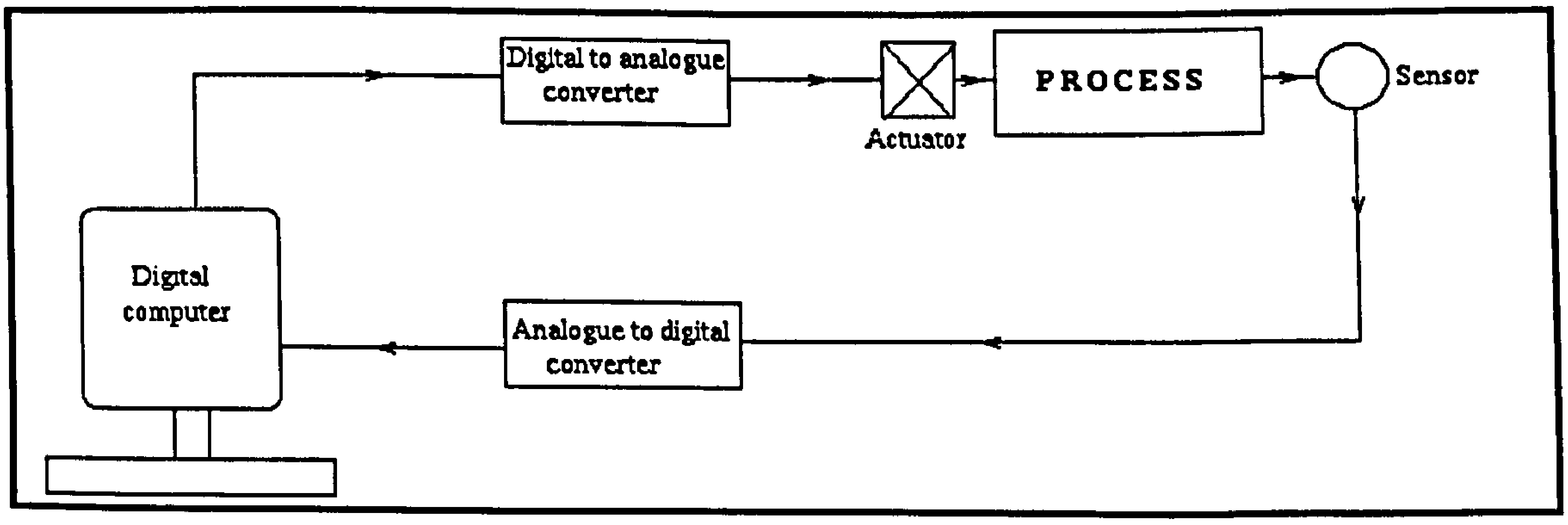


Figure 2.12 Digital control system.

For these systems *difference equations* rather than differential equations, and *z-transform* rather than the Laplace transform are used [Isermann 1981]. Essentially, all the design practices for continuous time systems have a discrete time equivalent. For example, frequency response analysis of discrete-time systems is carried out on the so-called ω-plane, which is equivalent to the s-plane for systems continuous in time [Ogata 1987]. The importance of discrete-time algorithms lies in the fact that they are directly realisable in a digital computer controller.

2.2.3 Numerical methods.

The classical and modern control design methods described above are based on sophisticated mathematical procedures resulting from several decades of research and development activity, with proven track records in many control engineering applications, e.g. food, manufacturing and chemical process industries [Newell and Lee 1989]. However, these analytical methods have limited applicability to many building/plant/control processes which have *time-dependent* thermal properties and highly non-linear characteristics not *all* of which are modelled by the (linear) operator $G(s)$ which assumes time-invariant properties. Factors accepted as contributing to building system non-linearity include [Kelly 1988, Virk *et al* 1990]:

- low valve authority and high valve hysteresis;
- HVAC systems operate over loads that can vary from 0% to 100% over a time period of a few hours causing large time delays;
- discontinuities result from on/off cycling;
- plant are sequenced from one controlled device to another (e.g. cooling coil valve, damper, heating coil valve);
- buildings are multi-variable in nature, since many inputs (climatic conditions, casual gains, heater/chiller flux, etc.) affect the many outputs (temperature, relative humidity, air flow rates, etc.);
- buildings are subject to stochastic effects such as fluctuations in occupancy levels, ventilation rate variations and climatic changes.

Also, as the complexity of the object system increases, as in the case of building and plant processes, analytical control strategies based on *controller-process* models often become infeasible:

- the model-building (identification) process becomes increasingly elaborate, iterative, error-prone and time-consuming;
- the collection of algorithms of system identification (based on methods of statistics, experiment design and multivariable-function optimisation) often loses a lot of its strength, power and applicability;
- this complexity can be due, for example, to non-linearities of the type mentioned previously.

Numerical methods, on the other hand, offer powerful techniques for the solution of many of the problem types insolvable by analytical techniques [Kup 1972]. With regard to building environmental control systems, numerical methods offer the following advantages:

- the modelling of *time-dependent, non-linear* characteristics of building systems not accounted for by the classical and modern control modelling approaches outlined earlier, is facilitated;
- it is possible to eliminate the need for separate controller and process models and elaborate identification procedures [Clarke 1985];
- numerical modelling methods are ideally suited to digital computing systems.

2.2.4 Computer based simulation programs.

The earliest computer simulations of building control systems were carried out using analogue computing techniques [Nelson 1965, Magnussen 1970]. Since the early 1970's, however, digital computing techniques have predominated [Ayres and Stamper 1995], the digital computer programs being based on the modelling methods outlined earlier [Winkelmann 1988]. In comparison to those for the building-side issues, the range of computer based modelling and simulation approaches for environmental control systems is much greater. Hensen [1993] reviewing current computer based building environmental systems simulation program types, classified them in terms of abstraction levels, characteristics and application (Figure 2.13), ranging from a purely conceptual representation of plant and control systems through to an explicit, subcomponent modelling level.

2.3 AREAS FOR DEVELOPMENT.

2.3.1 Issues to be addressed.

A recent review of the control options available in building energy simulation programs [Hitchin 1991], indicates the following typical program inadequacies:-

- control element dynamic response is often neglected;
- no mechanisms exist for the modelling of multiple input, multiple output (MIMO) systems;
- there is an inability to deal with multi-level, hierarchical systems;
- models for many microprocessor based controller strategies are omitted;
- no provision is made for *simulation-based controller design*, which would facilitate innovative control design strategies and on-line supervision of BEMS.

Accepting that these inadequacies exist, extending the modelling facilities and applicability of simulation programs are therefore the two main issues to be addressed in this work.

2.3.2 Accuracy of modelling.

The premise of this project is that the issue of modelling accuracy is of the utmost importance and, if disregarded, will greatly influence simulation predictions and, ultimately, the design and operation conditions, whilst also severely limiting model applicability.

	LEVEL	TYPE
A	Room processes only; ideal plant	Conceptual
B	System wise in terms of (real) systems like VAV, WCH, etc.	↓
C	Component wise in terms of duct, fan, pump, pipe, etc.	↓
D	Subcomponent level in terms of energy balance, flow balance, etc.	Explicit

Figure 2.13 Categories of building systems simulation programs [Hensen 1993].

The contention is that the accuracy of building control system modelling in the transient domain can only be increased and optimised if *all* relevant aspects, features and characteristics of real systems are taken into account during the modelling process. This requires tools that adopt a *fully integrated* approach, which considers all energy flow paths and the interaction of control systems with fabric, flow, plant and power systems. Lebrun *(et al)* [1985] observed that a full *dynamic* model of the building is necessary to obtain realistic simulation results, adding that the scattering of real control laws among the different zones necessitates the use of a *multi-zone* simulation model (capable of handling physical processes such as inter-zone convective couplings) if the control engineer is to have a means of establishing optimal control of the HVAC system.

2.3.3 Extending applicability.

Although building control requirements are not severe by standards in the process control industries, problems arise when trying to predict the performance of building control systems and assess the effect of the quality of control on system operation, energy consumption or comfort. Many of the available design and appraisal simulation tools based on the modelling methods described earlier are not domain-specific; in those that are, the control theory/models/algorithms are often contained and presented in a manner which is entirely foreign to many members of the building design team, such as architects. Such simulation tools are therefore often not adequate or employable for the building control system appraisal task in hand.

Applications of building control system simulators may be classified into three broad categories:

- *initial building design appraisal,* where control specification may be very basic and simple;
- *practical system design* necessitating more rigorous specification for purposes of operating characteristics, commissioning, operator training, etc;
- *ambitious and highly conceptualised control schema* involved in control systems

research programs.

It is evident that the potential of simulation in all three areas has hitherto not been fully realised. This is a key issue facing the energy modelling community.

2.3.4 A control systems modelling and simulation environment.

If the applicability of modelling tools is to be increased and the full potential of control systems simulation realised and utilised in the pursuit of the intelligent building, there are many additional and desirable features with which programs must be equipped, including:-

- improved user interfaces and problem definition procedures;
- advanced sensor and actuator modelling capabilities;
- installation of optimal, adaptive and artificial intelligence control algorithms;
- hierarchical control strategy modelling capability;
- time-step controllers which allow simulation-based predictive-iterative control schema to be modelled both for design purposes and also - hitherto not implemented - for on-line optimisation of practical BEMS.

An attempt must therefore be made to formally identify and classify *all* those elements and characteristics extant in real control systems, which require to be considered during the modelling process and subsequently included in simulation programs. The resulting taxonomy of building control system entities can then be used to guide the modelling development process and thus aid the quest for a comprehensive building controls system modelling facility.

The conceptual development of a taxonomy of control systems entities in terms of system logical, spatial and temporal elements, together with associated modelling schema is detailed in Chapters 4,5 and 6. Such schema, however, require a simulation environment which satisfies the twin criteria of modelling accuracy and also provides initially a test bed and subsequently a vehicle for their widespread application. Such an environment is the subject of Chapter 3.

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Chapter 3

THE ESP-r SIMULATION ENVIRONMENT.

The need for control simulation programs has been established (Chapter 1), and the traditional approaches have been discussed (Chapter 2). It was found that the main disadvantages and inadequacies of many of the commonly adopted approaches focus on the issues of integrity and containment. It was argued that what is required is a simulation program methodology capable of maintaining integrity of the modelling process of complex practical system, at any required level of abstraction, in a fully integrated manner and in the transient domain.

This Chapter describes a system which facilitates such an integrated modelling approach, namely ESP-r. A brief overall review of the system's capabilities is given, followed by a description of the theory encapsulation and numerical solution methods employed.

3.1 INTRODUCTION.

For the purposes of the present work, it was decided to work with a state-of-the-art simulation program based on a fully integrated approach - namely ESP-r (Environmental Systems Performance, research version). ESP-r is an energy simulation program which permits an assessment of the performance of existing or proposed building designs, incorporating traditional and/or advanced energy features. ESP-r uses numerical methods to solve the various equation types (algebraic, ordinary differential and partial differential) which can be used to represent the heat and mass balances within buildings. The system is not building type specific and can handle any plant system as long as the necessary component models are installed in the plant components' database. The system offers a way to rigorously analyse the energy performance of a building and its environmental control systems. For each real-world energy flow-path, ESP-r has a corresponding mathematical structure.

The numerical engine of ESP-r was researched between 1974 and 1977 when the various techniques for modelling energy flow in buildings were investigated and compared [Clarke 1977]. This seminal work led to a prototype model which used state-space equations and a numerical processing scheme to represent all building heat flux exchanges and dynamic interactions. Building and plant modelling approaches are theoretically compatible. Central to the model is its customised matrix equation processor which is designed to accommodate variable time-stepping, complex distributed control and treatment of stiff systems (i.e. systems with a large range of time constants). The customised matrix processors ensure that all flow-paths evolve simultaneously in order to fully preserve the important spatial and temporal relationships. Air flow modelling [Cockroft 1979, Hensen 1991 and Negrao 1995] and plant system modelling [McLean 1982, Tang 1985, Hensen 1991, Aasem 1993, Chow, 1995 and Kelly 1997], capabilities have since been refined and extended. Recent projects include the introduction of adaptive multi-gridding techniques [Nakhi 1995] enabling explicit modelling of three dimensional phenomena such as thermal bridging and constructional edge effects.

3.2 PROGRAM METHODOLOGY.

ESP-r operates in graphical, interactive modes by menu driven command selection. The system has a modular structure comprising several interrelated programs, as depicted in Figure 3.1. Essentially, it is composed of three main modules, the *Project Manager*, the *Simulator* and the *Results Analyser*.

Since the quantity and diversity of information required by simulation makes the human-computer interface especially difficult, a project management tool, *prj*, exists [Hand 1994] which manages the description of buildings, occupancy schedules, HVAC plant, control systems and related technical data.

The problem is specified accessing satellite modules, such as on-line databases (climatic sequences of differing severity, event profiles, plant components, pressure coefficients, window properties, etc.) and utility modules (shading and insolation, view factors, etc.). *Prj* subjects all input data to a range of legality checks and provides building perspective views. By relieving the user of much of the burden of managing the potentially large sets of descriptive files, the model creation process is more productive.

The *Simulator, bps*, performs prediction of building/plant energy and fluid flows according to the problem defined. Several modules, which are responsible for individual technical aspects of the simulation, comprise *bps*, such as control, fluid flow, plant system, power systems, etc. This modular structure allows each module to evolve independently, as a specialist need work only with those modules which are related to a specific research field. This preserves the integrity of the system when a model is modified or when a new model is included, since the modifications can be verified individually from the whole system.

The third main module, *res*, is responsible for the analysis of the results stored by the *Simulator*. Different forms of results are available: perspective visualisations, results interrogation, statistical analysis, graphical display, tabulations, etc.

The interaction between the three modules can be continuous in order to help the building designer with the decision making process. In other words, the user analyses the results, changes some parameters of the problem and executes simulations in an iterative loop.

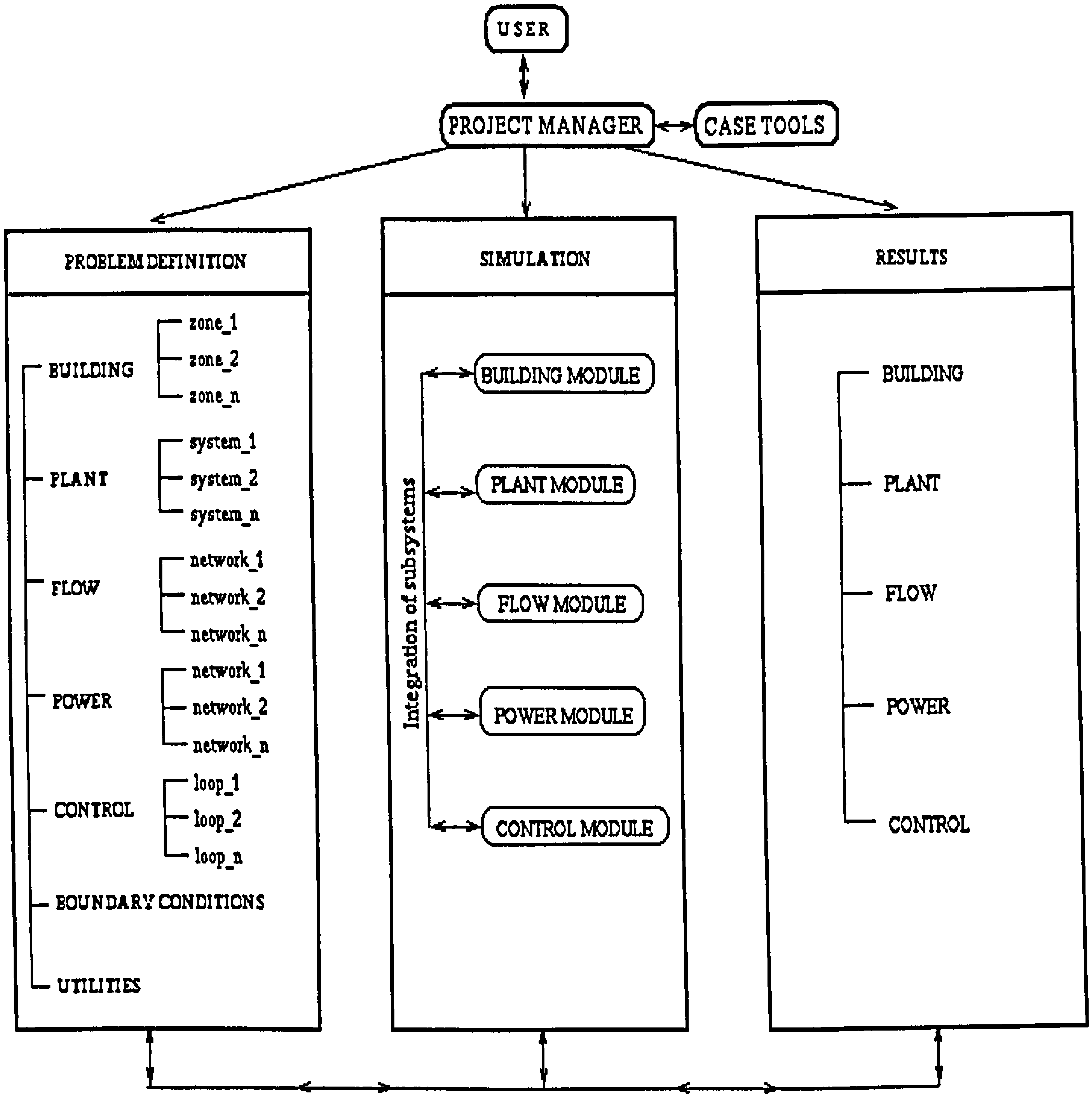

Figure 3.1 The ESP-r simulation environment.

3.3 RECENT ESP-r DEVELOPMENTS.

Recent ESP-r program developments include the following.

- *Combined heat and moisture transfer modelling.* To model constructions and/or thermal properties which change over time or as a function of hygroscopic phenomena, ESP-r offers various features with respect to nodal placement (including automatic adjustment) and time-dependent (and non-linear) modification of properties such as conductivity. These facilities form the basis of a combined heat and moisture transfer modelling capability [Nakhi 1995]. Via this option, the thermal conductivity of any layer can be defined to be a linear function of temperature and/or moisture content. An additional option for nonlinear thermophysical properties allows the properties of layers to be defined as polynomial functions of temperature and moisture content.

- *Electrical power flow modelling.* ESP-r is endowed with a power modelling module [Kelly 1997] which facilitates the modelling of photovoltaic facades and combined heat and power systems, and allows the imposition of an electrical grid incorporating loads (lights etc) and generators on the thermal/flow networks representing the building and its plant.

- *Modelling and simulation of renewable energy systems.* Since its inception ESP-r has been equipped to model solar thermal systems. The above power flow modelling developments imply that it is now possible to model (renewable energy) electrical components such as PV (Photo-Voltaic) cells, wind turbines and the like.

- *Detailed air flow modelling.* ESP-r now incorporates a CFD (computational fluid dynamics) module which enables prediction of detailed air velocity and temperature distributions within a zone [Negrao 1995]. The module can be operated in isolation and/or in fully integrated mode.

- *RADIANCE interface.* ESP-r now allows export of problem description data to various other packages; for example RADIANCE † [Ward 1992]. In addition, ESP-r features a "RADIANCE desk-top" which is an interface for running RADIANCE [Clarke 1995].

- *Plant Component Taxonomy by Primitive Parts.* Another project [Chow 1995] has established mathematical models for each of the physical processes that occur within plant components (boiling heat transfer, flame radiation, etc) and used these to explore the possibility of automatically constructing component models from primitive parts. This allows all component models to be synthesised from a small number of primitive models rather than each component requiring a unique mathematical model.

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† RADIANCE is a research tool developed to predict the distribution of visible radiation in illuminated spaces.

3.4 NUMERICAL APPROACH ADOPTED IN ESP-r.

3.4.1 System discretisation.

The *continuous* building, its contents and plant system are translated into a corresponding *discretised* nodal network. The building and plant are then composed of a number of interconnected finite regions possessing uniform thermophysical properties. The following conservation principle is observed within each control volume, CV, with control surface, CS:

[storage rate within CV] = [net flux through CS] + [generation rate within CV] *(3.1)*

Equation 3.1 for the finite region *p* can be written in the following mathematical form:

$$\frac{\partial}{\partial t}(\rho_p v_p \phi_p) = (J_\phi A)_{CS} + S_{\phi p} v_p \tag{3.2}$$

where ϕ represents a transport property such as temperature, moisture content, etc, ρ_p is the density of the region (kg/m^3), v_p is the volume of the region p (m^3), J_ϕ is the flux of the transport property ϕ through the control surface CS per unit of area (kg/m^2s), A_{CS} represents the control surface area m^2 and $S_{\phi p}$ is any energy or mass injected directly to the finite region (kg/m^3s). The transport property flux through the control surface is the result of the energy exchange mechanisms between the finite regions in energetic contact, through conduction, convection, radiation and fluid flow. As the flux at the control surface is usually difficult to estimate, it is treated as a function of the transport property differences. Therefore, the product $(J_\phi A)_{CS}$ is expressed as the sum of all inter-volume interactions concerning control volume *p:*

$$(J_\phi A)_{CS} = \sum_{j=1}^{n} K_{j,p}(\phi_j - \phi_p) \tag{3.3}$$

where *j* is a finite volume in contact with the volumes *p, n* is the total number of finite volumes in contact with *p and* $K_{j,p}$ is the (often non-linear) conductance coefficient (representing conduction, convection, mass flow rates, etc) between volumes *j* and *p*. The flux through the control surface can now be expressed as the energy interactions between finite regions. The technique necessary to obtain all coefficients related to the different energy transfer processes (conduction, convection, radiation, etc) is described by Clarke [1985].

3.4.2 System matrix generation.

Integration of Equation 3.2 over a finite time interval, δt gives:

$$v_p[\rho_p \phi_p - \rho_p^* \phi_p^*] = \sum_{j=1}^{n} K^{\zeta}_{j,p}(\phi^{\zeta}_j - \phi^{\zeta}_p)\delta t + S^{\zeta}{}_{(\phi p)} v_p \delta t \tag{3.4}$$

where the superscript * represents the property at the beginning of some time interval (present time row values) and the superscript ζ indicates the values within the time interval. The symbols without superscript are the values at the end of the time interval (future-row values). Variation of properties at

ζ may be approximated by present time-row values (explicit scheme), future time-row values (implicit scheme) or a weighting factor, γ, may be applied. In ESP-r, the weighting factor is user-specified with a default value of 0.5 assumed (Crank-Nicolson formulation). (Issues relating to implicitness, such as stability and error, are discussed by Hensen and Nakhi, 1994).

Equation 3.4 may be rearranged and expressed only in terms of future values (unknown) and present terms (known values) before it is solved. This gives:

$$a_p \phi_p - \sum_{j=1}^{n} a_j \phi_j = b_p \tag{3.5}$$

where

$$a_p = \gamma \sum_{j=1}^{n} K_{j,p} + \frac{v_p \rho_p}{\delta t}$$

$$a_j = \gamma K_{j,p}$$

and

$$b_p = \gamma S_\phi p v_p + (1-\gamma)\left[\sum_{j=1}^{n} K^*_{j,p} \phi^*_j - \phi^*_p) + S^*_{\phi p} v_p\right] + \frac{v_p \rho^*_p \phi^*_p}{\delta t}\,.$$

where γ is a weighting factor.

Equation 3.5 is applied to each finite volume to build the overall system matrix equation as exemplified in Section 3.4.4.

3.4.3 Solution procedure.

At each finite period of time, the interrelated algebraic energy equations derived from Equation 3.1 are established and gathered together according to a linking protocol in the form of a (sparse) system matrix. The matrix notation of the corresponding equation set can be written as:

$$\mathbf{A}\mathbf{T}^{(n+1)} = \mathbf{B}\mathbf{T}^{n} + \mathbf{C} \tag{3.6}$$

where **A** and **B** are the respective future and present time coefficient matrices, **T** is the temperature and plant flux vector and **C** is the boundary conditions vector. Boundary conditions define climate, ground conditions and known conditions (e.g. another zone not participating in the simulation). Since the right-hand-side of Equation 3.6 is known at each time-step, it can be written as:

$$\mathbf{A}\mathbf{T}^{(n+1)} = \mathbf{Z} \tag{3.7}$$

where **T** is the vector of unknown nodal temperatures and heat injections and **A** is a non-homogeneous sparse matrix containing the future time-row coefficients which are state dependent. The matrix holding the present values and the known boundary excitations at the present and future time-rows is represented by the column matrix **Z**. Because of the implicitness of the equations, the set of Equations 3.7 must be solved simultaneously at each time-step. However, A is a sparse matrix holding many non-zero coefficients and its inversion by a direct method is computationally expensive. Since the matrix A is composed of groups of equations referring to different subsystems, an efficient solution process consists of partitioning A into a series of subsystem matrices (representing each building zone and the plant system). Each partitioned matrix is then processed separately by using a direct reduction method and information is exchanged between each solution stream in order to allow the global solution to evolve. Each building zone and plant submatrix is processed independently; the integration of these sub-solutions is explained by Clarke [1985], Hensen [1991] and Aasem [1993].†

3.4.4 Single zone exemplar.

In order to exemplify the solution scheme, consider a single cubic zone bounded by six multi-layered constructions (Figure 3.2), with plant interaction assumed to be at the air point. For the 1-D heat conduction domain with the enclosed air volume represented by one node, the entire example problem is represented by 23 nodes and so there will be 23 simultaneous equations, each having a number of cross coupling and self-coupling terms evaluated at the present and future time-rows of the active time-step within the simulation process. The zone matrix (Figure 3.3.) is then decomposed into a series of sub-matrices, each one representing a multi-layered construction, and containing the coefficients relating to the intra-constructional nodal equations addressing material conduction and storage (Figure 3.4). Surface and air point equations are grouped into another sub-matrix (Figure 3.5). The matrix coefficients of Figure 3.5 represent the zone inter-surface radiation exchanges, surface convection, fluid flow and heat storage. The linkages between the construction sub-matrices and the zone balance sub-matrix are maintained by the coefficients $a_{4,5}$, $a_{7,8}$, $a_{10,11}$, $a_{15,16}$, $a_{18,19}$, $a_{21,22}$ of Figure 3.4. and $a_{6,5}$, $a_{9,8}$, $a_{12,11}$, $a_{17,16}$, $a_{20,19}$ and $a_{23,22}$ of Figure 3.5. These coefficients are connections between the inside surface nodes and the intra-construction, next-to-inside surface nodes. The derivation and generation of all these coefficients are explained by Clarke [1985].

A forward reduction process is performed on each construction sub-matrix of Figure 3.4, eliminating all coefficients below the main diagonal. Figure 3.7 shows the reduced matrix. This process modifies the diagonal coefficients and the coefficients representing present time-row and source terms. The last row of each reduced matrix of Figure 3.7 (which is the modified energy balance equation related to the next-to-inside surface node) now holds the coefficients related to the inside and next-to-inside surface temperatures.

These equations are now employed to eliminate the coefficients related to the next-to-inside surface nodes of Figure 3.5; coefficients $a_{5,4}$, $a_{8,7}$, $a_{11,10}$, $a_{16,15}$, $a_{19,18}$, and $a_{22,21}$. The zone balance matrix of Figure 3.8 now holds only surface and air node coefficients and therefore can be solved for the related variables. A forward reduction is conducted whilst carrying through all control node

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† A multi-dimensional heat conduction analysis based on this approach is described by Nakhi [1995].

coefficients, resulting in the reduced matrix of Figure 3.9. The equation to emerge will include two unknowns: the sensor temperature and the actuated plant flux:

$$B\theta_c + Cq_p = D \tag{3.8}$$

It should be noted that Equation 3.8, may be considered as the 'building system control equation set' since it embodies ALL the building process dynamics, expressed in terms of the control point and actuated states. The solution of this equation requires a control algorithm. For example, the control algorithm may give the actuated flux, q_p, for some deviation of the sensed controlled variable from the desired set point, subsequently allowing solution of the future time-row control point temperature, θ_c, from Equation 3.8. It is important to note that the q_p term represents the building-side requirement to maintain zone environmental conditions taking full account of sensor and actuator location. However, the plant system facilitating the required energy input/extract is assumed 'ideal' in the sense that no account is taken of plant dynamic response, inefficiencies, etc. As elaborated in the following section (3.4.5), plant characteristics may be taken into account by specification of a plant configuration file (which contains a description of the plant) and solving the plant system matrix simultaneously with the building-side matrix, the plant matrix replacing the q_p terms in the building matrix.

The above exemplar was for the case of both control (sensor) point and actuation point located at the air point node. Control point and actuator locations at surface points and intra-constructional points are described by Clarke [1985] and depicted in Figure 3.10. In any case, Equation 3.8 is solved according to the active control algorithm. Control discontinuities are avoided by time-step variation to ensure that an across-discontinuity integration is not attempted. The remaining temperatures are then determined by backward substitution.

The sparse storage technique which not only partitions the building into zones, but also partitions the zone matrix into construction matrices and one matrix for internal surface nodes and air node, is depicted in Figure 3.6. Each node within a construction, except the internal surface node requires 5 storage locations so that there are two locations for cross-coupling, one for the self-coupling, one for the plant and one for known (i.e. present and boundary) coefficients.

In conclusion, all energy equations representing the flow paths in a single zone are solved simultaneously by employing a direct method for one time-step. The *complete* solution for a certain simulation period is accomplished by re-establishing the matrix coefficients and solving for each subsequent time-step. For cases where the time-dependent conductance coefficients are dependent on the future time-row quantities (i.e. non-linear problems), the future time-row coefficients are derived from the immediate past information. This procedure is usually acceptable; if otherwise, then accuracy can be improved by reducing the time-step or by iteration.

For multi-zone solutions, two options exist: either each zone can be solved independently as above, with inter-zone processes being imposed one time-step in arrears; or the solution process can be made to iterate across all zones to achieve an overall simultaneous solution.

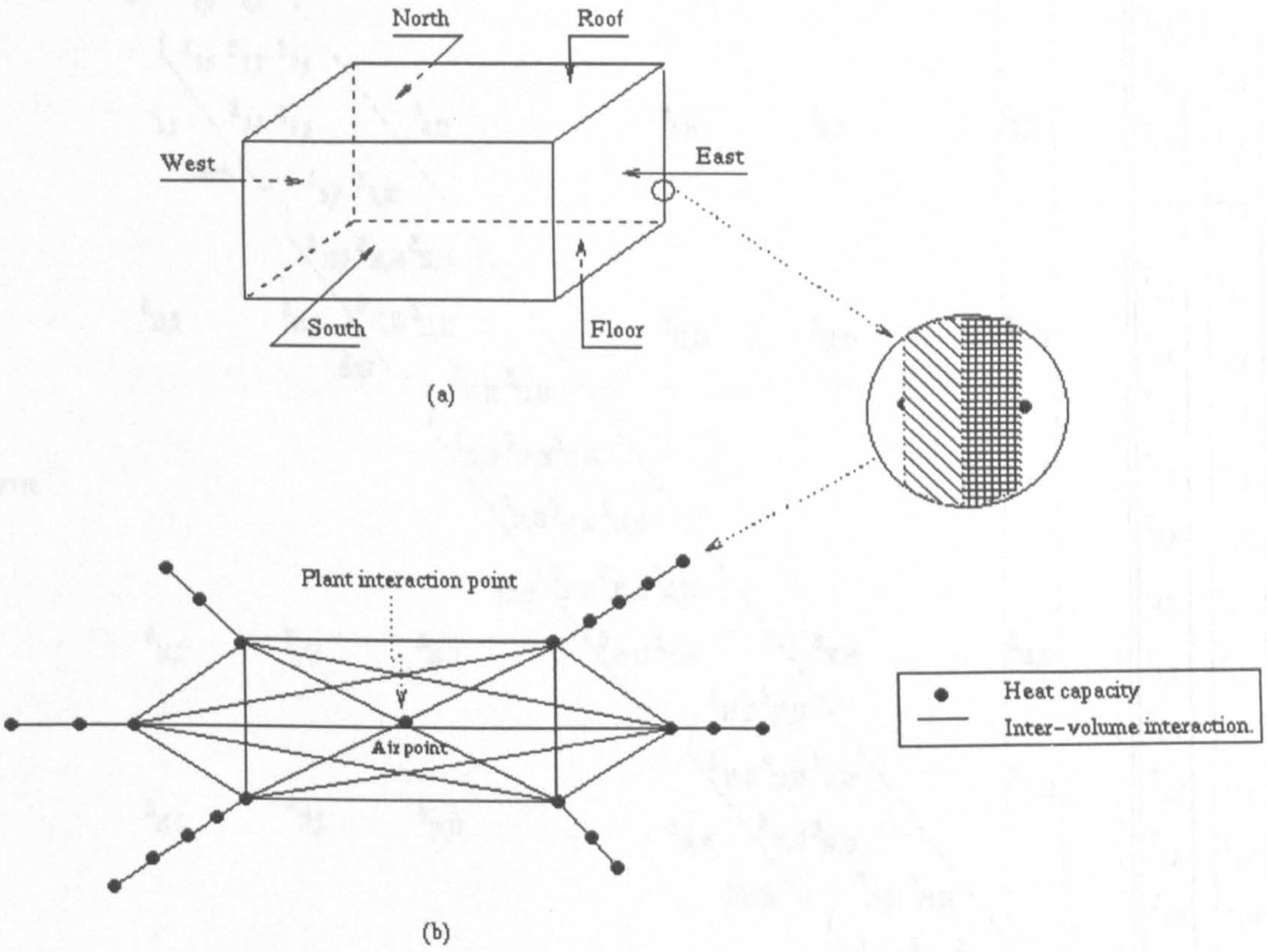


Figure 3.2 (a) A single zone system; and (b) the equivalent volume discretisation.

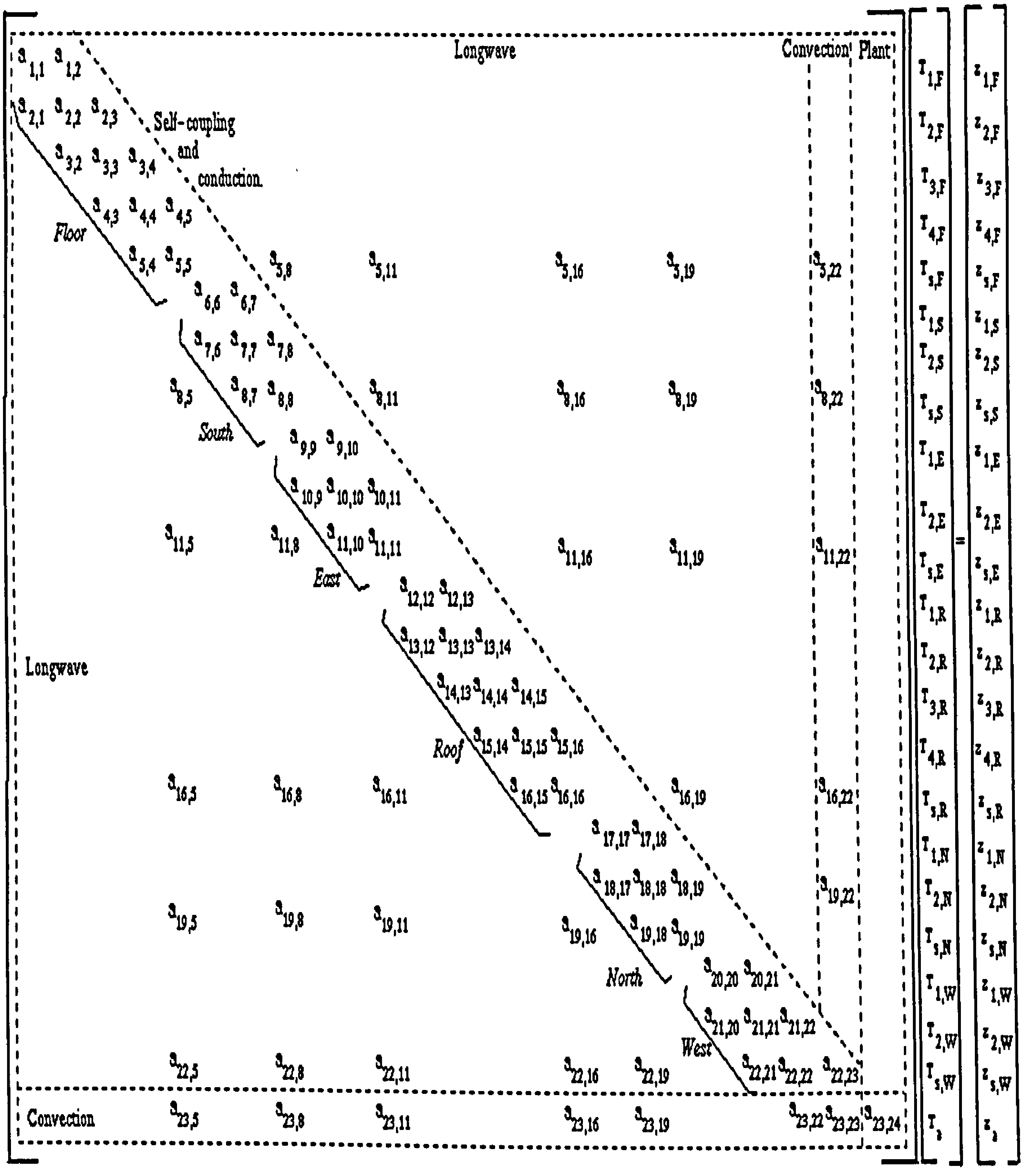


Figure 3.3 Overall single zone matrix (from Clarke, 1985).

Floor

$$\begin{bmatrix} a_{1,1} & a_{1,2} & & & \\ a_{2,1} & a_{2,2} & a_{2,3} & & \\ & a_{3,2} & a_{3,3} & a_{3,4} & \\ & & a_{4,3} & a_{4,4} & a_{4,5} \end{bmatrix} \begin{bmatrix} T_{1,F} \\ T_{2,F} \\ T_{3,F} \\ T_{4,F} \\ T_{s,F} \end{bmatrix} = \begin{bmatrix} z_{1,F} \\ z_{2,F} \\ z_{3,F} \\ z_{4,F} \end{bmatrix}$$

South

$$\begin{bmatrix} a_{6,6} & a_{6,7} & \\ a_{7,6} & a_{7,7} & a_{7,8} \end{bmatrix} \begin{bmatrix} T_{1,S} \\ T_{2,S} \\ T_{s,S} \end{bmatrix} = \begin{bmatrix} z_{1,S} \\ z_{2,S} \end{bmatrix}$$

East

$$\begin{bmatrix} a_{9,9} & a_{9,10} & \\ a_{10,9} & a_{10,10} & a_{10,11} \end{bmatrix} \begin{bmatrix} T_{1,E} \\ T_{2,E} \\ T_{s,E} \end{bmatrix} = \begin{bmatrix} z_{1,E} \\ z_{2,E} \end{bmatrix}$$

$$\begin{bmatrix} a_{12,12} & a_{12,13} & & & \\ a_{13,12} & a_{13,13} & a_{13,14} & & \\ & a_{14,13} & a_{14,14} & a_{14,15} & \\ & & a_{15,14} & a_{15,15} & a_{15,16} \end{bmatrix} \begin{bmatrix} T_{1,R} \\ T_{2,R} \\ T_{3,R} \\ T_{4,R} \\ T_{s,R} \end{bmatrix} = \begin{bmatrix} z_{1,R} \\ z_{2,R} \\ z_{3,R} \\ z_{4,R} \end{bmatrix}$$

Roof

$$\begin{bmatrix} a_{17,17} & a_{17,18} & \\ a_{18,17} & a_{18,18} & a_{18,19} \end{bmatrix} \begin{bmatrix} T_{1,N} \\ T_{2,N} \\ T_{s,N} \end{bmatrix} = \begin{bmatrix} z_{1,N} \\ z_{2,N} \end{bmatrix}$$

North

$$\begin{bmatrix} a_{20,20} & a_{20,21} & \\ a_{21,20} & a_{21,21} & a_{21,22} \end{bmatrix} \begin{bmatrix} T_{1,W} \\ T_{2,W} \\ T_{s,W} \end{bmatrix} = \begin{bmatrix} z_{1,W} \\ z_{2,W} \end{bmatrix}$$

West

Figure 3.4 Partitioned construction matrices (from Clarke, 1985).

$$\begin{bmatrix} a_{5,4} & a_{5,5} & & & & a_{5,11} & & a_{5,16} & & a_{5,19} & & a_{5,22} & a_{5,23} & \\ & a_{8,5} & a_{8,7} & a_{8,8} & & a_{8,11} & & a_{8,16} & & a_{8,19} & & a_{8,22} & a_{8,23} & \\ & a_{11,5} & & a_{11,8} & a_{11,10} & a_{11,11} & & a_{11,16} & & a_{11,19} & & a_{11,22} & a_{11,23} & \\ & a_{16,5} & & a_{16,8} & & a_{16,11} & a_{16,15} & a_{16,16} & & a_{16,19} & & a_{16,22} & a_{16,23} & \\ & a_{19,5} & & a_{19,8} & & a_{19,11} & & a_{19,16} & a_{19,18} & a_{19,19} & & a_{19,22} & a_{19,23} & \\ & a_{22,5} & & a_{22,8} & & a_{22,11} & & a_{22,16} & & a_{22,19} & a_{22,21} & a_{22,22} & a_{22,23} & \\ & a_{23,5} & & a_{23,8} & & a_{23,11} & & a_{23,16} & & a_{23,19} & & a_{23,22} & a_{23,23} & a_{23,24} \end{bmatrix} \begin{bmatrix} T_{4,F} \\ T_{s,F} \\ T_{2,S} \\ T_{s,S} \\ T_{2,E} \\ T_{s,E} \\ T_{4,R} \\ T_{s,R} \\ T_{2,N} \\ T_{s,N} \\ T_{2,W} \\ T_{s,W} \\ T_{s} \\ q_{s} \end{bmatrix} = \begin{bmatrix} z_{s,F} \\ z_{s,S} \\ z_{s,E} \\ z_{s,R} \\ z_{s,N} \\ z_{s,W} \\ z_{s} \end{bmatrix}$$

Figure 3.5 Partitioned inside zone energy balance matrix (from Clarke, 1985).

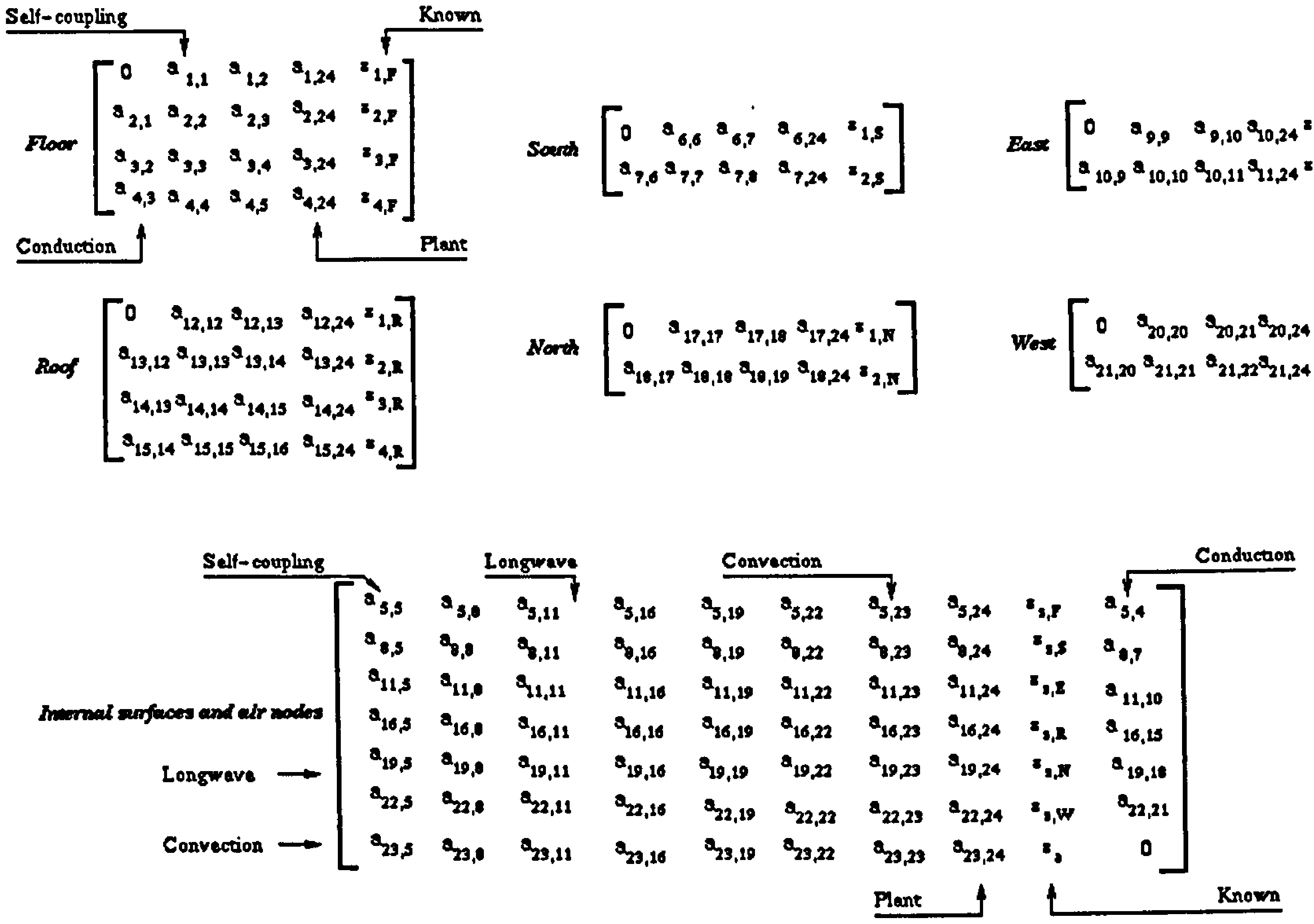


Figure 3.6 Sparse storage (from Clarke, 1985).

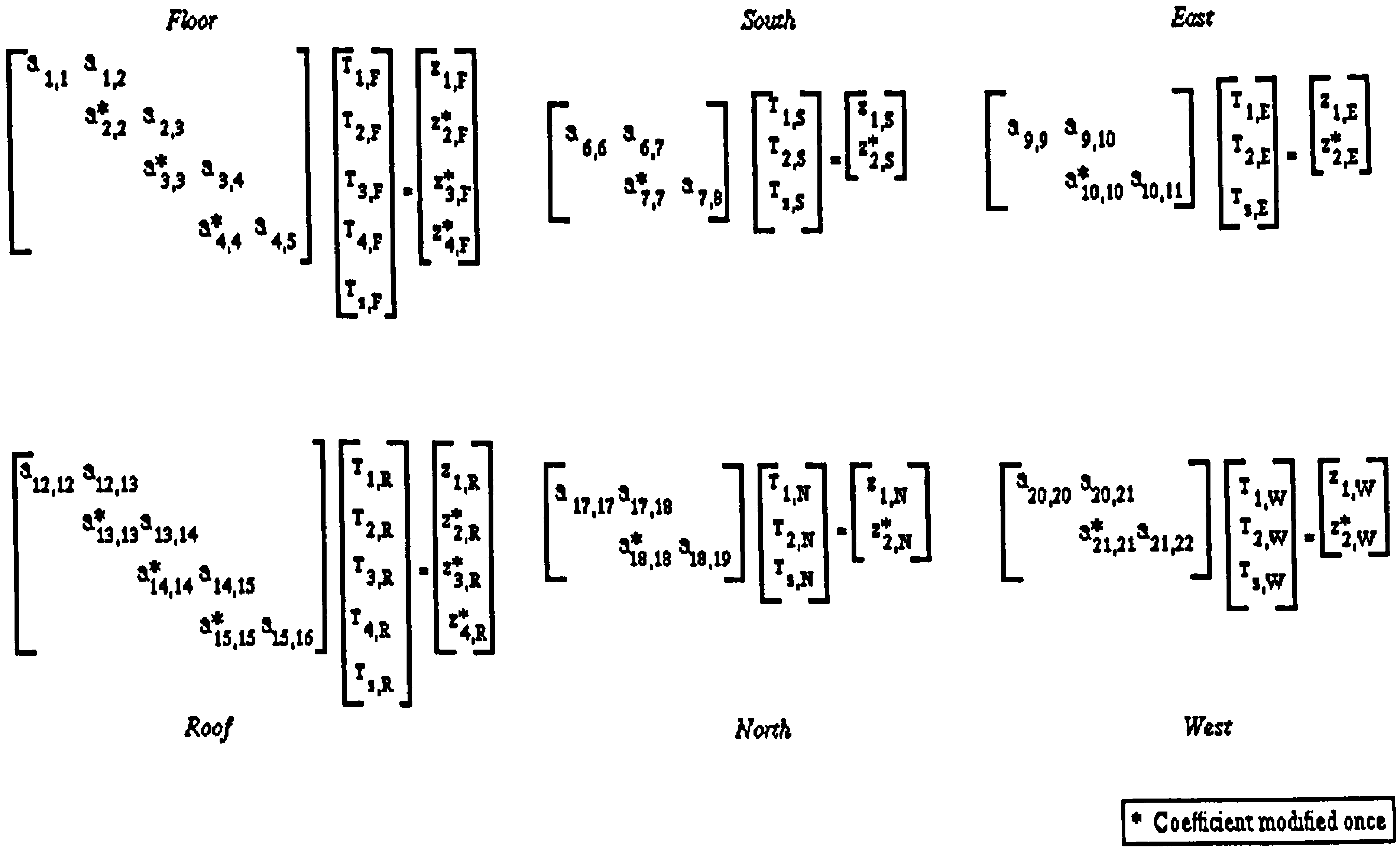


Figure 3.7 Reduced construction matrices (from Clarke, 1985).

$$\begin{bmatrix} a^*_{5,5} & a_{5,8} & a_{5,11} & a_{5,16} & a_{5,19} & a_{5,22} & a_{5,23} & \\ a_{8,5} & a^*_{8,8} & a_{8,11} & a_{8,16} & a_{8,19} & a_{8,22} & a_{8,23} & \\ a_{11,5} & a_{11,8} & a^*_{11,11} & a_{11,16} & a_{11,19} & a_{11,22} & a_{11,23} & \\ a_{16,5} & a_{16,8} & a_{16,11} & a^*_{16,16} & a_{16,19} & a_{16,22} & a_{16,23} & \\ a_{19,5} & a_{19,8} & a_{19,11} & a_{19,16} & a^*_{19,19} & a_{19,22} & a_{19,23} & \\ a_{22,5} & a_{22,8} & a_{22,11} & a_{22,16} & a_{22,19} & a^*_{22,22} & a_{22,23} & \\ a_{23,5} & a_{23,8} & a_{23,11} & a_{23,16} & a_{23,19} & a_{23,22} & a_{23,23} & a_{23,24} \end{bmatrix} \begin{bmatrix} T_{s,F} \\ T_{s,S} \\ T_{s,E} \\ T_{s,R} \\ T_{s,N} \\ T_{s,W} \\ T_a \\ q_a \end{bmatrix} = \begin{bmatrix} z^*_{s,F} \\ z^*_{s,S} \\ z^*_{s,E} \\ z^*_{s,R} \\ z^*_{s,N} \\ z^*_{s,W} \\ z_a \end{bmatrix}$$

* Coefficient modified once

Figure 3.8 Adjusted inside zone energy balance matrix (from Clarke, 1985).

$$\begin{bmatrix} a^{**}_{5,5} & a^*_{5,8} & a^*_{5,11} & a^*_{5,16} & a_{5,19} & a^*_{5,22} & a^*_{5,23} & \\ & a^{**}_{8,8} & a^*_{8,11} & a^*_{8,16} & a^*_{8,19} & a^*_{8,22} & a^*_{8,23} & \\ & & a^{**}_{11,11} & a^*_{11,16} & a^*_{11,19} & a^*_{11,22} & a^*_{11,23} & \\ & & & a^{**}_{16,16} & a^*_{16,19} & a^*_{16,22} & a^*_{16,23} & \\ & & & & a^{**}_{19,19} & a^*_{19,22} & a^*_{19,23} & \\ & & & & & a^{**}_{22,22} & a^*_{22,23} & \\ & & & & & & a^*_{23,23} & a^*_{23,24} \end{bmatrix} \begin{bmatrix} T_{s,F} \\ T_{s,S} \\ T_{s,E} \\ T_{s,R} \\ T_{s,N} \\ T_{s,W} \\ T_a \\ q_a \end{bmatrix} = \begin{bmatrix} z^{**}_{s,F} \\ z^{**}_{s,S} \\ z^{**}_{s,E} \\ z^{**}_{s,R} \\ z^{**}_{s,N} \\ z^{**}_{s,W} \\ z^*_a \end{bmatrix}$$

* Coefficient modified once
** Coefficient modified twice

Characteristic equation extracted: $a^*_{23,23} T_a + a^*_{23,24} q_a = z^*_a$

Figure 3.9 Reduced inside zone energy balance matrix (from Clarke, 1985).

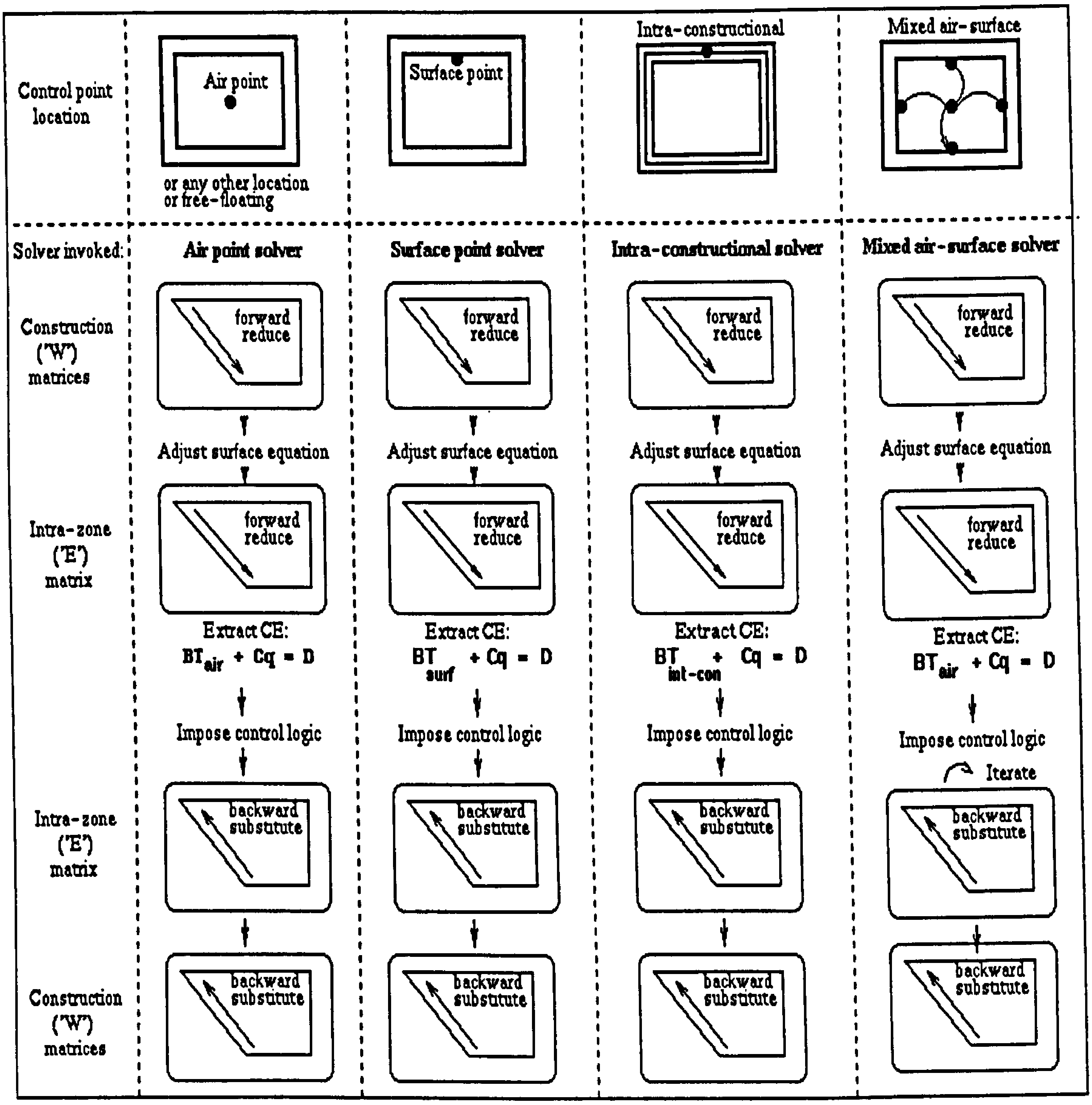


Figure 3.10 Numerical solution as a function of control point location (from Clarke, 1985).

3.4.5 Plant simulation.

The numerical techniques of Sections 3.1-3.4 may be extended to plant system modelling. The *continuous* plant system is translated into a corresponding *discretised* nodal network by means of a finite difference discretisation scheme. Energy balance and mass conservation equations are then derived for each node. The generated matrix of plant component equations (representing the entire plant system inter-connectivity over space and time dimensions) is then integrated with the building matrix - the integration facilitated by the common implicit finite difference approach - and solved by simultaneous solution at each time-step.

In order to demonstrate the procedure, consider the mixing box component of the air handling unit (AHU) depicted in Figure 3.11(a).† Energy and mass balance equations may be derived for each system component and allocated to the plant system matrices of Figures 3.11(b) and 3.11(c).

Energy balance.

An energy balance for any arbitrary time, ζ, yields:

$$\dot{m}_o h_o + \dot{m}_r h_r - \dot{m}_1 h_1 + q_{e1} = \left(\frac{d(\rho_1 V_1 h_1)}{dt} \right)_{t=\zeta} \tag{3.9}$$

where $\dot{m}$ is the mass flow rate (kg s^{-1}, h the mixture specific enthalpy (J kg^{-1}), q_{e1} the component heat exchange with surroundings (W), ρ the mean density of the component (kg m^{-3}) and V the total volume of the component (m^3), o and r relate to ambient and zone air states respectively and 1 is component reference number.

The energy simulation equation representing the mixing box component (node) is now obtained by an equal weighting of the explicit and implicit finite difference forms of Equation 3.9:

$$a_{11} h_1(t+\delta t) = b_{11} h_1(t) + c_1 \tag{3.10}$$

where

$$a_{11} = 2\rho_1(t+\delta t)V_1 + m_1(t+\delta t)\delta t \tag{3.11}$$

$$b_{11} = 2\rho_1(t)V_1 - m_1(t)\delta t \tag{3.12}$$

$$\begin{gathered} c_1 = m_o(t+\delta t)\delta t h_o(t+\delta t) + m_r(t+\delta t)\delta t h_r(t+\delta t) + \\ m_o(t)\delta t h_o(t) + m_r(t)\delta t h_r(t) + \delta t[q_{e1}(t+\delta t) + q_{e1}(t)]. \end{gathered} \tag{3.13}$$

Mass balance.

---

† In this example, each nodal region represents a complete plant component. It is possible, however, to consider a node as representing only part of a component (e.g. casing and working fluid), thus facilitating a more rigorous analysis of intra-component regions. This and other issues relating to the discrete simultaneous modelling of plant systems in the transient domain are elaborated elsewhere [Clarke 1985, Tang 1985, Hensen 1991, Aasem 1993, Chow 1995 and Kelly 1997].

A mass balance for the mixing box will yield at any time ζ:

$$m_o^d + m_r^d - m_1^d = 0_{t=\zeta} \tag{3.14}$$

$$m_o^d g_o + m_r^d g_r - m_1^d g_1 = 0_{t=\zeta} \tag{3.15}$$

where m^d is the mass flow rate of dry air (kg s^{-1}) and g the humidity ratio (kg kg^{-1}).

A simulation equation representing the mixing box nodal mass balance is now obtained by an equal weighting of the explicit and implicit finite difference forms of Equations 3.14 and 3.15:

$$m_1^d(t+\delta t) = m_o^d(t+\delta t) + m_r^d(t+\delta t) + m_o^d(t) + m_r^d(t) - m_1^d(t), \tag{3.16}$$

becoming from Figure 3.11(c):

$$d_{11} m_1^d(t+\delta t) = e_{11} m_1^d(t) + f_1 \tag{3.17}$$

and

$$\begin{aligned} m_1^d(t+\delta t) g_1(t+\delta t) &= m_o^d(t+\delta t) g_o(t+\delta t) + \\ m_r^d(t+\delta t) g_r(t+\delta t) &+ m_o^d(t) g_o(t) + m_r^d(t) g_r(t) - m_1^d(t) g_1(t) \end{aligned} \tag{3.18}$$

and, therefore,

$$d_{22}[m_1^d(t+\delta t) g_1(t+\delta t)] = e_{22}[m_1^d(t) g_1(t)] + f_2. \tag{3.19}$$

In a similar manner, energy and mass balance equations may be derived for the other AHU system components to generate the complete system matrices depicted in Figure 3.11. The matrix equations are now solved for any time-step in terms of component and control algorithms which establish the **C** and **F** matrices and on the basis of any specified control objectives.

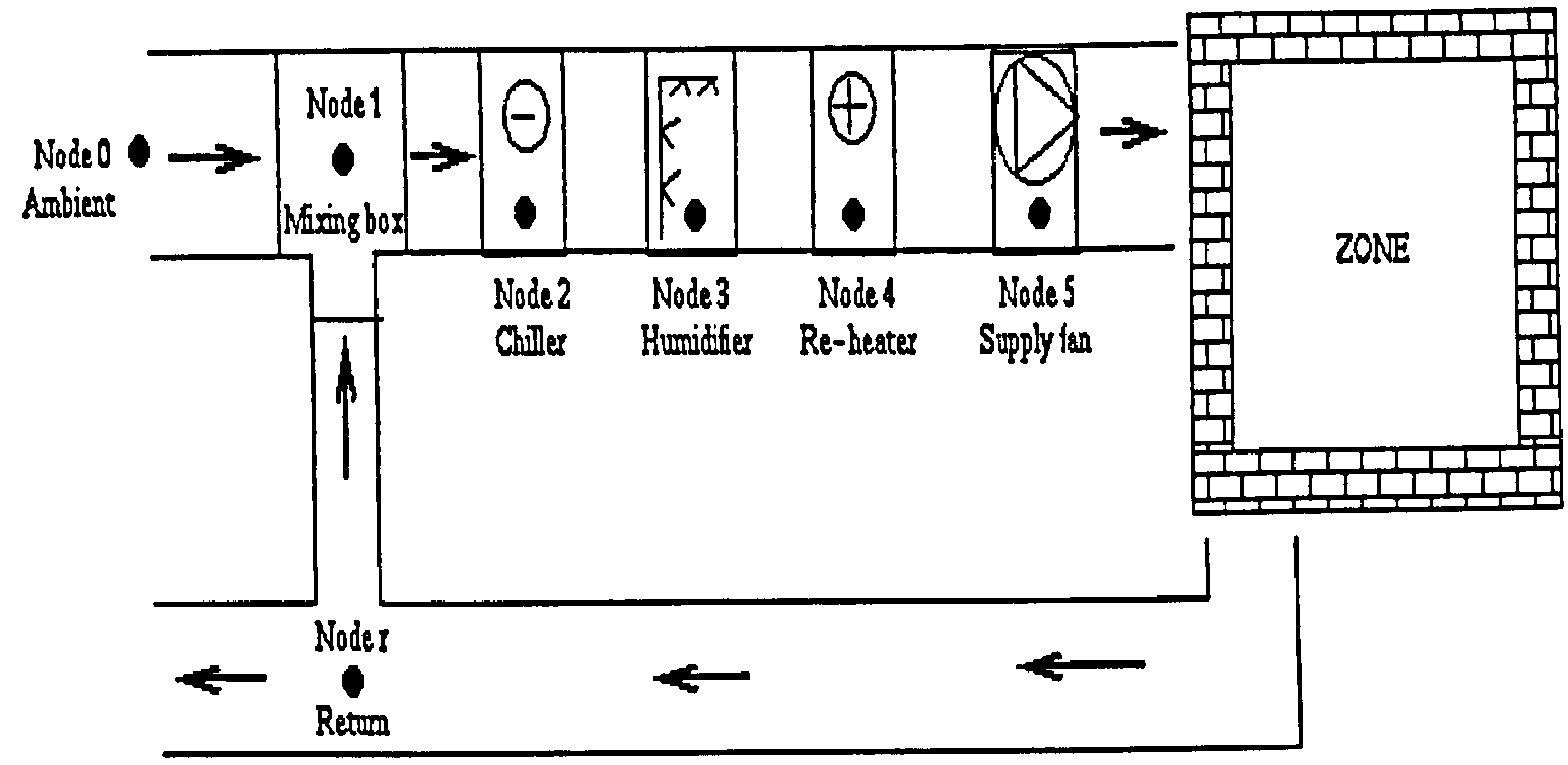
In a building and plant configuration at a given time-step, the building matrix is first processed to give zone temperatures. The plant matrix is then processed to determine the heating/cooling inputs based on the previously calculated zone temperatures. In order to ensure that the correct zone temperatures are used, iteration continues until the difference between the present and previous zone temperature values are within an acceptable accuracy level.

Consider the situation where heat, q_p (W), is injected to the zone with the plant interaction point located at the zone air point. This can be expressed by:

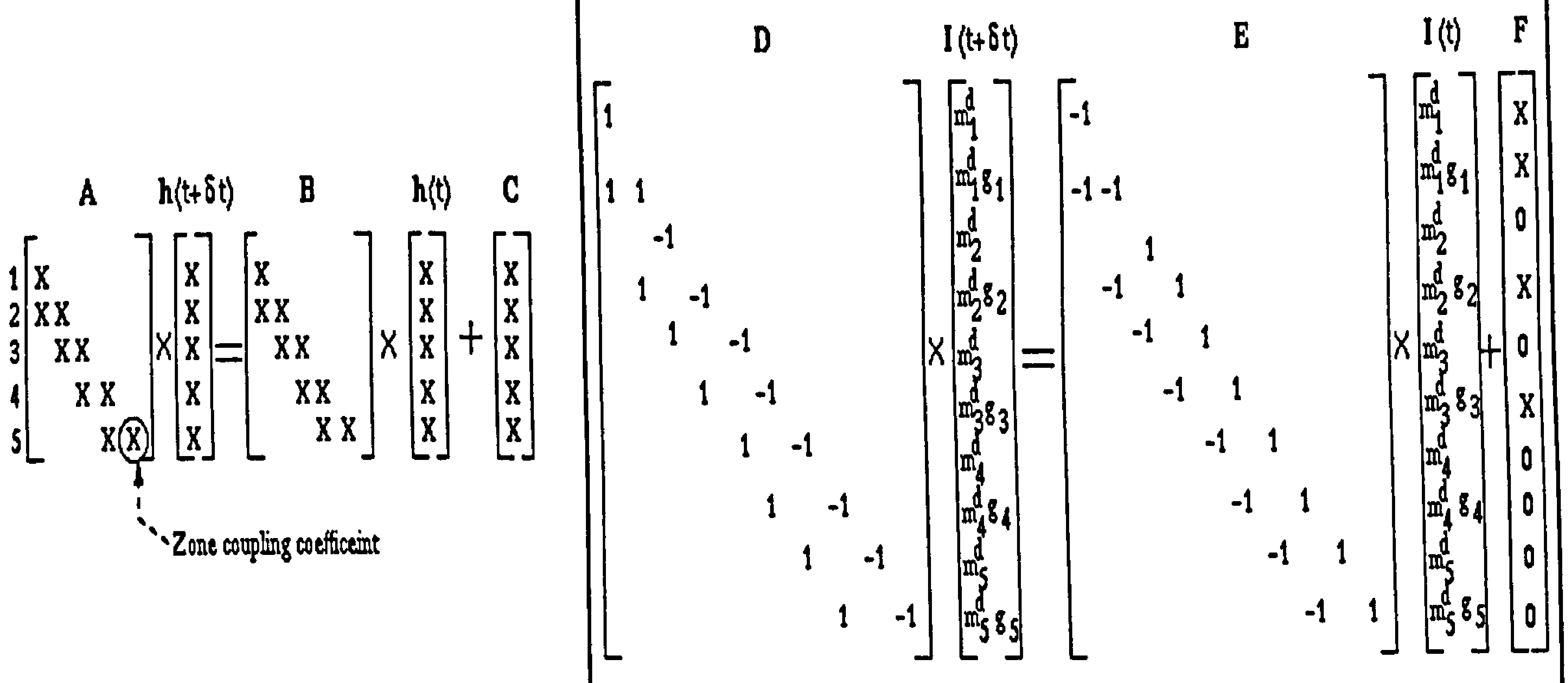
$$q_p = \dot{m}_a C_p(\theta_s - \theta_c) \tag{3.20}$$

where $\dot{m}_a$ is the dry air mass flow rate entering the zone (kg/s), C_p is the specific heat capacity of air at constant pressure (J/kg K), θ_s is the component node temperature (°C) and θ_c is the control point (zone air) temperature (°C). Equation 3.20 can then be solved simultaneously with the building system control equation set (Equation 3.8), to give the following expression:

$$q_p = \frac{\theta_s - \dfrac{D}{B}}{\dfrac{1}{\dot{m}_a C_p} - \dfrac{C}{B}}. \tag{3.21}$$



(a) Air handling unit plant



(b) System energy balance matrix equation: $Ah(t+\delta t) = Bh(t) + C$

(c) System mass balance matrix equation: $DI(t+\delta t) = EI(t) + F$

Figure 3.11 Plant modelling: practical network and associated system matrices (from Clarke, 1985).

3.5 CONTROL SYSTEMS MODELLING IN ESP-r.

3.5.1 Introduction.

In ESP-r, immediately prior to simulation commencement, in addition to the system configuration file [Clarke 1995] the user may define a system control configuration file (Figure 3.12), the absence of which means that the simulation will free float under the influence of the defined boundary conditions. Specification of the various control subsystems (Figure 3.13) follow similar definition patterns. Any number of control loops can be established, each one acting to influence energy or mass balances by affecting the matrix equation construction/solution at each time-step (Figure 3.14). In ESP-r, control loops act to do one of two things:

- (1) *Building-side control*: as described in Section 3.4.4, control acts to direct the building matrix solution, where the building matrix solution type is dependent on the location of the sensor (termed the control point) and the control algorithm allows solution of the 'building control system equation set' of Equation 3.8; for example, solving for zone air point temperature given some fixed actuated plant flux.
- (2) *All other subsystem control*: control acts to adjust coefficients in the energy balance matrices; for example, adjusting a valve component in a plant network (Section 3.4.5).

A number of standard controllers are offered and special procedures can be developed and entered by a user and subsequently assessed in terms of environmental impact and energy saving potential. These can be imposed during different periods of the day and can be activated on a weekly, monthly or seasonal basis.

Control loops comprise:

- a sensor to sense the property of interest - for example time, temperature, relative humidity and illuminance level;
- a controller to generate the actuator signal based on the sensed condition. The controller is defined in terms of some control action (e.g. proportional+integral+derivative) and the type of variables sensed and actuated (e.g. sensing relative humidity and actuating valve position);
- an actuator to allow some system state to be changed over time - for example zone flux input, boiler valve position, fan speed or electric lighting status.

The full list of variables capable of being sensed and actuated, together with the control law algorithms are listed in Tables 3.1 and 3.2. Sensor-law-actuator combinations from these lists may be specified and imposed on the various control subsystems described below. For example, controller type *007-005-081* indicates a weather compensating control loop:

- a sensor sensing outside dry bulb conditions;

- a proportional controller algorithm;.
- an actuator adjusting fluid flow rate.

Clearly, although all the variables listed in Tables 3.1 are *capable* of being both sensed and actuated, the spectrum of possible combinations ranges from the frequently used, practical cases (e.g. as in the weather compensation loop described above) to more focussed, specialised modelling applications (e.g. sensing CO2 level [*078*]), through to the highly conceptualised situations encountered occasionally in research and development studies (e.g. actuating clothing level [*058*]).

It should also be noted that a sensed variable does not necessarily mean a control point variable. For example, in a given control loop, the variable under control may be zone air point temperature; however, there may be many other variables being sensed simultaneously (e.g. occupancy level, external relative humidity, etc.) which are to be used in the control logic algorithm. Similarly, an actuated variable may not necessarily refer to the manipulated variable (e.g. flowrate) signal, but rather to the controller output signal. For example, in cascade control, a primary controller output signal (e.g. temperature) may be used to establish the set point of a secondary controller whose output signal could *directly* change the manipulated variable value in the system matrix equation.

The influence of control on the building-side and plant-side subsystems of ESP-r has been described in Sections 3.4 and 3.5, respectively. Other ESP-r control subsystems are now briefly discussed.

3.5.2. Fluid flow control

The fluid flow modelling capabilities of ESP-r are discussed at length elsewhere: Cockroft [1979] and Hensen [1991] (network approach); and Negrao [1995] (CFD approach). It is possible to impose control on a fluid flow network, the procedure being similar to that outlined above for the building and plant. This allows pressure and temperature-driven flow control over any component and/or connection of the network.

Two actuator types are possible with flow control: one acting on a specified flow connection, the other acting on a specified flow component. In the latter case, it is possible to actuate all the connections defined by the controlled component or to restrict the action to a sub-set.

In a building *and* plant *and* flow configuration, the solution process is that depicted in Figure 3.14. As indicated in the diagram, the plant control solver is by-passed in the case where the fluid network solver is active and the first phase flow balance is being processed, i.e. the controls acting on the energy balance or the second phase flow balance are not by-passed. By this mechanism, it is ensured that any flow control action which is defined and activated in the flow network is preserved in the plant system mass balance [Hensen 1991].

Identifying character string for overall control.

Then if global control functions exist ...

*** Global**
Identifying character string for global control regime.
Number of global control functions.
Sensor details
Actuator details
For each day type ...
Start and finish dates of validity (day numbers)
Number of distinct global control periods.
For each global control period ...
Controller type, global control law, period start time.
Number of data items associated with the control law, then data values.

Then if building control functions exist ...

*** Building**
Identifying character string for building control regime.
Number of building control functions.
Sensor details
Actuator details
For each day type ...
Start and finish dates of validity (day numbers)
Number of distinct building control periods.
For each building control period ...
Controller type, building control law, period start time.
Number of data items associated with the control law, then data values.
If final building control function ... ...
List of associated building control functions for each zone in system configuration..

Then if plant control functions exist ...

*** Plant**
Identifying character string for plant control regime.
Number of plant control functions.
Sensor details
Actuator details
For each day type ...
Start and finish dates of validity (day numbers)
Number of distinct plant control periods.
For each plant control period ...
Controller type, plant control law, period start time.
Number of data items associated with the control law, then data values.

Then if mass flow control functions exist ...

*** Mass flow**
Identifying character string for mass flow control regime.
Number of mass flow control functions.
Sensor details
Actuator details
For each day type ...
Start and finish dates of validity (day numbers)
Number of distinct mass flow control periods.
For each mass flow control period ...
Controller type, mass flow control law, period start time.
Number of data items associated with the control law, then data values.

Then if CHP control functions exist ...

*** CHP**
Identifying character string for CHP control regime.
Number of CHP control functions.
Sensor details
Actuator details
For each day type ...
Start and finish dates of validity (day numbers)
Number of distinct CHP control periods.
For each CHP control period ...
Controller type, CHP control law, period start time.
Number of data items associated with the control law, then data values.

Figure 3.12 ESP-r system configuration control file.

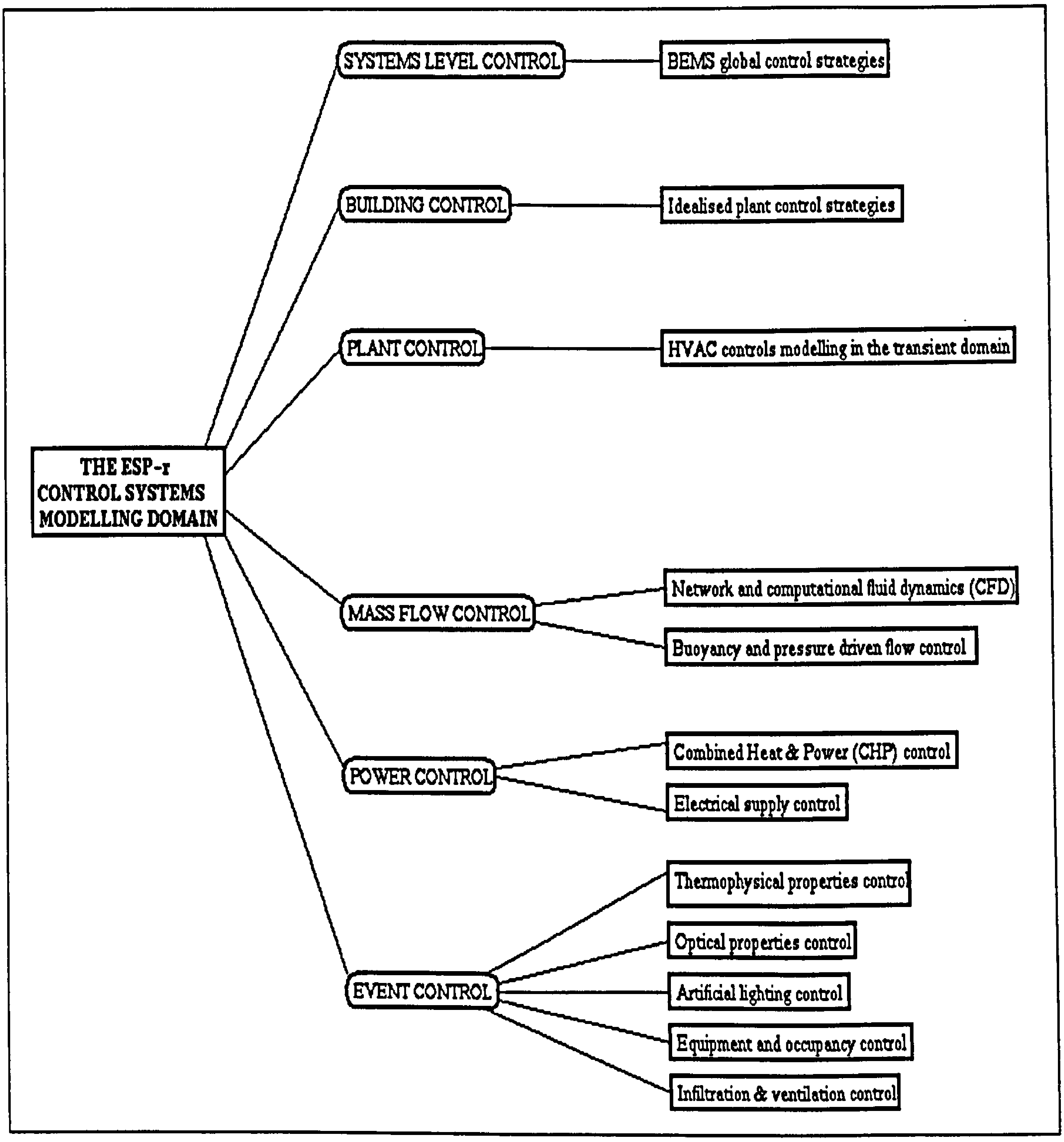


Figure 3.13 ESP-r control systems modelling domain.

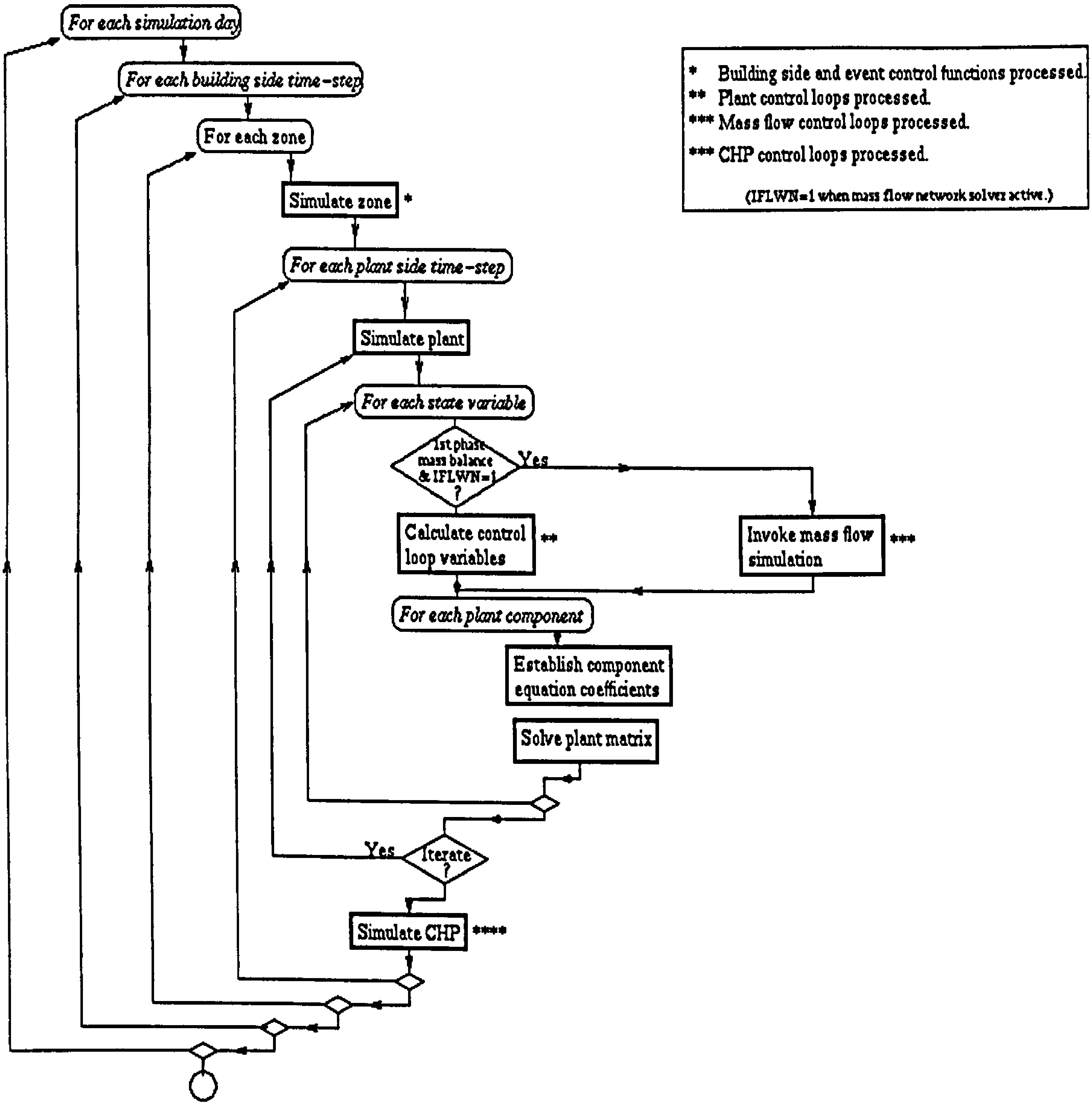


Figure 3.14 Combined building, plant and flow domain in ESP-r.

001	Active climate database	002	Ext. absolute humidity	003	External rel. humidity	004	External moisture content
005	Sun azimuth angle	006	Atmospheric turbitity	007	External d.b temperature	008	External w.b temperature
009	Sol-air temperature	010	Diffuse hor. solar radiation	011	Direct nor. solar radiation	012	Air density
013	Atmospheric pressure	014	Wind speed	015	Wind direction	016	Day lighting levels
017	Dawn/dusk	018	Cloud cover	019	Zonal orientation	020	Latitude/longitude
021	Simulation type	022	Simulation run	023	Simulation month number	024	Simulation day number
025	Simulation time-step	026	Simulation start day	027	Simulation finish day	028	Simulation year
029	Simulation time (present)	030	Simulation time (future)	031	Active time step controller	032	Time-clock re-sets
033	Number of zones	034	Ground reflectivity	035	Site exposure	036	Number of obstruction blocks
037	No. inter-zonal connections	038	Connection type	039	Construction material	040	Heat transfer coefficient
041	Specific heat capacity	042	UA value	043	Number of doors	044	Number of windows
045	Material density	046	Construction rotation angle	047	Luminosity	048	Glazing maintenance factor
049	Surface emissivity	050	Surface absorptivity	051	Surface transmittance	052	Surface reflectivity
053	No. of construction elements	054	Nodal discretisation	055	Occupancy levels	056	Casual gains
057	Activity level	058	Clothing level	059	Du Bois surface area	060	Bodily heat evaporation rate
061	Glare index	062	Mean radiant temp	063	w b. air temperature	064	d.b air temperature
065	Globe temperature	066	Environmental temperature	067	Resultant temperature	068	Dew point temperature
069	Mixed air-surface temp.	070	Effective draught temperature	071	Operative temperature	072	Relative humidity
073	Absolute humidity	074	Surface temperature	075	Intra-constructional temp.	078	Local air velocity/flow rates
077	Relative air velocity	078	CO2 level	079	per cent people dissatisfied	080	Predicted mean vote (PMV)
081	Nodal 1st ph. mass flow	082	Nodal 2nd ph. mass flow rate	083	Nodal abs. humidity	084	Nodal rel. humidity
085	No. mass flow connections	086	No. mass flow components	087	Nodal abs. pressure	088	Nodal rel. pressure
089	Ventilation rate	090	Infiltration rate	091	CFD parameters	092	Interstitial condensation risk
093	Moisture transfer rate	094	Moisture transfer process	095	Mould growth types	096	Mould growth rates
097	No. of plant components	098	Plant component type	099	Overall plant efficiency	100	Component efficiency
101	No. of plant connections	102	Connection type	103	Component output flux	104	Component mass flow rate
105	Parasitic losses	106	Cumulative run time	107	Current levels	108	Voltage levels
109	Power levels	110	Power factor	111	Real power	112	reactive power
113	Phase angle	114	Number of phases	115	Power losses	116	Transformer type
117	Mean time to failure	118	Mean time between failure	119	Mean active repair time	120	Redundancy level
121	Component expected life	122	Downtime	123	Failure rate	124	Maintainability
125	Active control loops	126	Active control laws	127	Active control day type	128	Active control period
129	Sensor input	130	Actuator output	131	Dead time	132	Distance/velocity lag
133	Sen/act cum. uncertainties	134	Sen/act r.m.s error	135	Dead band	136	Hysteresis
137	Sen/act interchangeability	138	Sen/act random error	139	Sen/act repeatabilty	140	Resolution
141	Sen/act sensitivity	142	Sen/act settling time	143	Sen/act span	144	Speed of response
145	Sen/act systematic error	146	Sen/act time constant	147	Sensor ambient limits	148	Range
149	External file data	150	Step function	151	Ramp function	152	Sine function
153	Cosine function	154	Saw-tooth function	155	Square function	156	Triangular function
157	Abs. actuator travel	158	Rel. actuator distance moved	159	Abs. actuator speed	160	Actuator speed
161	Set point	162	Throttling range	163	Absolute error signal	164	Relative error signal
165	Rate of change of error	166	Integral of absolute error signal	167	max/min error signal	168	Controller gain

Table 3.1 Sensed and actuated variables.

001	Ideal
002	Two position
003	Three-position
004	Multi-stage
005	Proportional+Integral+Derivative (PID)
006	Time-proportioning
007	Fuzzy logic
008	Pro-rata
009	Hesitation
010	Seasonal reset
011	Monthly reset
012	Weekly reset
013	Daily reset
014	Hourly reset
015	Minutely reset
016	Second-by-second reset
017	Time-step reset
018	Sequencing
019	Split range
020	Cascade
021	Null control
022	Optimum start
023	Optimum stop
024	Enthalpy cycle
025	Zero energy band
026	Weather ompensation
027	Economiser cycle
028	Enthalpy cycle
029	Night purge
030	Set back
031	Duty cycling
032	Load scheduling
033	Capacity management
034	Equalised run time
035	Current control
036	Voltage control
037	Power factor control
038	Power loss control
039	Phase control
040	Maximum demand control
041	Material properties substitution
042	Optical properties substitution
043	Database control
044	Site/exposure control
045	Geometry control
046	Plant network definition control
047	Mass flow network definition control
048	Condensation control
049	Obstruction control
050	Casual gain control
051	Simulation time-step control
052	Simulation time-clock control
053	Predictive-iterative control (for all above)

Table 3.2 Controller modes.

3.5.3 Power systems control.

Power systems modelling capabilities (including CHP) in ESP-r are fully elaborated by Kelly [1997]. Briefly, power control systems modelling is harmonised with the other ESP-r subsystems, with similar definition procedures and control system elements of sensor-controller-actuator combinations being specified (Tables 3.1 and 3.2) to direct and influence matrix set-up and solution. This facility offers the possibility of modelling demand-side electrical system control schema such as maximum demand and load switching within a fully integrated simulation environment. The CHP subsystem's numerical processing in relation to the other subsystems is depicted in Figure 3.14.

3.5.4 Event control.

3.5.4.1 Zone blind/shutter control

Modelling blind/shutter control can be imposed on window and transparent constructions in general. Window solar coverings or insulating devices can be controlled as a function of time, solar intensity or ambient temperature. The controlled variables are shortwave transmittance and overall thermal transmittance.

A day period is sub-divided into control periods. For each period, a set of window properties are defined which will only be accepted if:

- the *total* radiation intensity (direct + diffuse) exceeds the user-defined set point, or,
- the ambient temperature exceeds the user-defined set point, or,
- the windows are deemed to operate for the entire period regardless of the solar intensity or temperature magnitude.

In the case of radiation control of the blind/shutter, the surface on which the radiation sensor is situated can be specified and the operation of all external windows in the zone will depend on the radiation on that one surface. Alternatively, each external surface containing windows can be treated separately, in which case windows in those surfaces receiving greater than the specified radiation limit will inherit the replacement properties.

In the default case, no nodes are used to represent the window layers. Essentially, this means that windows are treated as a resistance only, with an approximate treatment of longwave radiation and no explicit modelling of shortwave absorption.

Within ESP-r, there is a facility which allows windows to be treated with more precision than is the case with the standard default case [Clarke 1995]. Here, the window is considered as a *transparent multi-layered construction* (TMC) with layers being declared transparent as appropriate. Thus windows are assigned a nodal scheme so that convective, conductive and longwave radiative exchanges are handled separately and explicitly, with solar absorption treated in an exacting manner.

With regard to control, each TMC can be given a replacement set of transmission coefficients and absorptivities in each control period. The TMCs are controlled independently, with similar control options as for the default case described above.

Line	Description of fields
1	Identifier (three integer type numbers) of the casual gains to be controlled during Weekdays, Saturdays and Sundays. Default identifier for casual gain from artificial lighting is "2".
2	Number (an integer type number) of distinct casual gain control periods during a typical day. Maximum three control periods currently allowed.
3	For each control period in turn give the start hour (0-24) and finish hour (two integer type numbers) on separate lines.
4	Number (an integer type number) of lighting zones within this thermal zone. Maximum of four lighting zones allowed.
5	For each individual lighting zone:
5.1	Numbers (four real type numbers) indicating respectively: reference light level (set point) (Lux), switch-off light level (-), minimum dimming light output (-) and switch-off delay time (-).
5.2	Percentage (a real type number) of total zone controlled casual gain associated with this lighting zone (-), number (an integer type number) of internal illuminance sensors and calculation type (an integer type number 1-4): 1 ESP-r internal daylight factor preprocessor; 2 user supplied daylight factors; 3 external sensor; 4 coupling with lighting simulation.
5.3	For each defined sensor: x, y & z coordinates (relative to zone origin) defining location of sensor, or for calculation type 3: surface number (external only) that the sensor is placed on, flag specifying vertical mounting (1.0) or horizontal mounting (0.0), dummy value,
5.4	For calculation type 2 (user supplied daylight factors) additional info:
5.4.1	Number (an integer type number) of windows (transparent multi-layer construction).
5.4.2	For each defined window its TMC surface identification number (an integer type number) and corresponding daylight factors for each defined sensor (a real type numbers).
5.5	The control law (-1 ON regardless; 0 OFF regardless; 1 ON if sensed condition is below set point (otherwise OFF); 2 as 1 but with step down/up action (0%, 50%, 100%); 3 as 1 but with proportional action; 4 as 1 but based on the Hunt probability switching function; 5 as 1 but with a top-up control and fixed ballast).

Table 3.3 ESP-r casual gains control file.

3.5.4.2 Casual gain and artificial lighting control.

In ESP-r, control schemes which represent casual gain levels are possible. These schemes are specified by means of a *zone operations file,* which contains user-specified casual gain profiles for equipment, occupancy, infiltration and zone-coupled air flow. As the design evolves, it is possible to override these profiles by more detailed data placed in a *casual gains* file (Table 3.3) and/or a *fluid flow network definition* file, and in the latter case, selecting simultaneous energy and mass flow simulation.

The switched level of casual gains is normally controlled on the basis of available natural light. Control of lighting is possible using a variety of control modes - on-off, dimming, probability switching, etc. In addition, user-specified lighting profiles and schedules are possible. The daylighting contributions from all the exterior windows in the zone are tracked and any contribution from sunlight evaluated. The following modelling features are available:

- Single or multiple zonal sensors may be defined;
- Vertical (unobstructed) and horizontal external illuminance sensors are available;
- In the case of multiple sensors, the aggregate casual gain may be obtained from a variety of functions of the sensed conditions: e.g. arithmetic mean, cumulative total, etc;
- Illuminance from adjacent zones is included. Effects of blind/shutter operation in these zones is also accounted for;
- As an alternative to ESP-r's normal daylight calculations, the user has the option to input daylight factors from third party software e.g. RADIANCE into the casual gain control file.

3.6 Applicability of ESP-r to the modelling and simulation of building control systems.

The applicability and suitability of discrete, modular, simultaneous type programs such as ESP-r to the modelling and simulation of building control systems may be assessed in terms of strategic approach, solution method and functionality.

The suitability of numerical methods for the modelling of building control systems was discussed briefly in 2.2.3 where such methods were stated as being appropriate for handling the time-dependent, non-linear characteristics commonly encountered in the problem domain. Unlike algorithmic/algebraic type modelling procedures, numerical methods cannot *directly* yield a solution representing component/system performance; rather, they generate coefficients which are passed onto a remote formalised process [Hanby, 1987]. However, numerical methods do facilitate a *unified solution process* since all subsystems (building, plant, etc) may be generated in a compatible form. With ESP-r, the integrated building/plant system matrix accounts for all time-dependent energy transfers, whilst the building and plant systems are constrained to conform to control action. Techniques such as variable time-stepping and the 'one time-step in arrears' principle (i.e. using the value of the variable from the preceding time-step), are used to overcome non-linearities. Numerical type programs are well suited to a whole range of time-step control techniques, which in addition to handling non-linearities, also enable, for example, the conceptual development of simulation-assisted control strategies. (Time-step controllers and simulation-assisted control strategies are discussed in Chapters 5 and 6, respectively).

Most building simulation programs with a control modelling capability fall into the *sequential* category. In such programs the components are represented by input-output relationships. These are connected to comprise the whole system in such a way that the output from one component is fed into the input of the next. The calculation proceeds from a suitable starting point (e.g. boiler supply temperature) and continues around the system in the prescribed manner. A sequential approach offers several advantages such as the incorporation of a mixture of modelling methods (e.g. simple/complex, analytical/numerical) facilitating piecemeal component development. However, a sequential type approach may cause problems when the evaluation of one component needs information of a component further down the calculation stream. Component linking protocols and iterative schemes have been utilised in order to overcome such problems.

In *simultaneous* type programs, however, system values are obtained for all unknown variables irrespective of the order in which the variables are processed through the system. In ESP-r, for example, the whole-system building/plant matrix *is* the linking protocol, thus overcoming some of the problems inherent in sequential type programs. The notion of a system matrix and associated matrix inversion techniques also facilitates the modelling of system-level supervisory control strategies (a theme elaborated in Chapter 6).

It is clear from Sections 3.1-3.5 that with the ESP-r system there exists a highly modularised control modelling facility. From a control system modeller's viewpoint, a highly modular program structure is attractive since the individual subsystems may be considered in isolation thus simplifying the following modelling process:

- subsystem model development;
- changes in controller model;
- subsystem model testing and validation;
- program archiving and documentation;
- program maintenance.

A unified system definition procedure and a diverse range of sensor/actuator variable and location are extremely useful features in a control modelling environment. In the ESP-r program, subsystem control structures are fully harmonised with a similar problem definition procedure. The range and location of variable which may be sensed and/or actuated is extremely wide and includes fabric, flow, lighting, plant and power parameters (refer Table 3.1).

So far, the suitability of ESP-r to control system modelling has been elaborated. However, it should be noted that several other programs (e.g. TRNSYS [SEL, 1983] and HVACSIM+ [Clark 1985]) incorporate sophisticated numerical solvers offering many desirable plant/control modelling features, together with convenience and flexibility of use. TRNSYS, previously considered as a sequential type program, now uses multi-variable Newton-Raphson techniques (as opposed to using single variable Newton-Raphson convergence promoters for key variables, as is done with the old TRNSYS sequential solver) and can now be considered to be simultaneous. HVACSIM+ [Clark 1985] was developed specifically for building control simulation and may be considered as a simultaneous type program. Investigation of such programs was, however, outwith the scope of the present work.

3.7 COMMENT.

As discussed earlier, the issues of *containment* and *applicability* are of crucial importance. The modelling approach adopted in ESP-r - despite its theoretical and mathematical complexity - facilitates a means by which both specialists and non-specialists can simulate and assess building control system design and operational strategies (existing or projected, practical or highly idealised) in a fully integrated manner and at any level of abstraction. Using the system, different professionals within the building design team - architects, mechanical and electrical engineers and control specialists - are able to conduct cross-disciplinary, high integrity, first principle performance appraisal, modelling all aspects of the control subsystem simultaneously and in the transient domain.

There is, however, scope for enhancement and refinement of this control systems modelling environment. Issues requiring to be addressed include:

- multiple input, multiple output (MIMO) systems modelling;
- installation of BEMS controller algorithms;
- hierarchical (systems and zone level) control modelling;
- time-step control manipulation;
- simulation-based control;
- improved user interface.

The features described in the following chapters are a necessary step in bridging the gap between modelling future generation control systems complexity and the design and operation of building energy management systems. A specification for a building control system modelling facility is presented in the form of a taxonomy of building control system entities. The use of ESP-r as a test bed for a number of numerical techniques and schema, designed to enhance the modelling functionality and applicability of system simulation programs, is discussed.

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Chapter 4

BUILDING CONTROL SYSTEMS: THE SPATIAL ELEMENT

It was stated in Chapter 2 that all advanced building control systems, despite their apparent complexity, can be considered as consisting of essentially three main elements: spatial, temporal and logical. This Chapter specifies the spatial elements required in a fully comprehensive control systems modelling facility. Methods and techniques designed to improve the integrity and flexibility of spatial element modelling are discussed, and the numerical schemes as developed and subsequently installed in ESP-r are described.

4.1 INTRODUCTION.

The specification of sensors and actuators is a crucial aspect of practical system design, and can only be done with correct knowledge of the performance of these elements when integrated and coupled with the object systems to be controlled [IEA 1991]. Modelling the spatial element of building control systems requires consideration of the following sensor and actuator features: location, sensed variable, actuated variable and operational characteristics (Figure 4.1). Modelling and simulation of spatial elements can help optimise the objective system by providing answers to the following questions:

- What temperature gradients will result from a given sensor/actuator location?
- What is the optimum location within a structure - in terms of comfort and energy requirements - for an underfloor heating element?
- What are the effects of office geometries and radiative exchanges on sensor locations?
- What are the implications for energy costs, of controlling zones to comfort criteria?

The following general observations can be made regarding present generation simulation programs [Hitchin 1991]:

- They typically have a capability for sensing a relatively very narrow range of sensed variables, e.g. temperature (environmental, dry bulb, radiant, globe, dry resultant, sol-air and external) external climate variables, plant and flow state variables.
- There is a very narrow range of actuated variables available for processing; typically valve/damper regulation of flow rate, heat flux and shading devices.
- There are usually modelling limitations on the combinations of sensed variable/control mode/actuated variable.
- Sensor/actuator location is often restricted to zone air point and surface point with no facility for intra-constructional and mixed (i.e air-surface) sensing/actuation.

- Operational characteristics such as accuracy, adaptability, frequency response, reliability and thermal stability are rarely considered in the modelling process.

These limitations and restrictions create a major barrier to the successful modelling and simulation of advanced BEMS control strategies. Clearly, then, for the integrity of such advanced systems to be preserved, a modelling facility is required which can handle multi-sensor, multi-actuator, discriminating, majority voting strategies, split-range schema with the spatial elements capable of being positioned at locations such as lighting system, shading devices, fluid flow/CFD networks, plant and CHP components (Figure 4.1).

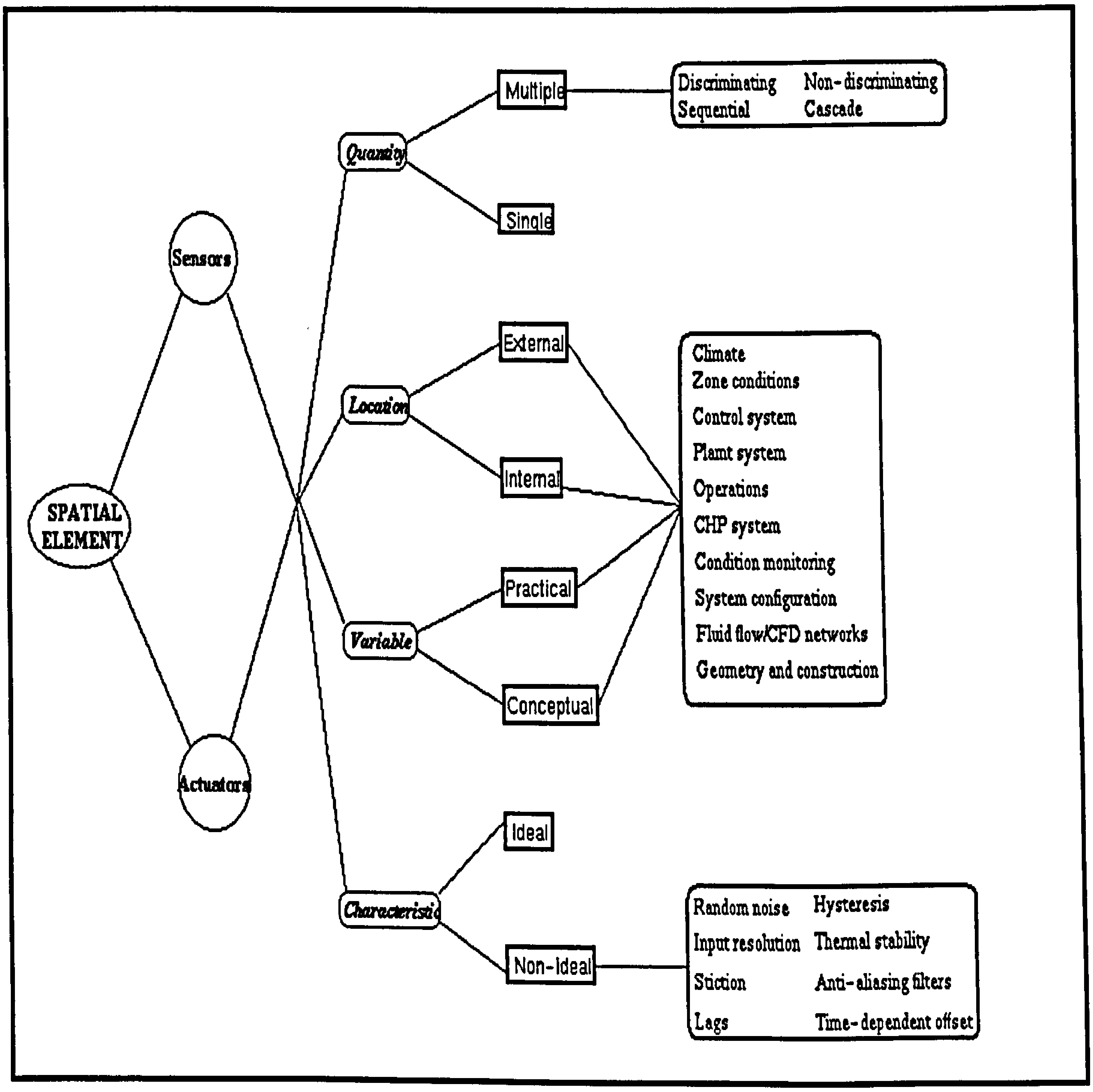


Figure 4.1 Building control systems: the spatial element.

4.2 SENSED/ACTUATED VARIABLES.

An advanced control system modelling facility, as with a practical BEMS, requires an adaptable and dynamic sensor/actuator positioning capability. The fact that a variable cannot be sensed and/or actuated in reality should not deter modellers and simulationists from attempting to do so in a software environment. For example, there is no *practical* equivalent of a 'simulation time-step sensor/actuator'. However, it is highly desirable to have such a simulation capability to allow, e.g. the following time-step control logic to be applied at some junction in the simulation:

IF rate-of-change of sensed value > 1°C per minute THEN reset simulation time-step to 20 seconds.

Clearly, this requires actuation of the simulation time-step variable.

Again, in practice, not all variables capable of being sensed will be capable of being (directly) actuated, e.g. temperature, etc. However, such sensor/actuator combinations are a desirable simulation program feature, allowing simulation control restraints to be applied, e.g:

IF zone air temperature > 20°C THEN reset zone air temperature to 20°C;

In practice, the control variable cannot usually be directly manipulated by the automatic controls. For example, for room temperature control, the controller can often only alter the position of some valve stem and it is this which indirectly affects the room temperature. The valve stroke or the flow rate would be considered as the 'manipulated variable'. In a software simulation environment, however, it is possible to 'actuate' any simulation parameter as deemed necessary and relevant by the intelligent controller. The reason why programs do not have the capability to sense/actuate all the variables listed in Table 3.1, is because of limitations and nature of these programs, i.e. time-step control can only be sensed/actuated if there is a program facility for time-step control; similarly, sensing/actuation of CFD variables requires a CFD modelling capability.

The following points can be made regarding these variables identified and listed in Table 3.1, all of which may potentially be required to be sensed/actuated during simulation:

- Many of these variables cannot be sensed/actuated in practical systems, but are nevertheless essential constructs for control system design and research investigations.
- All sensed variables can, in principle, also be actuated;
- Many of the variables listed (e.g. CFD parameters and CHP parameters) are not capable of being sensed/actuated in most present-day building energy simulation programs.

Moreover, not only must the identified variables be capable of being sensed/actuated, they must also be capable of being operated on in single, multiple and composite modes as discussed in the following sections.

4.3 SINGLE POINT SENSING/ACTUATION.

Single point sensing and actuation is the most common control system arrangement used in both conventional and BEMS-based systems. Two exemplar single point sensing/actuation schemes installed in ESP-r - one practical, the other highly conceptual - are now discussed.

4.3.1 Practical single point control: intra-constructional control point.

A numerical scheme for modelling a control point located at the air point was described in Section 3.4, with single point surface control point schemes detailed by Clarke [1985]. Implementation, in ESP-r, of a numerical solver for the modelling of an intra-constructional control point (necessary, for example, for modelling underfloor heating strategies) is now presented:

Stage 1. At each building-side simulation time-step, the partitioned construction sub-matrix of Section 3.4.4 is processed to the end of the forward reduction stage as depicted in Figure 4.2(a) and Figure 4.2(b) for the case of a single zone.

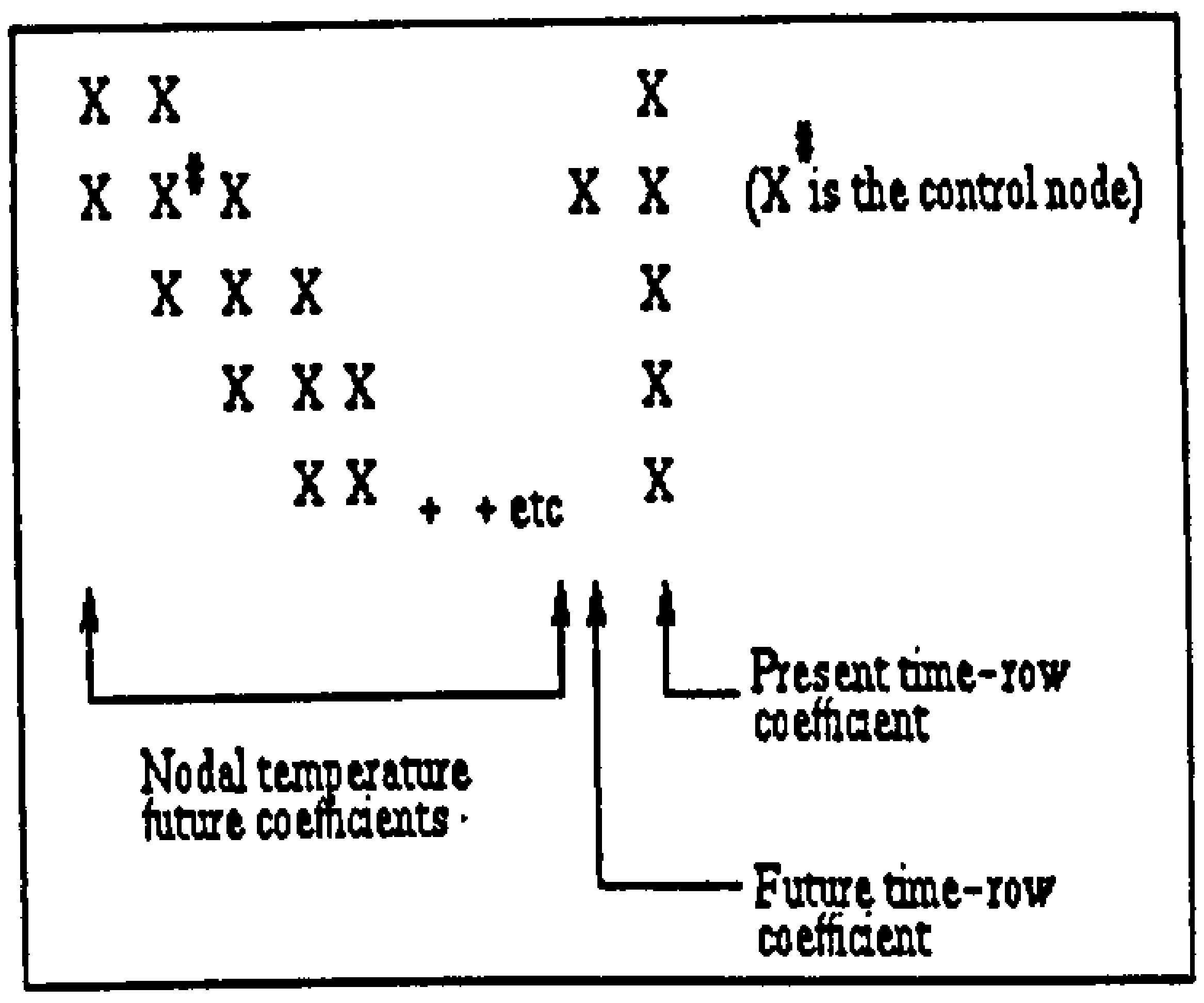
Stage 2. As for the case of the control point located at the air node, the surface equation is then adjusted, but in this case *two* sets of adjusted coefficients are extracted, relating to:- the internal constructional control node (future time-row); right-hand side (present term); surface term (future time-row); next-to-inside surface term (future time-row); and the intra-constructional plant term (future time-row) if any.

Stage 3. The terms a1, a2, a3, a4, b1, b2, b3 and b4 of Figure 4.2(b) are then used to eliminate the next-to-surface coefficient and the surface node coefficient from the corresponding surface equation, as depicted in Figure 4.2(c).

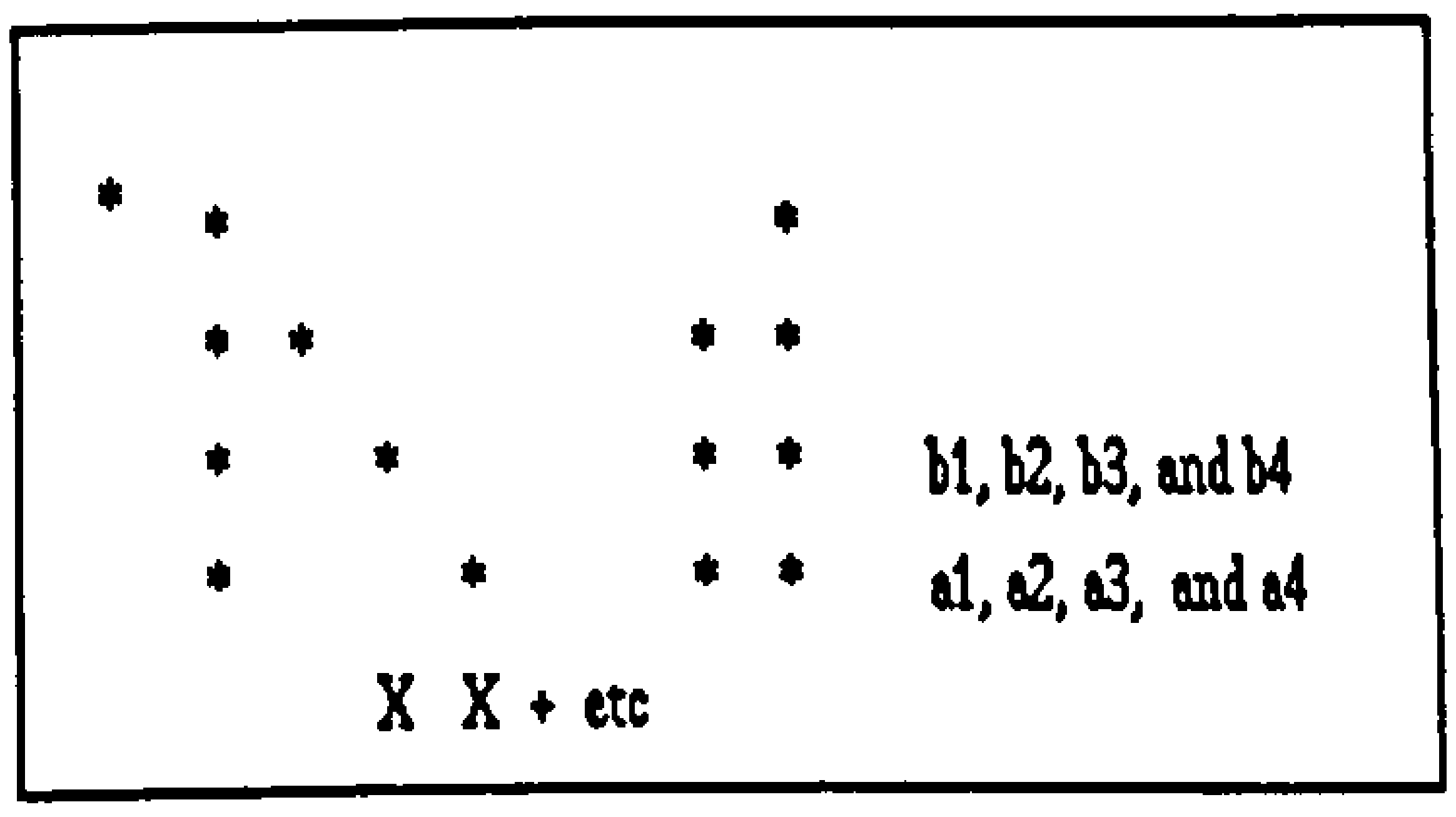
Stage 4. The coefficients of the surface and air point node equations are then reduced to the end of the forward reduction stage (Figure 4.2(d), and Figure 4.2(e)). The surface, air and plant (carried through) coefficients thus form the building system control equation set equation.

Stage 5. This equation, containing two unknowns, is solved by introducing control law algorithms representing control system performance characteristics and criteria such as set points, hysteresis, limiting flux values, etc.

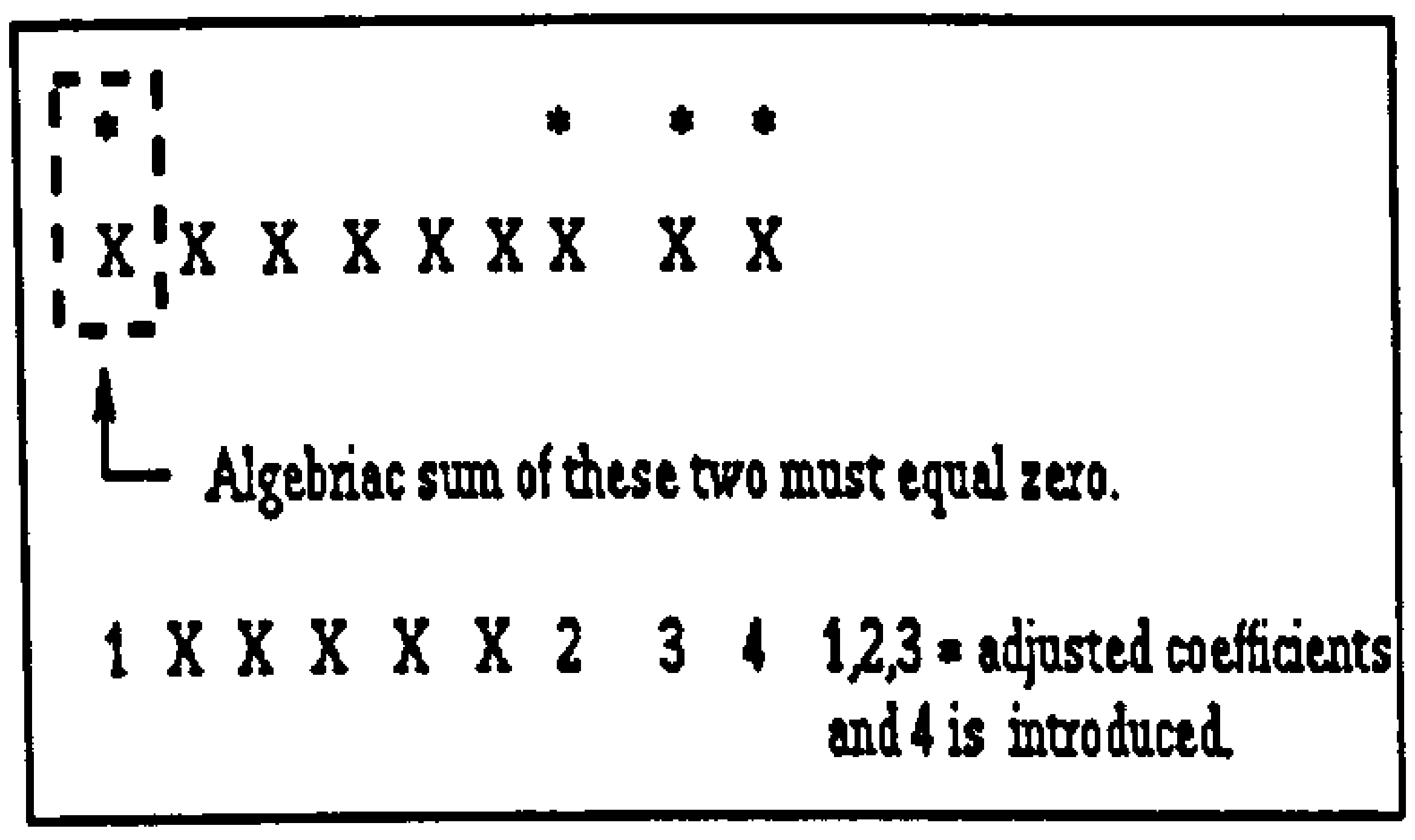
Stage 6. The surface node temperatures are established by means of backward substitution in the reduced construction matrices.



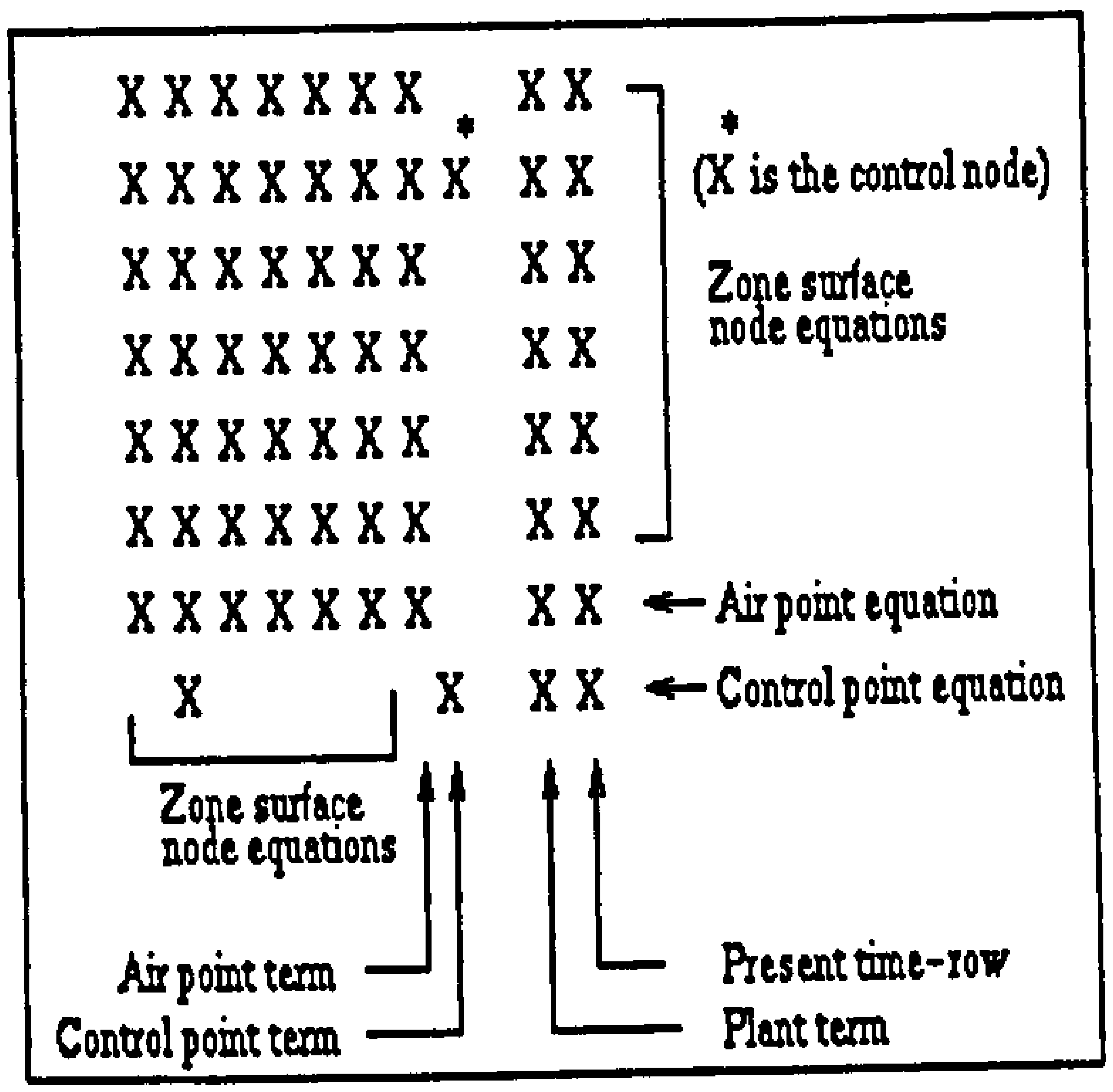
(a) Construction ('W') matrix



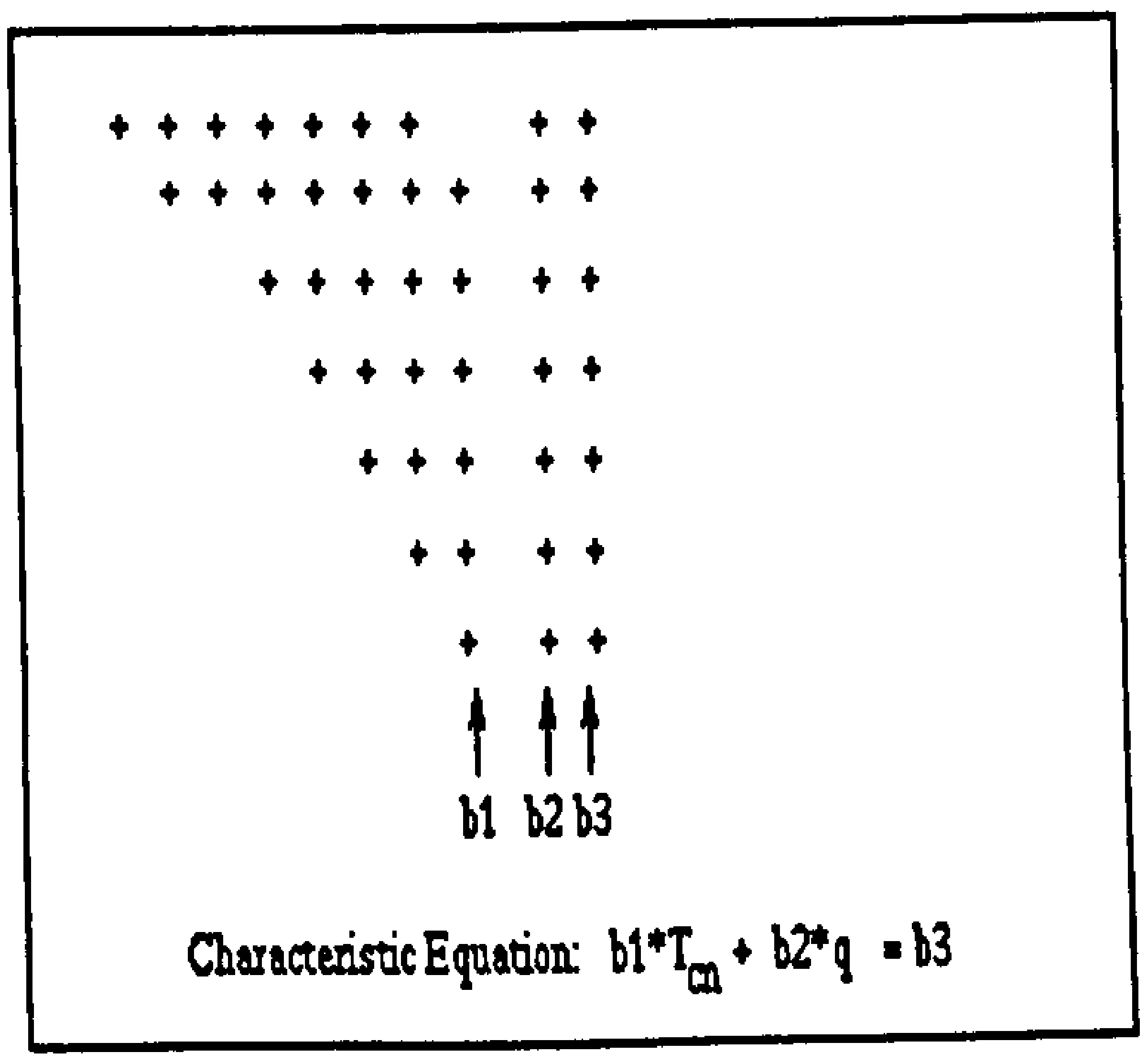
(b) Reduced construction ('WA') matrix



(c) Surface equation adjustment.



(d) Intra-zone ('E') matrix



(e) Intra-zone matrix adjustment.

Figure 4.2 Intra-constructional control point solution process.

Consider the case of intra-constructional control point location as adopted in the control strategy used in an attempt to eliminate the so-called 'Monday morning blues' phenomenon occurring in many buildings unoccupied over the weekend period [Levermore, 1992]. If control is solely enacted on the basis of air temperature, then, as the air temperature typically rises ahead of the fabric temperature, the heating may be switched off giving a low dry resultant temperature especially on a Monday morning when the fabric has lost heat over the weekend period. Many BEMS manufacturers thus recommend that a temperature sensor be placed *within* an internal wall to control pre-heating on internal fabric temperature rather than air temperature. The location of a (secondary) sensor within the construction itself allows initial control on the intra-construction point until the fabric temperature has risen to acceptable levels, at which juncture control is transferred to air point temperature.

Figure 4.3 shows the affects of pre-heat based on an intra-constructional control point as opposed to control on air node for a test zone problem† - the control system specifications (Table 4.1) being otherwise identical. In the case of control on air point node (Figure 4.3(a)), the set point (20 °C) is reached at the 'desired time of arrival' (DTOA) of 09.00 hours; however, the resultant temperature at this time is only 17.8 °C. For the case of intra-constructional point control (Figure 4.3(b)), the air point and resultant temperatures at the DTOA are now 23 °C and 19.7 °C, respectively; together with a greater energy requirement than for air point control.∞

Table 4.1 Control on intra-constructional point: control schedule.

Sensed property	Actuator location	Actuated variable	Day 8 (All day)	Day 9 (0.00-09.00)			
			Mode	Mode	Set point	Throt'g range	Capacity
Temperature	Air point	Flux	Free-float	Proportional	20.0 °C	6.0 K	3000 W

---

† The test zone problem file listings used for demonstration purposes in Chapters 4,5, and 6 are available on-line as an archived ESP-r training exemplar: *../ESP-r/training/basic.*

∞ Note that the set point for the proportional controller is assumed to be in the middle of the proportional band. Also, the error is defined as *set-point - sensed condition* where the sensed condition is the future time-row nodal condition *prior* to any plant input, i.e. θ_c when q_p is set to zero in the Building Control Systems Equation Set (Equation 3.8).

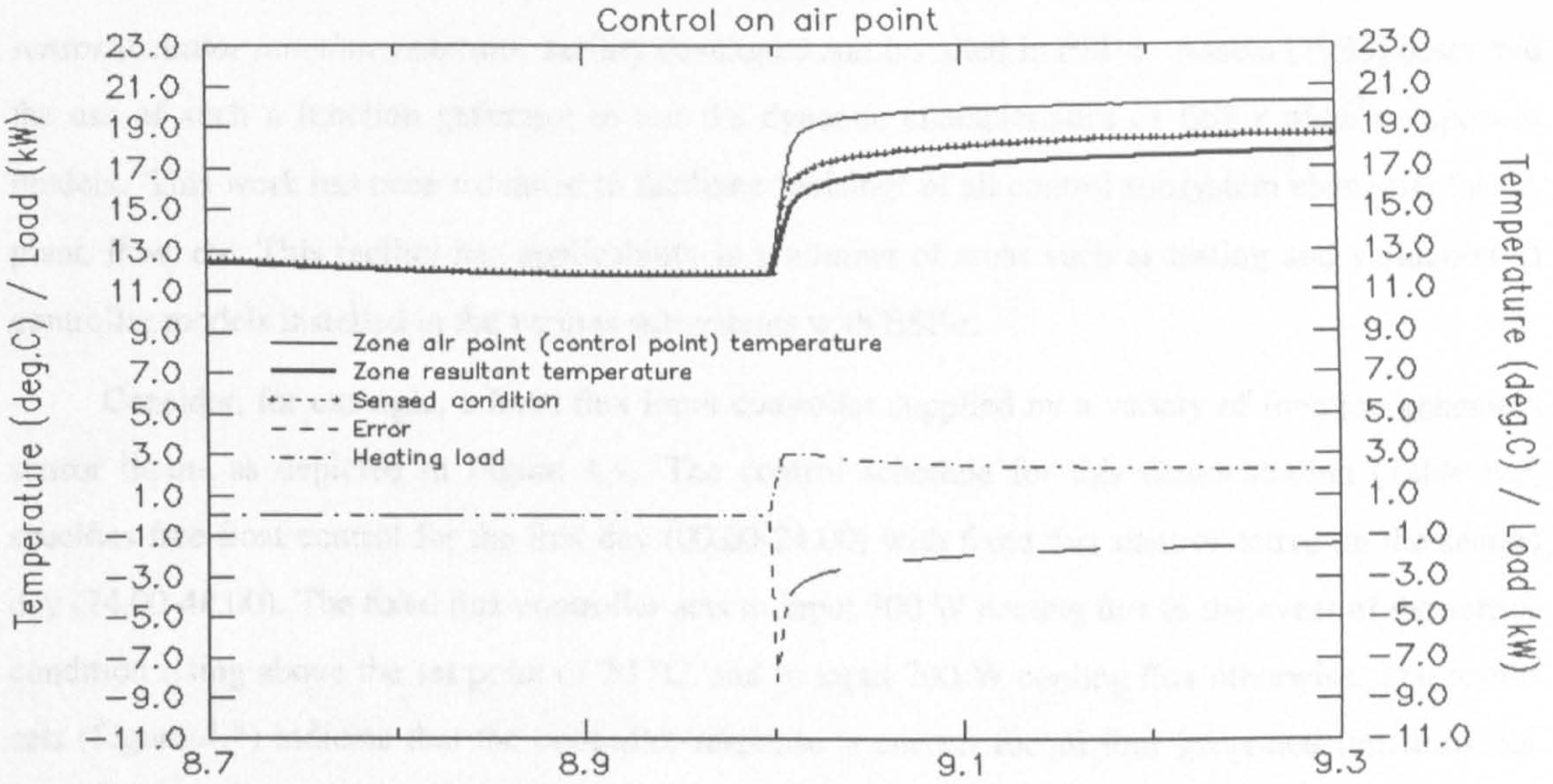


Figure 4.3(a) Control on air node temperature.

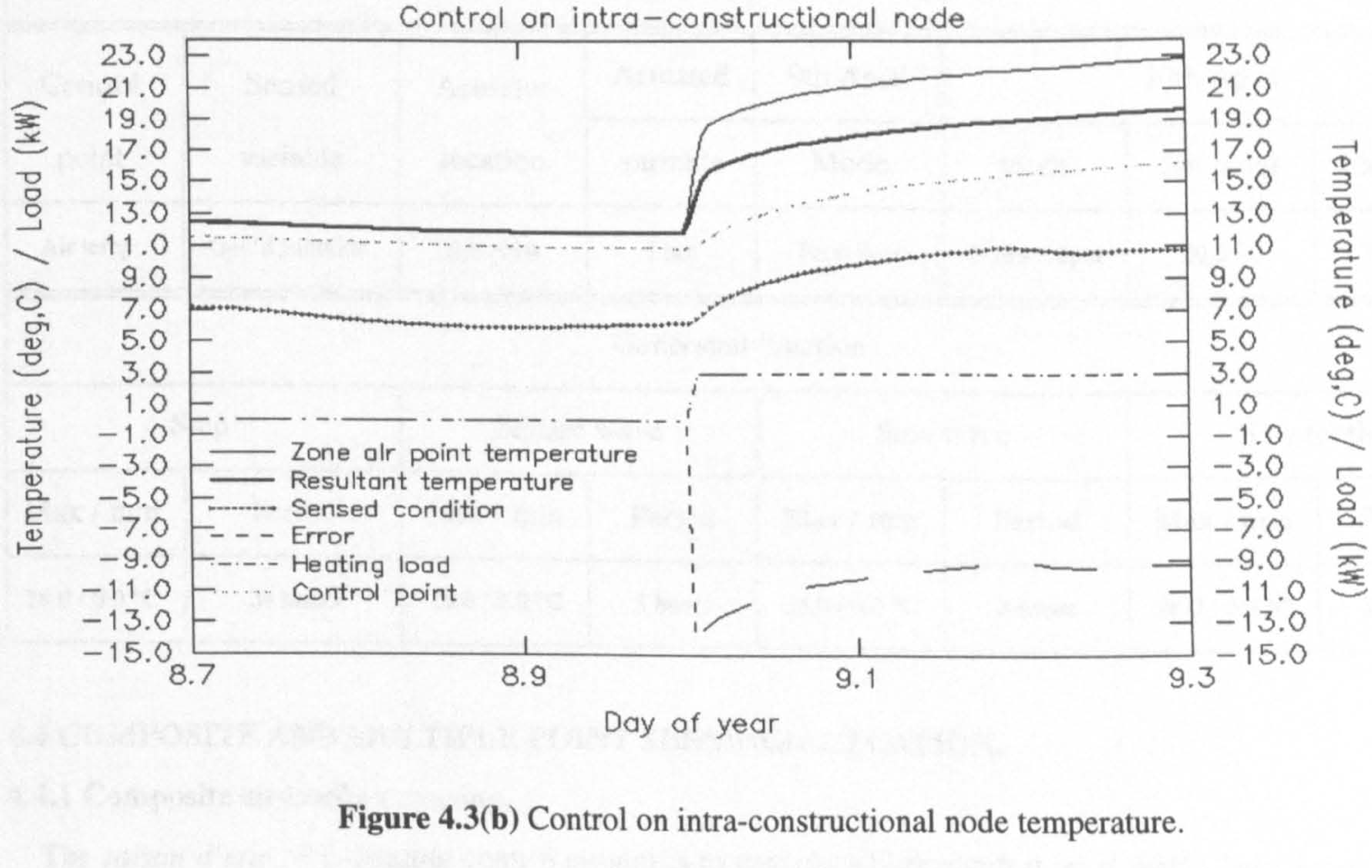


Figure 4.3(b) Control on intra-constructional node temperature.

4.3.2 Conceptualisd single point control: function generators.

An example of a conceptualisd sensed/actuated signal is found in the case of the *sensor/actuator function generator* facility developed and installed in ESP-r. Aasem [1993] described the use of such a function generator to test the dynamic characteristics of ESP-r *plant* component models. This work has been extended to facilitate 'pulsing' of all control subsystem elements: fabric, plant, flow, etc. This facility has applicability in a number of areas such as testing and validation of controller models installed in the various subsystems with ESP-r.

Consider, for example, a fixed flux input controller supplied by a variety of function generated sensor inputs as depicted in Figure 4.4. The control schedule for this demonstration (Table 4.2) specifies free-float control for the first day (00.00-24.00) with fixed flux control active on the second day (24.00-48.00). The fixed flux controller acts to input 700 W heating flux in the event of the sensed condition rising above the set point of 20 °C, and to input 700 W cooling flux otherwise. The results sets (Figure 4.4) indicate that the controller response is correct for all four generated functions, i.e. heating when the sensed condition rises above the set point, cooling otherwise. This demonstrates the applicability of a function generator facility in verifying controller response to a variety of input signals.

Table 4.2 Control on function generated sensor signals: control schedule.

Control point	Sensed variable	Actuator location	Actuated variable	9th April	10th April		
				Mode	mode	Set point	Capacity
Air temp.	Gen'd function	Air point	Flux	Free-float	Fixed output	20.0 °C	700 W

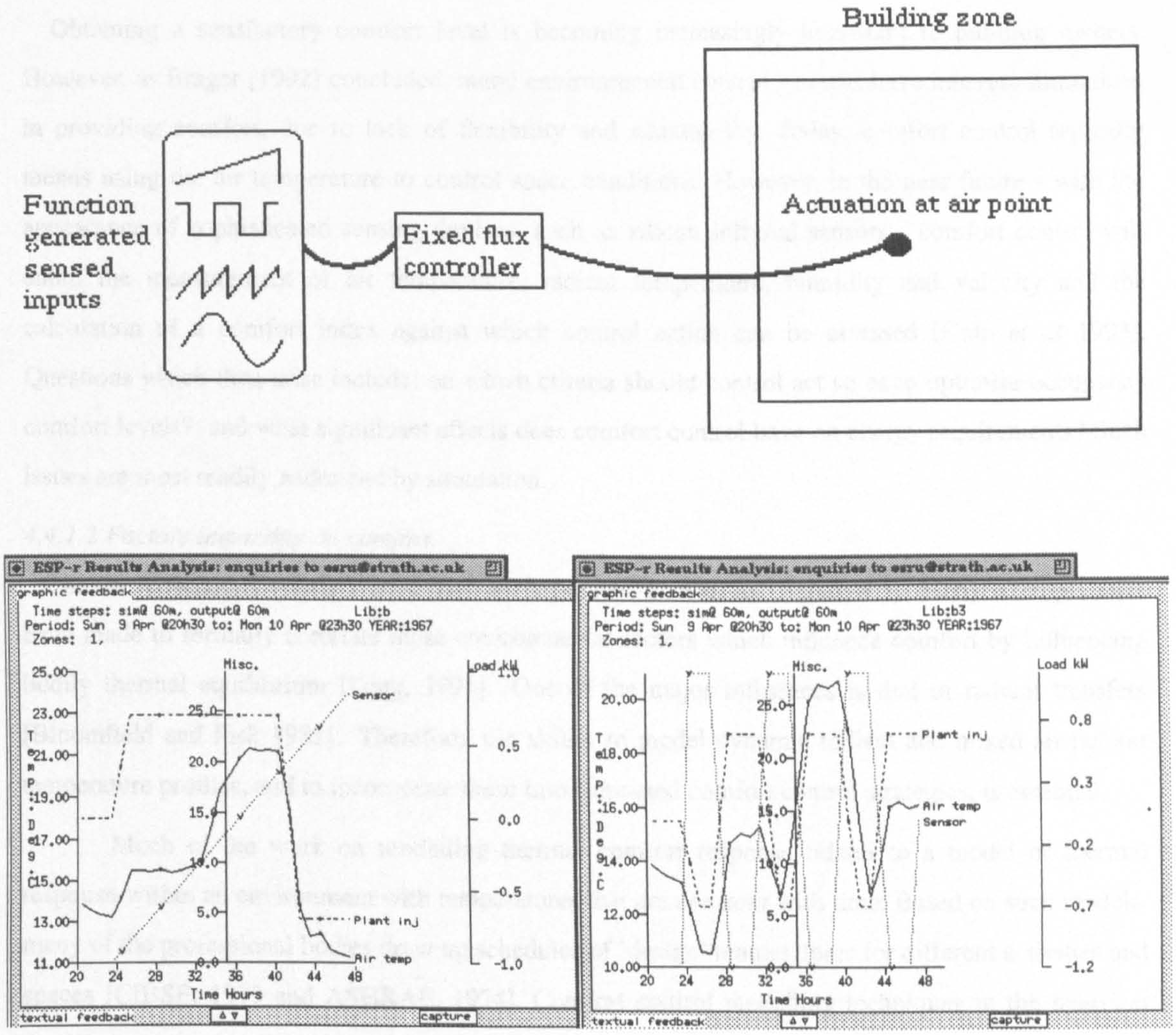
Generated function

Step		Square wave		Sine wave		Saw tooth	
Max / min	Period	Max / min	Period	Max / min	Period	Max / min	Period
28.0 / 0.0 °C	24 hours	28.0 / 0.0 °C	8 hours	28.0 / 0.0 °C	8 hours	28.0 / 0.0 °C	8 hours

4.4 COMPOSITE AND MULTIPLE POINT SENSING/ACTUATION.

4.4.1 Composite air-surface sensing.

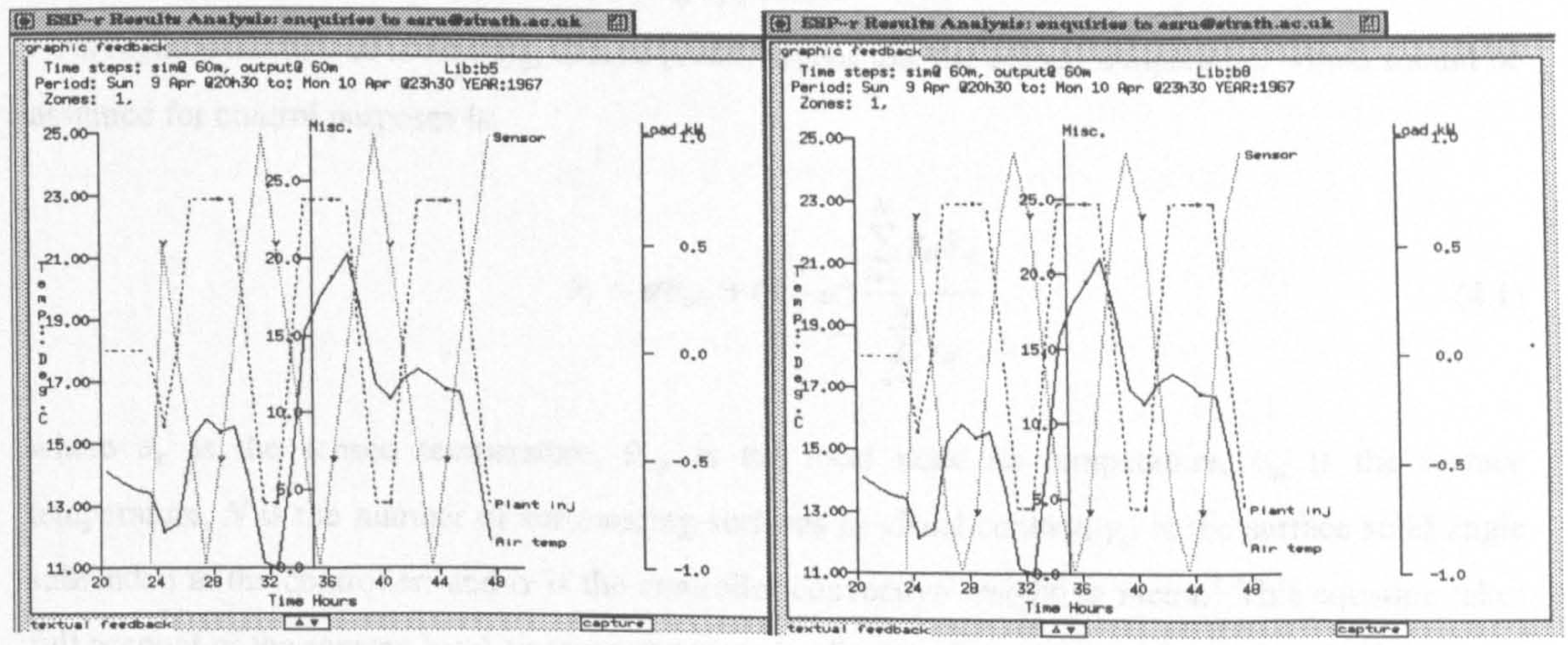
The *raison d'etre* of a building control system is to provide a high comfort level with a low energy requirement. As discussed in Chapters 1 and 2, the modelling and simulation of such system can help to achieve this goal. Such a modelling and simulation facility requires a means of controlling on the basis of comfort criteria.



```
Time steps: sim@ 60m, output@ 60m             Lib:b
Period: Sun  9 Apr @20h30 to: Mon 10 Apr @23h30 YEAR:1967
 Zones:  1,
```

```
Time steps: sim@ 60m, output@ 60m             Lib:b3
Period: Sun  9 Apr @20h30 to: Mon 10 Apr @23h30 YEAR:1967
 Zones:  1,
```

(a) ramp **(b)** square wave (sine series)



```
Time steps: sim@ 60m, output@ 60m             Lib:b5
Period: Sun  9 Apr @20h30 to: Mon 10 Apr @23h30 YEAR:1967
 Zones:  1,
```

```
Time steps: sim@ 60m, output@ 60m             Lib:b8
Period: Sun  9 Apr @20h30 to: Mon 10 Apr @23h30 YEAR:1967
 Zones:  1,
```

(c) sine wave **(d)** saw tooth wave

Figure 4.4 Function generated sensor signals applied to a building zone.

4.4.1.1 Control to comfort criteria: the requirement.

Obtaining a satisfactory comfort level is becoming increasingly important to building owners. However, as Brager [1992] concluded, many environmental control systems have inherent limitations in providing comfort, due to lack of flexibility and adaptability. Today, comfort control typically means using the air temperature to control space conditions. However, in the near future - with the appearance of sophisticated sensing devices, such as silicon infrared sensors - comfort control will entail the measurement of air temperature, radiant temperature, humidity and velocity and the calculation of a comfort index against which control action can be assessed [Culp *et al* 1993]. Questions which then arise include: on which criteria should control act so as to optimise occupancy comfort levels?; and what significant effects does comfort control have on energy requirements? Such issues are most readily addressed by simulation.

4.4.1.2 Factors impacting on comfort.

Comfort conditions within a zone vary for a number of reasons (Figure 4.5). Many attempts have been made to formally correlate those environmental factors which influence comfort by influencing bodily thermal equilibrium [Legg, 1991]. One of the major influences is that of radiant transfers [Bloomfield and Fisk 1981]. Therefore, the ability to model dynamic radiant and mixed air-radiant temperature profiles, and to incorporate these into simulated comfort control strategies, is essential.

Much of the work on modelling thermal comfort response relates to a model of thermal response within an environment with temperatures that are *constant* with time. Based on such models, many of the professional bodies draw up schedules of 'design' temperatures for different activities and spaces [CIBSE, 1979 and ASHRAE, 1974]. Comfort control modelling techniques in the *transient* domain are now described.

4.4.1.3 Comfort control: numerical modelling approach.

As regards thermostat modelling, Clarke [1985] argues that the sensed temperature which should be assumed for control purposes is:

$$\theta_c = \alpha\theta_{air} + (1-\alpha)\frac{\sum_{i=1}^{N}\gamma_{si}\theta_{si}}{\sum_{i=1}^{N}\gamma_{si}} \tag{4.1}$$

where θ_c is the sensed temperature, θ_{air} is the local node air temperature, θ_{si} is the surface temperature, N is the number of surrounding surfaces in visual contact, γ_{si} is the surface solid angle subtended at the controller; and α is the controller convective weighting factor.† This equation takes full account of the sensors local air temperature and radiant exchanges with surrounding surfaces.

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† Numerical approaches for modelling mixed air-surface temperature control together with mixed air-surface actuation are described by Clarke [1985].

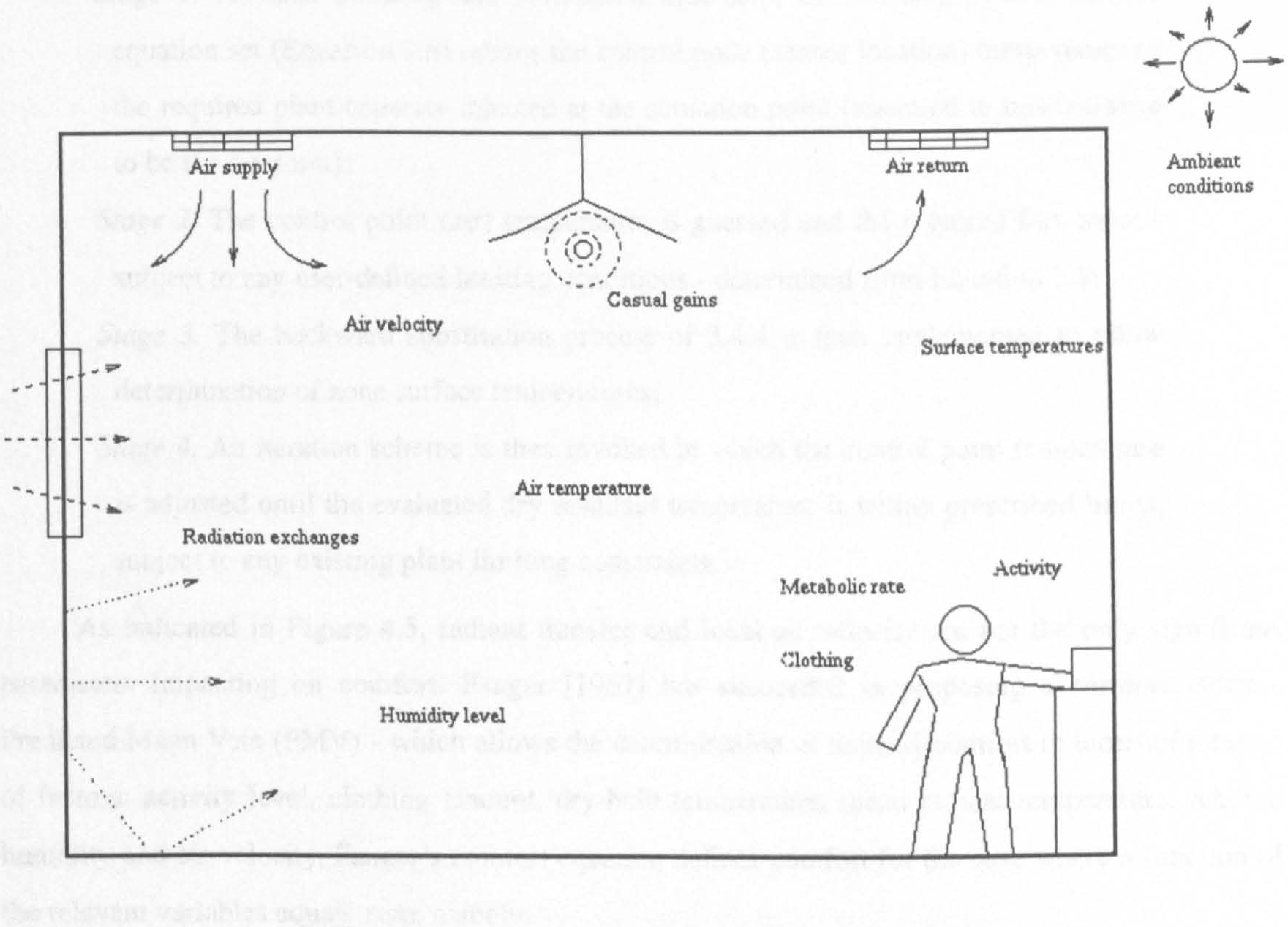


Figure 4.5 Parameters impacting on comfort levels.

To account for local velocity effects, control may be on dry resultant temperature. Dry resultant temperature is formally defined as the temperature recorded by a thermometer located at the centre of a blackened sphere, 100mm in diameter [Jones, 1985]. It is approximately defined for most practical purposes by:

$$\theta_{res} = \frac{\theta_{mrt} + 3.17\theta_{air}\sqrt{v}}{1 + 3.17\sqrt{v}} \tag{4.2}$$

where θ_{mrt} is the zone mean radiant temperature and v is the air velocity (m/s). Assuming an air velocity of 0.1 m/s for sedentary occupation, Equation 4.2 reduces to the commonly used form:

$$\theta_{res} = 0.5(\theta_{mrt} + \theta_{air}) \tag{4.3}$$

where the following conditions need to be satisfied [IHVE (now CIBSE) 1970]:

$$19 \leq \theta_{res} \leq 23 \tag{4.4}$$

and

$$-5 \leq (\theta_{mrt} - \theta_{air}) \leq 8. \tag{4.5}$$

A numerical scheme similar to that described by Clarke [1985] for control on the mixed air-surface temperature of Equation (4.1) is then possible, only in this case iteration being based on the dry resultant temperature (Equations 4.3-4.5) satisfying desired conditions, subject to user-defined plant limiting conditions.

Stage 1. At each building-side simulation time-step, the building system control equation set (Equation 3.8) relates the control node (sensor location) temperature to the required plant capacity injected at the actuation point (assumed in this instance to be the air point);

Stage 2. The control point (air) temperature is guessed and the required flux input - subject to any user-defined limiting conditions - determined from Equation 3.8;

Stage 3. The backward substitution process of 3.4.4 is then implemented to allow determination of zone surface temperatures;

Stage 4. An iteration scheme is then invoked in which the control point temperature is adjusted until the evaluated dry resultant temperature is within prescribed limits, subject to any existing plant limiting constraints.

As indicated in Figure 4.5, radiant transfer and local air velocity are not the only significant parameters impacting on comfort. Fanger [1967] has succeeded in proposing a comfort index - Predicted Mean Vote (PMV) - which allows the determination of thermal comfort in terms of a range of factors: activity level, clothing amount, dry-bulb temperature, mean radiant temperature, relative humidity and air velocity. Fanger's comfort equation defines comfort for the case where a function of the relevant variables equals zero, namely:

$$f\left(\frac{H}{A_D}, I_{cl}, t_a, T_{mrt}, \phi_a, v\right) = 0 \qquad (4.6)$$

where H is the internal rate of bodily heat production (relative to the activity) (W), A_D is the Du Bois bodily surface area (m^2),I_{cl} is the insulating value of the clothing (m^2 K/W), t_a is the zonal dry-bulb temperature (°C), T_{mrt} is the zonal mean radiant temperature (°C), ϕ_a is the zonal relative humidity (%) and v is the local air velocity (m/s).

This index predicts the mean value of the vote of a large group of persons on a seven-point thermal sensation scale, ranging from hot (+3) to cold (-3), with zero being a neutral or 'most comfortable' state. The aim with PMV control is to hold the PMV as near to zero as possible, thus indicating a high level of comfort for the majority of occupants within the zone; a PMV value of zero indicating 95% of people being satisfied. An associated parameter is the Predicted Percentage Dissatisfied (PPD), which is determined from the PMV for several positions in a room.

Henderson [1992] details how energy can be reduced if, under certain circumstances, control is related to the predicted mean vote (PMV) levels in a building. Fisk [1981] argues that the mean square error about the preferred resultant temperature is simple to implement and relates to both the mean value of the PPD and to the probability of occupants taking unprompted action to change their thermal environment.

Pernot [Clarke 1995] describes the installation in ESP-r of algorithms for the determination of PMV and other comfort performance criteria. Enhancement and extension of this work allows the development of a numerical scheme - similar to that described in Section 4.4.1.3 for modelling dry resultant temperature control - for modelling of control based on the PMV comfort parameter. In this case, iteration is now on PMV rather than on dry resultant temperature, the acceptable tolerance of iteration on PMV being user-defined. When comfort is calculated, assumptions are usually made for the metabolic rate and clothing values, and these parameters, too, are user-defined.

In order to demonstrate controlling on comfort criteria (PMV) for the test zone problem, consider the control schedules shown in Table 4.3 in which two schemes are specified: one for fixed set point control on air temperature; the other attempting to hold the PMV value within prescribed limits. The results for a 1 day simulation using a 30 minute time-step are shown in Figure 4.6 from which it can be seen that, in this instance, whilst both schemes offer satisfactory comfort levels during the occupied period (09.00-17.00), control on PMV provides both reduced overall energy demand and also increased comfort levels during the morning period. Generally, PMV control would be expected to yield better comfort conditions (assuming the tolerance band is small), but not always with a reduced energy requirement. Clearly the *overall* benefits of occupant comfort may be more than any perceived savings from energy costs alone, e.g. decreased absenteeism and increased productivity.

Table 4.3: Schedule for control on comfort conditions.

Fixed flux, fixed set point controller

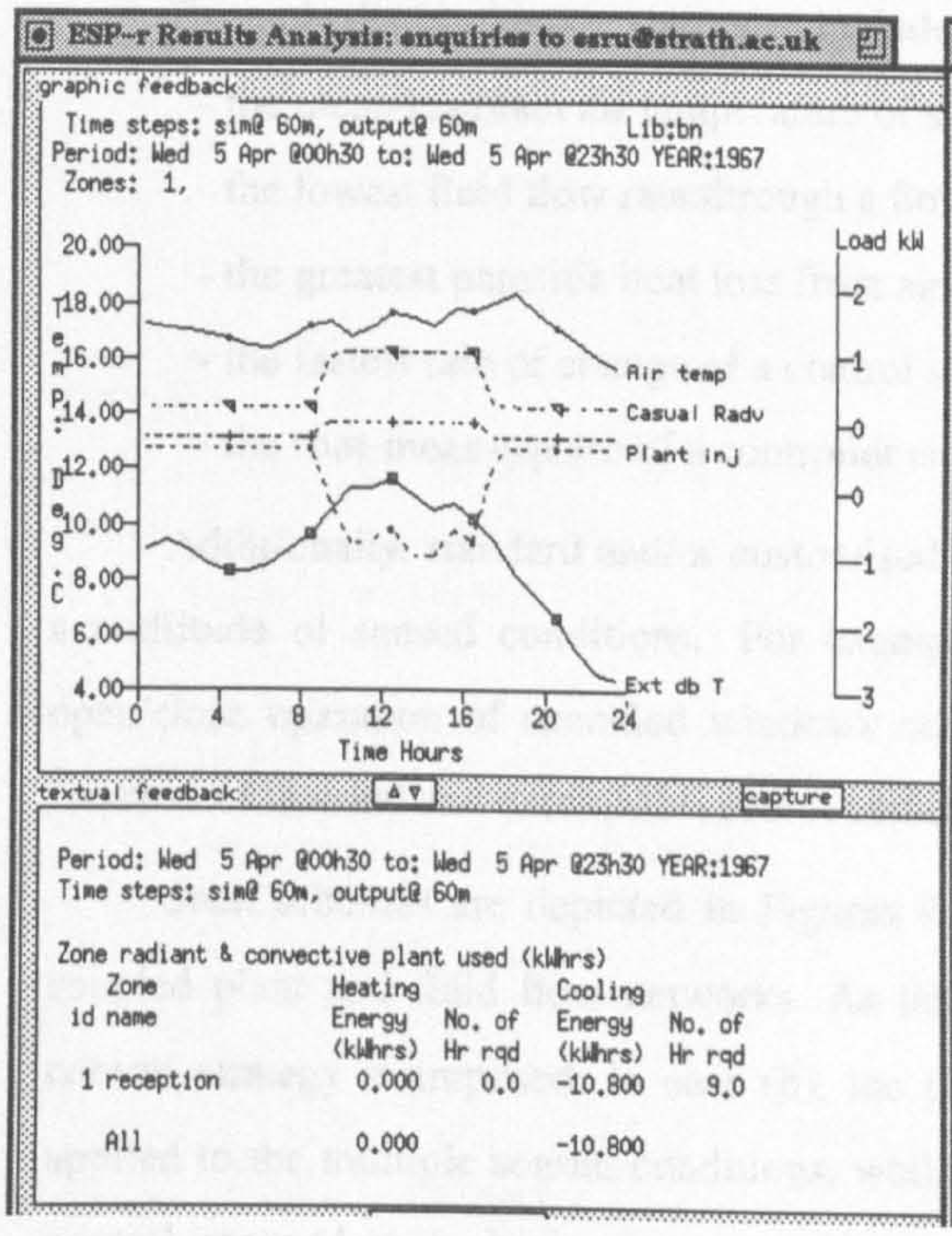
Sensed property	Actuator location	Actuated variable	00.00-09.00	09.00-17.00			17.00-24.00
			Mode	Mode	Set point	Capacity	Mode
Temperature	Air point	Flux	Free-float	Fixed flux	18.0 °C	2000 W	Free-float

PMV controller.

Sensed property	Actuator location	Actuated variable	00.00-09.00	09.00-17.00			17.00-24.00
			Mode	Mode	Set point	Capacity	Mode
Temperature	Air point	Flux	Free-float	PMV	0.0 +/- 1.0	2000 W	Free-float

4.4.2 Multiple point sensing.

Multiple point sensing capabilities are possible in all ESP-r control subsystems. In each subsystem, a control point sensor requires to be specified as for the case of single point sensing. For building-side control, this control point sensor then acts to direct the numerical solution type (Section 3.4). Auxiliary sensors are then specified. These sensors do not influence the solution *type*, only the solution itself. The auxiliary sensed condition(s) may be any nodal property, boundary condition, control system parameter, etc, as listed in Table 3.1. There is no theoretical limit to the number of auxiliary sensors although software considerations may impose some practical limit.

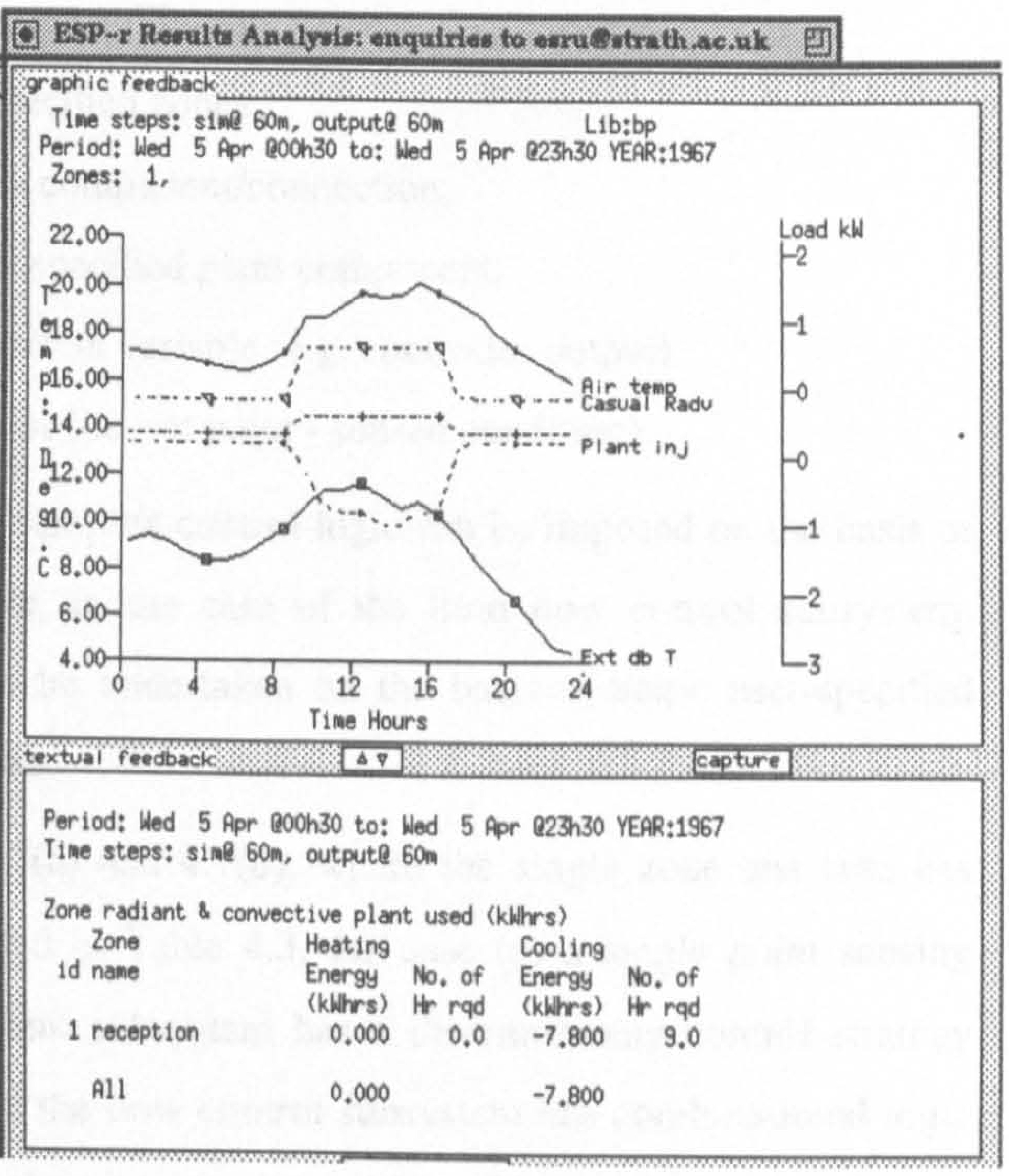


```
Time steps: sim@ 60m, output@ 60m                Lib:bn
Period: Wed  5 Apr @00h30 to: Wed  5 Apr @23h30 YEAR:1967
 Zones:  1,
```

```
Period: Wed  5 Apr @00h30 to: Wed  5 Apr @23h30 YEAR:1967
Time steps: sim@ 60m, output@ 60m

Zone radiant & convective plant used (kWhrs)
   Zone              Heating            Cooling
  id name            Energy   No. of    Energy   No. of
                     (kWhrs)  Hr rqd    (kWhrs)  Hr rqd
   1 reception         0.000     0.0    -10.800     9.0

     All               0.000            -10.800
```



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Time steps: sim@ 60m, output@ 60m                Lib:bp
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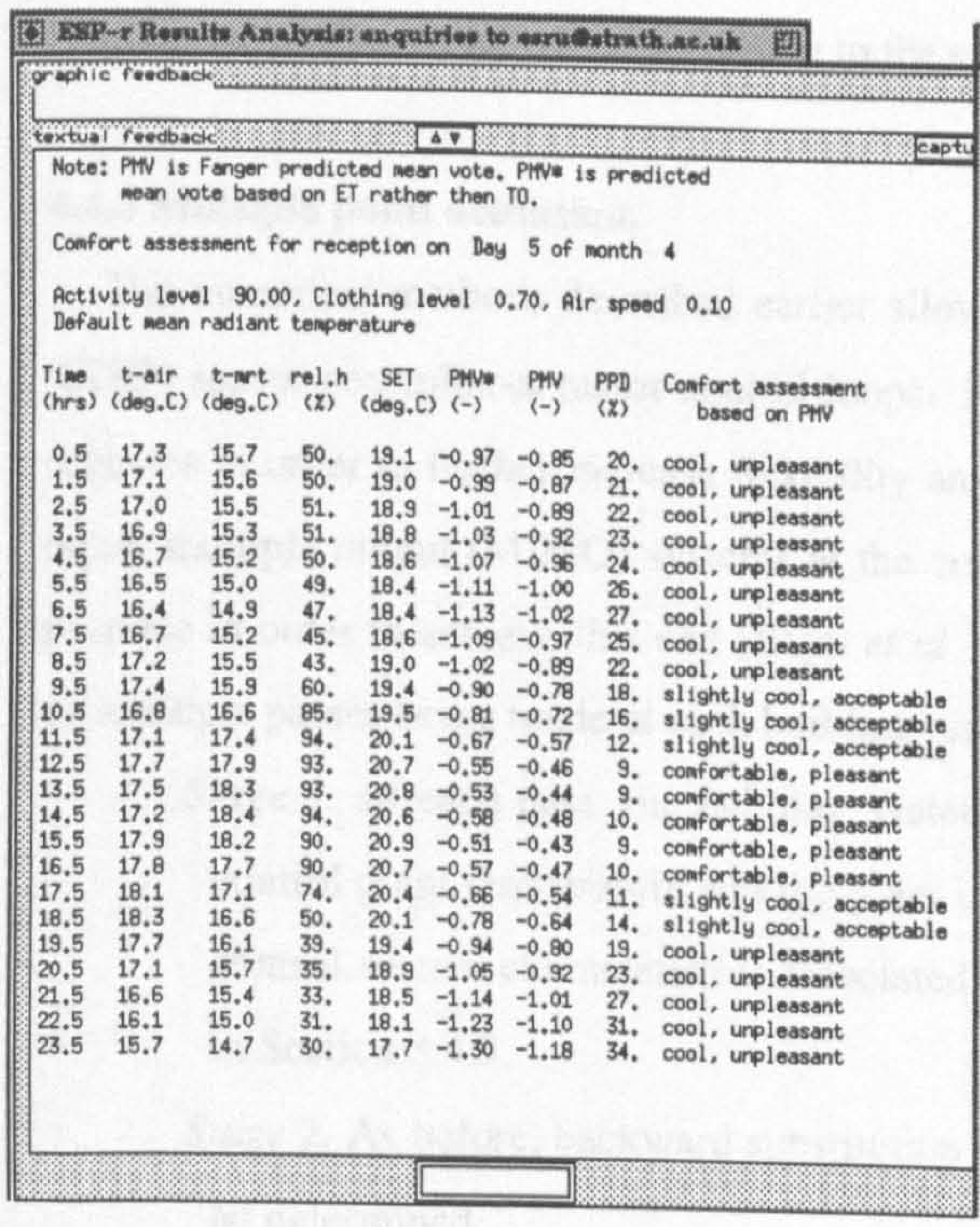
 Zones:  1,
```

```
Period: Wed  5 Apr @00h30 to: Wed  5 Apr @23h30 YEAR:1967
Time steps: sim@ 60m, output@ 60m

Zone radiant & convective plant used (kWhrs)
   Zone              Heating            Cooling
  id name            Energy   No. of    Energy   No. of
                     (kWhrs)  Hr rqd    (kWhrs)  Hr rqd
   1 reception         0.000     0.0     -7.800     9.0

     All               0.000             -7.800
```



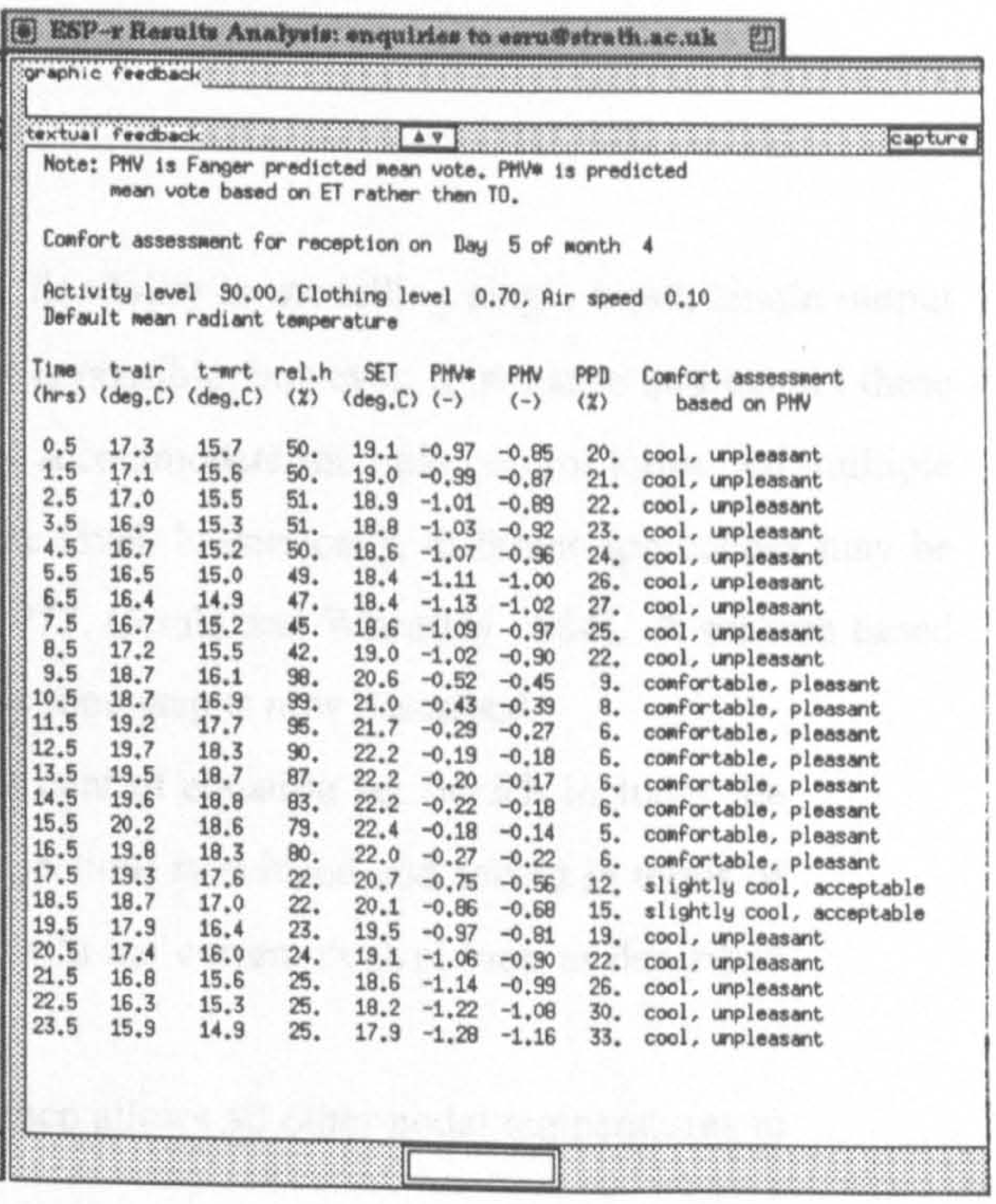
```
Note: PMV is Fanger predicted mean vote. PMV* is predicted
      mean vote based on ET rather then TO.

Comfort assessment for reception on  Day  5 of month  4

Activity level  90.00, Clothing level  0.70, Air speed  0.10
Default mean radiant temperature

Time   t-air    t-mrt   rel.h   SET    PMV*    PMV    PPD  Comfort assessment
(hrs) (deg.C) (deg.C)   (%)  (deg.C)  (-)     (-)    (%)     based on PMV

 0.5   17.3     15.7    50.   19.1  -0.97  -0.85   20.  cool, unpleasant
 1.5   17.1     15.6    50.   19.0  -0.99  -0.87   21.  cool, unpleasant
 2.5   17.0     15.5    51.   18.9  -1.01  -0.89   22.  cool, unpleasant
 3.5   16.9     15.3    51.   18.8  -1.03  -0.92   23.  cool, unpleasant
 4.5   16.7     15.2    50.   18.6  -1.07  -0.96   24.  cool, unpleasant
 5.5   16.5     15.0    49.   18.4  -1.11  -1.00   26.  cool, unpleasant
 6.5   16.4     14.9    47.   18.4  -1.13  -1.02   27.  cool, unpleasant
 7.5   16.7     15.2    45.   18.6  -1.09  -0.97   25.  cool, unpleasant
 8.5   17.2     15.5    43.   19.0  -1.02  -0.89   22.  cool, unpleasant
 9.5   17.4     15.9    60.   19.4  -0.90  -0.78   18.  slightly cool, acceptable
10.5   16.8     16.6    85.   19.5  -0.81  -0.72   16.  slightly cool, acceptable
11.5   17.1     17.4    94.   20.1  -0.67  -0.57   12.  slightly cool, acceptable
12.5   17.7     17.9    93.   20.7  -0.55  -0.46    9.  comfortable, pleasant
13.5   17.5     18.3    93.   20.8  -0.53  -0.44    9.  comfortable, pleasant
14.5   17.2     18.4    94.   20.6  -0.58  -0.48   10.  comfortable, pleasant
15.5   17.9     18.2    90.   20.9  -0.51  -0.43    9.  comfortable, pleasant
16.5   17.8     17.7    90.   20.7  -0.57  -0.47   10.  comfortable, pleasant
17.5   18.1     17.1    74.   20.4  -0.66  -0.54   11.  slightly cool, acceptable
18.5   18.3     16.6    50.   20.1  -0.78  -0.64   14.  slightly cool, acceptable
19.5   17.7     16.1    39.   19.4  -0.94  -0.80   19.  cool, unpleasant
20.5   17.1     15.7    35.   18.9  -1.05  -0.92   23.  cool, unpleasant
21.5   16.6     15.4    33.   18.5  -1.14  -1.01   27.  cool, unpleasant
22.5   16.1     15.0    31.   18.1  -1.23  -1.10   31.  cool, unpleasant
23.5   15.7     14.7    30.   17.7  -1.30  -1.18   34.  cool, unpleasant
```



```
Note: PMV is Fanger predicted mean vote. PMV* is predicted
      mean vote based on ET rather then TO.

Comfort assessment for reception on  Day  5 of month  4

Activity level  90.00, Clothing level  0.70, Air speed  0.10
Default mean radiant temperature

Time   t-air    t-mrt   rel.h   SET    PMV*    PMV    PPD  Comfort assessment
(hrs) (deg.C) (deg.C)   (%)  (deg.C)  (-)     (-)    (%)     based on PMV

 0.5   17.3     15.7    50.   19.1  -0.97  -0.85   20.  cool, unpleasant
 1.5   17.1     15.6    50.   19.0  -0.99  -0.87   21.  cool, unpleasant
 2.5   17.0     15.5    51.   18.9  -1.01  -0.89   22.  cool, unpleasant
 3.5   16.9     15.3    51.   18.8  -1.03  -0.92   23.  cool, unpleasant
 4.5   16.7     15.2    50.   18.6  -1.07  -0.96   24.  cool, unpleasant
 5.5   16.5     15.0    49.   18.4  -1.11  -1.00   26.  cool, unpleasant
 6.5   16.4     14.9    47.   18.4  -1.13  -1.02   27.  cool, unpleasant
 7.5   16.7     15.2    45.   18.6  -1.09  -0.97   25.  cool, unpleasant
 8.5   17.2     15.5    42.   19.0  -1.02  -0.90   22.  cool, unpleasant
 9.5   18.7     16.1    98.   20.6  -0.52  -0.45    9.  comfortable, pleasant
10.5   18.7     16.9    99.   21.0  -0.43  -0.39    8.  comfortable, pleasant
11.5   19.2     17.7    95.   21.7  -0.29  -0.27    6.  comfortable, pleasant
12.5   19.7     18.3    90.   22.2  -0.19  -0.18    6.  comfortable, pleasant
13.5   19.5     18.7    87.   22.2  -0.20  -0.17    6.  comfortable, pleasant
14.5   19.6     18.8    83.   22.2  -0.22  -0.18    6.  comfortable, pleasant
15.5   20.2     18.6    79.   22.4  -0.18  -0.14    5.  comfortable, pleasant
16.5   19.8     18.3    80.   22.0  -0.27  -0.22    6.  comfortable, pleasant
17.5   19.3     17.6    22.   20.7  -0.75  -0.56   12.  slightly cool, acceptable
18.5   18.7     17.0    22.   20.1  -0.86  -0.68   15.  slightly cool, acceptable
19.5   17.9     16.4    23.   19.5  -0.97  -0.81   19.  cool, unpleasant
20.5   17.4     16.0    24.   19.1  -1.06  -0.90   22.  cool, unpleasant
21.5   16.8     15.6    25.   18.6  -1.14  -0.99   26.  cool, unpleasant
22.5   16.3     15.3    25.   18.2  -1.22  -1.08   30.  cool, unpleasant
23.5   15.9     14.9    25.   17.9  -1.28  -1.16   33.  cool, unpleasant
```

Figure 4.6 Control on comfort criteria (PMV).

As described in Section 3.4, at each simulation time-step the subsystem control functions are processed in order to establish control system influence, at which juncture all specified sensors (control point and auxiliary) are established for subsequent processing by the active control algorithm.

Example discrimination strategies include controlling on:

- the mean resultant air temperature of specified zones;
- the lowest fluid flow rate through a flow component/connection;
- the greatest parasitic heat loss from any specified plant component;
- the fastest rate of change of a control system variable (e.g. controller output)
- the root-mean-square of a controller error (i.e. set point - sensed condition).

Additionally, standard and/or customised complex control logic can be imposed on the basis of a multitude of sensed conditions. For example, in the case of the fluid flow control subsystem, open/close operation of specified windows can be undertaken on the basis of some user-specified function of internal and external sensed conditions.

Such schemes are depicted in Figures 4.7(a) and 4.7(b), where the single zone test case has coupled plant and fluid flow networks. As listed in Table 4.3, for case (a) a single point sensing control strategy is imposed; in case (b), the plant subsystem has a discriminating control strategy applied to the multiple sensed conditions, whilst the flow control subsystem has combinational logic control imposed on the basis of a range of internal and external conditions. The results indicate that, in both single and multiple point sensing cases, chiller flux (Figures 4.7(c,d)) and window air flow rates (Figures 4.7(e,f)) are controlled according to the specified schedules.

4.4.3 Multiple point actuation.

The numerical methods described earlier allow flexibility in modelling single input, single output (SISO) sensor-controller-actuator control loops. It is possible, however, to enhance and extend these schemes in order to further increase flexibility and accommodate multiple control loops and multiple input, multiple output (MIMO) systems at the zone level. Numerically, different approaches may be possible in order to achieve this end [Bajai *et al* 1977, Gerald and Wheatley 1984]. A scheme based on multiple passes being made at each building-side time-step is now described.

Stage 1. At each pass, the building system control equation set (which includes the control point temperature and the plant injection) is reduced and solved in terms of control system characteristics associated with the current control loop as described in Section 3.4.3.

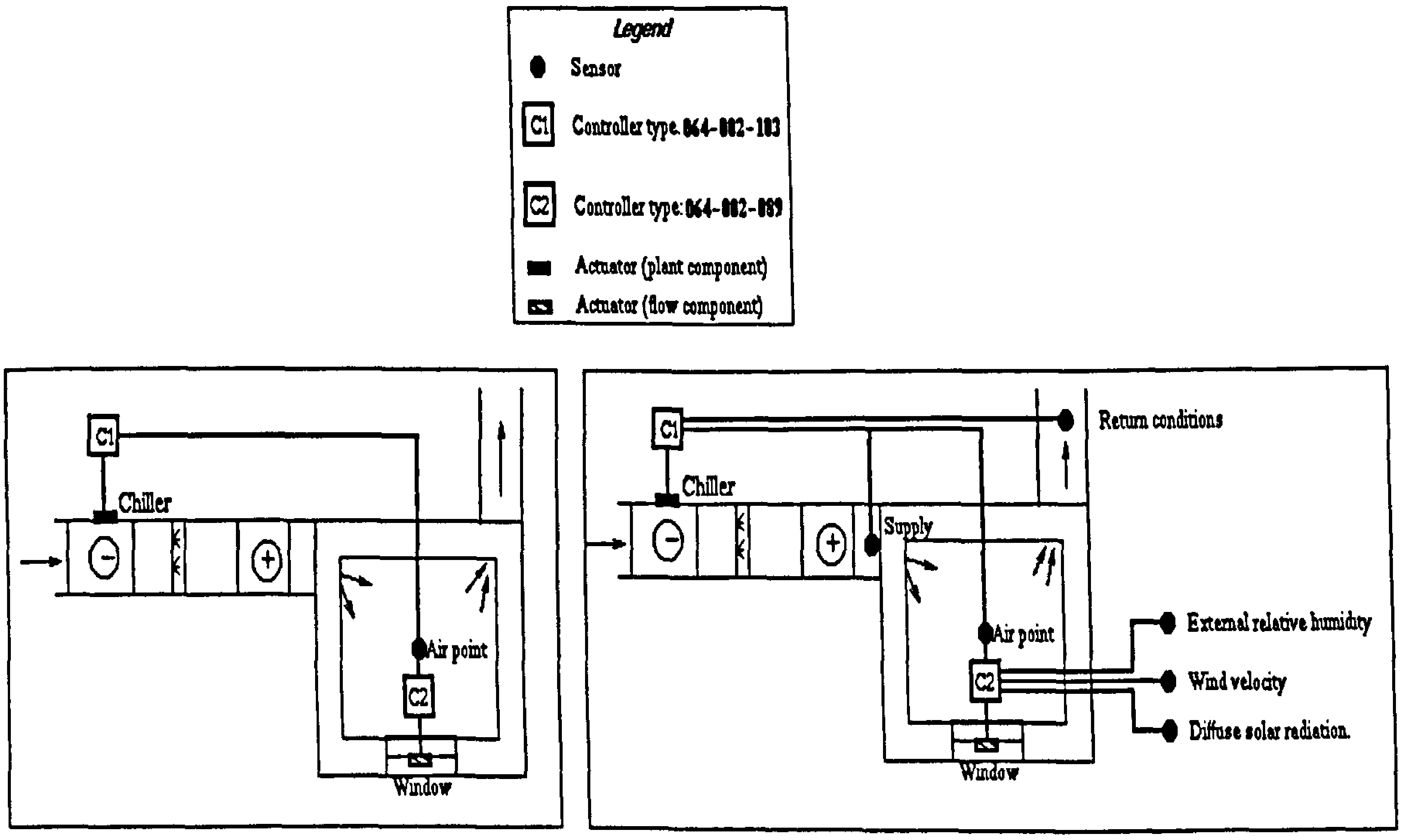
Stage 2. As before, backward substitution then allows all other nodal temperatures to be determined.

Table 4.3(a): Single point sensing control schedule

Control loop	Sensor		Actuator		Controller output		Control action	Set point (^{0}C)	Throttling range (^{0}C)
	Location	Variable	Location	Variable	Max	Min			
Plant	Zone air point	Temperature	Chiller	Flux	2000 (W)	500 (W)	Proportional	18.5	3
Flow	Zone air point	Temperature	Window	Flow rate	Open	Closed	On-off	20	—

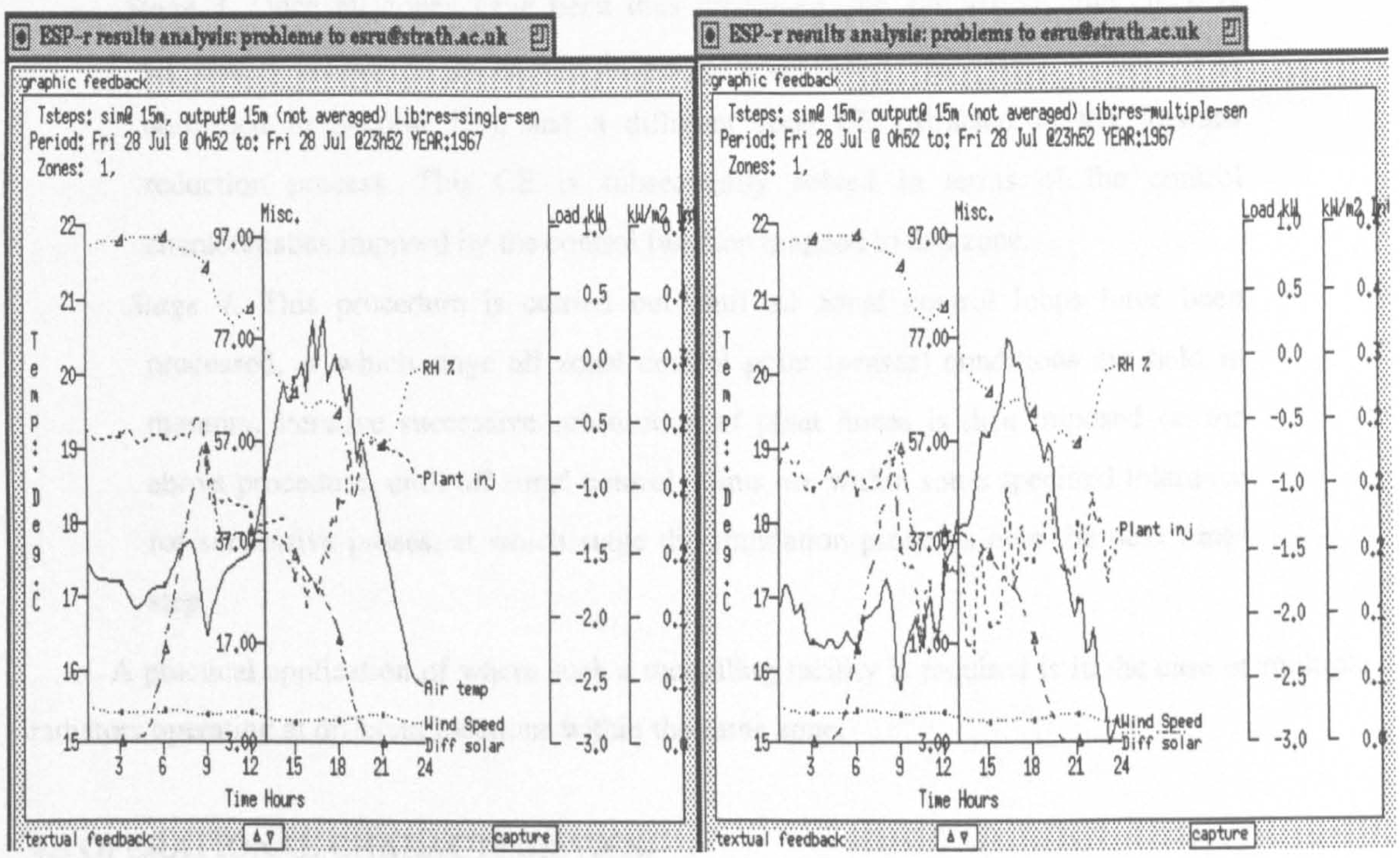
Table 4.3(b): Multiple point sensing control schedule

Control loop	Sensors		Actuator		Controller output		Control action	Control logic	Throttling range (^{0}C)
	Locations	Variables	Location	Variable	Max	Min			
Plant	Zone air point Supply duct Return duct	Temperature Temperature Temperature	Chiller	Flux	2000 (W)	500 (W)	Proportional	The controller modulates if the arithmetic mean of the sensed temperatures falls within the throttling band: 17 - 20 (^{0}C)	3
Flow	Zone air point External External External	Temperature Rel. humidity Wind speed Diffuse radiation	Window	Flow rate	Open	Closed	On-off	The window opens if the: zone air temperature > 18(^{0}C) AND relative humidity < 70% AND wind speed < 4 m/s AND diffuse radiation > 100 W/m2	—



(a) Single point sensing control strategy (b) Multiple point sensing control strategy

Figure 4.7 (a-b) Single and multiple point sensing control strategies.

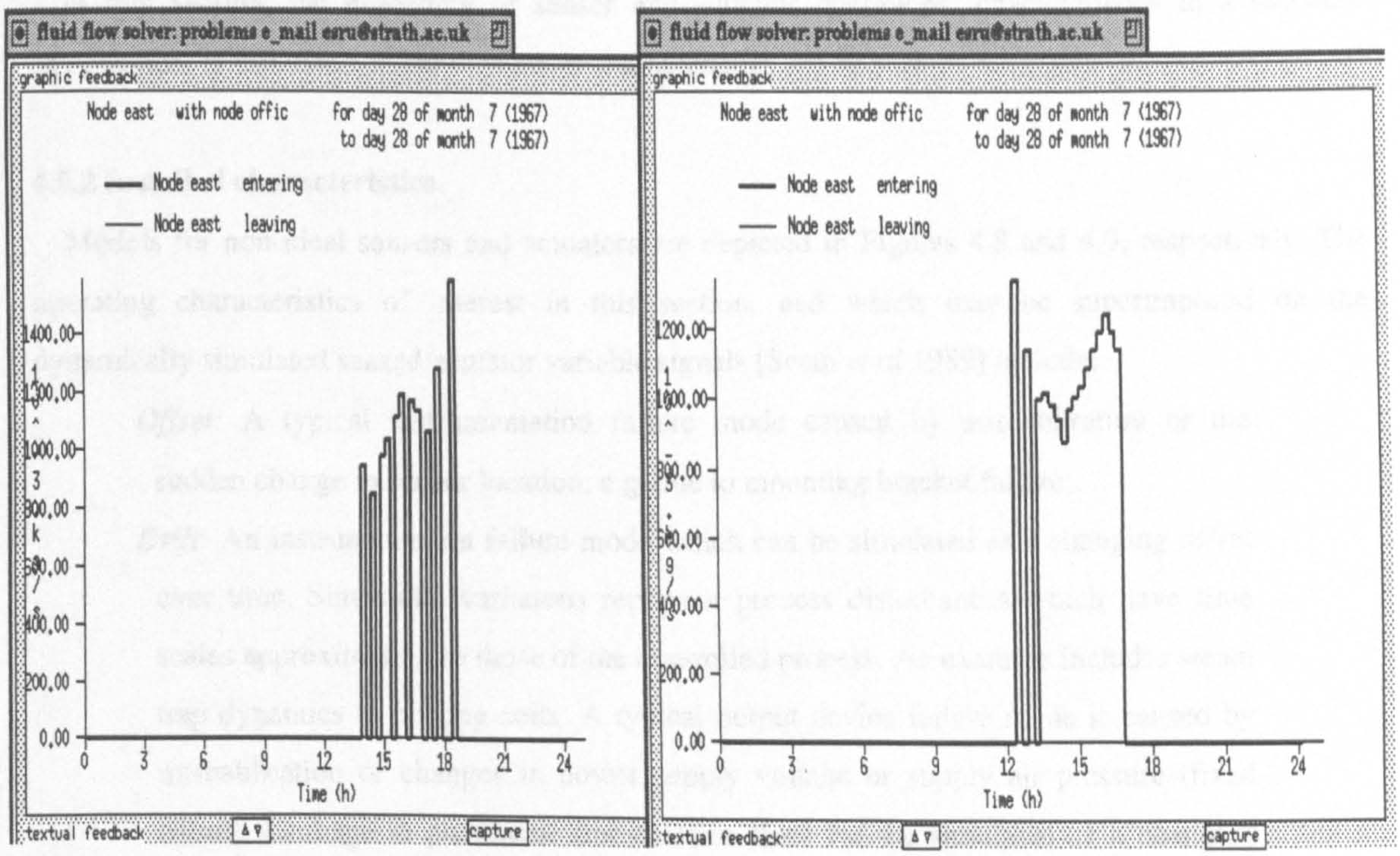


```
Tsteps: sim@ 15m, output@ 15m (not averaged) Lib:res-single-sen
Period: Fri 28 Jul @ 0h52 to: Fri 28 Jul @23h52 YEAR:1967
Zones: 1,
```

```
Tsteps: sim@ 15m, output@ 15m (not averaged) Lib:res-multiple-sen
Period: Fri 28 Jul @ 0h52 to: Fri 28 Jul @23h52 YEAR:1967
Zones: 1,
```

(c) Single point sensing

(d) Multiple point sensing



```
Node east   with node offic   for day 28 of month  7 (1967)
                               to day 28 of month  7 (1967)
```

(e) Single point sensing

(f) Multiple point sensing

Figure 4.7 (c-e) Single and multiple point sensing results sets.

Stage 3. Once all zones have been thus processed, the simulation time clock is adjusted to the start of the current time-step (using time-clock control techniques as described in Section 5.3), and a different zone CE extracted in the forward reduction process. This CE is subsequently solved in terms of the control characteristics imposed by the control function mapped to this zone.

Stage 4. This procedure is carried out until all zonal control loops have been processed, at which stage all zonal control point (sensor) conditions are held in memory. Iterative successive substitution of plant fluxes is then imposed on the above procedure, until *all* zonal control points are within some specified tolerance for successive passes, at which stage the simulation proceeds onto the next time-step.

A practical application of where such a modelling facility is required is in the case of multiple radiators operating at different locations within the same zone.

4.5 OPERATIONAL CHARACTERISTICS.

4.5.1 Scope.

In this Section, the modelling of sensor and actuator operational characteristics in a software environment is discussed. Time-dependent characteristics are elaborated in Chapter 5.

4.5.2 Installed characteristics.

Models for non-ideal sensors and actuators are depicted in Figures 4.8 and 4.9, respectively. The operating characteristics of interest in this section, and which may be superimposed on the dynamically simulated sensed/actuator variable signals [Seem *et al* 1989] include:

Offset: A typical instrumentation failure mode caused by miscalibration or the sudden change in sensor location, e.g. due to mounting bracket failure;

Drift: An instrumentation failure mode which can be simulated as a changing offset over time. Sinusoidal variations represent process disturbances which have time scales approximating to those of the controlled process. An example includes steam trap dynamics in heating coils. A typical output device failure mode is caused by miscalibration or changes in power supply voltage or supply air pressure (fixed offset). Leakage in pneumatic transmission lines can be simulated as a changing offset over time.

Minimum output change (Preload): Incremental interface devices sometimes produce proportionately larger control signals for small changes than for larger changes;

Output stiction: Most mechanical devices which change position in response to a change in control signal exhibit static frictional effects to some degree. This effect retards system response to small output changes;

Actuator hysteresis: Mechanical backlash is a characteristic non-linearity of most HVAC control components, and can greatly influence the dynamics of the control system.

Fixed and time-dependent offset (for sensed and actuator signals) can be described mathematically by a fixed constant, a linear function of time and a sinusoidal function of time according to the following relation:

$$Offset = o_f + o_l t + A\sin\left\{\frac{2\pi t}{P}\right\}, \tag{4.7}$$

where o_f is the fixed offset (W), o_l is the slope of the linear variation in offset with elapsed time t (W/hour), A is the amplitude of the sinusoidal variation (W), P is the time period (hours).

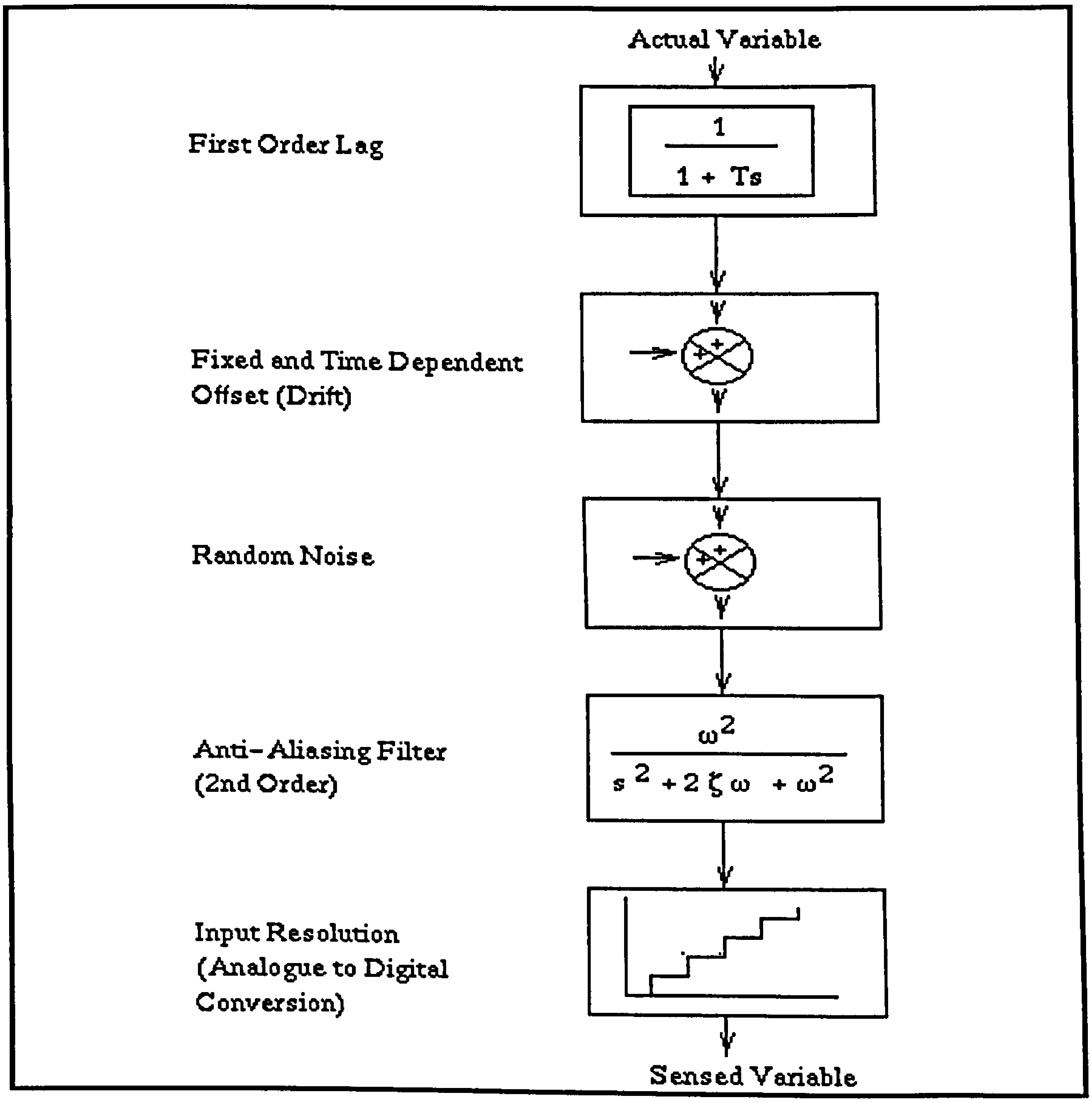


Figure 4.8 Block diagram of non-ideal sensing element (Seem *et al* 1989).

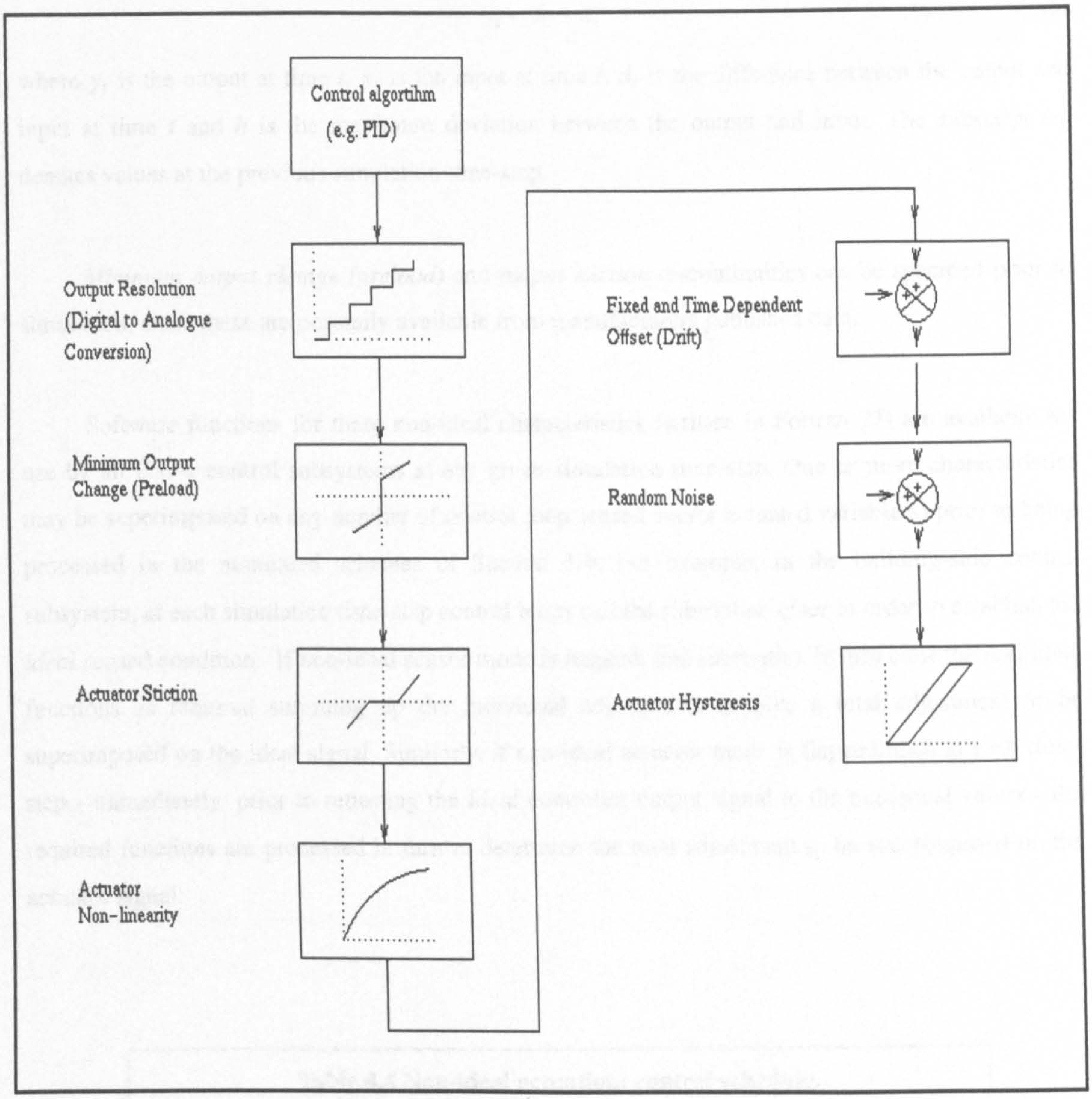


Figure 4.9 Block diagram of non-ideal controller output (Seem *et al* 1989).

The effects of offset on an actuator signal are shown in Figure 4.10, where fixed, linear and sinusoidal offsets are superimposed on the actuator signal of a building-side controller (all other simulation parameters being unchanged). The control schedule is listed in Table 4.4. The actuator signal (flux) profile indicates a sinusoidal characteristic gradually being offset in the vertical axis, resulting in an increase in the control point (air) temperature.

Hysteresis may be estimated by employing the following relationship:

$$IF(x_t > x_{t-1})THEN$$

$$d_t = \text{MAXIMUM}[d_{t-1} + x_{t-1} - x_t, -\text{h}]$$

$$\textit{ELSE}$$

$$d_t = \text{MINIMUM}[d_{t-1} + x_{t-1} - x_t, \text{h}]$$

$$y_t = x_t + d_t \tag{4.8}$$

where y_t is the output at time t, x_t is the input at time t, d_t is the difference between the output and input at time t and h is the maximum deviation between the output and input. The subscript $t\text{-}1$ denotes values at the previous simulation time-step.

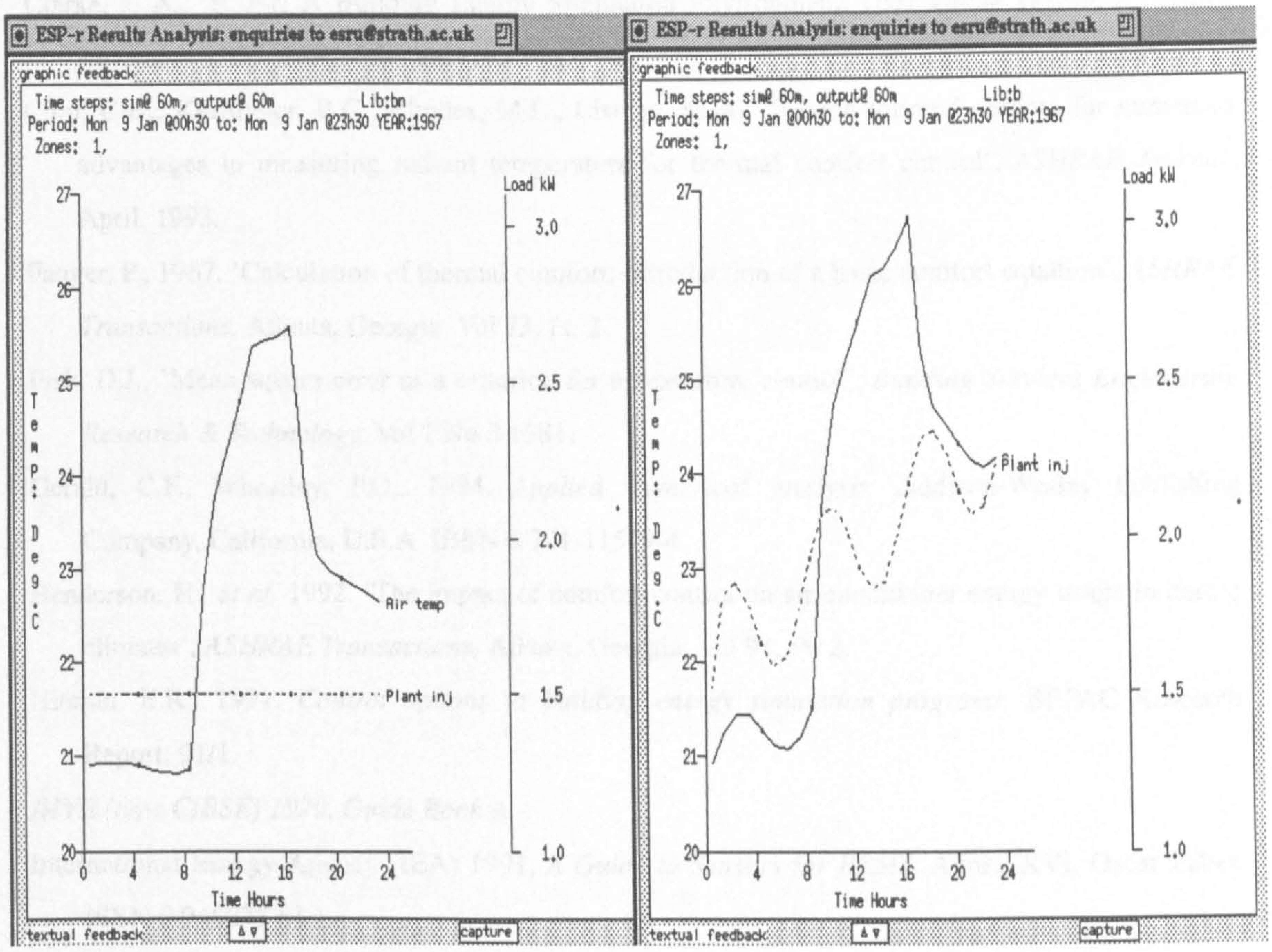
Minimum output change (preload) and *output stiction* discontinuities can be specified prior to simulation, since these are normally available from manufacturers published data.

Software functions for these non-ideal characteristics (written in Fortran 77) are available for use by all ESP-r control subsystems at any given simulation time-step. One or more characteristics may be superimposed on any number of control loop sensed and/or actuated variable(s) prior to being processed in the numerical schemes of Section 3.4. For example, in the building-side control subsystem, at each simulation time-step control loops call the subroutine *cfvar* in order to establish the *ideal* sensed condition. If non-ideal sensor mode is flagged, this subroutine in turn calls the non-ideal functions as required summing up the individual adjustments to give a total adjustment to be superimposed on the ideal signal. Similarly, if non-ideal actuator mode is flagged, then at each time-step - immediately prior to returning the *ideal* controller output signal to the numerical solver - the required functions are processed in turn to determine the total adjustment to be superimposed on the actuator signal.

Table 4.4 Non-ideal actuation: control schedule.

Control law	Heating capacity	Sensed property	Actuated variable	Actuator location	Set point
Fixed flux	1500 W	Air	Flux	Air point	26 °C

Control period		Offset parameters			
Start	Stop	Fixed offset	Linear offset	Amplitude	Period
00.00	24.00	100.0 W	30.0 W/hour	200 W	8 hours



```
Time steps: sim@ 60m, output@ 60m              Lib:bn
Period: Mon  9 Jan @00h30 to: Mon  9 Jan @23h30 YEAR:1967
Zones:  1,
```

```
Time steps: sim@ 60m, output@ 60m              Lib:b
Period: Mon  9 Jan @00h30 to: Mon  9 Jan @23h30 YEAR:1967
Zones:  1,
```

(a) Ideal actuator **(b)** Actuator with offset superimposed

Figure 4.10 Effect of non-ideal characteristic (time-dependent offset) on an actuator signal.

Several schemes for modelling building control systems spatial elements have been described, The following two Chapters proceed to explore techniques for modelling system temporal and logical elements.

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Henderson, H., *et al.* 1992. 'The impact of comfort control on air conditioner energy usage in humid climates', *ASHRAE Transactions,* Atlanta, Georgia. Vol 98, Pt. 2.

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Chapter 5

BUILDING CONTROL SYSTEMS: THE TEMPORAL ELEMENT

This Chapter outlines methods and techniques designed to improve the accuracy and flexibility of modelling the temporal element of building control systems. Numerical schema developed and subsequently installed in ESP-r are presented.

5.1 INTRODUCTION.

The temporal elements of building control system simulation may be classified as depicted in Figure 5.1. Two main classes of elements exist, namely, simulation time-clock parameters and time-dependent system component design/operating characteristics. The former includes time-schedules and simulation time clock and time step manipulation features necessary for inclusion in a control modelling facility; the latter includes time-delays (both designed and operational), and also time-dependent control (sub)system definition and specification. These elements are now considered in turn.

5.2 TIME CO-ORDINATED MULTI-FUNCTIONAL CAPABILITY.

5.2.1 Time-and-event scheduling.

Practical BEMS control strategies are based on time schedules which can range in duration from a matter of seconds (e.g. start-up sequences) to a year or more (e.g. holiday shut downs). Similarly, in a software modelling environment, control strategies (typically complex and hierarchical in nature) imposed on the simulation must be co-ordinated and synchronised with the simulation time-clock and matched to the simulation time-steps. The entire simulation period then requires to be broken down in terms of control day types and control periods within these day types (Figure 5.2). Day *types* include weekdays, weekends, holidays, and seasons. Day *periods* include morning, afternoon, evening, night, working hours, periods of occupancy, etc. The techniques used to ensure the necessary time-coordination and synchronisation will differ according to the nature of the program, e.g. sequential or simultaneous.

In a modularised, numerical based, simultaneous program such as ESP-r, each subsystem (building, plant, flow, etc) has a capability for varying the frequency of matrix inversion in accordance with the dynamics of the individual subsystems. Thus, in order to harmonise the constituent control systems participating in the simulation, at each simulation time-step, the following factors must be established:

- which control subsystems are currently active?
- for each active control subsystem, how many control functions are operating?
- what are the time schedules in terms of control day types and control day periods?

- what is the nature of each active control function, as regards sensor location and quantity, controller type, and actuator location and quantity?
- what control system triggered time-step controllers are currently active, and what is the priority logic?

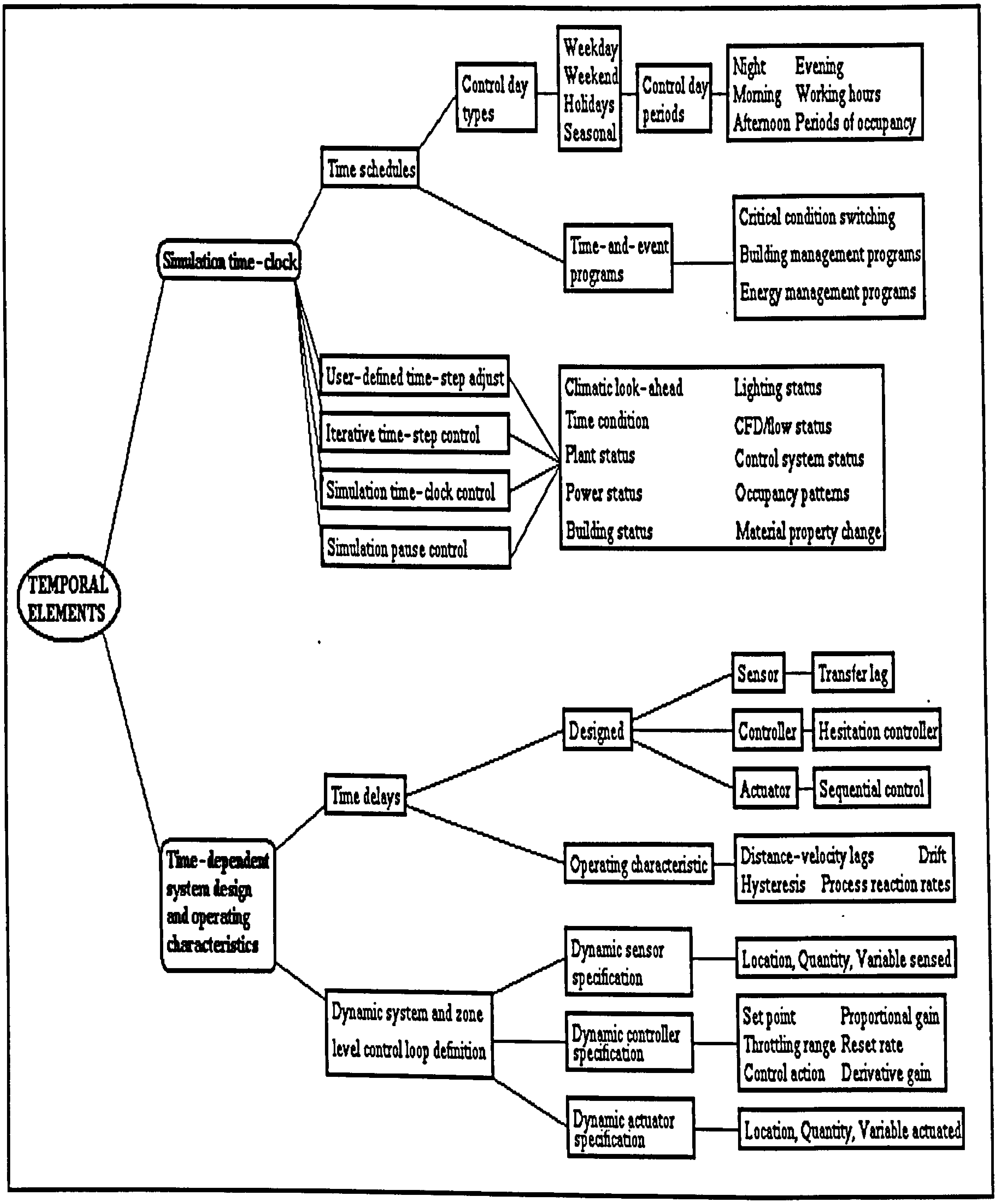
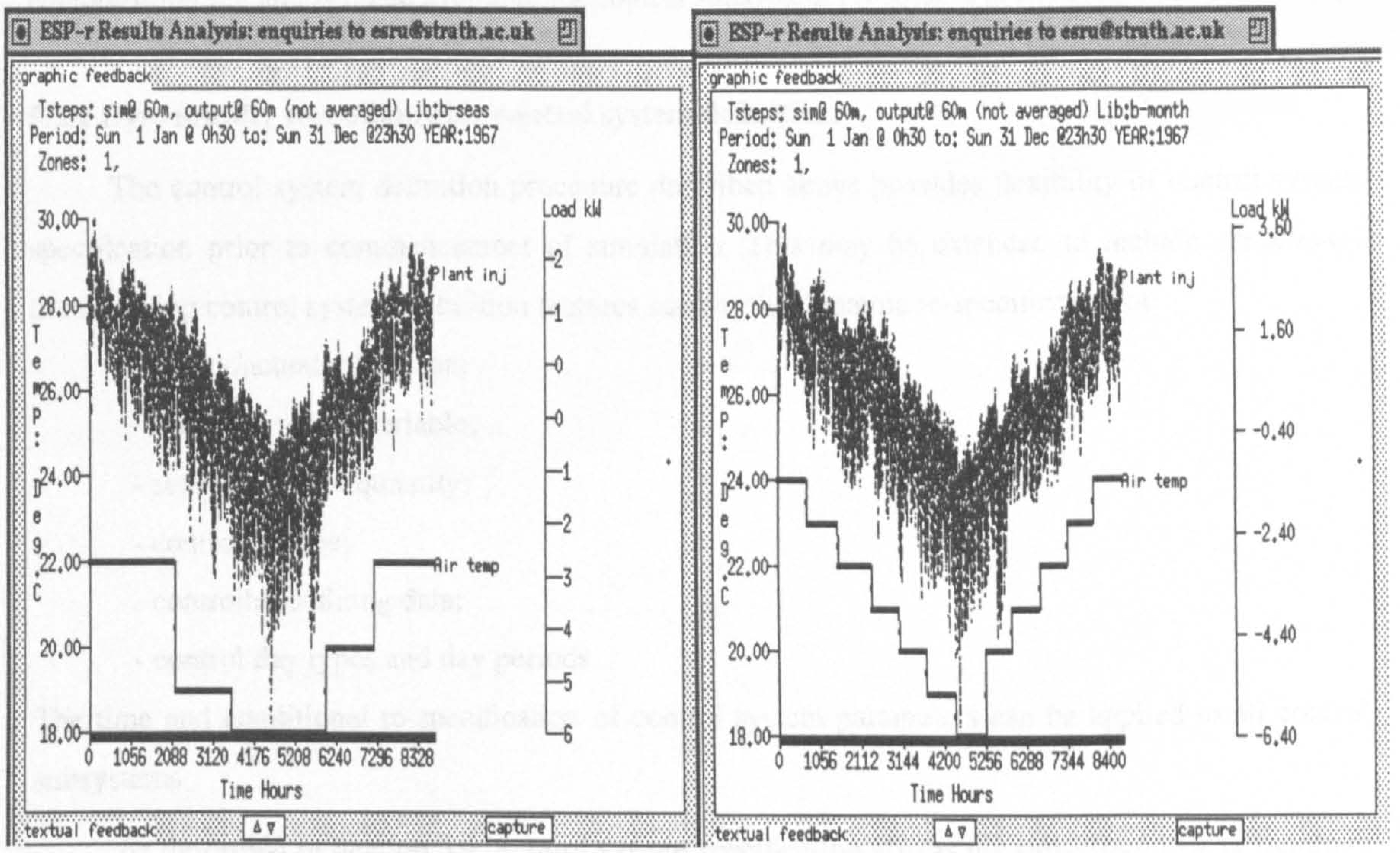


Figure 5.1 Building control systems modelling: the temporal element.



ESP-r Results Analysis: enquiries to esru@strath.ac.uk

graphic feedback

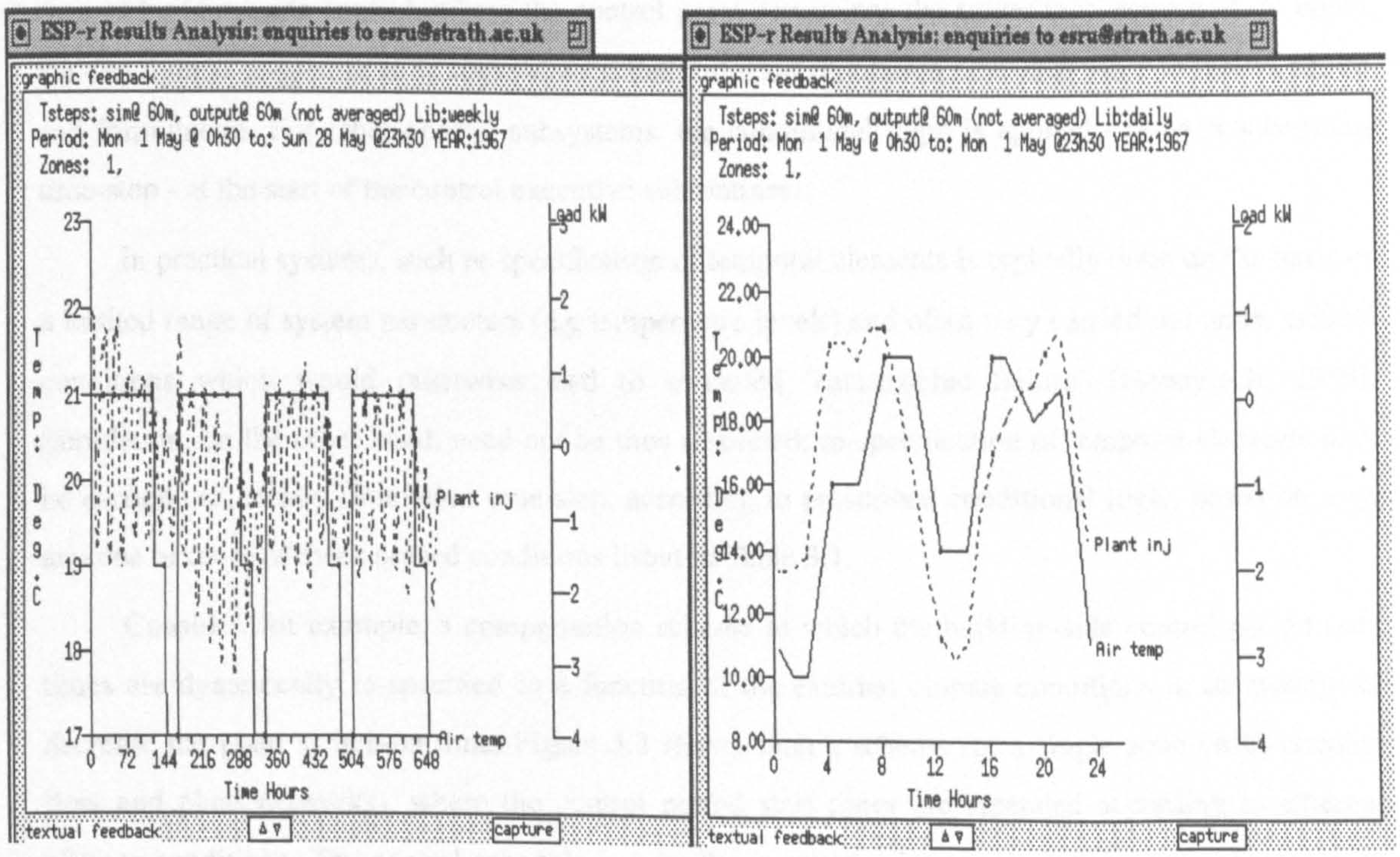
Tsteps: sim@ 60m, output@ 60m (not averaged) Lib:b-seas
Period: Sun 1 Jan @ 0h30 to: Sun 31 Dec @23h30 YEAR:1967
Zones: 1,

ESP-r Results Analysis: enquiries to esru@strath.ac.uk

graphic feedback

Tsteps: sim@ 60m, output@ 60m (not averaged) Lib:b-month
Period: Sun 1 Jan @ 0h30 to: Sun 31 Dec @23h30 YEAR:1967
Zones: 1,

(a) Seasonly **(b)** Monthly



ESP-r Results Analysis: enquiries to esru@strath.ac.uk

graphic feedback

Tsteps: sim@ 60m, output@ 60m (not averaged) Lib:weekly
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Zones: 1,

ESP-r Results Analysis: enquiries to esru@strath.ac.uk

graphic feedback

Tsteps: sim@ 60m, output@ 60m (not averaged) Lib:daily
Period: Mon 1 May @ 0h30 to: Mon 1 May @23h30 YEAR:1967
Zones: 1,

(c) Weekly **(d)** Daily

Figure 5.2 Control time schedules.

Within ESP-r, as described in Section 3.4.1. this information is held in the *system control configuration file* and is made available for control subsystem processing at each simulation time-step.

5.2.2 Dynamically reconfigurable control system definition.

The control system definition procedure described above provides flexibility of control system specification prior to commencement of simulation. This may be extended to include *conditional* time-varying control system definition features such as the dynamic re-specification of:

- sensor/actuator location;
- sensed/actuated variable;
- sensor/actuator quantity;
- controller type;
- controller defining data;
- control day types and day periods.

The time and conditional re-specification of control system parameters can be applied to all control subsystems.

As described in Section 3.4, control system specification affects the subsystem matrix topology and/or topography, and altering control specification at some juncture in the simulation process will dynamically alter the type of numerical solution processes invoked. It is necessary, therefore, for the case of building-side control, where the control point determines the solver type employed, to apply the conditional re-specification logic at each building-side simulation time-step *prior* to matrix set-up and formulation. For other control subsystems, the conditional logic is applied - at each subsystem time-step - at the start of the control executive subroutines.

In practical systems, such re-specification of temporal elements is typically done on the basis of a limited range of system parameters (e.g temperature levels) and often only carried out under critical conditions which would otherwise lead to so-called 'catastrophic failure' [Honeywell, 1989]. Simulation, on the other hand, need not be thus restricted; re-specification of temporal elements may be carried out, at any simulation time-step, according to prescribed conditional logic, based on, say, any one or more of those sensed conditions listed in Table 3.1.

Consider, for example, a compensation scheme in which the building-side control period start times are dynamically re-specified as a function of the external climate conditions in an attempt to decrease the plant switch-on time. Figure 5.3 shows such a scheme for a single zone (with coupled flow and plant networks), where the control period start times are amended according to external climate conditions. The control schedule is initially specified prior to simulation commencement. In the case of conditional re-specification then, if at the original start time for control periods 2 and 3 (06.00 hours and 19.00 hours, respectively), the external dry bulb temperature *AND* ambient relative humidity exceed predefined limits (16 °C and 50% respectively), the control schedule changes to that shown in Figure 5.3(b), where the start time for *control period 2* is retarded to 08.00 hours and that for *control period 3* is brought forward to 1600 hours. Thus, in dynamic re-specification mode, the upper set point (20 °C) is (conditionally) active for a shorter period of time than for the original case. The results for such a strategy are shown on Figure 5.4.

Conditional re-specification of a plant-side control loop output is depicted in Figure 5.5, where the control loop actuator output for a single zone test case is amended according to the rate of change of the sensed condition in order to capture the system dynamics. Here, the conditional logic is that the loop actuator's maximum and minimum values change from 1500 W and 300 W respectively, to 2000 W and 500 W respectively, in the event of the rate of change of the supply air dry bulb temperature exceeding the user-specified value of 0.1 °C in a given plant-side time-step.

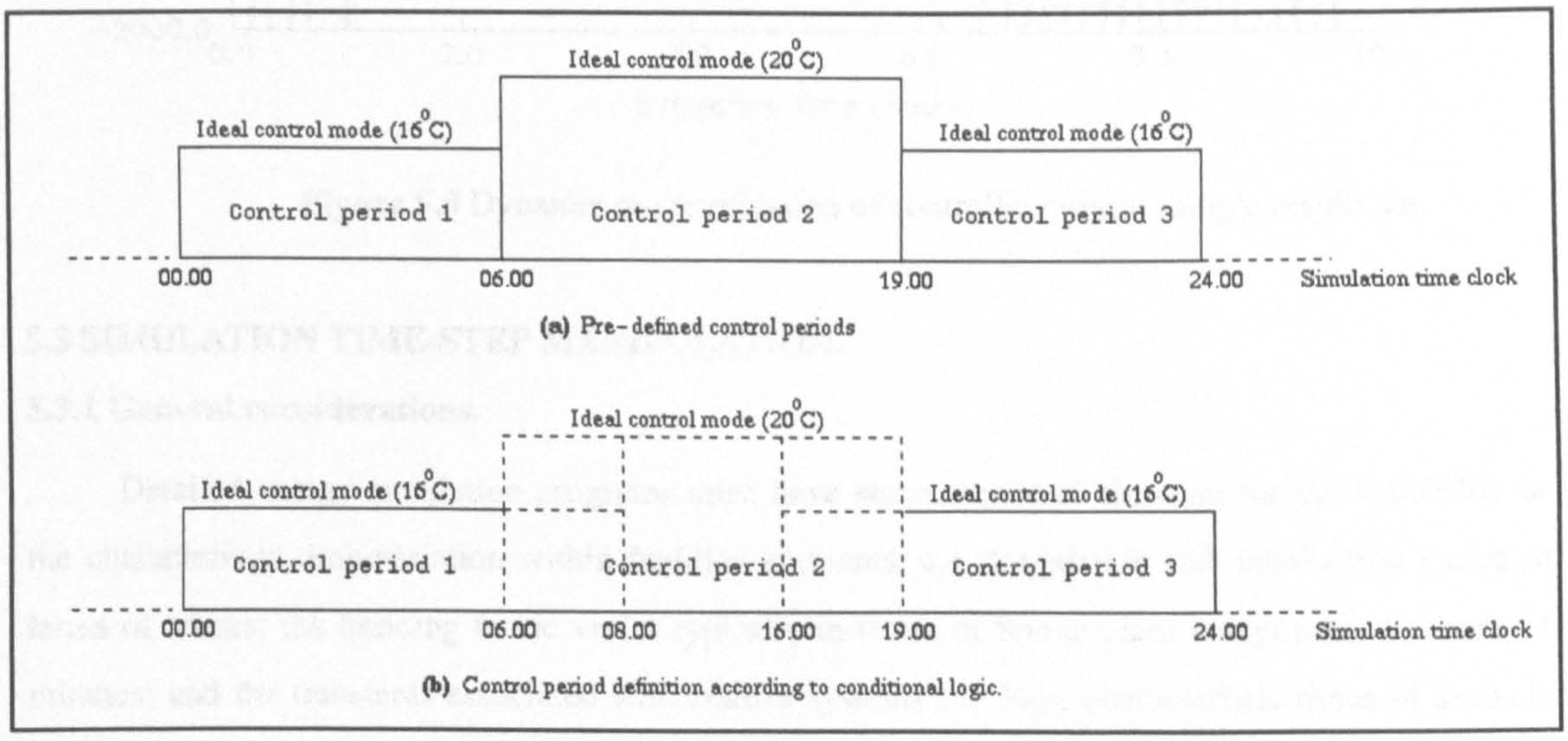
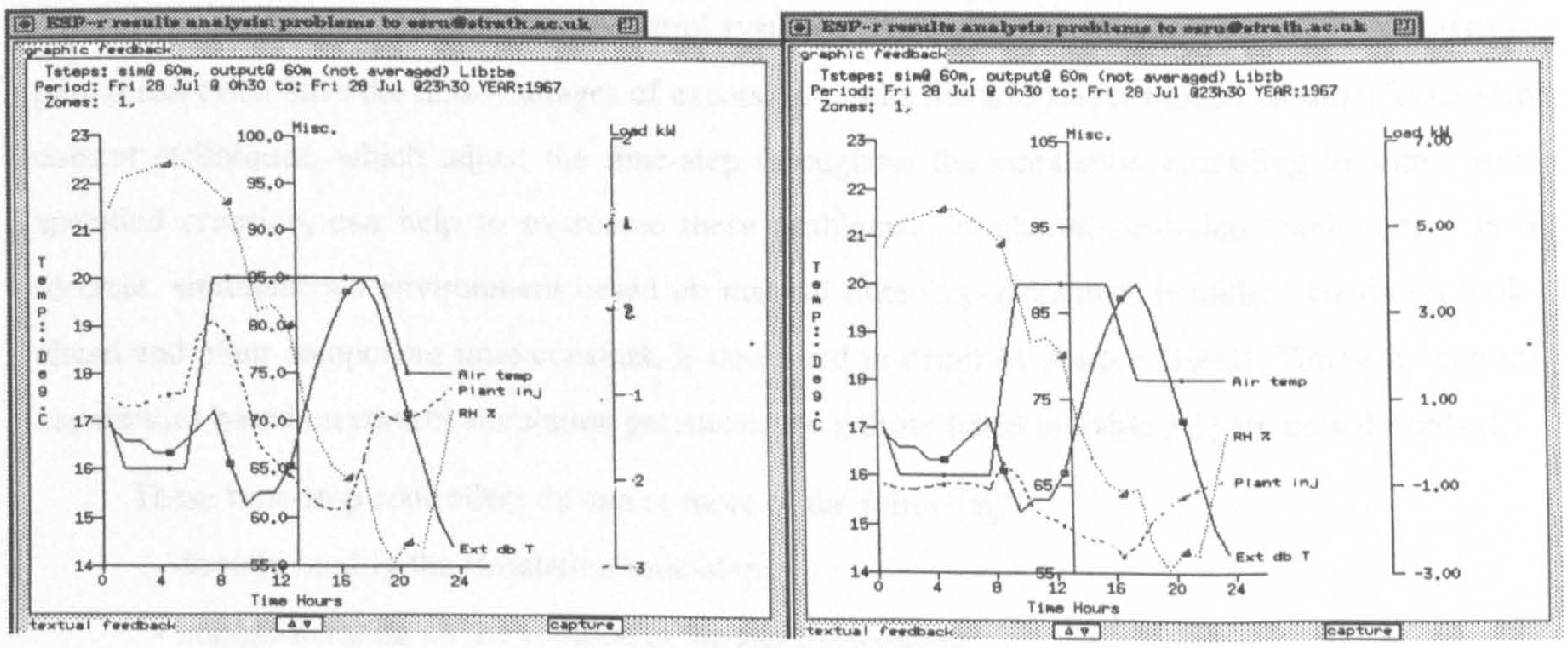


Figure 5.3 Dynamic re-specification of control period: control schedule



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Period: Fri 28 Jul @ 0h30 to: Fri 28 Jul @23h30 YEAR:1967
 Zones:  1,
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 Tsteps: sim@ 60m, output@ 60m (not averaged) Lib:b
Period: Fri 28 Jul @ 0h30 to: Fri 28 Jul @23h30 YEAR:1967
 Zones:  1,
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(a) Control period pre-defined **(b)** Control period dynamically respecified

Figure 5.4 Dynamic re-specification of control period; sample results set

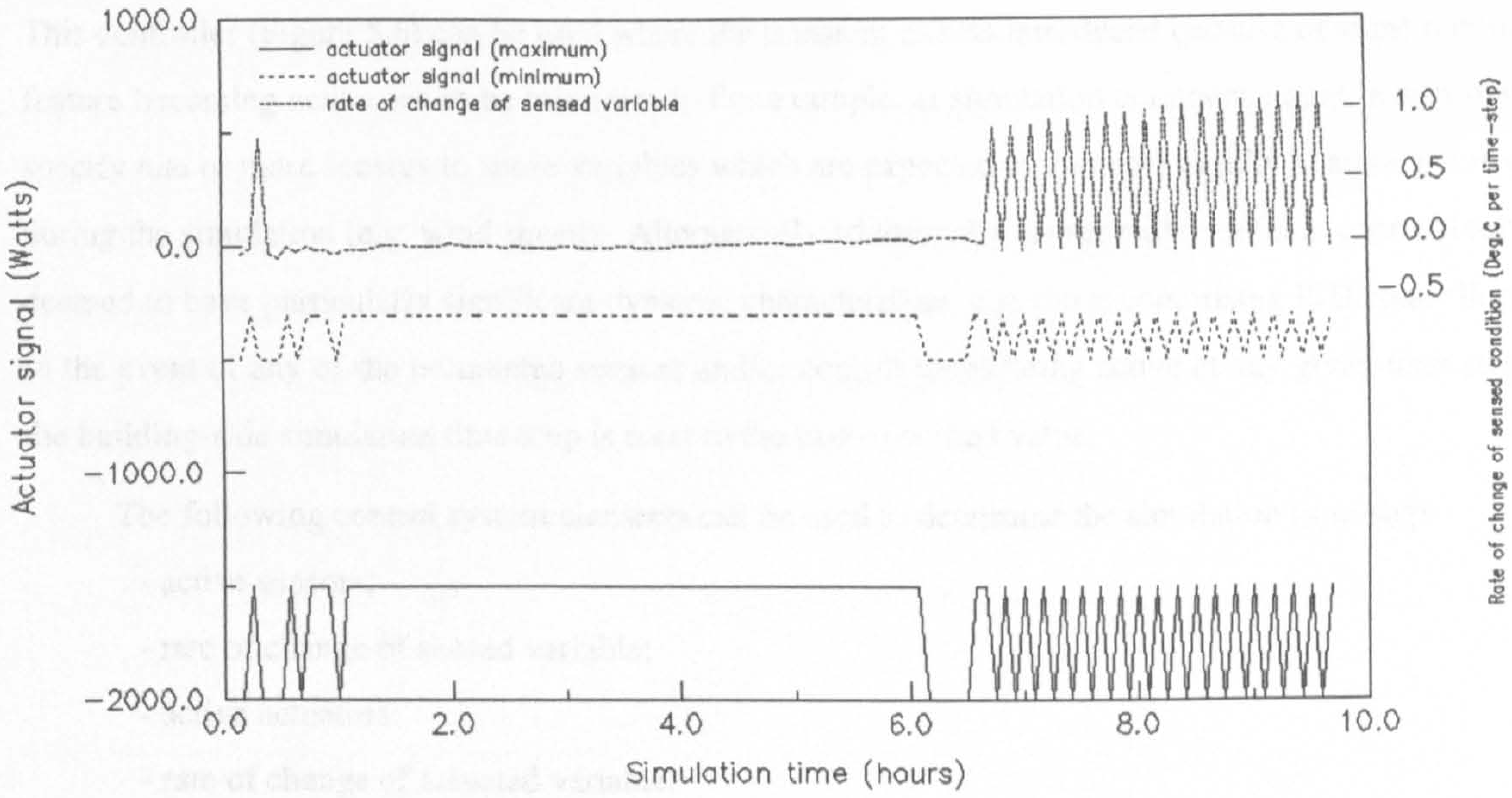


Figure 5.5 Dynamic re-specification of controller output: sample results set

5.3 SIMULATION TIME-STEP MANIPULATION.

5.3.1 General considerations.

Detailed energy simulation programs must have some means of allowing for the variability of the characteristic time-variation within building elements, e.g. foundation slab conduction varies in terms of weeks; the building fabric varies typically in terms of hours; plant components in terms of minutes; and the transients associated with control systems can have characteristic times of seconds [Winklemann and Clarke 1986]. Numerical methods for integrating differential equations representing heat and mass balance within buildings may require iterative or time-step reduction techniques for the successful modelling of control system dynamics, particularly those of a non-linear nature as commonly found in building control systems. Time-step reduction for the whole simulation period can often have the disadvantages of excessive results file size and computation time. Time-step control techniques, which adjust the time-step throughout the simulation according to some user-specified criterion, can help to overcome these problems. Simulation time-step manipulation in a discrete, simultaneous environment based on manual time-step reduction, boundary condition look-ahead and plant component time-constant, is described in detail by Aasem [1993]. Time-step control capabilities based on control simulation parameters (e.g those listed in Table 3.1) are now described.

These time-step controllers do one or more of the following:

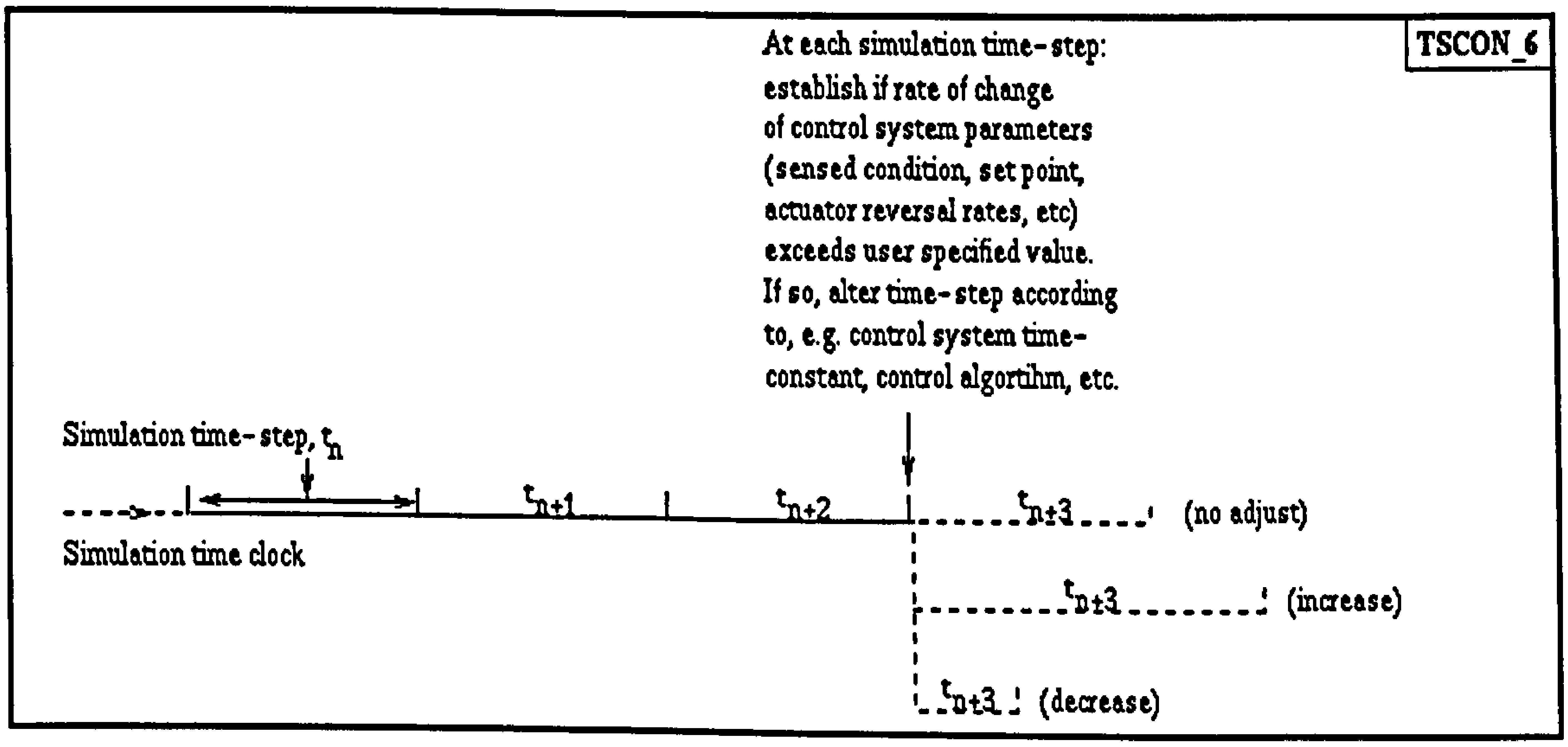
- directly modify the simulation time-step;
- impose iteration on the solution at the same time-step;
- reposition the simulation time-clock to any simulation time-step.
- pause the simulation time-clock to allow control system interrogation and re-design.

5.3.2 TSCON_6: Automatic reset time-step controller.[†]

This controller (Figure 5.6) can be used where the transient effects introduced because of some control feature becoming active are to be minimised. For example, at simulation commencement, a user may specify one or more sensors to sense variables which are expected to fluctuate rapidly at some point(s) during the simulation (e.g. wind speed). Alternatively/additionally, a user may nominate control loops deemed to have particularly significant dynamic characteristics, e.g. those comprising PID controllers. In the event of any of the nominated sensors and/or control loops being active at any given time-step, the building-side simulation time-step is reset to the user-specified value.

The following control system elements can be used to determine the simulation time-step:

- active sensors;
- rate of change of sensed variable;
- active actuators;
- rate of change of actuated variable;
- active control laws;
- active control loops;
- deviation from set point.



At each simulation time-step: establish if rate of change of control system parameters (sensed condition, set point, actuator reversal rates, etc) exceeds user specified value. If so, alter time-step according to, e.g. control system time-constant, control algortihm, etc.

Figure 5.6 TSCON_6: Automatic time-step reset controller.

[†] Time-step controllers TSCON_1-5 were installed prior to project commencement.

5.3.3 TSCON_7: Control system based iterative time-step controller.

The rate of change of one or more control system variables (e.g. those listed above for the *TSCON_6*) can be evaluated and, if greater than the user-specified threshold value, the time-step is halved (Figure 5.7). 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 is subsequently used in the numerical solution. More than one system variable can be specified. In this case, time-step reduction will occur if the above condition is not satisfied by any control variable.

This type of controller is suitable for situations where the rate of change of a control variable is relatively large, such as in the case of controller set point changes in some cascade control applications. A rigorous investigation of control system stability over a range of simulation time-steps is thus enabled.

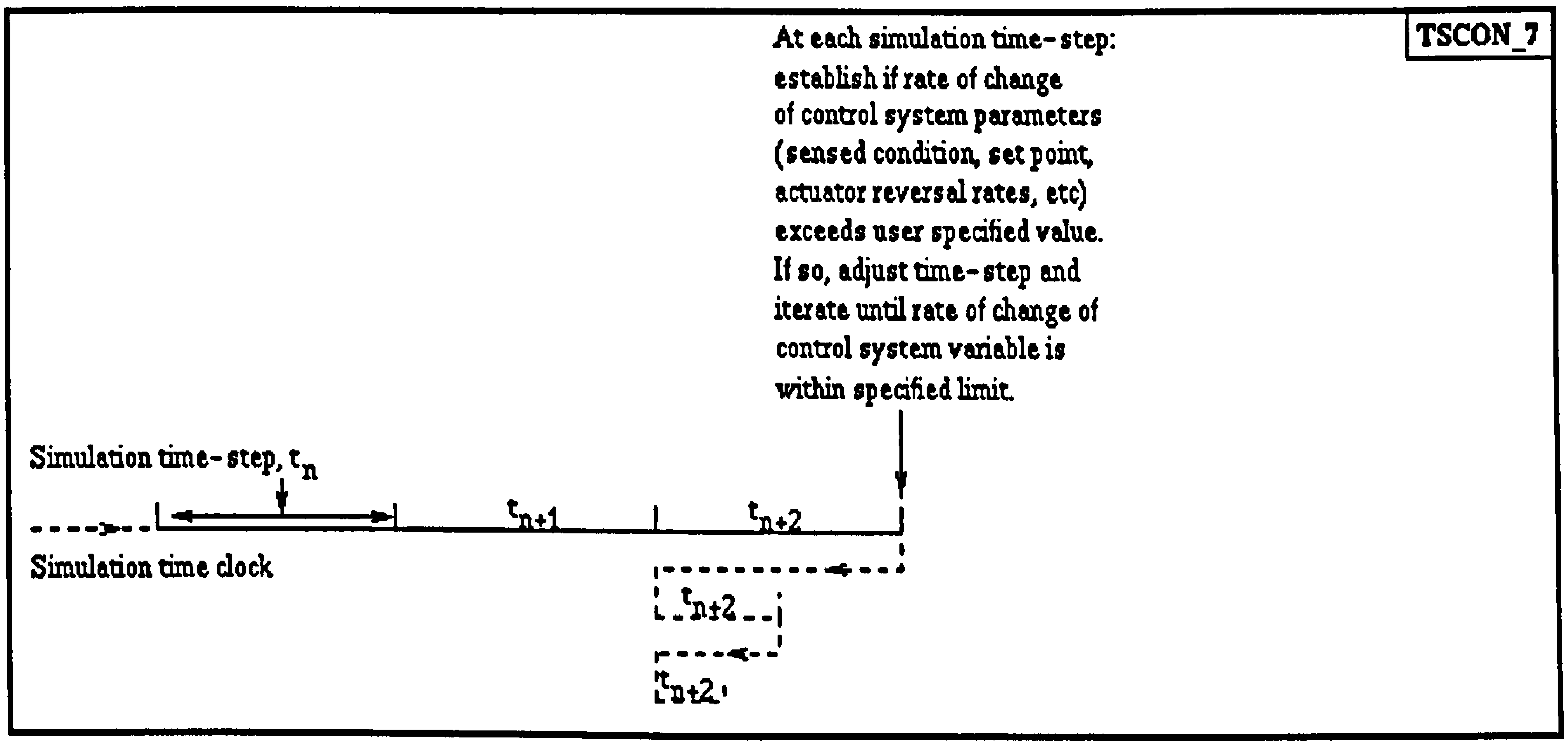


Figure 5.7 TSCON_7: Iterative time-step reset controller.

5.3.4 TSCON_8: Simulation time-clock reset to time-step controller.

This time-step controller resets the simulation time-clock to *any* previous simulation time-step on the basis of any simulated control system parameter. After reset, the simulation time-step can remain the same or may be adjusted. Such a time-step controller is necessary for the BEMS system-level modelling techniques described in Section 6.4.2. It is also required for the ESAC (Energy Simulation Assisted Control) predictive-iterative control strategies such as determination of optimum start times, load shedding schedules, etc, described in Section 6.6. Two methods of achieving simulation time-clock manipulation in discrete time programs are now described.

The first method (Figure 5.8(a)) involves saving all relevant simulation parameters at the time-step to which the simulation time clock is to be reset. Aasem [1993] details the procedure of saving all time-dependent state variables in ESP-r to allow the system matrix equation coefficient set-up for the time-step in consideration to be identical to that at a previous pass.

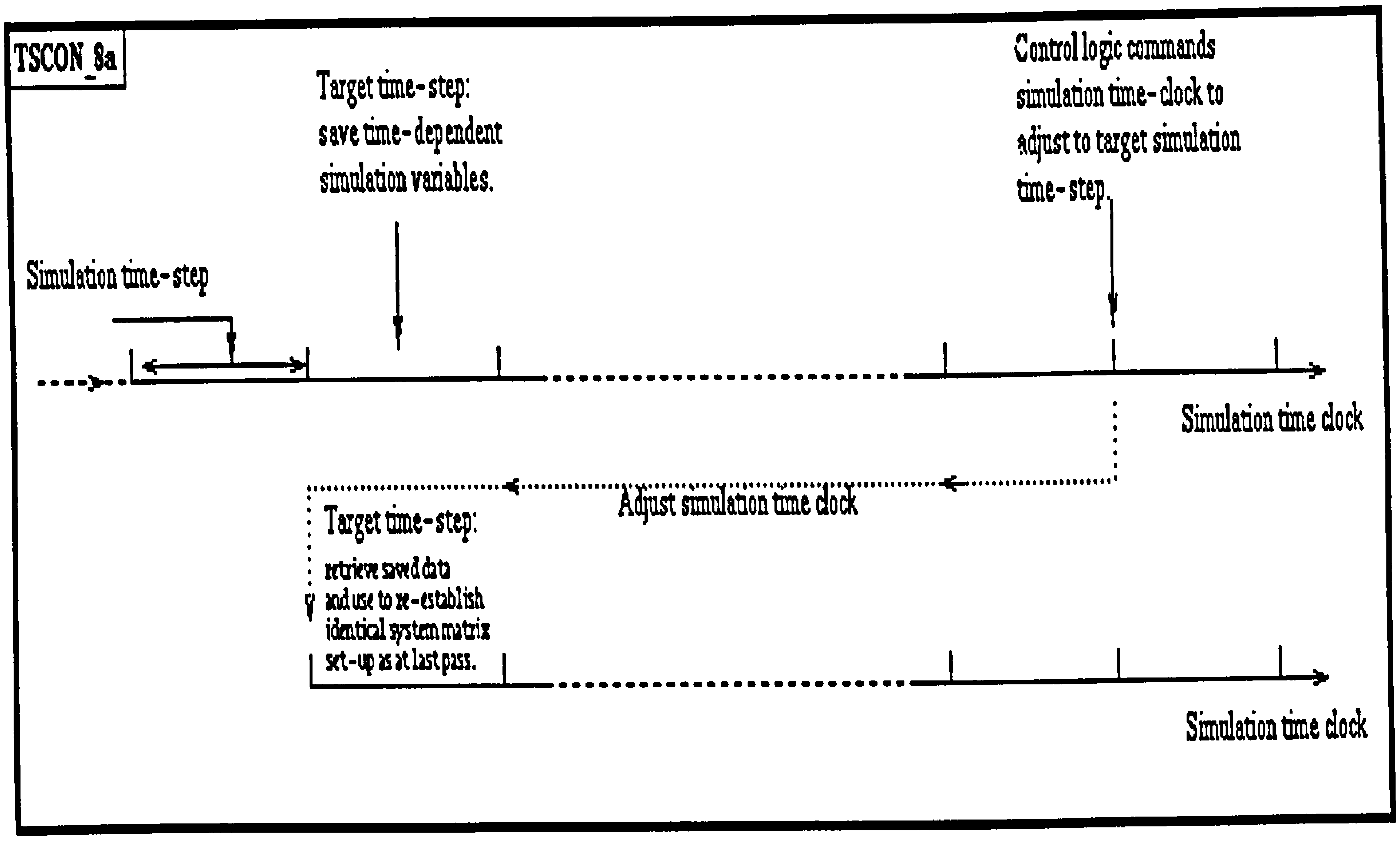


Figure 5.8(a) TSCON_8: Simulation time-clock reset controller (data save).

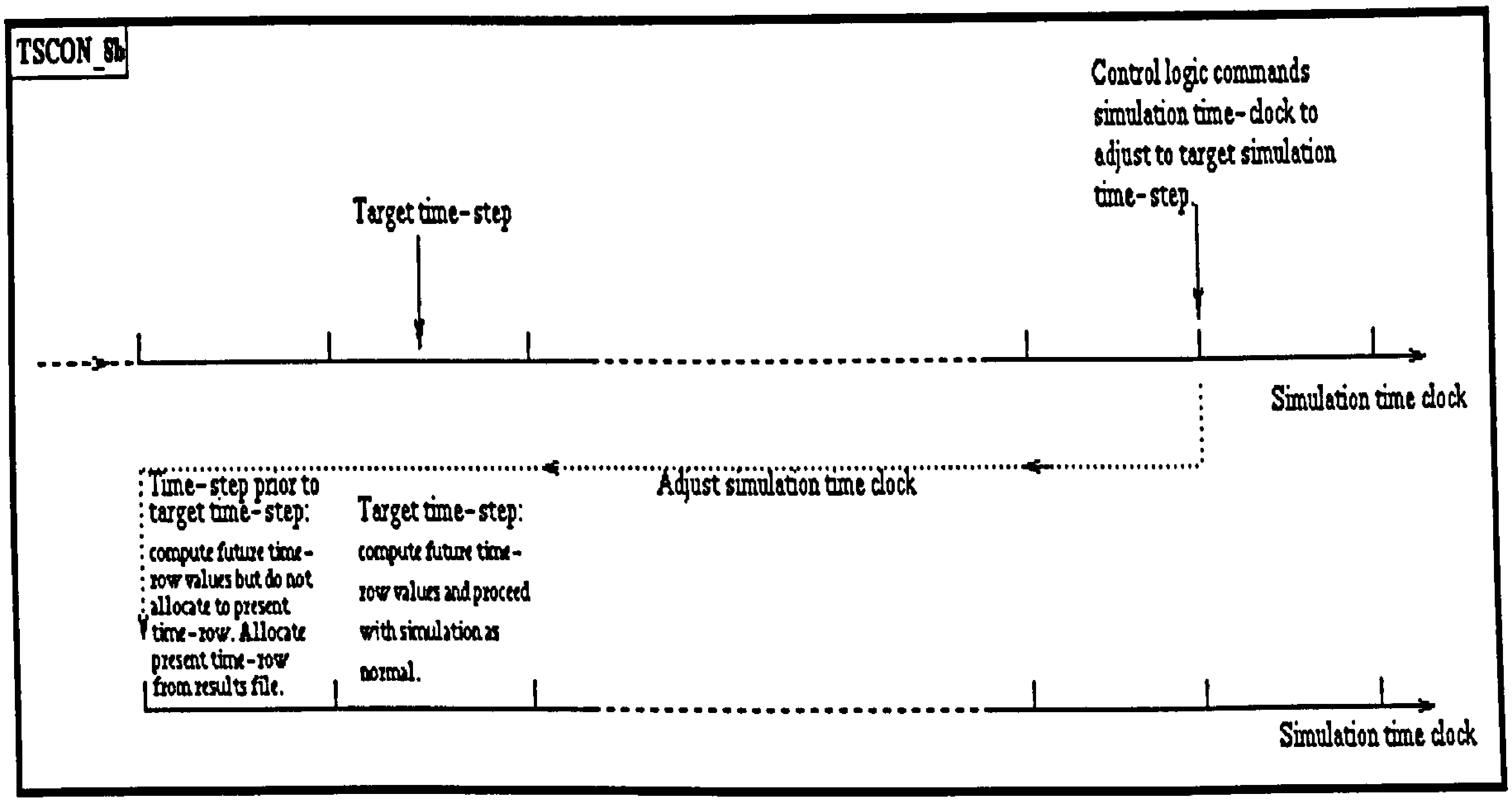


Figure 5.8(b) TSCON_8: Simulation time-clock reset controller (no data save).

The time-step controller is invoked at a command from one or more logic (controller) elements. The simulation time-clock is then adjusted to the desired time-step at which data was saved, the data retrieved, and the simulation recommenced. The data may be saved in memory or, alternatively, saved to an external file.

The second method of simulation time-clock control (Figure 5.8(b)) involves no saving of simulation time-dependent data. The technique involves the following steps:

(1) The time-step controller is invoked at a command from one or more logic elements (controller).

(2) The simulation time-clock is reset to the time-step immediately *preceding* the target time-step, as opposed to the target time-step itself.

(3) In processing this time-step, the computed future time-row values will be erroneous since the present time-row values do not apply to this time-step, but rather to the time-step prior to simulation time-step adjustment.

(4) The time-step is processed as normal with the exception that, at the end of the time-step, the (erroneous) future time-row values are *not* set to present-row time-step values for the next time-step. Instead, present-row time-step values for the next time-step are read and allocated from the results file (calculated at this time-step at the previous pass).

(5) The target time-step is then processed and the results allocated as normal, with the future time-row values being computed on the basis of correct present time-row values.

The time-step preceding the target time-step can therefore be thought of as a 'dummy' time-step to allow the allocation of the correct present time-row values.

With this approach, software requirements are not as demanding as with the save/retrieve strategy discussed earlier, involving only an extra (dummy) simulation time-step. Clearly, though, the approach adopted will be program-dependent.

5.3.5 TSCON_9: Simulation pause time-step controller.

Simulation-assisted control system design efficiency may be improved if some means can be provided of speeding up the 're-definition and re-run' process. Haves and Dexter [1989] describe a method whereby the simulated control system may be retuned *without* restarting the simulation. It is possible to incorporate automated re-run into the ESP-r simulation process by means of *UNIX Shell Script programs* [Kernighan and Pike 1984]. However, it is not always necessary to re-simulate the *entire* period; often, the preferred option is to *pause* the simulation time clock, adjust the desired control system parameters, and then proceed to simulate from this time-step.

The *TSCON_9* time-step controller acts to temporarily pause the simulation time clock to allow alteration of system control function parameters such as throttling range, set point, controller gains, etc, (Figure 5.9). The simulation time clock is paused by user command. Once the simulation clock is paused, a parameterised UNIX Shell Script program - contained within an external file - is invoked which then processes parameters in accordance with some user-defined control algorithm. At each pause, the user may alter parameters and/or the algorithm itself. Updated parameters are subsequently passed back to the simulation program and the simulation recommences from the time-step at which it was paused.

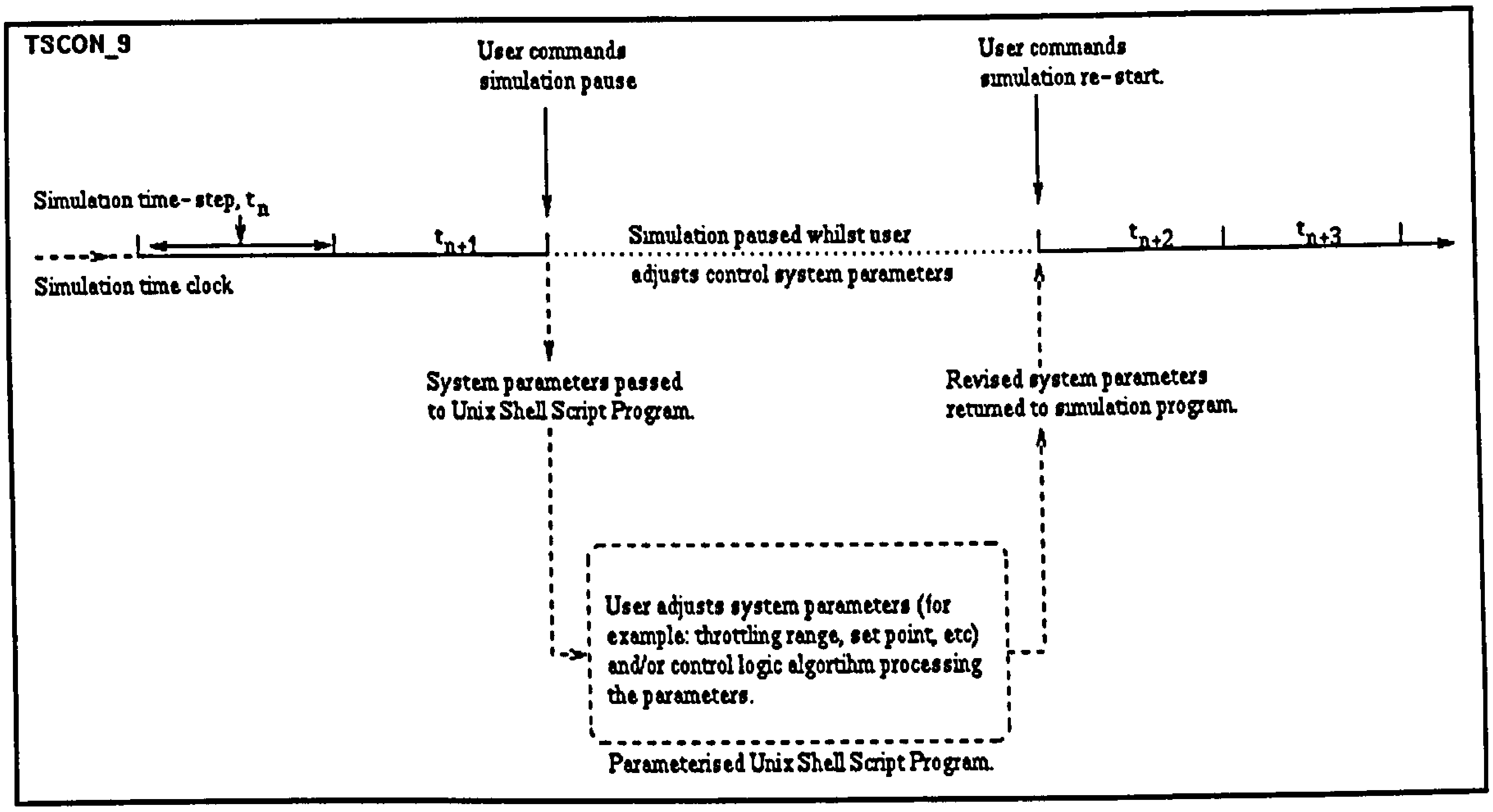


Figure 5.9 TSCON_9: Simulation pause time-step controller.

The simulation time-clock may be paused at any time-step during the simulation and as often as desired, according to the monitored simulation results. In this way, interactive graphics tools are combined with computer-assisted methods to facilitate comparative assessment of control performance and commissioning of control system networks. It is also possible to maintain a log of the different control strategies invoked, by appending the system control configuration file at each pause-adjust, thus allowing the simulation to be entirely reproducible.

The simulation time clock and time-step techniques described above will be utilised in Chapter 6 to facilitate *energy simulation assisted control* strategies. For the present, however, consider a single zone subjected to the building-side control schedules depicted in Figures 5.10-5.12. *TSCON_6* is active in the first case, and *TSCON_7* is active in the second. Figure 5.13 shows the resulting temperature and plant injection/extraction profiles for these time-step control regimes.

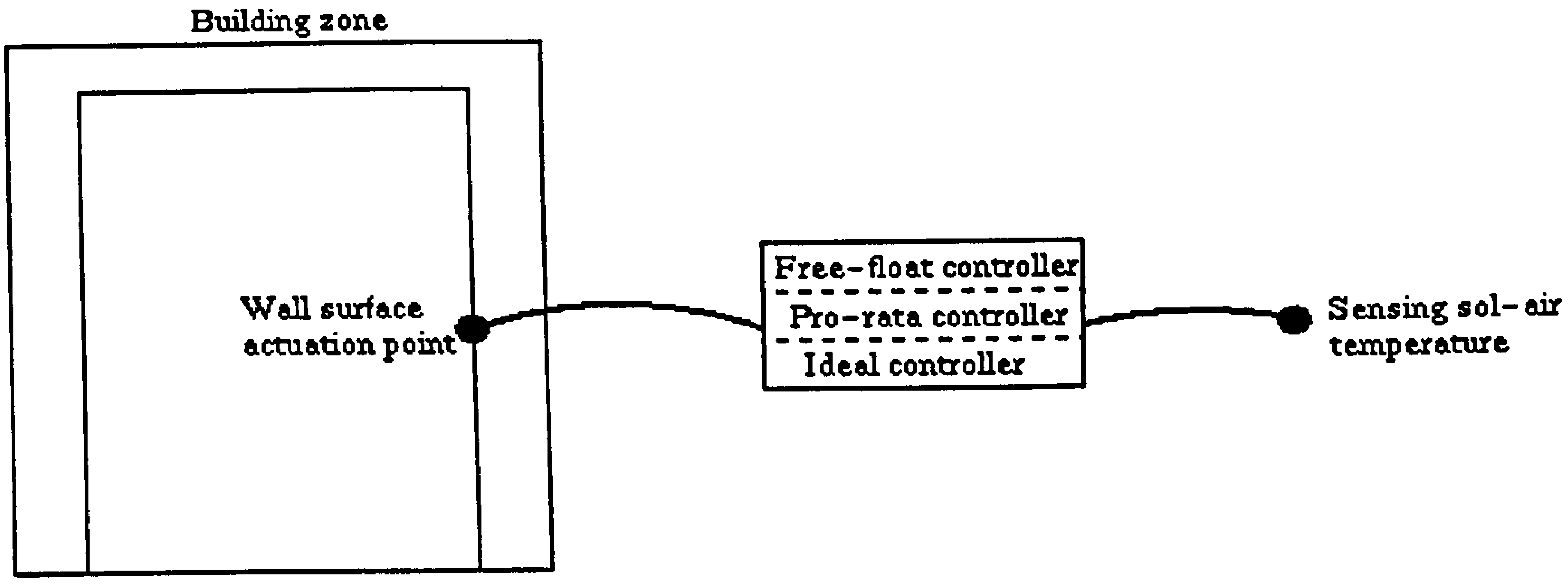


Figure 5.10 Control loop for time-step control test case.

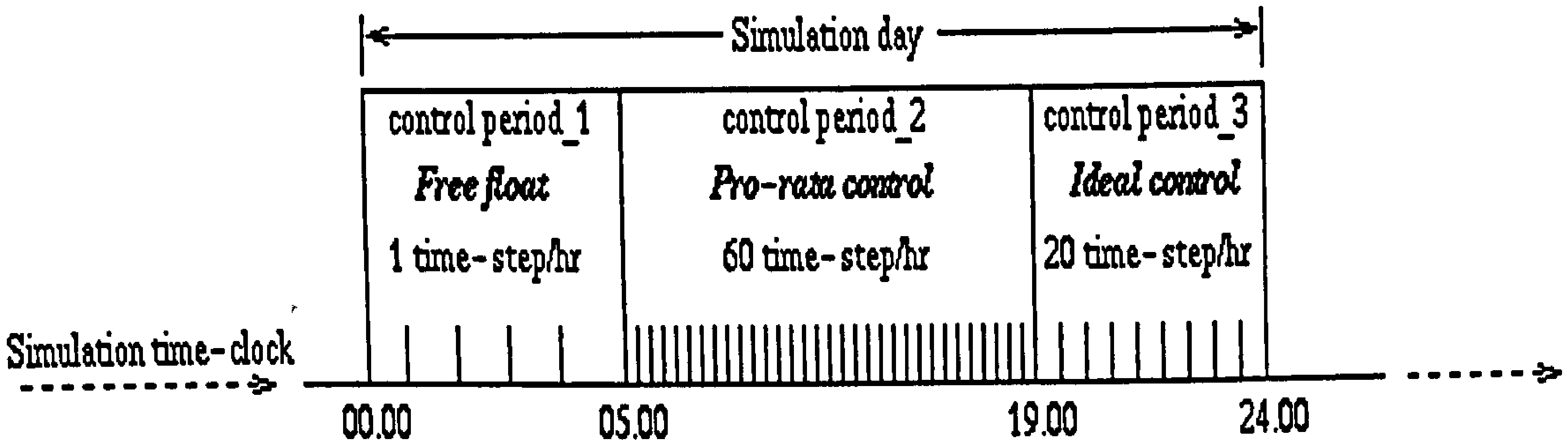


Figure 5.11 Time-step control schedule according to active control law (TSCON_6).

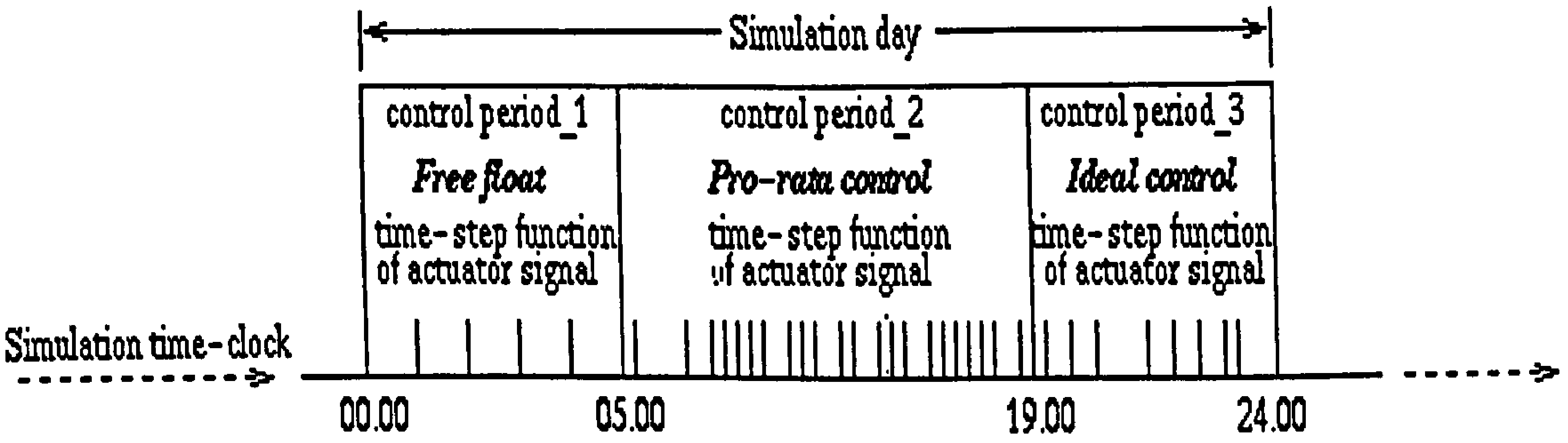
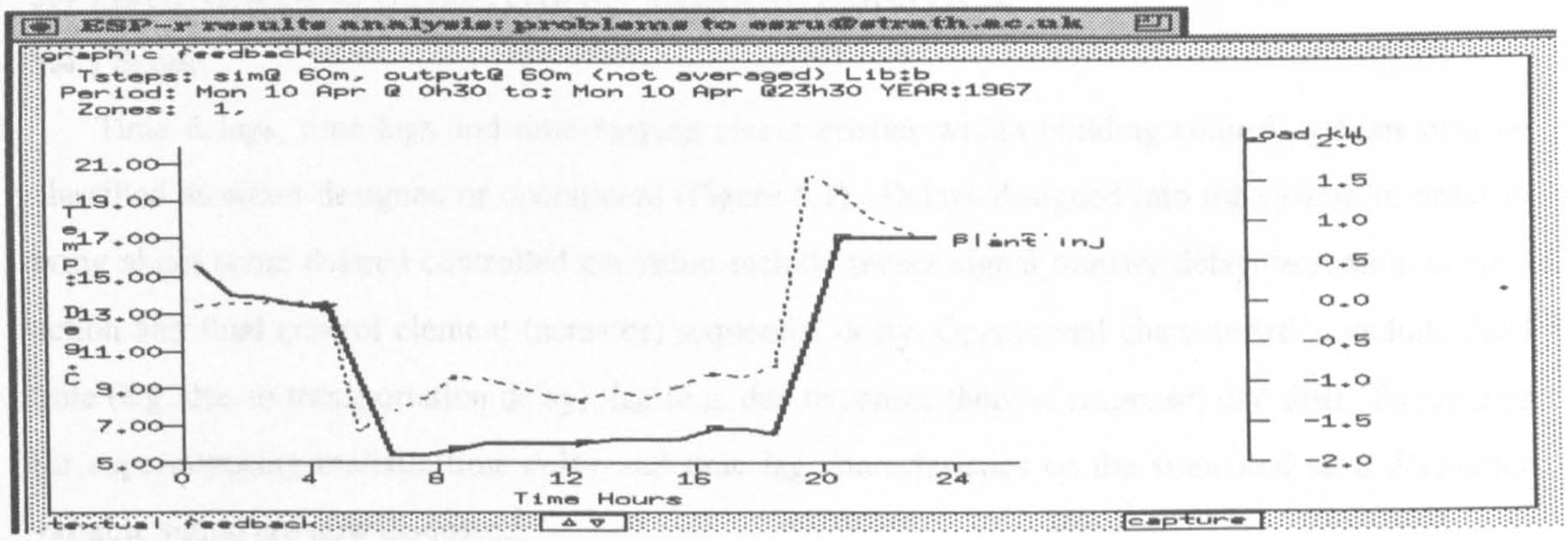
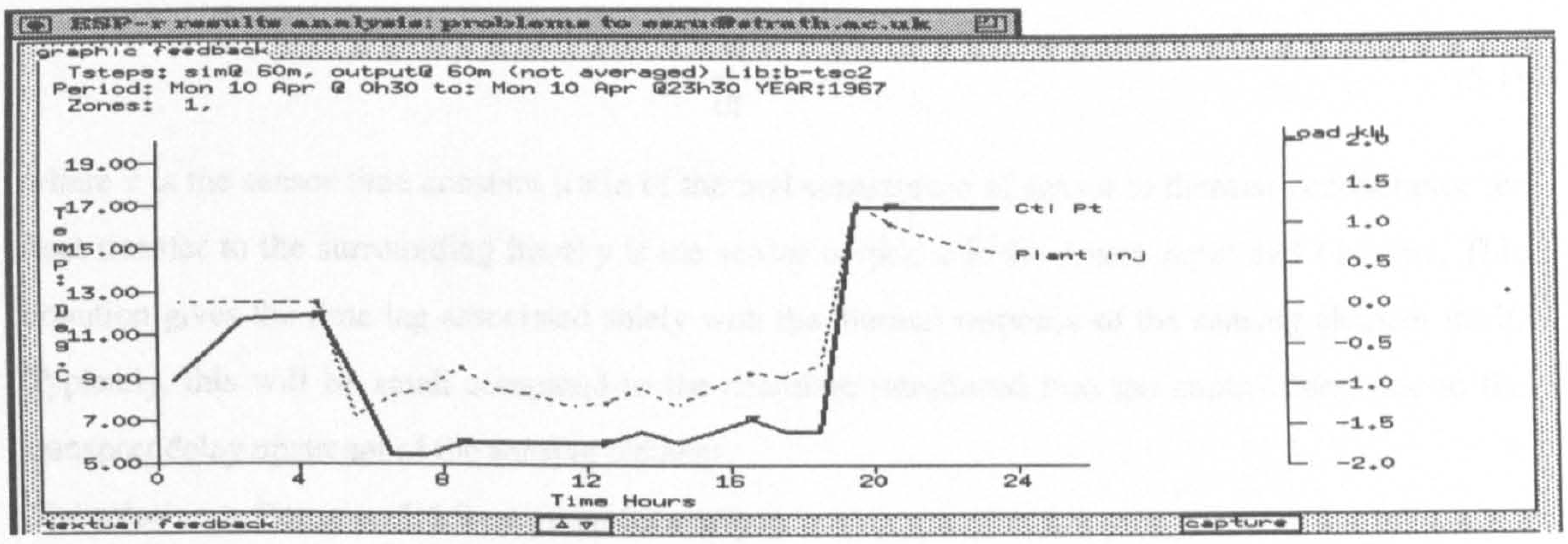


Figure 5.12 Time-step control schedule according to active actuator signal (TSCON_7).



```
 Tsteps: sim@ 60m, output@ 60m (not averaged) Lib:b
Period: Mon 10 Apr @ 0h30 to: Mon 10 Apr @23h30 YEAR:1967
 Zones:  1,
```

(a) No time-step control



```
 Tsteps: sim@ 60m, output@ 60m (not averaged) Lib:b-tsc2
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 Zones:  1,
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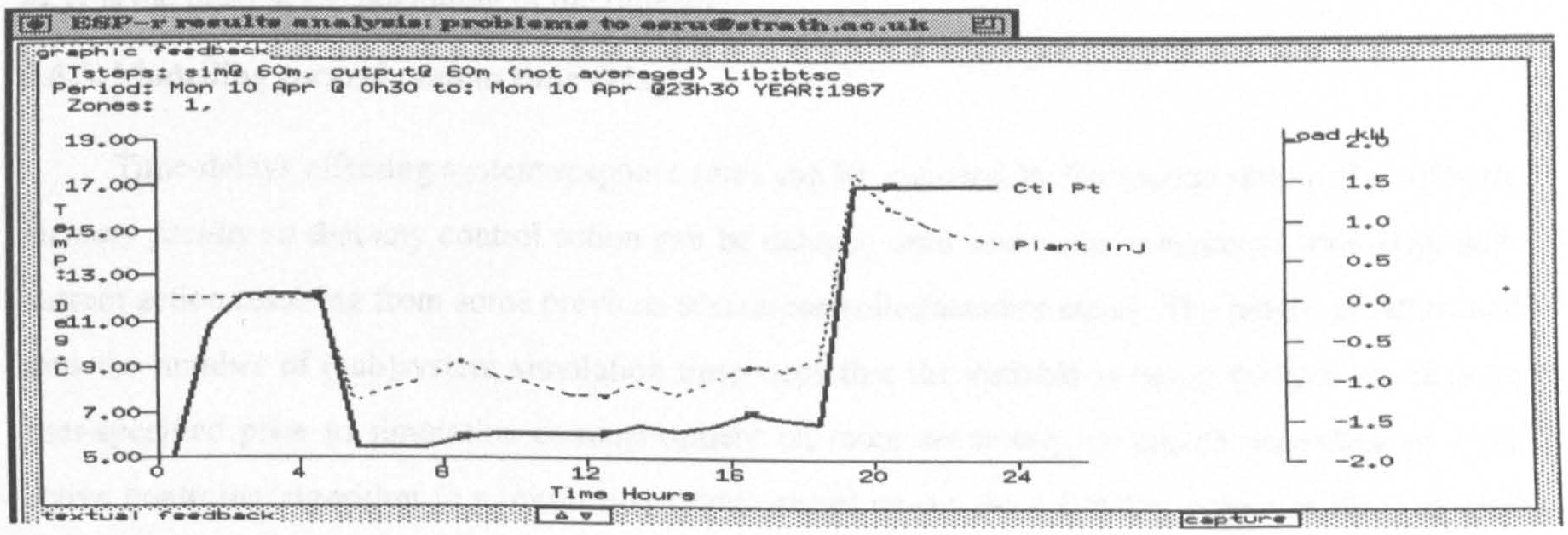
(b) Time-step control on active control law



```
 Tsteps: sim@ 60m, output@ 60m (not averaged) Lib:btsc
Period: Mon 10 Apr @ 0h30 to: Mon 10 Apr @23h30 YEAR:1967
 Zones:  1,
```

(c) Time-step control on actuator signal

Figure 5.13 Simulation time-step control according to control system parameters.

5.4 TIME-VARYING OPERATIONAL CHARACTERISTICS.

5.4.1 Scope.

Time delays, time lags and time-varying characteristics within building control systems may be classified as either designed or operational (Figure 5.1). Delays designed into the system in order to bring about some desired controlled condition include sensor signal transfer delay, hesitation control action and final control element (actuator) sequential delay. Operational characteristics include dead time (e.g. due to transportation delay), lag (e.g. due to sensor thermal response) and drift. Techniques for superimposing realistic time delay and time lag characteristics on the simulated sensed/actuator variable signal are now discussed.

5.4.2. Modelling sensor time lags.

First order lags in temperature sensors are typically modelled by assuming the sensor dynamic response may be described by the following differential equation:

$$\tau \frac{dy}{dt} + y = u \tag{5.1}$$

where τ is the sensor time constant (ratio of thermal capacitance of sensor to thermal conductance for heat transfer to the surrounding fluid) y is the sensor output, u is the sensor input and t is time. This equation gives the time lag associated solely with the thermal response of the sensing element itself. Typically, this will be small compared to the deadtime introduced into the control loop due to the transport delay upstream of the sensing element.

The solution to Equation 5.1 for a given time-step is:

$$y_t = u_{t-\Delta t} - (u_{t-\Delta t} - y_{t-\Delta t})e^{-\frac{\Delta t}{\tau}} \tag{5.2}$$

where Δ t is the simulation time-step, $y_{t-\Delta t}$ is the sensor output at the beginning of the time-step and $u_{t-\Delta t}$ is the input at the beginning of the time-step.

5.4.3. Modelling control system time delays.

Time-delays affecting system response rates can be included by the incorporation of a *software memory facility* so that any control action can be delayed until some later simulation time-step, with current action resulting from some previous sensor/controller/actuator status. The length of delay, and thus the number of (sub)system simulation time-steps that the variable is being delayed by, may be user-specified prior to simulation commencement or, more accurately, computed according to some active controller algorithm (e.g. *hesitation relay control* where the controller output is delayed until some system state is reached).

Such a modelling scheme enables the following modelling features:

- each control subsystem (i.e. building, flow, plant, etc.) has an independent time delay processing capability, due to ESP-r's modular structure which allows different frequencies of matrix inversion;

- within each subsystem, sensor, controller and actuator elements can have different time delays;
- time delays can vary from one control period to another; indeed time delay can be specified as varying according to some algorithm which then dynamically resets the delay as a function of some simulation parameter, boundary condition or function generator.

In order to exemplify several of the time delay modelling facilities based on the numerical techniques described above, consider a building zone with coupled flow and plant networks. Figures 5.14-5.17 show, for the case of single point sensing and actuation, how plant sensor inputs and actuator outputs vary as a function of user-specified time delays - representing designed and operational system deadtimes - imposed on the plant system.

The effects of fixed delay are shown in Figures 5.14-5.15, where the single point sensor (sensing zone air dry bulb temperature) and single point actuator (actuating cooling flux) are specified as having *fixed* time delays for different control periods during the simulation. Figures 5.16-5.17 show the effect of using *function-generated* time delay values for both sensor (step function) and actuator (sine wave function) signals throughout the entire control day period.

Several novel schemes for modelling the temporal elements of building control systems have been presented. Chapter 7 proceeds to describe techniques for modelling the corresponding logical elements.

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Haves, P., Dexter, L.A., 'Simulation of Local Loop Controls', *Proc. Building '89*, IBPSA Vancouver, June, 1989

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Winklemann, F., Clarke, J.A., 1986. 'Implementation of Time-step Control in ESP-r', Technical Note, Lawrence Berkley Laboratory, USA.

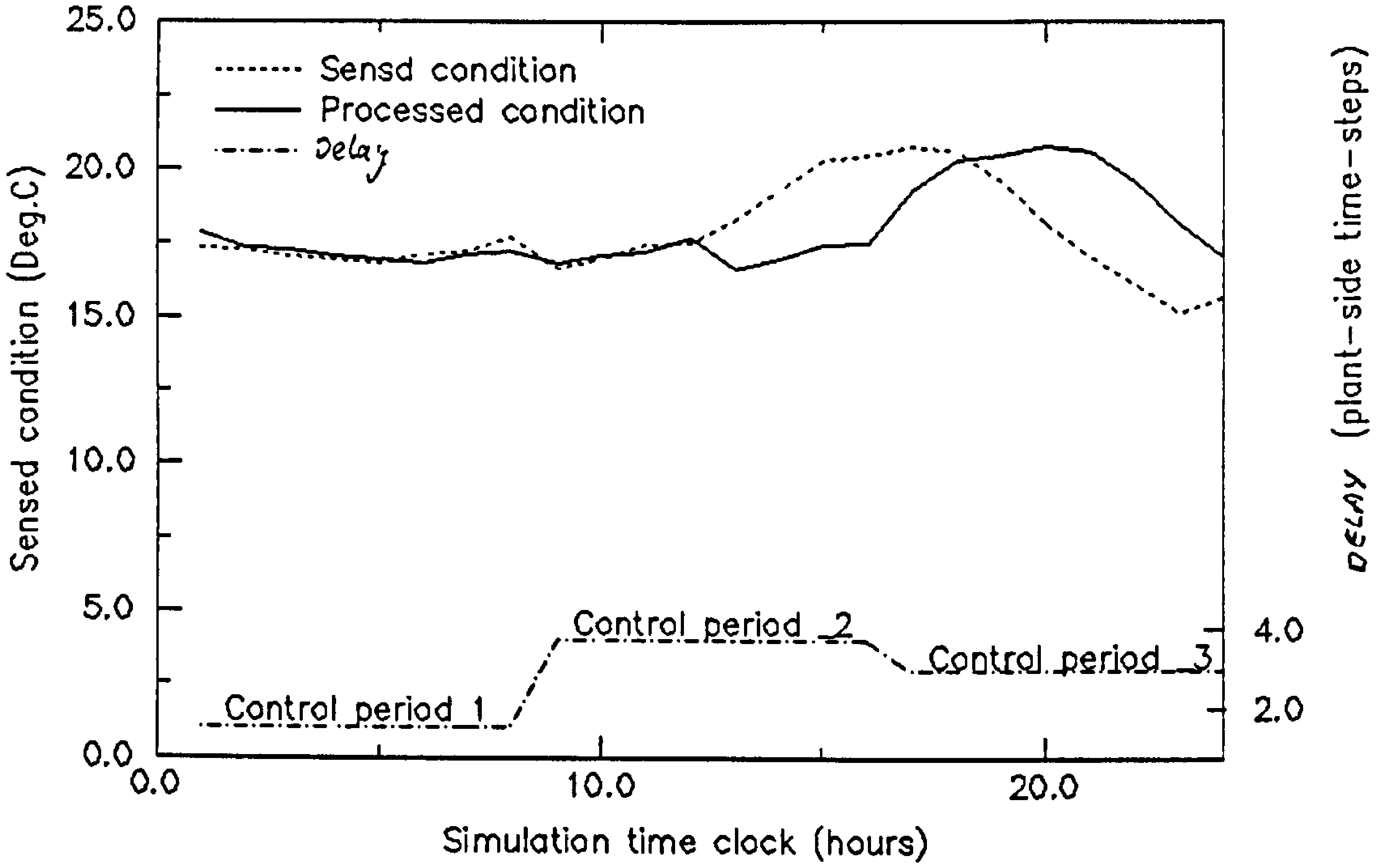


Figure 5.14 Fixed sensor time delay

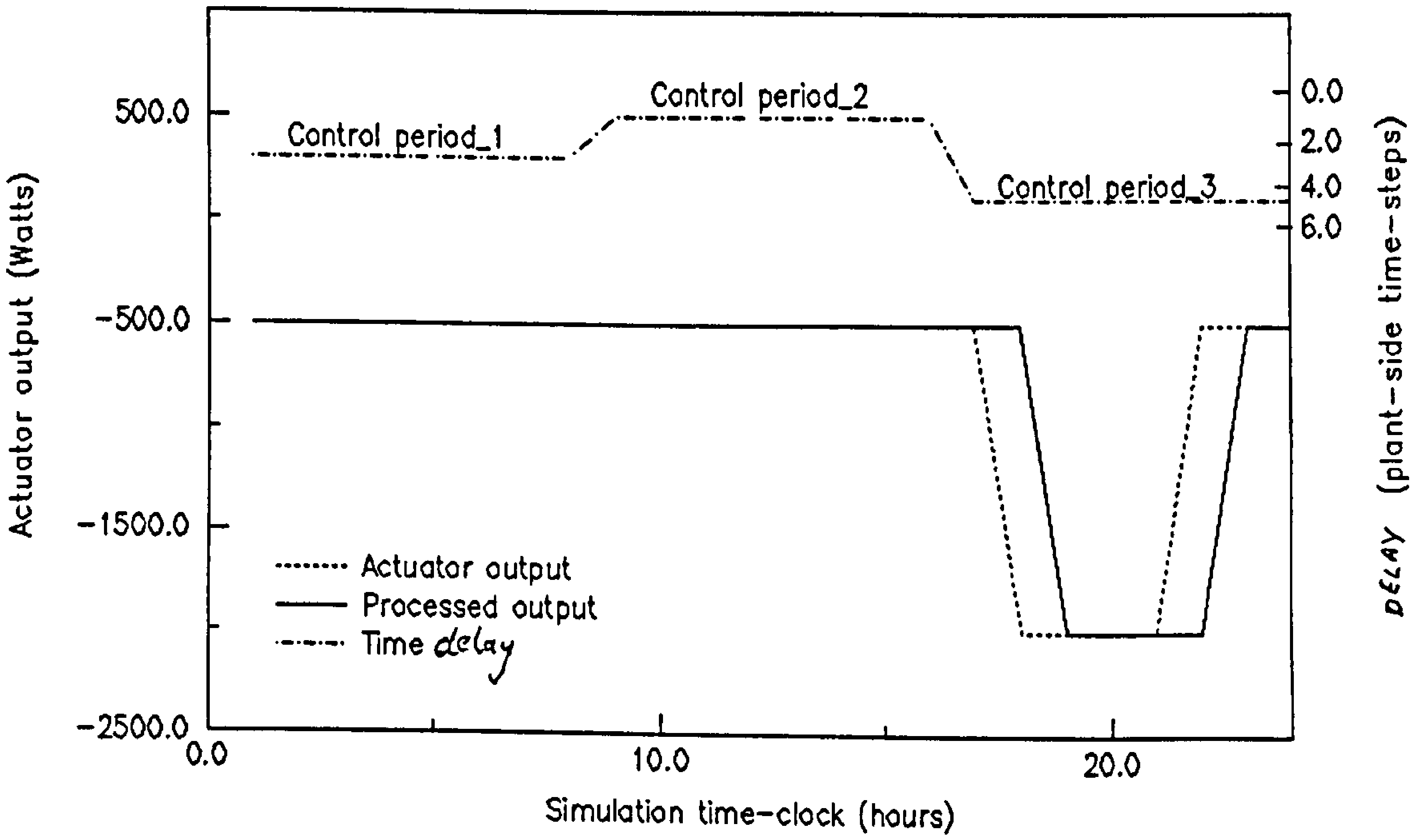


Figure 5.15 Fixed actuator time delay

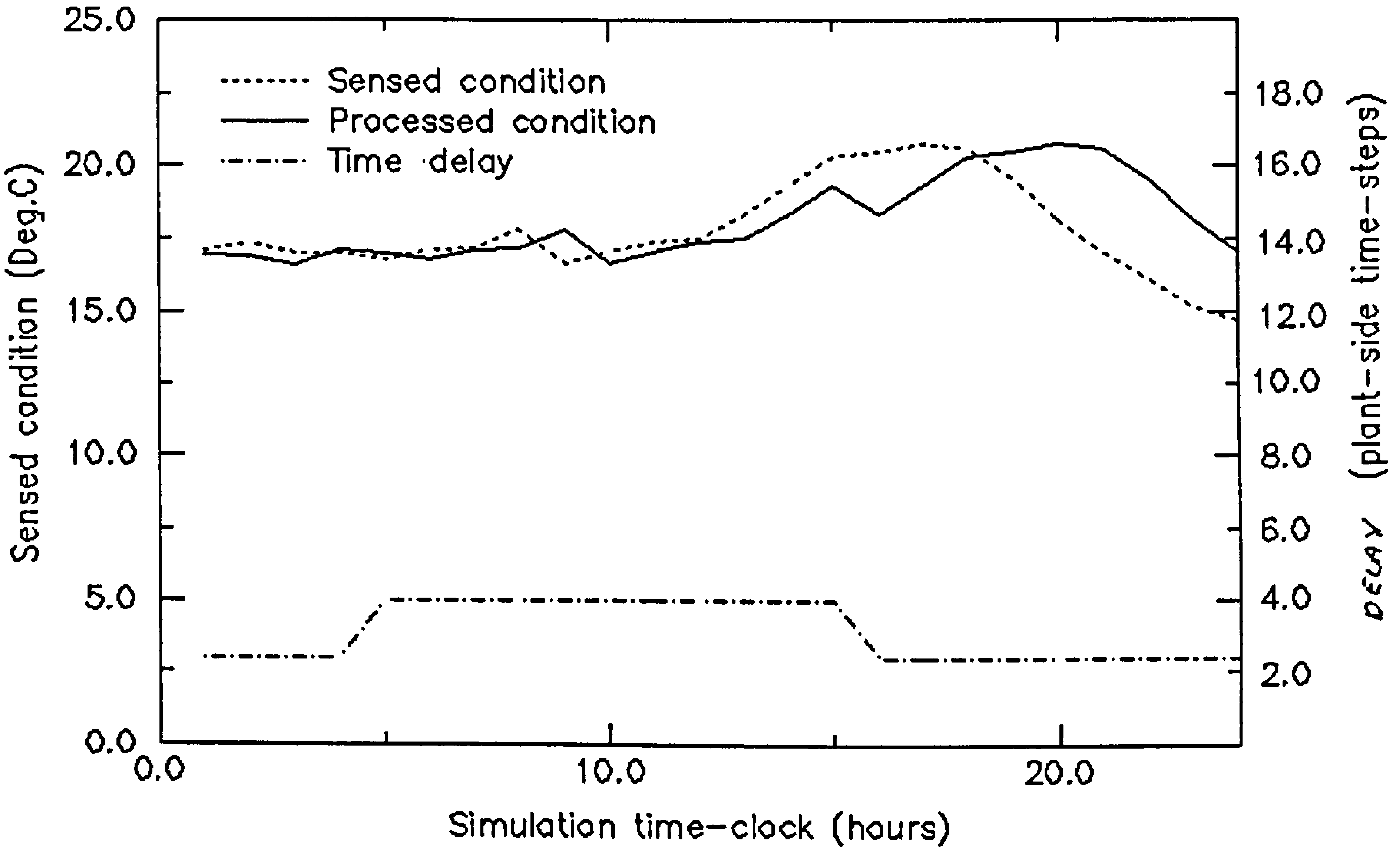


Figure 5.16 Variable sensor time delay

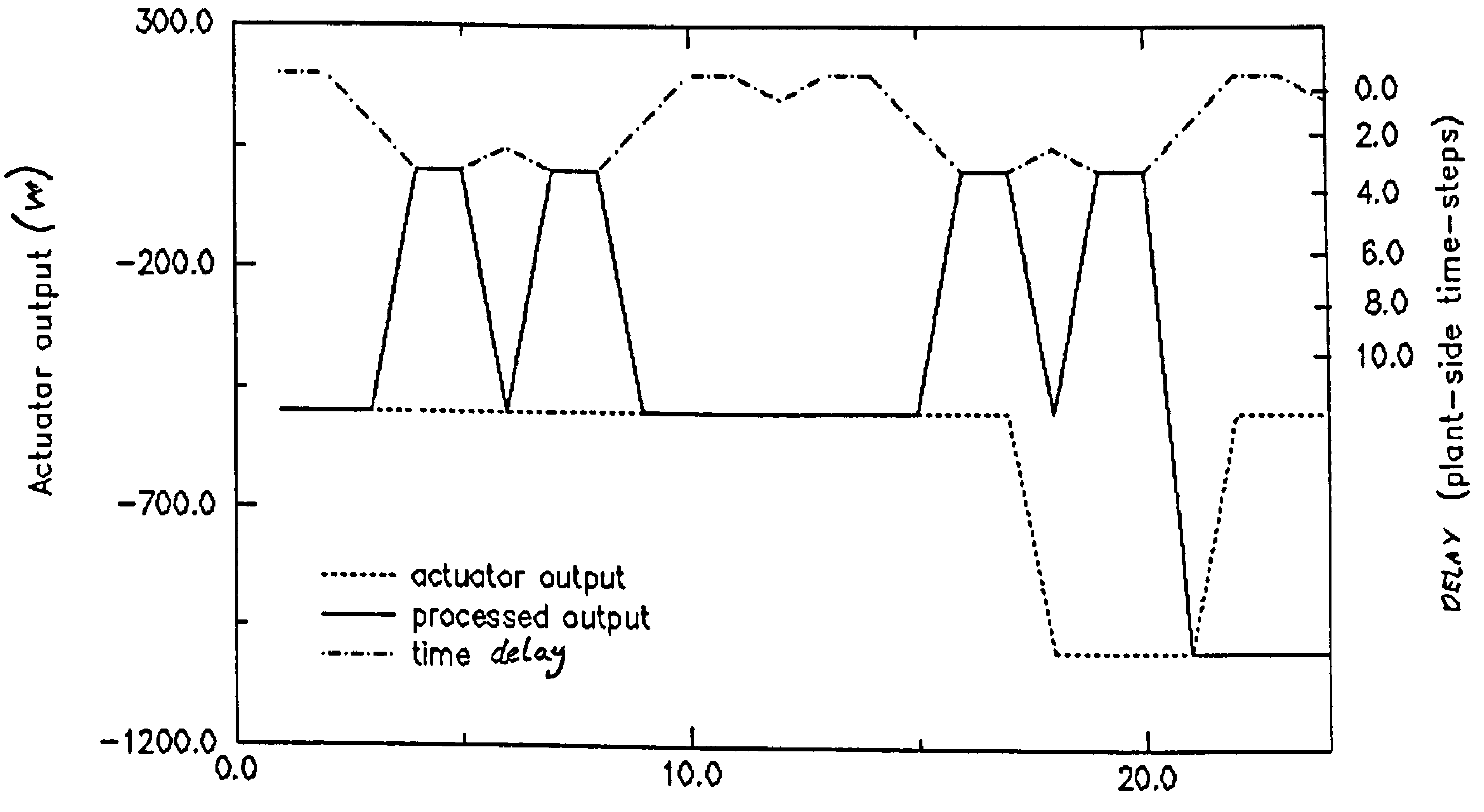


Figure 5.17 Variable actuator time delay

Chapter 6

BUILDING CONTROL SYSTEMS: THE LOGICAL ELEMENT

This Chapter focuses on modelling the logical element of building control systems. Two main themes are pursued: firstly, modelling the hierarchical nature of practical system logic structures; and, secondly, introduction of the concept of energy simulation assisted control.

6.1 INTRODUCTION.

The 'logical element' is a generic term encompassing the functional and strategic aspects of building control systems. BEMS exist primarily to optimise comfort and energy levels and increase occupant and building safety. The principal logical element deployed to achieve these conditions is the controller. Modelling this element requires consideration of the hierarchical nature of BEMS, the development of simulation assisted control techniques, together with an assessment of commissioning methodologies and reliability appraisal schema adopted in building control systems (Figure 6.1).

6.2 HIERARCHICAL CONTROL SYSTEMS.

Microprocessor-based controllers used as data gathering panels (DGPS) have led to a hierarchical configuration in BEMS, with management, operations, system and zone-based levels of control as depicted in Figure 6.2. Energy systems modelling facilitates system-level and zone-based levels of control.

Systems-level controllers have greater processing capacity than zone-level controllers in terms of number of points and control programs, and can therefore handle multiple direct digital control (DDC) loops and the complex sequences associated with air handling units, VAV systems and central chiller plants. They serve to integrate the multiple subsystems and provide global supervision such as closing down all plant in the event of some limiting and/or safety condition being reached. Controllers at this level interface with controlled equipment either directly through sensors and actuators, or indirectly through communication links with zone-level controllers. The strategy and logic underlying systems-level control are contained within *global functions;* these functions being resident in either system-level or the operations-level processors (Figure 6.2). Processors containing these functions affect inputs and outputs throughout the BEMS network and act to optimise, supervise and orchestrate the lower level zone-based control loops and, as necessary, serve as a conflict resolver should contention exist between control loops. For example, a zone-level controller may call for ventilation during the 'off' cycle of a duty cycle for the ventilation fan; the system-level controller then decides whether or not to override the duty cycle.

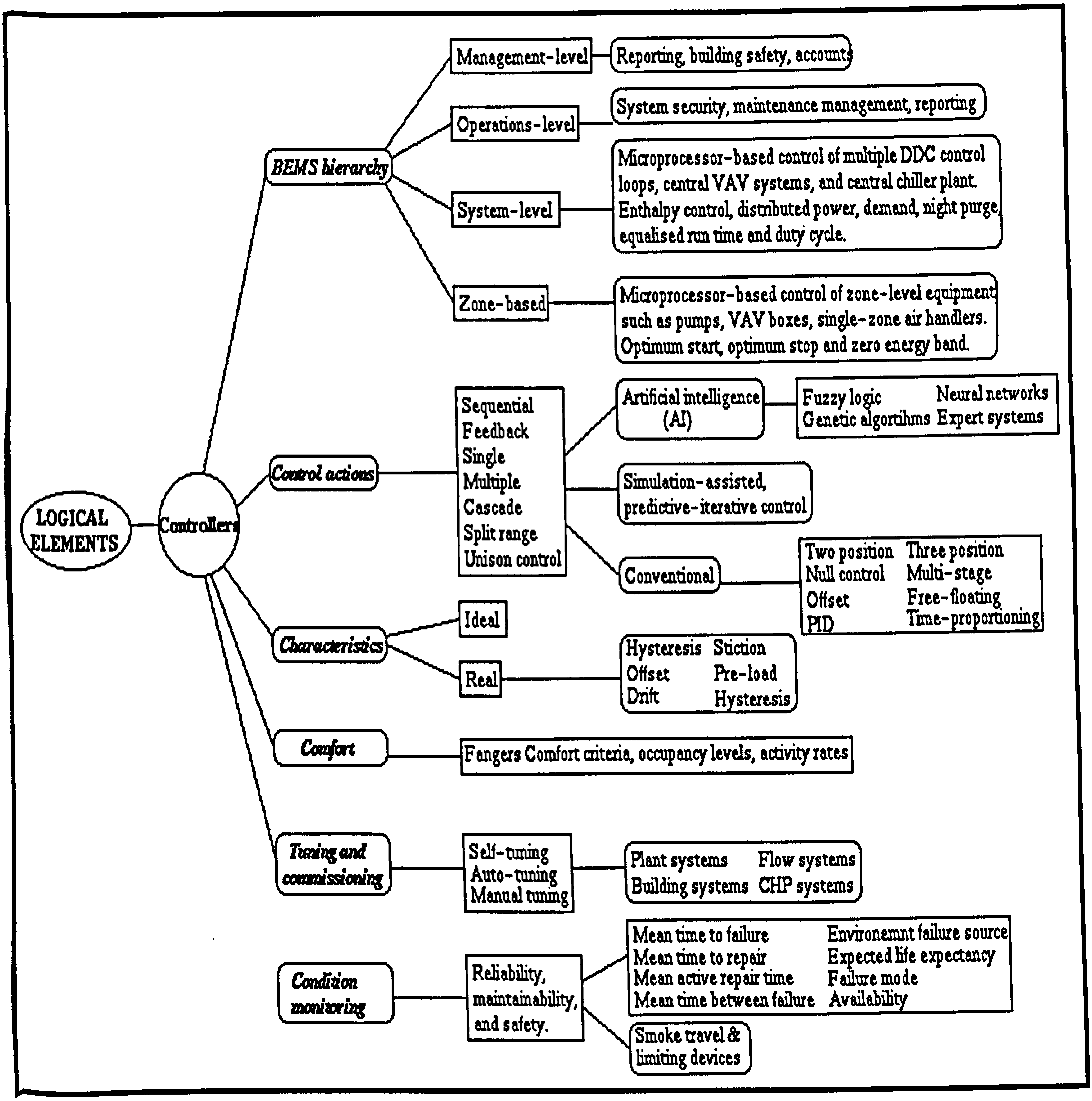


Figure 6.1 Building control systems: the logical element.

Zone-level controllers are microprocessor-based controllers that provide direct digital control of zone-level equipment, including items such as VAV boxes, heat pumps, single-zone air handlers, etc. Energy management software can also be resident within the zone-level controller. At the zone level, the sensors and actuators interface directly with the controlled equipment.

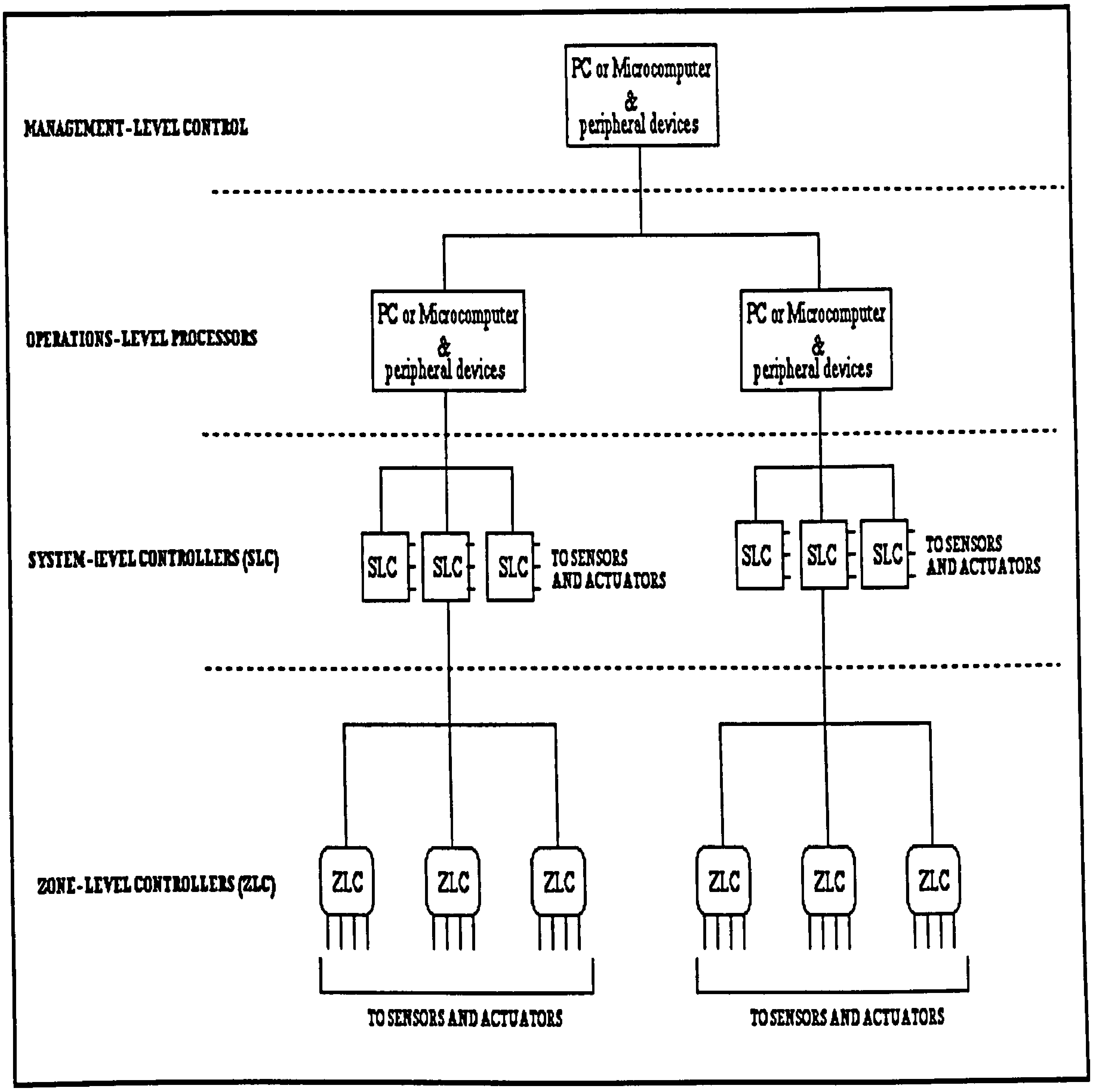


Figure 6.2 Hierarchical BEMS Configuration.

The performance of each control loop will depend on the performance of the loop above and below it in the hierarchy, and the behaviour of local loop controls can only be evaluated in the context of the whole system [Haves and Dexter 1989]. Moreover, the accuracy with which the microcomputer controller's operation must be modelled and simulated will depend on the nature of the associated control loop and its importance within the overall control structure [Dexter 1988]. Models for higher level loops can often assume ideal behaviour of the lower level loops, whilst models require to be more detailed and realistic as the level of control decreases down to sensor/actuator ('local loop') level.

The modelling of control systems logical elements is now described. Tables 6.1-6.5 summarise developments made to the ESP-r controller library during the course of the present work.

Table 6.1 Building-side control functions.

00	Mixed temperature control	01	Ideal control	02	Free-floating control
03	Ideal pre-heat/cool control	04	Fixed flux injection/extraction	05	Proportional+Integral+Derivative (PID) control‡
06	Building-plant linker	07	Multi-stage control	08	Constant-air-volume control (CAV)
09	Heat pipe control	10	On-off control	11	Pro-rata control (ideal)‡
12	Pro-rata control (on-off)‡	13	Time-proportioning control‡	14	Floating ('three-position') control‡
15	Fuzzy logic control‡	16	Null control‡	17	PMV control†
18	Humidity control†	19	Variable Air Volume (VAV) control†	20	Materials thermo-physical properties change control∞

Table 6.2 Plant-side control functions.

00	Switch off control	01/02	PID flux/flow control‡
03	Numerical control	04	Optimum start control∞
05	Proportional damper control	06	Null control‡
07	Duty cycle control‡	08	Two-Position control‡
09	Multiple input two-position control‡	10	Zero energy band control†

Table 6.3 Flow-side control functions.

00	Two-position control
01	Controller with hysteresis∞

Table 6.4 Global control functions.

01	Switch off control‡	02	Capacity management control‡	03	Sequence control‡
04	Parameter reset control†	05	Scale and offset control‡	06	Free-float control‡

Table 6.5 Energy simulation assisted control (ESAC) functions.

01a	Optimum start‡	01b	Optimum stop‡	02	Optimum set-back†	03	Optimum sensor/actuator location†
04	Control mode optimisation†	05	Duty cycling†	06	Load shedding†	07	Load balancing†

∞ Refined during the course of project.

† Developed during the course of project.

‡ Developed and installed in ESP-r during the course of project.

6.3 ZONE-LEVEL CONTROL FUNCTIONS.

BCL05: Proportional+Integral+Derivative (PID) controller.

Modulating controllers may use one or a combination of three modes: proportional, integral or derivative [Ogata 1987]. When all three modes of control are used together in the same controller, the mode of control is called 'three-term', or 'PID control'. (At project commencement, this controller was a basic proportional only controller).

Two forms of microprocessor PID regulator exist: *positional* and *velocity* (or *incremental.*) Controllers using the positional algorithm are used with continuous (analogue) actuating devices. Velocity PID regulators are often used with actuators that have naturally incremental output, e.g. stepper motors, where a pulse moves the shaft through a certain rotation, or step [Bristol 1977].

The classical PID algorithm has the following form:

$$u(t) = K_p \left\{ e(t) + \frac{1}{TI} \int e(t)dt + TD \frac{de}{dt}(t) \right\} \tag{6.1}$$

where u(t) is the control action at time t, e(t) is the error at time t, Kp is the gain (= 100%/PB, where PB is the 'proportional band'), TI is the integral action time constant (seconds) and TD is the derivative action time (seconds).

This equation can be transformed into a difference equation by discretisation. The derivative is replaced by a difference of first order and the integral by a sum. The continuous integration may be approximated by rectangular or trapezoidal integration. Applying rectangular integration [Isermann 1981] gives:

$$u(kt) = K_p \left\{ (e(k)t) + \frac{TS}{TI} \sum_{h=1}^{k} (e(h-1)t) + \frac{TD}{TS} ((e(k)t) - (e(k-1)t)) \right\} \tag{6.2}$$

where TS is the sampling interval.

Equation (6.2) is a *non-recursive* control algorithm. This is because the sum is taken over *all* past errors e(k) which have to be stored. Also as the overall change, u(k), of the manipulated variable is produced, this algorithm is called a *positional* algorithm.

However, recursive algorithms are more suitable for programming on computers, and it is for this reason that they are installed in microprocessor-based PID controllers. These algorithms are characterised by the calculation of the current manipulated variable, u(k), based on the previous previous manipulated variable, u(k-1), and correction terms. To derive the recursive positional algorithm, the integral term is approximated by the more accurate trapezoidal integration, and the derivative term by a two-point difference form [Ogata 1987], giving:-

$$u(kt) = K_p \left\{ (e(k)t) + \frac{TS}{TI} \sum_{h=1}^{k} (e(h-1)t) + \frac{e(ht)}{2} + \frac{TD}{TS} [e(kt) - e((k-1)t)] \right\}. \tag{6.3}$$

If instead of the 'overall change', u(kT), of the manipulated variable being produced, only the current change in the manipulated variable, u(kT) - u((k-1)T), is calculated then the resulting algorithm is called a *velocity algorithm.* Doing this for a PI controller, and using a rectangular integration approximation [Levermore, 1992], gives:

$$u(kt) = u((k-1)t) + K_p[e(kt) - e((k-1)t)] + \frac{TS}{TI}e((k-1)t). \tag{6.4}$$

In the case of the full velocity PID controller, and using a rectangular integration approximation [Clark 1985]:

$$u(kt) = u((k-1)t) + Ae(kt) + Be((k-1)t) + Ce((k-2)t) \tag{6.5}$$

where:

$$A = K_p\left\{1 + \frac{TS}{TI} + \frac{TD}{TS}\right\} \tag{6.6}$$

$$B = -K_p\left\{1 + 2\frac{TD}{TS}\right\} \tag{6.7}$$

$$C = K_p\frac{TD}{TS}. \tag{6.8}$$

Alternatively, if a trapezoidal integration approximation is used for the velocity PID controller [Isermann 1981], this gives:

$$u(kt) = u((k-1)t) + Ae(kt) + Be((k-1)t) + Ce((k-2)t) \tag{6.9}$$

where:

$$A = K_p\left\{1 + 0.5\frac{TS}{TI} + \frac{TD}{TS}\right\} \tag{6.10}$$

$$B = -K_p\left\{1 + 2\frac{TD}{TS} - 0.5\frac{TS}{TI}\right\} \tag{6.11}$$

$$C = K_p\frac{TD}{TS}. \tag{6.12}$$

Note that whilst the discrete-time algorithms are only an *approximation* to continuous-time controllers, they are *identical* to those algorithms installed in the actual processors [Dexter 1988].

All the PID controller types described above are available with the *BCL05* function. As an iterative solution is employed in ESP-r, there is the complication that it is not known whether the current iteration is the final iteration of the current time-step until the iteration is completed. Thus, the updated state of the PID controller is saved at each iteration, along with the old state. If another iteration is required at that time-step the updated state is discarded and the controller reverts to the previous state. On the first call to the next time-step, the updated state (saved from the last iteration of the previous time-step) becomes the old state of the controller for the next time-step.

The proportional gain (Kp), integral action time (TI) and derivative action time (TD) parameters are required as input to ESP-r. Establishing suitable values is known as 'tuning', a process which is non-trivial. In addition, a controller that is tuned for one load is unlikely to perform in an optimal manner at another load because of the non-linearities that are typically encountered in HVAC systems. Furthermore, the *sequence* in which multi-loop systems are tuned may also be critical in practical situations. Several methods for manually tuning these algorithms are used in practice, ranging from 'trial and error' to the more systematic use of rules developed from those proposed by Ziegler and Nichols [1942]. However, for more complex processes such as those with significant dead-time, these rules can be difficult to apply and moreover tuning needs to be re-initiated if the plant dynamics vary significantly during operation.

The tuning process for simulation purposes is identical to that which has to be carried out in practice by control engineers. Firstly, the gain has to be selected. For close, accurate control, the PB must be narrow. For example, consider a heater battery; if the PB is too narrow, the heater is constantly changing its output, forcing the actuator (e.g. a valve) to operate more frequently than is necessary. This can cause excessive wear and tear and result in poor control. Too wide a proportional band results in poor control since a large offset occurs.

Having determined the gain, the TI and TD constants must now be determined. Building plant systems are typically 'stiff' in nature, i.e. they have a wide range of time constants. For this reason, TI and TD will vary from plant item to plant item. Typically for building services plant TI and TD will have values around 200 and 500 seconds respectively [BEMS Centre 1988]. For example, a hot water cylinder will respond slowly, its temperature creeping up over hours rather than minutes; a heater battery, on the other hand, can change the temperature of the hot air supplied to it within seconds or minutes. The integral action time constant and the derivative action time constant have to relate to the response of the particular system they are controlling. If the PID settings are guessed or determined incorrectly, the temperature may continually oscillate. If the TI constant is set too low, then this will produce continual oscillation of the controlled variable around the set-point.

In practice, the sampling interval must be selected with care. Typically, it should be 10 to 30 seconds for temperature control and 1 to 5 seconds for pressure systems. In discrete simulation, such as with ESP-r, the time-step can be matched to the sampling interval or some (sub)multiple of it as deemed necessary to cope with system dynamics (Section 5.3).

BCL11: Ideal multi-sensor pro-rata controller,

BCL12: On-Off multi-sensor pro-rata controller.

These controllers act to bring the temperature of the associated zone to a value determined as a function of the sensed temperature at other locations: the former in an ideal manner, the latter in on-off mode.

The flux injected to a zone may be expressed in terms of the present time-row temperature:

$$q_p = \frac{B3 - B1\theta_{aux}}{B2} \tag{6.13}$$

where q_p is the plant flux injection (W), θ_{aux} is a function (i.e. maximum, minimum, average or weighting) of the multiple 'auxiliary' sensed conditions at the present time-row (°C) and B1, B2 and B3 are the adjusted system matrix coefficients. This equation is used to evaluate the heat flux according to ideal or on-off regulation and any specified capacity constraints. In any event, the future time-row control point temperature may be evaluated from:

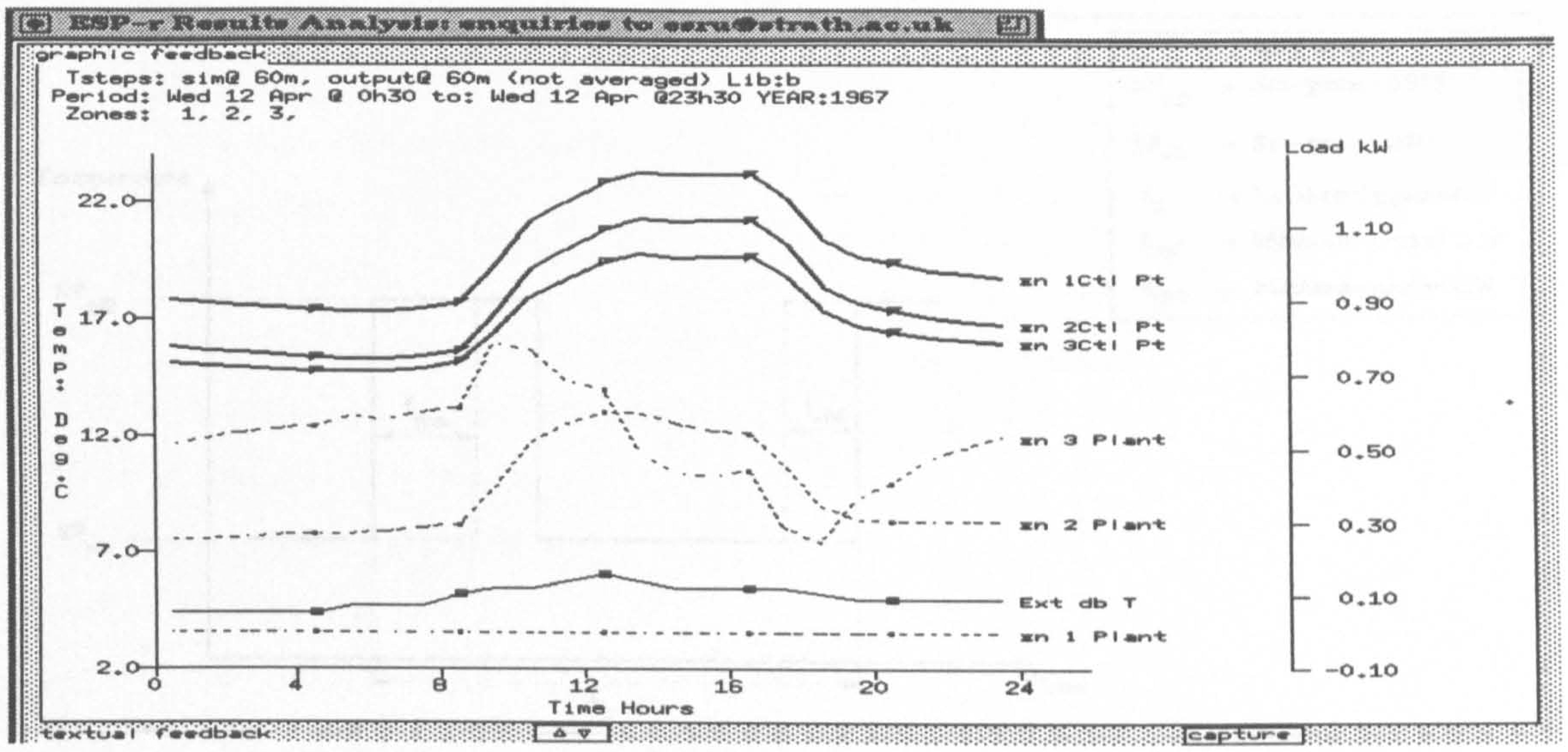
$$\theta_c = \frac{B3 - B2q_p}{B1} \tag{6.14}$$

where θ_c is the zonal control point temperature (^{o} C), q_p is the plant flux injection (W) and B1, B2 and B3 are the building control system equation set coefficients.

Consider a 3-zone building with Zone_1 free-floating and pro-rata control (ideal mode) applied to both Zone_2 and Zone_3. Here, the control strategy, for the entire simulation period, is for the Zone_2 air point to track Zone_1 with a -2 °C offset, and for the Zone_3, surface_4 temperature to be held to a weighted average of the external and Zone_1 dry bulb air temperatures (20% and 80% respectively) offset by -3 deg.C. (The control logic for Zone_2 models practical situations such as store-rooms, corridors, etc, where the air point temperature is held several degrees lower than an occupied zone. The control logic for Zone_3 is representative of research and development applications, e.g validation studies.). The results for this control regime are shown in Figure 6.3. Heating and cooling restrictions are also allowed in this model.

BCL13: Time-proportioning on/off controller.

In proportional modulating controllers, the output signal is proportional to the error signal. However, a commonly adopted BEMS strategy is to switch ON/OFF devices for *periods of time* proportional to the error signal [Honeywell 1989]. This is *time proportional control,* implemented with a loop module connected to a time proportional driver (Figure 6.4(a)).



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Tsteps: sim@ 60m, output@ 60m (not averaged) Lib:b
Period: Wed 12 Apr @ 0h30 to: Wed 12 Apr @23h30 YEAR:1967
Zones:  1, 2, 3,
```

Figure 6.3 Pro-rata control.

The user-specified *total* cycle period time (t_c) and the minimum ON and minimum OFF cycle periods (t_{mn} and t_{mf} respectively) are converted from seconds into equivalent numbers of simulation time-steps from:

$$N_c = t_c \frac{N_t}{3600} \tag{6.15}$$

and

$$N_{mn} = t_{mn} \frac{N_t}{3600} \tag{6.16}$$

and

$$N_{mf} = t_{mf} \frac{N_t}{3600} \tag{6.17}$$

where N_c is the total cycle period (time-steps), N_{mn} is the minimum ON period (time-steps), N_{mf} is the minimum OFF period (time-steps) and N_t is the number of simulation time-steps per hour. The proportionality ratio is then calculated from:

$$K_p = \frac{N_c - (N_{mn} + N_{mf})}{(SP_{off} - SP_{on})} \tag{6.18}$$

where SP_{off} and SP_{on} are the OFF and ON set-points respectively.

At the start of each complete cycle period, the number of simulation time-steps that the plant is set ON, N_{on}, is evaluated from:

$$N_{on} = (N_c - N_{mf}) + K_p(\theta_s - SP_{on}) \tag{6.19}$$

where θ_s is the sensed condition.

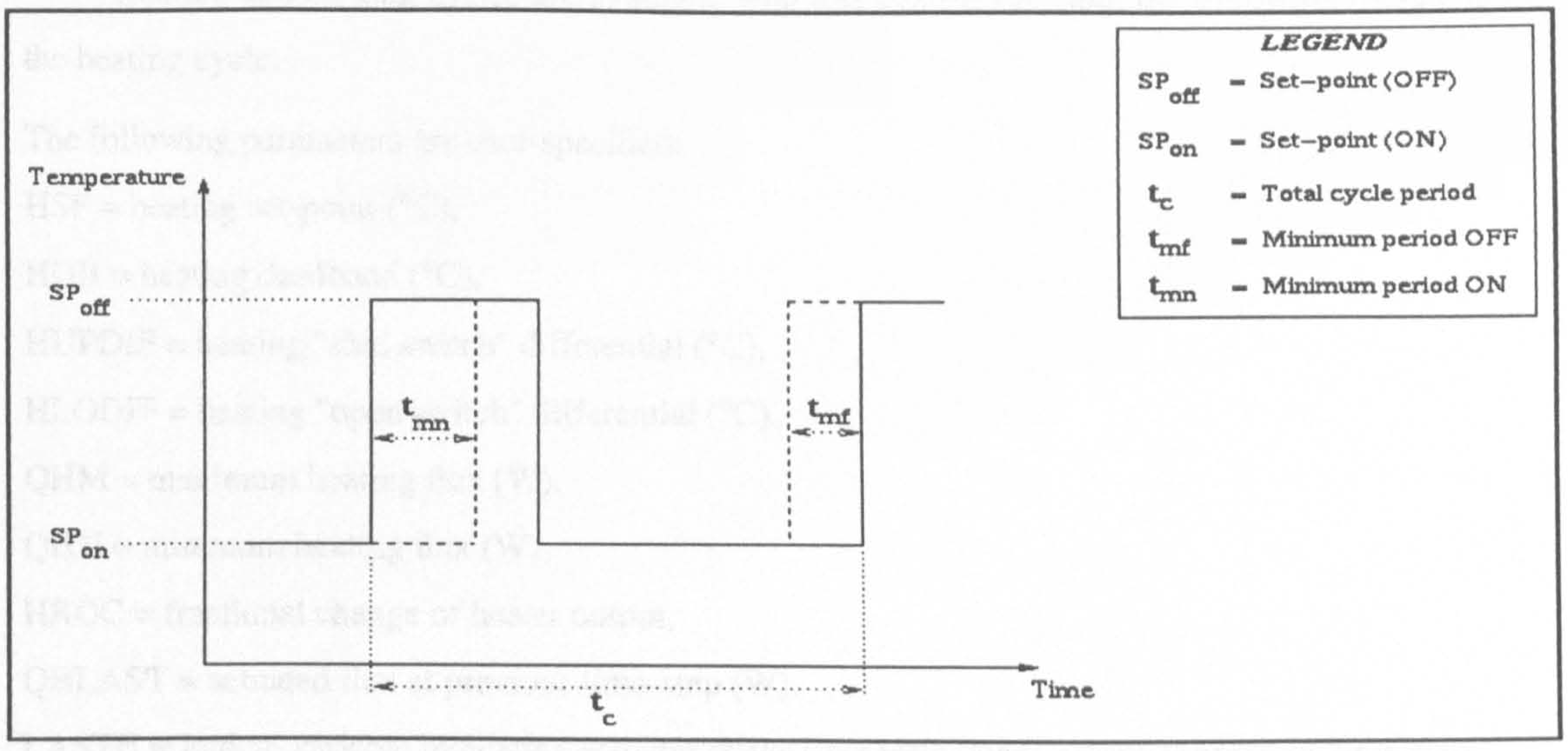
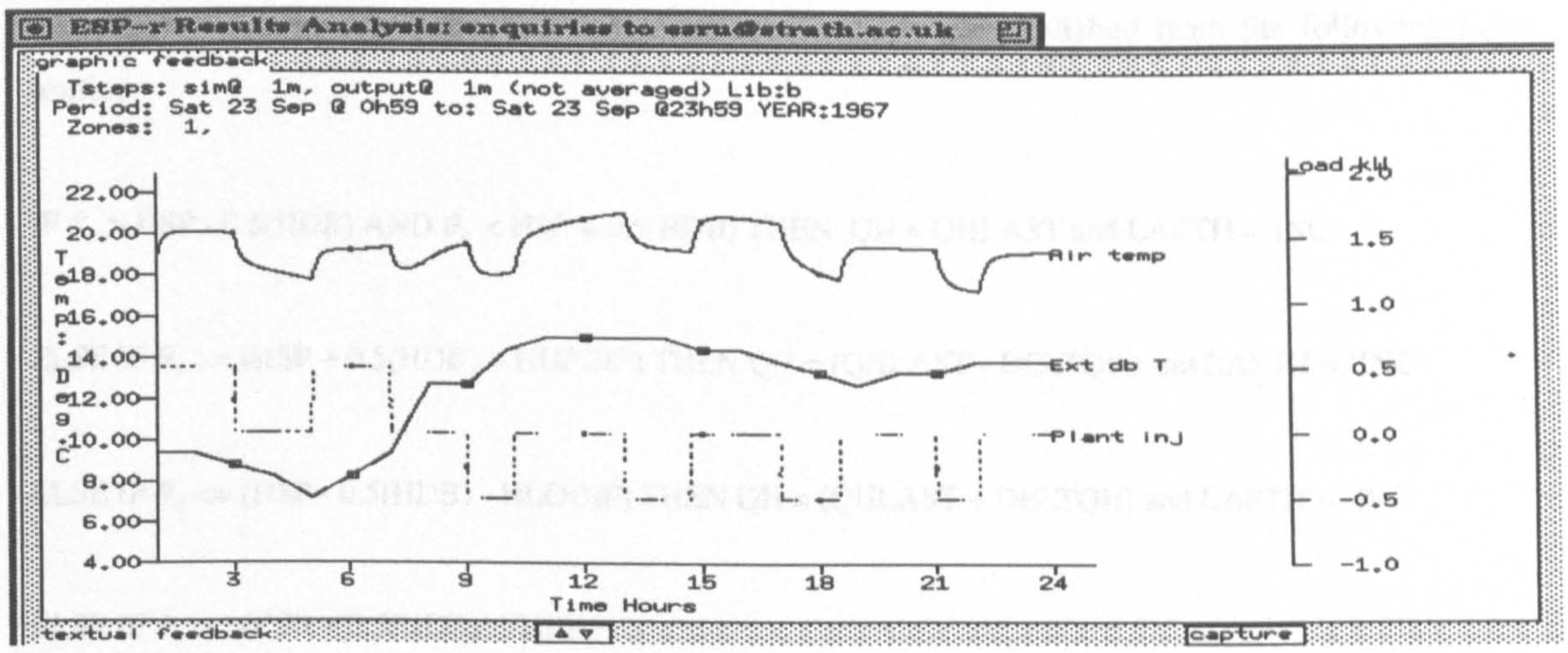


Figure 6.4 (a) Time-proportional driver



```
Tsteps: sim@  1m, output@  1m (not averaged) Lib:b
Period: Sat 23 Sep @ 0h59 to: Sat 23 Sep @23h59 YEAR:1967
Zones:  1,
```

Figure 6.4 (b) Time-proportional control results set

The model installed in ESP-r incorporates time-step counters to track the building-side time-step in order to synchronise ON/OFF times and maintain the specified heating and cooling time proportions. Discrete time simulation of this type of controller necessarily requires a small building-side simulation time-step (i.e. 1 or 2 minutes) in order to capture the dynamics and describe any benefits accruing from the control action. The characteristic variation in ON-OFF times resulting from time-proportioning control action is shown in Figure 6.4(b) for a 1 minute simulation time step.

BCL14: Floating ('three-position') controller.

Floating control (often called *three-position control*) is a variation of two-position control and is available in most practical microprocessor-based control systems. Floating control is so called because the final control element floats in a fixed position as long as the value of the controlled variable lies within a dead band or 'neutral zone' (Figure 6.5(a)).

Heating and cooling cycles are available with this control function; the following routine is for the heating cycle.

The following parameters are user-specified:
HSP = heating set-point (°C),
HDB = heating deadband (°C),
HUPDIF = heating "shut switch" differential (°C),
HLODIF = heating "open switch" differential (°C),
QHM = maximum heating flux (W),
QHN = minimum heating flux (W),
HROC = fractional change of heater output,
QHLAST = actuated flux at previous time-step (W),
LASTH = logical variable indicating actuator status (increasing/decreasing) at previous time-step.
DELTQH = QHN + (QHM-QHN)xHROC

At each simulation time-step, the future time actuated flux is established from the following logic routine:

```
IF $\theta_c$ > HSP - 0.5(HDB) AND $\theta_c$ < HSP + 0.5(HDB) THEN  QH = QHLAST and LASTH ='INC'

ELSE IF $\theta_c$ >= (HSP + 0.5(HDB) + HUPDIF) THEN QH = (QHLAST - DELTQH) and LASTH = 'INC'

ELSE IF $\theta_c$ <= (HSP - 0.5(HDB) - HLODIF) THEN QH = (QHLAST + DELTQH) and LASTH = 'INC'

ELSE IF $\theta_c$ >= (HSP + 0.5(HDB)) THEN
            IF LASTH = 'INC' THEN QH = QHLAST - DELTQH and LASTH = 'INC'
            ELSE QH = QHLAST and LASTH = 'DEC'

ELSE IF $\theta_c$ <= (HSP - 0.5(HDB)) THEN
            IF LASTH = 'INC' THEN QH = QHLAST + DELTQH and LASTH = 'INC'
            ELSE QH = QHLAST and LASTH = 'DEC'
```

If necessary, limit controller output:

```
IF QH < QHN THEN QH = QHN
IF QH > QHM THEN QH = QHM
```

where θ_c is the sensed control point temperature (°C) and QH is the actuated flux at the future time-row (W).

As with the time-proportioning controller, time-step considerations are of particular importance. In this case, the building-side time-step must be matched to the system dynamics, which will be largely dependent on the rate of change of the actuator signal. (In this respect, the time-step controller, *TSCON_6*, (Section 5.3.4), which tracks control system dynamics and adjusts the simulation time-step accordingly, may be employed with this control function). Figure 6.5(b) shows the response of a floating, three-position controller for a simulation time-step of 1 minute.

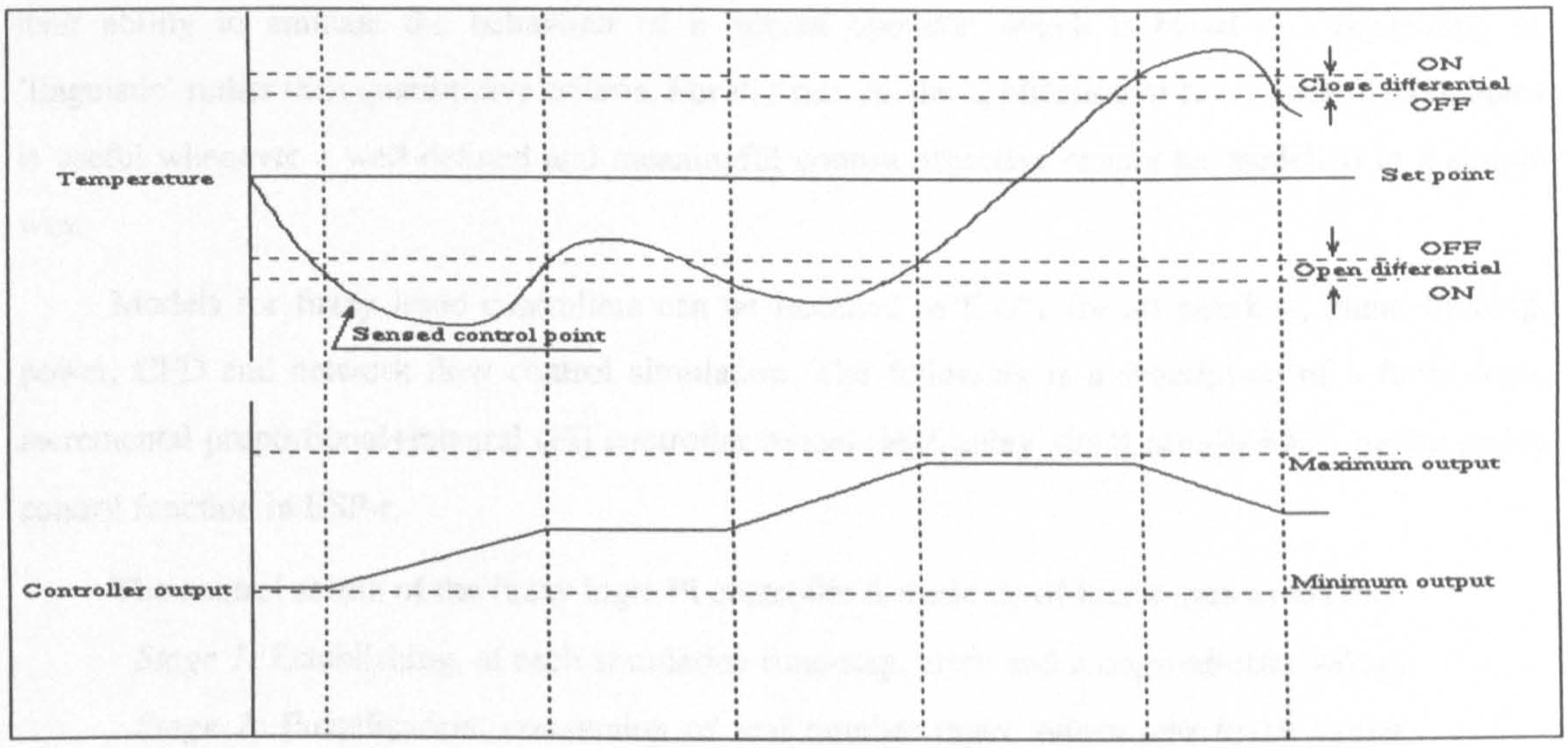
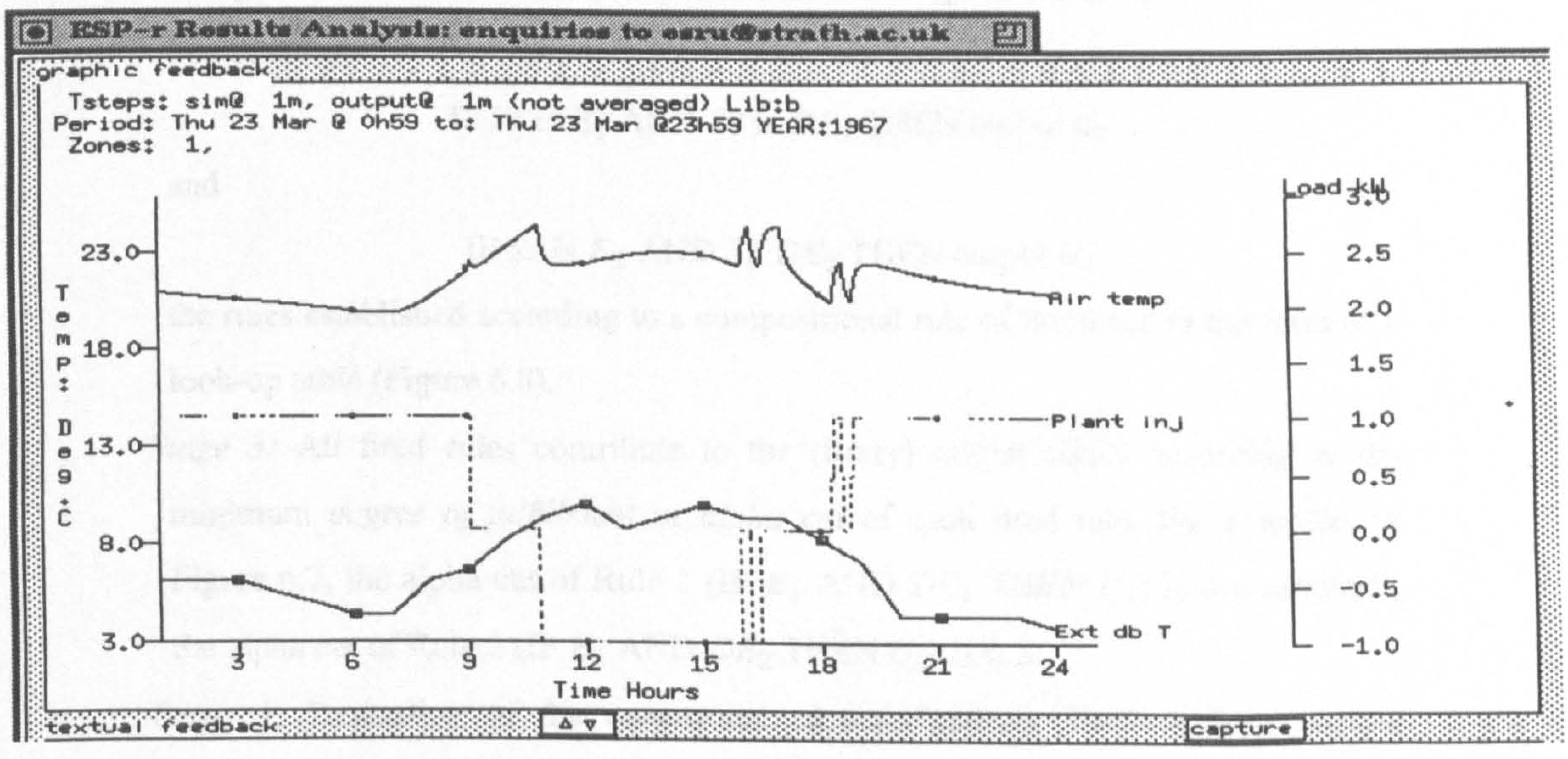


Figure 6.5(a) Floating ('Three position') control action.



```
Tsteps: sim@  1m, output@  1m (not averaged) Lib:b
Period: Thu 23 Mar @ 0h59 to: Thu 23 Mar @23h59 YEAR:1967
Zones:  1,
```

Figure 6.5(b) Floating control action: sample results set.

A variation of floating control is *proportional-speed control.* In this type of controller, the farther the control point moves beyond the dead band, the *faster* the actuator moves to correct the deviation. This is modelled by varying the number of time-steps before implementing controller output, in accordance with deviation from the user-specified dead band.

BCL15: Fuzzy logic controller.

Recent research in the field of building control systems design has focused on the use of so-called 'fuzzy logic' controllers [Jamshidi *et al* 1993]. The advantage of fuzzy logic controllers lies in their ability to emulate the behaviour of a human operator, which is based on 'vagueness' or 'linguistic' rather than quantitative criteria. For this reason, the application of fuzzy control techniques is useful whenever a well-defined and meaningful control objective cannot be modelled in a simple way.

Models for fuzzy logic controllers can be installed in ESP-r for all building, plant, lighting, power, CFD and network flow control simulation. The following is a description of a fuzzy logic incremental proportional+integral (PI) controller model [McCauley 1994] installed as a building-side control function in ESP-r.

The control action of the fuzzy logic PI controller is made up of four stages as follows.

Stage 1: Establishing, at each simulation time-step, error and change-of-error values.

Stage 2: Fuzzification: conversion of real number input values into fuzzy values, within a quantised universe of discourse (Figure 6.6). This entails mapping the error and change-of-error values onto the error and change-of-error membership sets. For example, in Figure 6.7, the error signal, *S1*, is mapped onto the error fuzzy membership sets E_1 and E_2 and the change-of-error signal, *S2* is mapped onto the change-of-error fuzzy membership sets DE_1 and DE_2. *S1* and *S2* thus 'fire' rules of the form:

IF *S1* is E_1 AND *S2* is DE_1 THEN output U_1

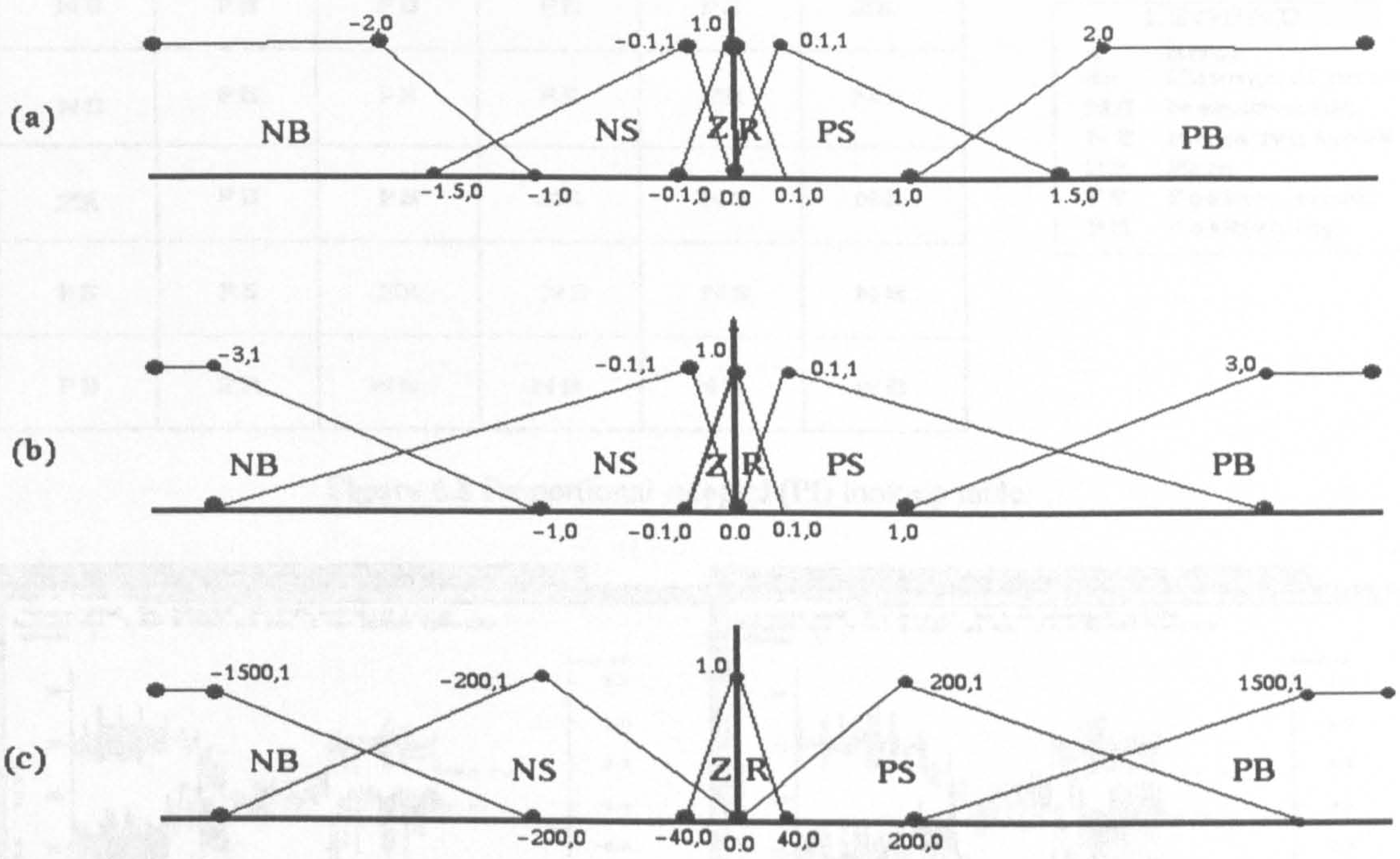
and

IF *S1* is E_2 AND *S2* DE_2 THEN output U_2

the rules established according to a compositional rule of inference in the form of a look-up table (Figure 6.8).

Stage 3: All fired rules contribute to the (fuzzy) output signal according to the minimum ***degree of fulfillment*** or ***alpha cut*** of each fired rule. For example, in Figure 6.7, the alpha cut of Rule 1 (IF E_1 AND DE_1 THEN U_1) is 0.4; similarly, the alpha cut of Rule 2 (IF E_2 AND DE_2 THEN U_2) is 0.2.

Stage 4: Evaluation of the consequent (defuzzification). The cut fuzzy output membership set resulting from *Stage 3* is reduced to a single numerical value representing an actuator signal. Techniques used to achieve this include the *centre-of-area* or *mean-of-max methods* [Tong 1977].



(PB=Positive Big, PS=Positive Small, ZR=Zero, NS=Negative Small and NB=Negative Big)

Figure 6.6 PI membership functions for **(a)** error, **(b)** change of error and **(c)** output

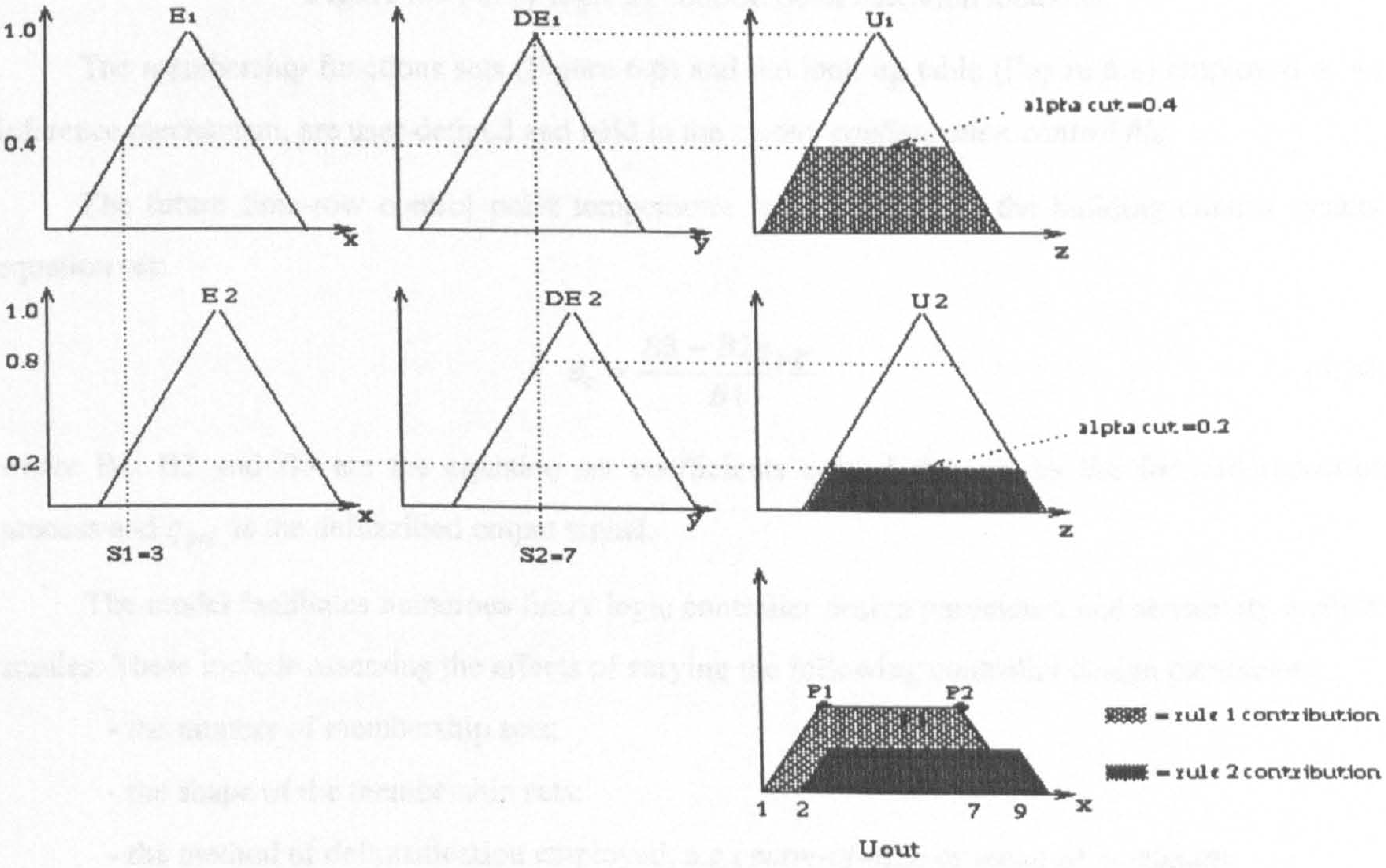


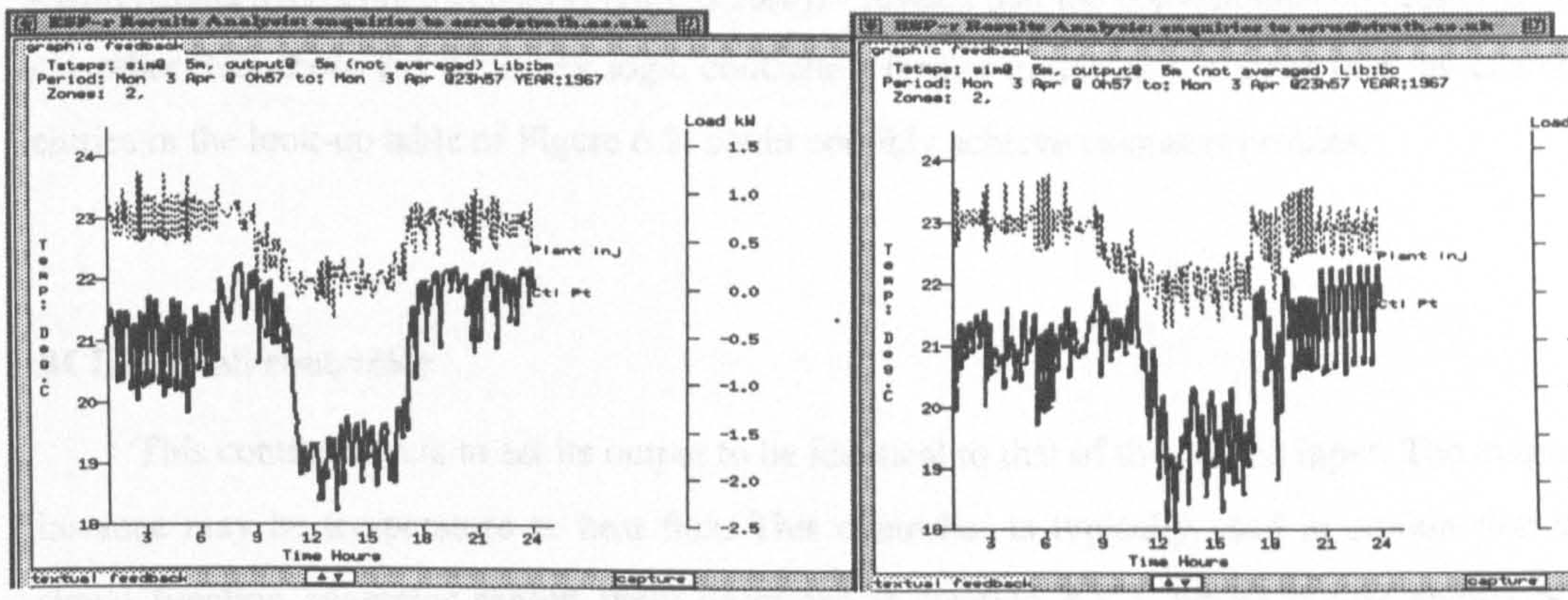
Figure 6.7 Fuzzy logic control action: the fuzzification process.

e \ de	NB	NS	ZR	PS	PB
NB	PB	PB	PB	PS	ZR
NS	PB	PS	PS	ZR	NS
ZR	PB	PS	ZR	NS	NB
PS	PS	ZR	NS	NS	NB
PB	ZR	NS	NB	NB	NB

LEGEND

e	Error
de	Change of error
NB	Negative big
NS	Negative small
ZR	Zero
PS	Positive small
PB	Positive big

Figure 6.8 Proportional-integral (PI) look-up table.



(a) Mean-of-maximum defuzzification (b) Centre of area defuzzification

Figure 6.9 Fuzzy logic PI control: defuzzification methods.

The membership functions sets (Figure 6.6) and the look-up table (Figure 6.8) employed as an inference mechanism, are user-defined and held in the *system configuration control file.*

The future time-row control point temperature is obtained from the building control system equation set:

$$\theta_c = \frac{B3 - B2q_{pdf}}{B1} \tag{6.20}$$

where B1, B2 and B3 are the equation set coefficients carried through by the forward reduction process and q_{pdf} is the defuzzified output signal.

The model facilitates numerous fuzzy logic controller design parametric and sensitivity analysis studies. These include assessing the effects of varying the following controller design parameters:

- the number of membership sets;
- the shape of the membership sets;
- the method of defuzzification employed, e.g *centre-of-area* or *mean-of-maximum.*

The effect of changing a single fuzzy logic PI controller parameter (using the membership functions and look-up table definitions of Figure 6.6 and Figure 6.8 respectively) is shown in Figure 6.9, where the defuzzification method is varied from *mean-of-maximum* to *centre-of-area.* Both controllers maintain a control point close to the set-point (19 °C), with slightly less fluctuation in controlled variable for the case of *mean-of-maximum* defuzzification.

A comparison between the *BCL05* PI controller and the *BCL15* fuzzy logic PI controller is shown in Figure 6.10 for a 1-day simulation period run with a 1 minute time-step, using the control parameters listed Table 6.6. The results indicate that both controllers act to maintain (by cooling) the zone air point temperature close to the set-point of 18°C; the conventional control requiring marginally less energy to do so. Comparing the temperature and energy profiles for the control period - with results averaging disabled (Figure 6.10(b)) - reveals that the conventional controller profiles are smoother than those for the fuzzy logic controller; further tuning of the latter (e.g. by changing the entries in the look-up table of Figure 6.8) could possibly achieve smoother profiles.

BCL16: Null controller.

This controller acts to set its output to be identical to that of the sensed input. The output in this instance may be temperature or heat flux. This controller is typically used in conjunction with the signal function generator sensed input described in Section 4.3.2, where it was shown how it is possible to 'pulse' the building, flow and plant components with a wide variety of inputs (e.g. sinusoidal, square wave, saw-tooth and ramp), for either temperature or flux.

If the future time-row control point temperature is being pulsed, the future time-row plant flux input/extract is computed from:

$$q_p = \frac{B3 - B1\theta_{pulse}}{B2}. \tag{6.21}$$

Alternatively, if the future time-row plant flux input/extract is being pulsed, the future time-row control point temperature is evaluated from;

$$\theta_c = \frac{B3 - B2q_{pulse}}{B1}. \tag{6.22}$$

An option available with this controller model is a scale and offset feature which allows adjustment of the controller input, e.g. amplitude and mean value adjustment of a sine wave function.

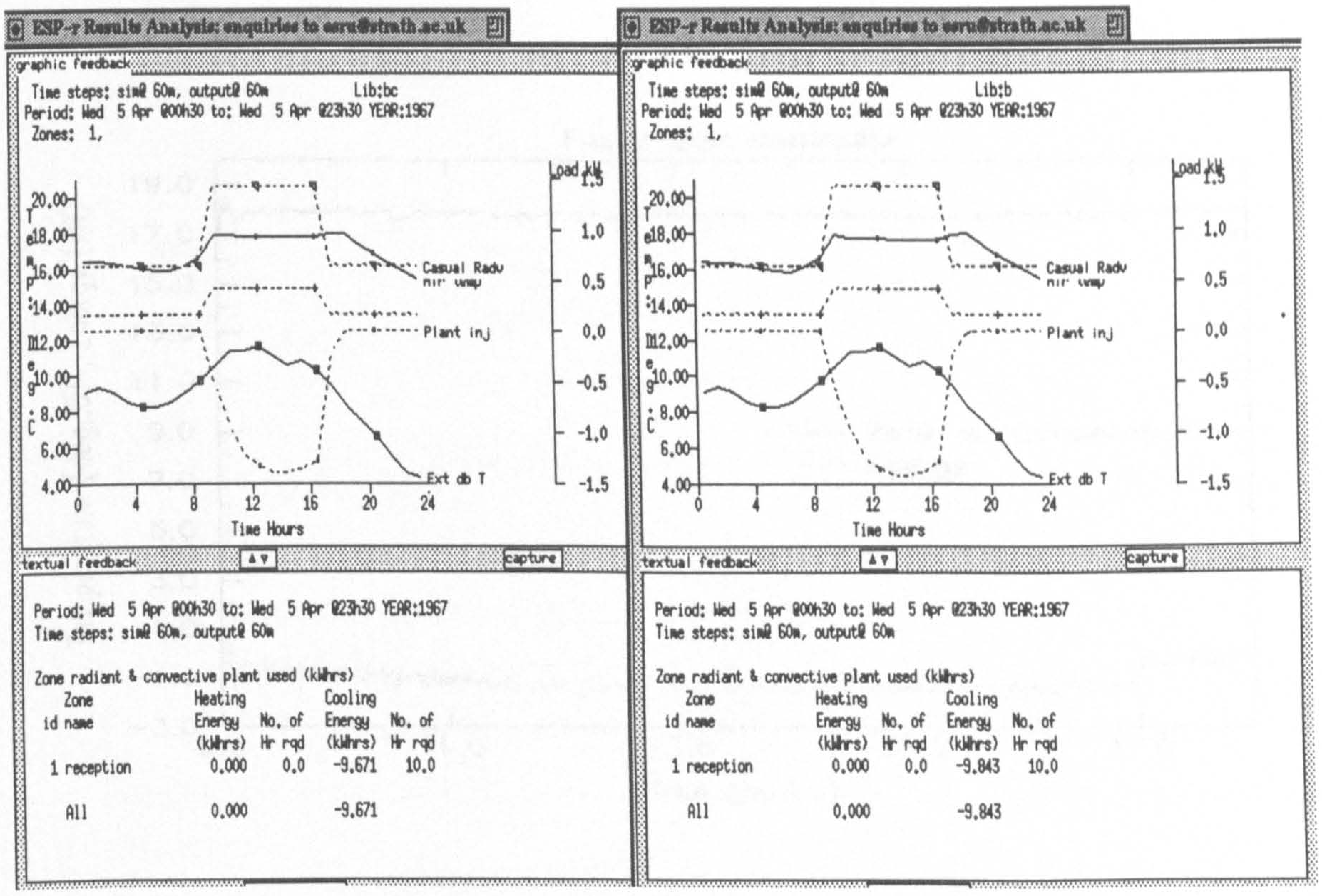
Table 6.6: Schedule for conventional and fuzzy logic PI control.

Conventional PI controller

Sensed property	Actuator location	00.00-09.00	09.00-18.00					18-24.00
		Mode	Mode	SP	PB	IAT	Capacity	Mode
Air temperature	Air point	Free-float	PI	18.0 °C	2.0°C	60 s	2000 W	Free-float

Fuzzy logic PI controller

Sensed property	Actuator location	00.00-09.00	09.00-18.00					18-24.00
		Mode	Mode	SP	I/P sets	O/P sets	Capacity	Mode
Air temperature	Air point	Free-float	PI	18.0 °C	5	5	2000 W	Free-float



```
Time steps: sim@ 60m, output@ 60m          Lib:bc
Period: Wed  5 Apr @00h30 to: Wed  5 Apr @23h30 YEAR:1967
Zones:  1,
```

```
Period: Wed  5 Apr @00h30 to: Wed  5 Apr @23h30 YEAR:1967
Time steps: sim@ 60m, output@ 60m

Zone radiant & convective plant used (kWhrs)
   Zone              Heating           Cooling
 id name             Energy  No. of   Energy  No. of
                     (kWhrs) Hr rqd   (kWhrs) Hr rqd
  1 reception          0.000    0.0   -9.671   10.0

   All                 0.000          -9.671
```

(a) Conventional PI control

```
Time steps: sim@ 60m, output@ 60m          Lib:b
Period: Wed  5 Apr @00h30 to: Wed  5 Apr @23h30 YEAR:1967
Zones:  1,
```

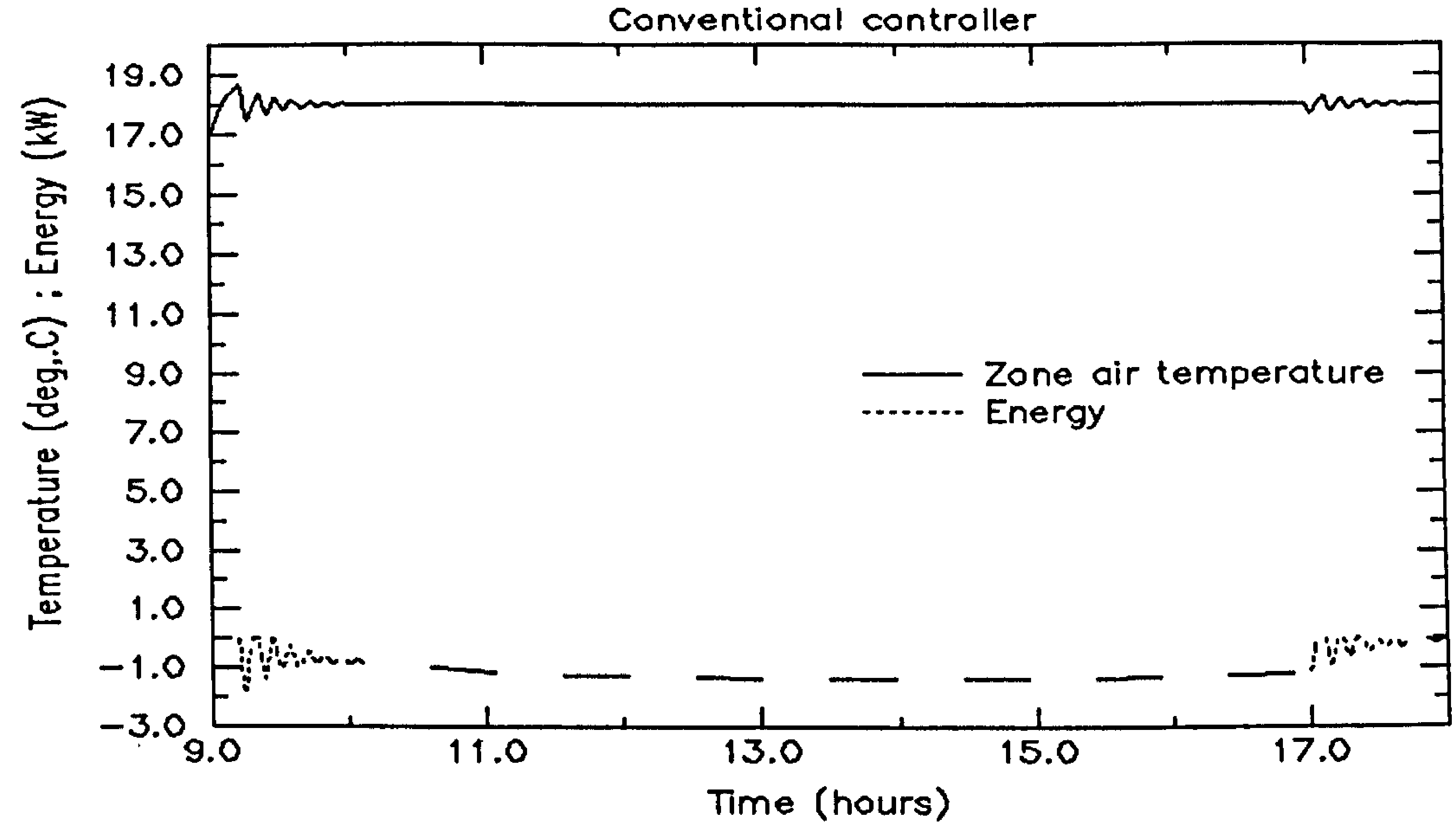
```
Period: Wed  5 Apr @00h30 to: Wed  5 Apr @23h30 YEAR:1967
Time steps: sim@ 60m, output@ 60m

Zone radiant & convective plant used (kWhrs)
   Zone              Heating           Cooling
 id name             Energy  No. of   Energy  No. of
                     (kWhrs) Hr rqd   (kWhrs) Hr rqd
  1 reception          0.000    0.0   -9.843   10.0

   All                 0.000          -9.843
```

(b) Fuzzy logic PI control

Figure 6.10(a) Results for conventional PI and fuzzy logic PI control.



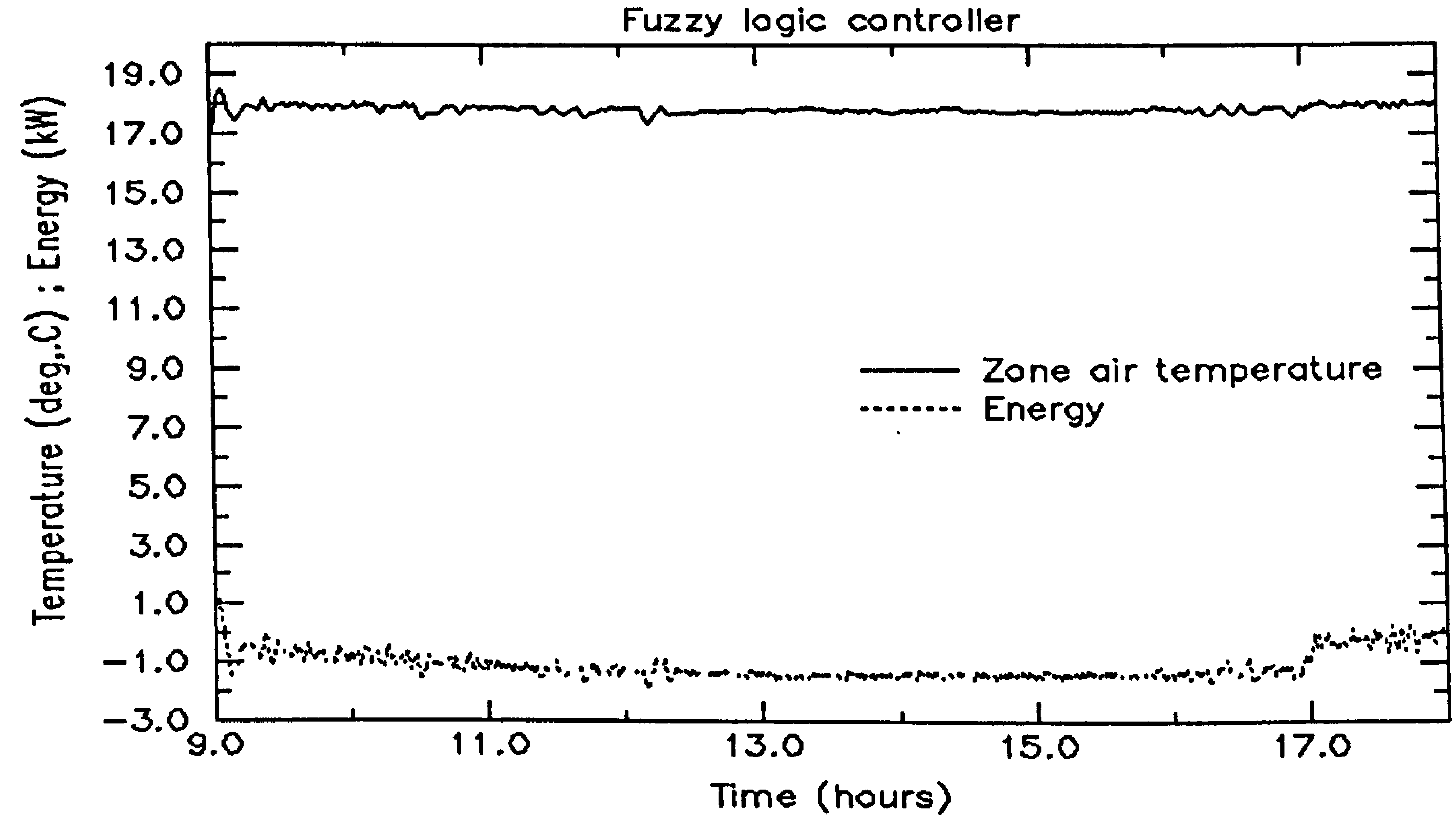


Figure 6.10(b) Conventional and fuzzy logic control: temperature and energy profiles.

BCL17: PMV controller.

The theoretical basis, modelling procedure and a sample results set for this controller were presented in Section 4.4.1, where control on sensed variables other than temperature was discussed.

BCL18: Humidity controller.

This controller acts to control zone relative humidity levels under the influence of an ideal plant network. An iteration process (similar to that of the PMV controller) takes place at each building-side simulation time-step. At each iteration the following procedure is invoked:

- the future time-row flux input/extract is adjusted and the control point temperature evaluated from the building control system equation set;
- backward substitution in the reduced zone and construction matrices then allows all future time-row nodal temperatures to be computed;
- the future time-row zone relative humidity level is then evaluated from [Jones, 1985]:

$$RH = \frac{p_v}{p_{sv}} 100.0 \tag{6.23}$$

where

$$p_v = \frac{g_s p_{atmos}}{f_s(0.62197 + g_s)} \tag{6.24}$$

and

$$p_{sv} = 10^{10.54-(2663.91/(T-0.01))} [ice] \tag{6.25}$$

or

$$p_{sv} = 1000x10^{(28.59-8.21xLOG_{10}(T)+0.0025xT-3142.31/T))} [water] \tag{6.26}$$

where p_v is the vapour pressure (mbar), p_{sv} is the saturated vapour pressure (mbar), p_{atmos} is the atmospheric pressure (N m^{-2}), g_s is the moisture content (kg per kg of dry air), f_s is a dimensionless coefficient (= T_{db}x7.3x10^{-6} +1.00444, where T_{db} is the dry bulb temperature (°C)) and T is the absolute dry bulb temperature (K).

This process continues until the relative humidity is within prescribed limits, or limiting conditions occur.

BCL19: Variable Air Volume (VAV) controller.

One approach to the modelling of variable-air-volume (VAV) systems (ideal plant) is now presented. Air at constant temperature is supplied at variable volumetric flow rate to the zone under VAV control. The flow rate required to satisfy prescribed zone temperature conditions is based on the simultaneous solution of the [$q_p = \dot{m}.\mathrm{Cp}.(\theta_s\text{-}\theta_c)$] and [$\mathrm{B1}.\theta_c + \mathrm{B2}.q_p = \mathrm{B3}$] equations, to give the required fluid flow rate:

$$\dot{m} = \frac{B3 - B1.\theta_c}{B2.C_p(\theta_s - \theta_c)} \tag{6.27}$$

where $\dot{m}$ is the fluid flow rate (kg/s), T_c and T_n are the control point and supply temperatures respectively (°C), C_p is the specific heat capacity of the supply air (J/(kg K)) and B1, B2 and B3 are the building control system equation set future time-row control point, future time-row plant and present time-row coefficients respectively.

If the required fluid flow rate to obtain the prescribed required conditions is not available, the limiting value of $\dot{m}$ is used in Equation 6.27 which is subsequently solved for T_c. This, in turn, allows evaluation of the future time-row plant input/extract from the building control system equation set.

BCL99: Materials thermo-physical properties change controller.

During an active control period, this controller modifies the thermo-physical properties of nominated multi-layered constructions. The thermo-physical properties (thermal conductivity (W/m.K), density (kg/m^3) and specific heat capacity (J/kg.K)) are modified if (1) the zonal dry bulb air temperature falls outside the temperature range specified by the control function sensor data, or (2) according to a time-schedule. (The latter option was the contribution from the present work). This control function is 'nested' within some other building control function.

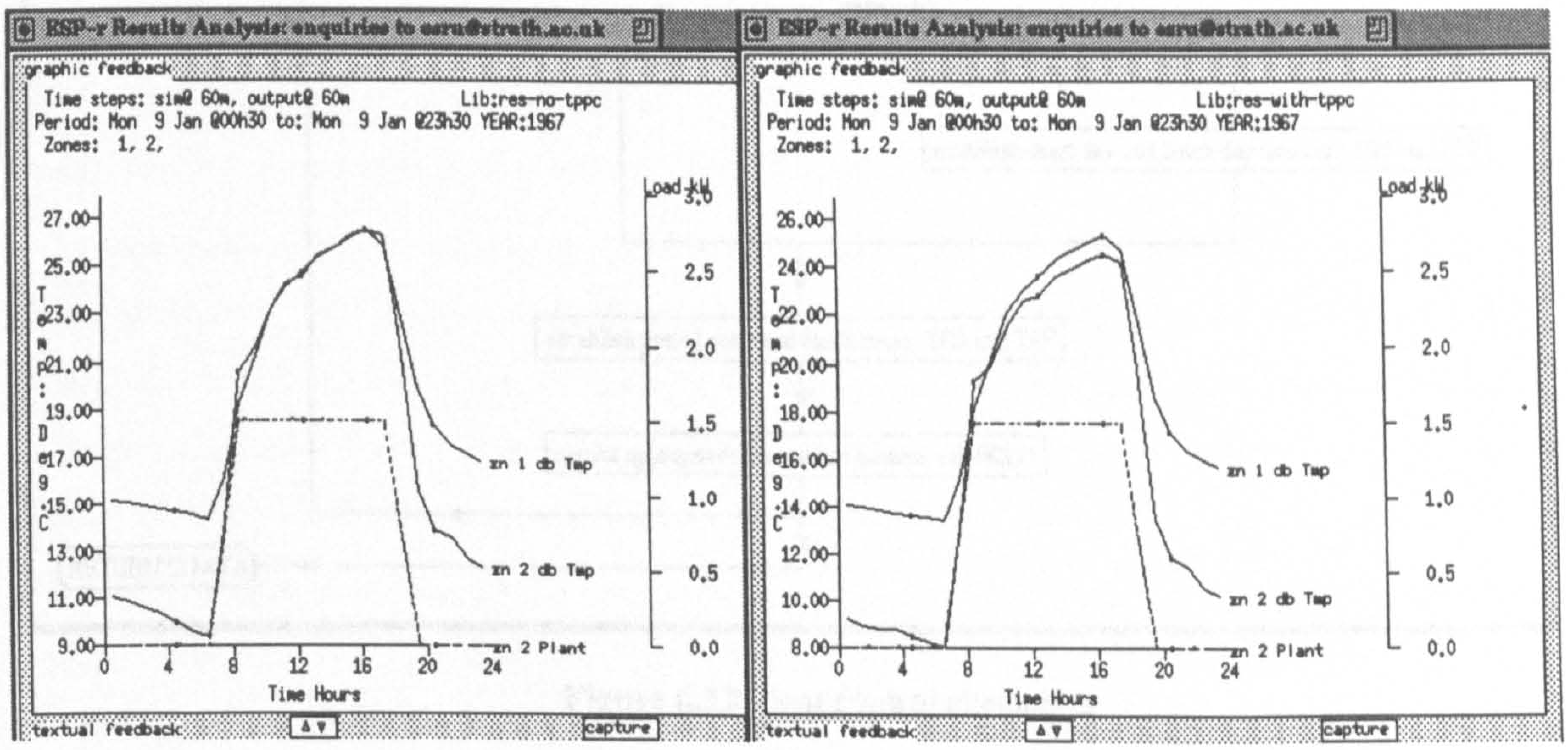
This control function is able to manipulate and impose up to three substitute constructions as follows:

- the sensed condition (air point temperature or time) is tested to see if it is within the specified substitution range;
- if so, for each specified construction, the substitute thermophysical properties are read from the construction database, and assigned to the appropriate item;
- if *adaptive gridding* is active, then redistribution of nodes throughout the new construction is necessary [Nakhi 1995].
- the building-side matrix equation is then re-established, as described in Section 3.3.3.

In order to demonstrate thermo-physical properties change control, consider the 3-zone building with time-scheduled property substitution control applied to two constructions partitioning zone_1 and zone_2. The control function models the time-dependent positioning of sliding partitions by substituting replacement sets of properties (Table 6.7) for the (identical) constructions between 07.00 and 18.00 hours - all other building configuration parameters remaining unchanged. Figure 6.11 shows the air point temperature and energy requirement profiles for a 1-day simulation, revealing a decrease in temperature levels for both zones when no partition is present.

Table 6.7. Materials thermo-physical properties change control schedule.

Control period	Layer_1 Thermal conductivity (W/m.K)	Layer_1 Density (kg/m^3)	Layer_1 Specific heat (J/kg.K)	Layer_2 Thermal conductivity (W/m.K)	Layer_2 Density (kg/m^3)	Layer_2 Specific heat (J/kg.K)	Layer_3 Thermal conductivity (W/m.K)	Layer_3 Density (kg/m^3)	Layer_3 Specific heat (J/kg.K)
Period_1 00.00-07.00	180	800.0	837.0	0.02	1.2	1005	180	800.0	837.0
Period_2 07.00-18.00	0.02	1.2	1005	0.02	1.2	1005	0.02	1.2	1005
Period_3 18.00-24.00	180	800.0	837.0	0.02	1.2	1005	180	800.0	837.0



```
Time steps: sim@ 60m, output@ 60m           Lib:res-no-tppc
Period: Mon  9 Jan @00h30 to: Mon  9 Jan @23h30 YEAR:1967
Zones:  1, 2,
```

```
Time steps: sim@ 60m, output@ 60m           Lib:res-with-tppc
Period: Mon  9 Jan @00h30 to: Mon  9 Jan @23h30 YEAR:1967
Zones:  1, 2,
```

(a) Original properties (b) Properties adjusted.

Figure 6.11 Thermo-physical properties change control.

6.3.2 PLANT CONTROL FUNCTIONS.

As elaborated elsewhere [Tang 1985, Hensen 1991 and Aasem 1993], plant components may have variables which are subjected to some control strategy. The plant-side control executive is depicted in Figure 6.12.

The functions now described are used to impose plant-side control function characteristics and constraints on the plant network. These functions firstly establish some sensed condition (based on latest computed values), process it according to the active control logic and subsequently return the result for processing by the plant-side solvers.

The supplementary data items required for each function are listed in Appendix B.

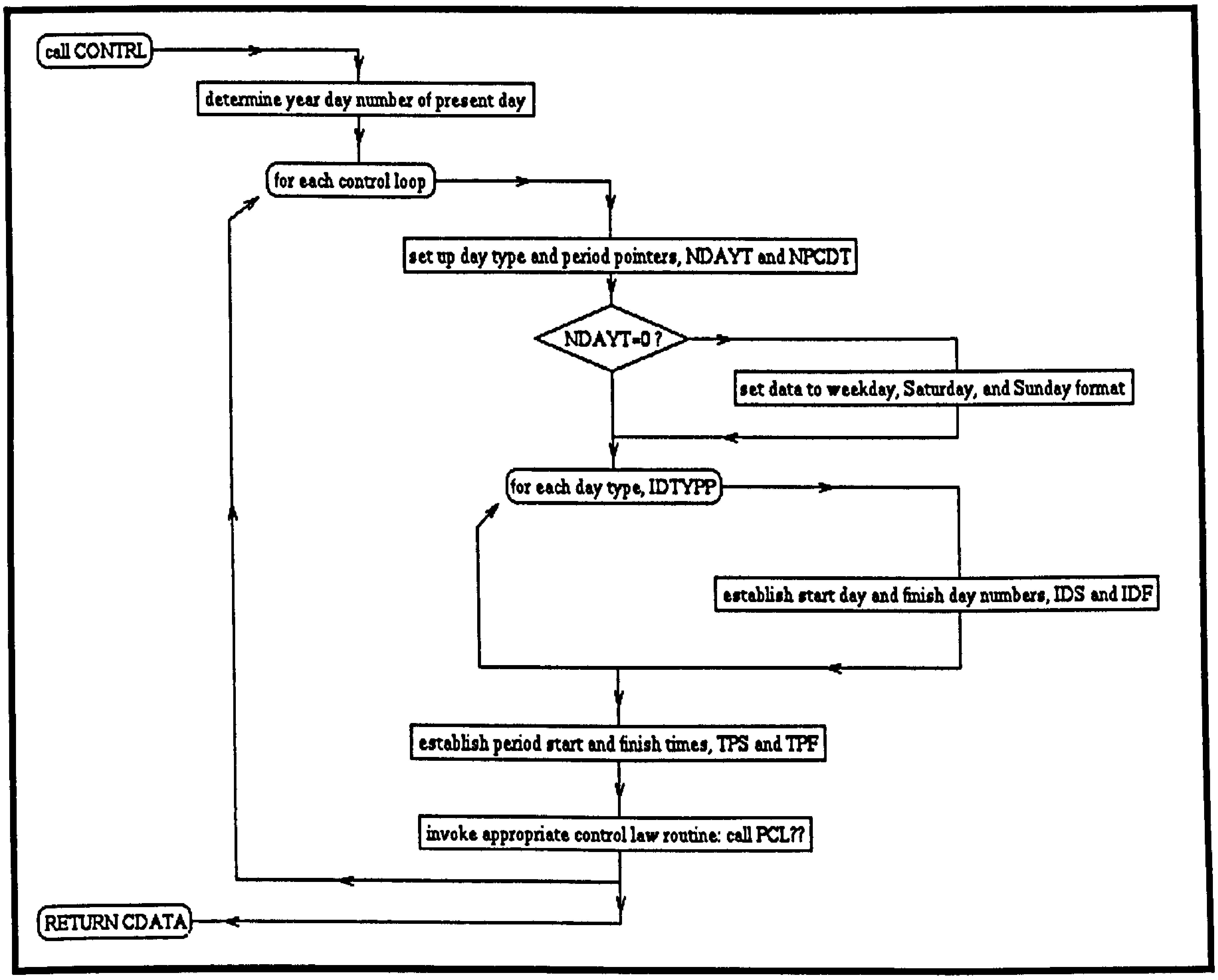


Figure 6.12 Plant control executive.

PCL01: PID (Proportional+integral+derivative) flux control function

PCL02: PID flow control function.

At project commencement, these functions existed as basic fixed set-point, non-recursive, positional PID controllers [Aasem 1993]. Several positional and incremental PID controller algorithms (recursive and non-recursive) described previously for the building-side, *BCL05* have been added during the present work. Additionally, two options are now available with these control functions: (i) *fixed set-point* for the duration of the control period and (ii) *dynamic set-point allocation* according to psychrometric principles. A fixed set-point is appropriate when modelling plant systems where the set-point is deemed not to change over the control period, e.g. thermostatic zone control for a wet central heating system. A dynamic set-point mode is required when modelling air conditioning PID control functions, such as year round change-over systems.

The dynamic set-point option invokes, at each simulation time-step, routines which access ESP-r psychrometric libraries in order to establish heating and cooling set-points for a range of air conditioning processes. The routines which compute the set-points access the ESP-r psychrometric library. All psychrometric-based control functions found in practical situations, and also customised routines, may be referenced from these control functions. One routine installed in ESP-r is now described.

Year round air-handling system. One of the most common and effective approaches to controlling temperature and relative humidity within a zone is to pre-heat the air, pass it through an air washer where it undergoes adiabatic saturation, and then re-heat/cool to the temperature at which it is to be supplied to the zone (Figures 6.13 and 6.14) [CIBSE 1979]. The pre-heating and adiabatic saturation permit the relative humidity in the zone to be controlled and re-heating allows the temperature therein to be properly regulated during year-round conditions. Two control loops need to be specified for this system: one for the pre-heat process and one for the re-heat process. An algorithm developed for the purposes of establishing (at every plant time-step) the setpoints for the pre-heater, re-heater, cooling coil and humidifier plant components [Kelly 1997] is described in Appendix B. This algorithm has been installed as an option in control functions *PCL01* and *PCL02*.

Humidity control employing psychrometric-based dynamic set-point adjustment can be contrasted with fixed pre-heat and re-heat set-points for the test zone problem. The controller schedules for this demonstration are listed in Table 6.8 from which it can be seen that in both cases, the control systems attempt to hold the zone relative humidity and zone air point temperature to set-points of 50% and 18 °C, respectively for the control period 06.00-18.00.

The results for a 1-day simulation period are shown in Figures 6.15(a) and 6.15(b) for fixed and dynamic set point cases, respectively. The temperature and plant profiles are both oscillatory, due to time-step averaging being disabled, use of a relatively large simulation time-step (15 minutes for building-side and 4 minutes for plant-side) and also that basic proportional control mode is active over the control period. As expected, the psychrometric-based controller, which dynamically adjusts set-points according to varying load conditions, holds the zone condition control points closer to the desired values than the fixed set-point controller.

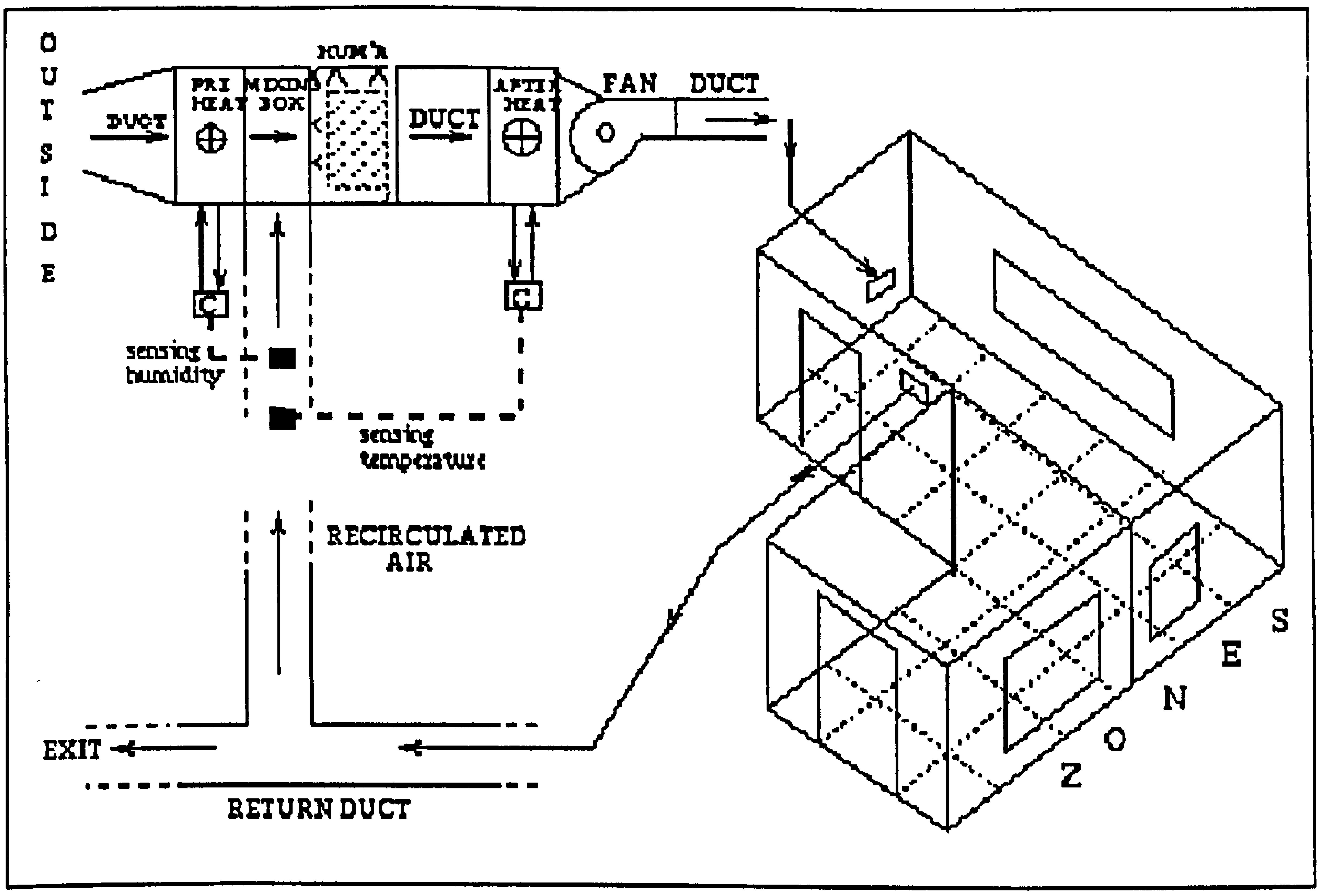


Figure 6.13 Year-round air-handling plant.

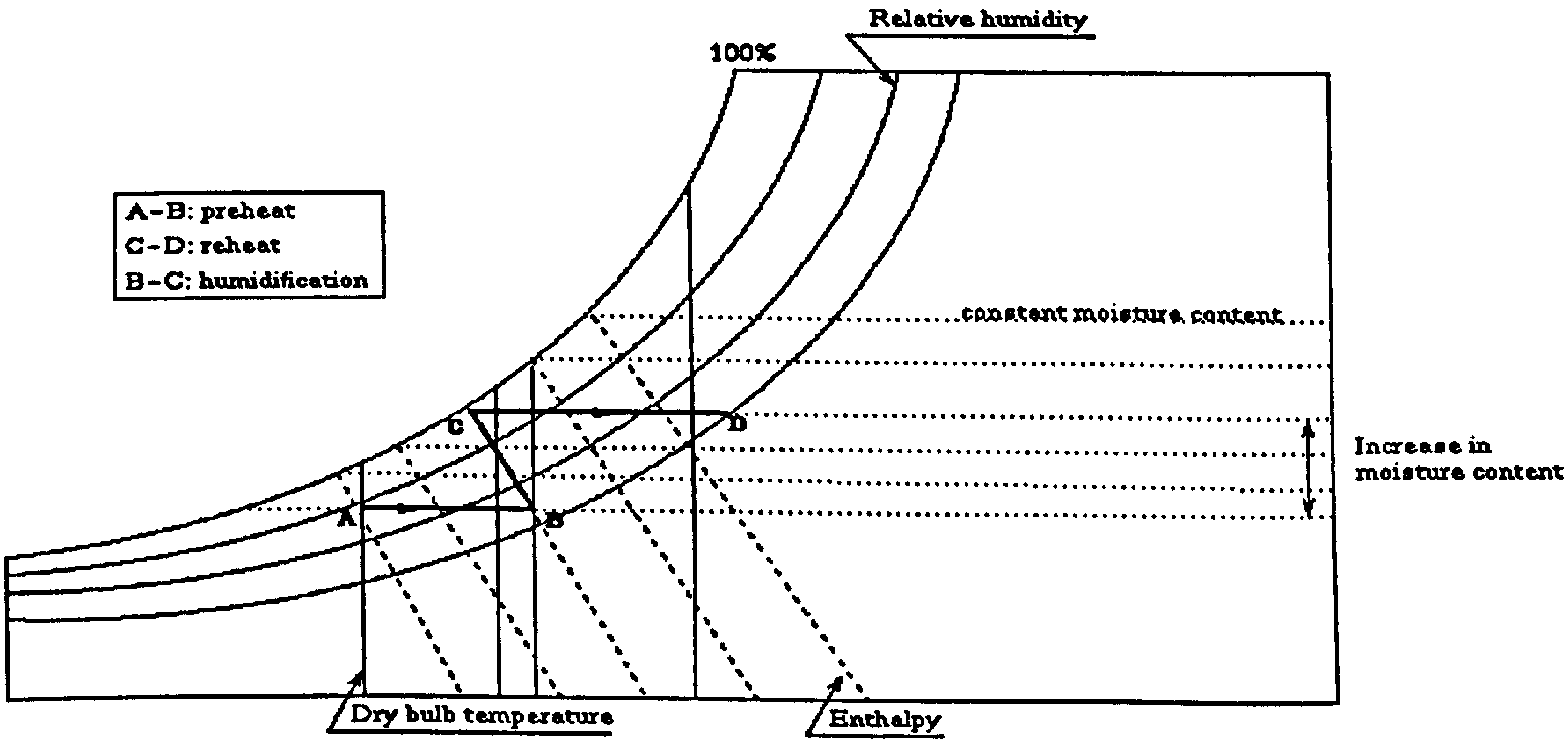
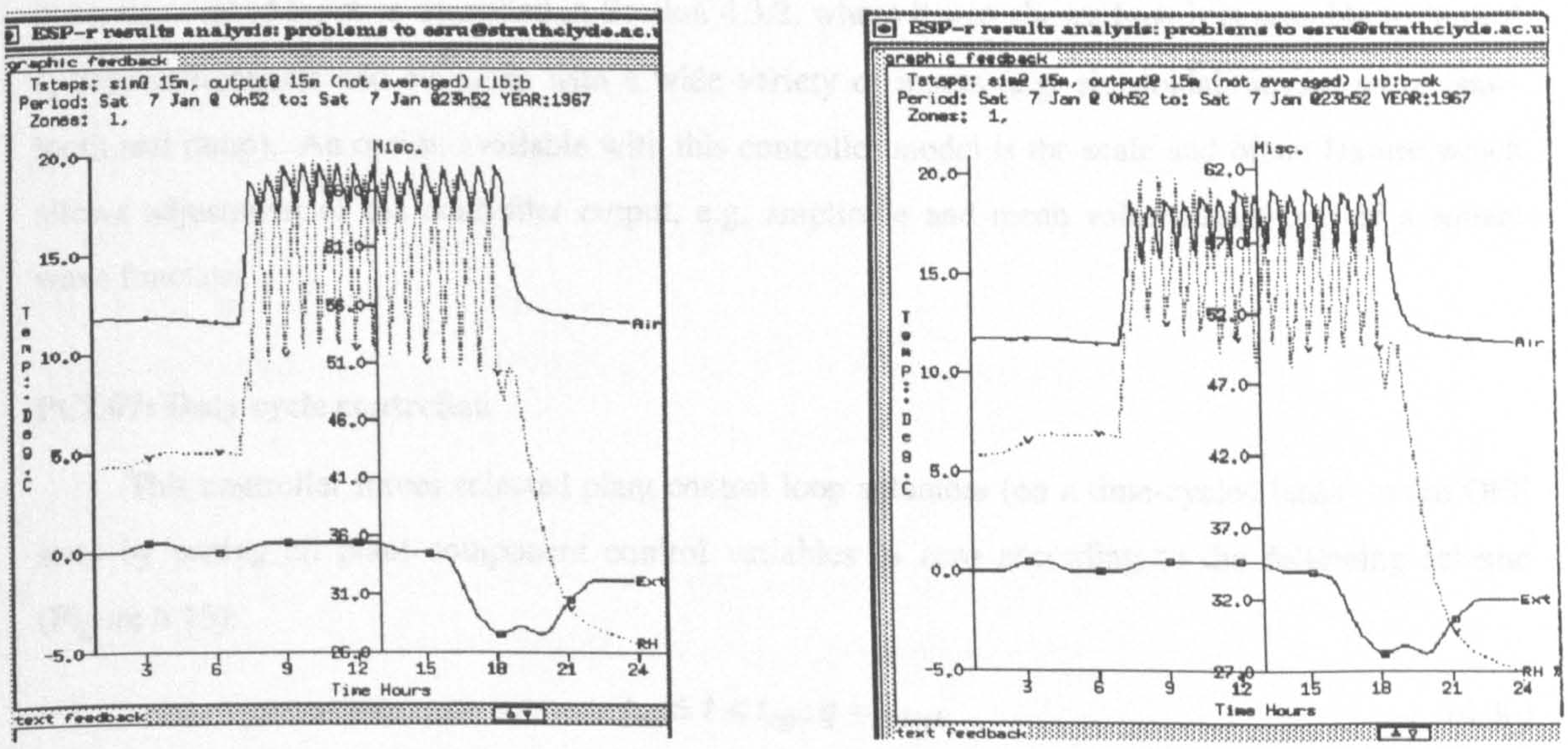


Figure 6.14 Heating cycle: psychrometric analysis.

Table 6.8: Air handling unit: controller schedules.

Sensing	Actuating	00.00-07.00	07.00-18.00		18.00-24.00
Pre-heat control loop.					
Sensing	Actuating	Mode	Mode	Set-point	Mode
Pre-heater exit air temp.	Heating flux	Free-float	Proportional	(a) 19 °C; (b) DS	Free-float
Re-heater control loop.					
Sensing	Actuating	00.00-07.00	07.00-18.00		18.00-24.00
		Mode	Mode	Set-point	Mode
Re-heater exit air temp.	Heating flux	Free-float	Proportional	(a) 30 °C; (b) DS	Free-float
Building link control loop.					
Sensing	Actuating	00.00-07.00	07.00-18.00		18.00-24.00
		Mode	Mode	Set-point	Mode
Zone air temperature	Zone air point	Free-float	Coupling function	50% RH; 18 °C	Free-float

Case (a): set-point fixed. Case (b) set-point adjusted according to pyschrometric-based algorithm



```
ESP-r results analysis: problems to esru@strathclyde.ac.u
graphic feedback
 Tsteps: sim@ 15m, output@ 15m (not averaged) Lib:b
Period: Sat  7 Jan @ 0h52 to: Sat  7 Jan @23h52 YEAR:1967
 Zones:  1,
```

```
ESP-r results analysis: problems to esru@strathclyde.ac.u
graphic feedback
 Tsteps: sim@ 15m, output@ 15m (not averaged) Lib:b-ok
Period: Sat  7 Jan @ 0h52 to: Sat  7 Jan @23h52 YEAR:1967
 Zones:  1,
```

(a) Fixed set-points **(b)** Dynamic set-points

Figure 6.15 Air-handling plant: zone humidity levels.

PCL04: Optimum start controller.

PCL04 is an optimum start controller which computes the optimum start time according to equation of Birtles and John [1985], which indicates the necessary start-up time necessary to reach desired temperature level at some specified time:

$$ln(DT) = A_o(T_p - T_d) + A_1 \qquad (6.28)$$

where DT is the preheat temperature difference (°C) between the desired temperature, T_d and the present sensed temperature, T_p, A_o is a constant associated with the thermal weight of the building and A_1 is a constant associated with the time between switching on the heating and the interior starting to heat up.

This algorithm (originally installed by Hensen [1991]) performs well in practical systems except at low outside temperature [Levermore 1992]. Thus the original Birtles and John algorithm was later amended by adding an outside air term to give:

$$ln(DT) = A_o(T_p - T_d) + A_1 + A_2 T_{ao} \qquad (6.29)$$

where A_2 is a constant associated with the outside air temperature, T_{ao}.
PCL04 generates either an OFF signal (before the optimum start time), or an ON signal (when at/past the optimum start).

PCL06: Null controller.

In a similar manner to the building-side version, this controller acts to set its output to be identical to that of the sensed input. This controller is typically used in conjunction with a signal generator sensed input as described in Section 4.3.2, where it was shown how it is possible to 'pulse' system components and elements with a wide variety of inputs (e.g. sinusoidal, square wave, saw-tooth and ramp). An option available with this controller model is the scale and offset feature which allows adjustment of the controller output, e.g. amplitude and mean value adjustment of a square wave function.

PCL07: Duty cycle controller.

This controller forces selected plant control loop actuators (on a time-cycled basis) to the OFF state by setting all plant component control variables to zero according to the following scheme (Figure 6.16):

$$t_{on} \le t < t_{off} : q = q_{high} \qquad (6.30)$$

$$t_{off} \le t < t_{on} : q = q_{low} \qquad (6.31)$$

where t is the simulation time, t_{on} and t_{off} are the times corresponding to the *ON* and *OFF* periods, respectively, q is the controller output signal and q_{high} and q_{low}, the respective maximum and minimum flux capacities (W).

Sensor and actuator delays (described in Section 5.4.2) are possible with this function.

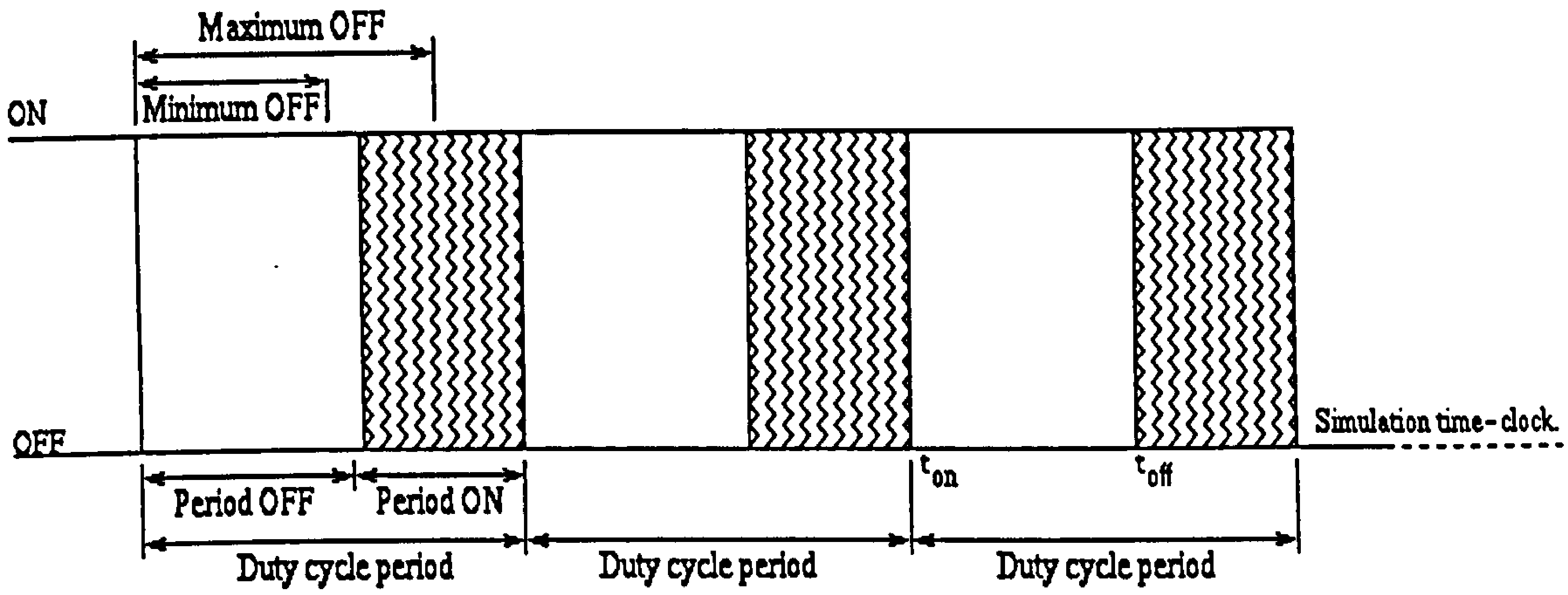


Figure 6.16 Duty cycle energy management function.

PCL08: 'Two-Position' controller.

This function models two-position control action according to the following scheme:

$$Z_{low} > \theta_c : q = q_{high} \tag{6.32}$$

$$Z_{high} > \theta_c > Z_{low} \text{and} q_{prev} > 0 : q = q_{high} \tag{6.33}$$

$$Z_{high} > \theta_c > Z_{low} \text{and} q_{prev} \leq 0 : q = q_{low} \tag{6.34}$$

$$Z_{high} < \theta_c : q = q_{low} \tag{6.35}$$

where Z_{low} and Z_{high} are the throttling range limits (°C), θ_c is the sensed condition, q is the controller output signal, q_{high} and q_{low} the respective maximum and minimum flux capacities (W) and q_{prev} the actuator output at the present time row.

Sensor and actuator delays (described in Section 5.4.2) are possible with this function.

PCL09: Multiple input two-position controller.

This function models two-position control action where the sensed value, θ_c, is a specified function (e.g. high, low, mean or weighted average) of the multiple sensed condition. For example, the controller output may be switched according to the lowest of a number of monitored zonal air point temperatures.

Sensor and actuator delays (described in Section 5.4.2) are available with this function.

PCL10: Zero energy band controller.

This function models *zero energy band* energy management, which is widely used in practical BEMS [Scheepers, 1991]. The user specifies the set-point and associated zero energy band (assumed to be symmetrical around the set-point). When the sensed condition is within the zero energy band, the actuator output is set to zero; otherwise the controller output is (within prescribed limits) a linear function of the sensed condition according to the following scheme (Figure 6.17):

$$Z_{d1} > \theta_c : q = q_h \tag{6.36}$$

$$Z_{u2} < \theta_c : q = q_c \tag{6.37}$$

$$Z_{d1} \le \theta_c \le Z_{d2} : q = k_h(Z_{d2} - \theta_c) \tag{6.38}$$

$$Z_{u1} \le \theta_c \le Z_{u2} : q = k_c(\theta_c - Z_{u1}) \tag{6.39}$$

where Z_{d1} and Z_{d2} are the heating throttling range limits (°C), Z_{u1} and Z_{u2} are the cooling throttling range limits (°C), θ_c is the sensed condition, q is the controller output signal, and k_h and k_c are the heating and cooling proportionality constants defined as follows:

$$k_h = \frac{q_h}{Z_{d2} - Z_{d1}} \tag{6.40}$$

and

$$k_c = \frac{q_c}{Z_{u2} - Z_{u1}} \tag{6.41}$$

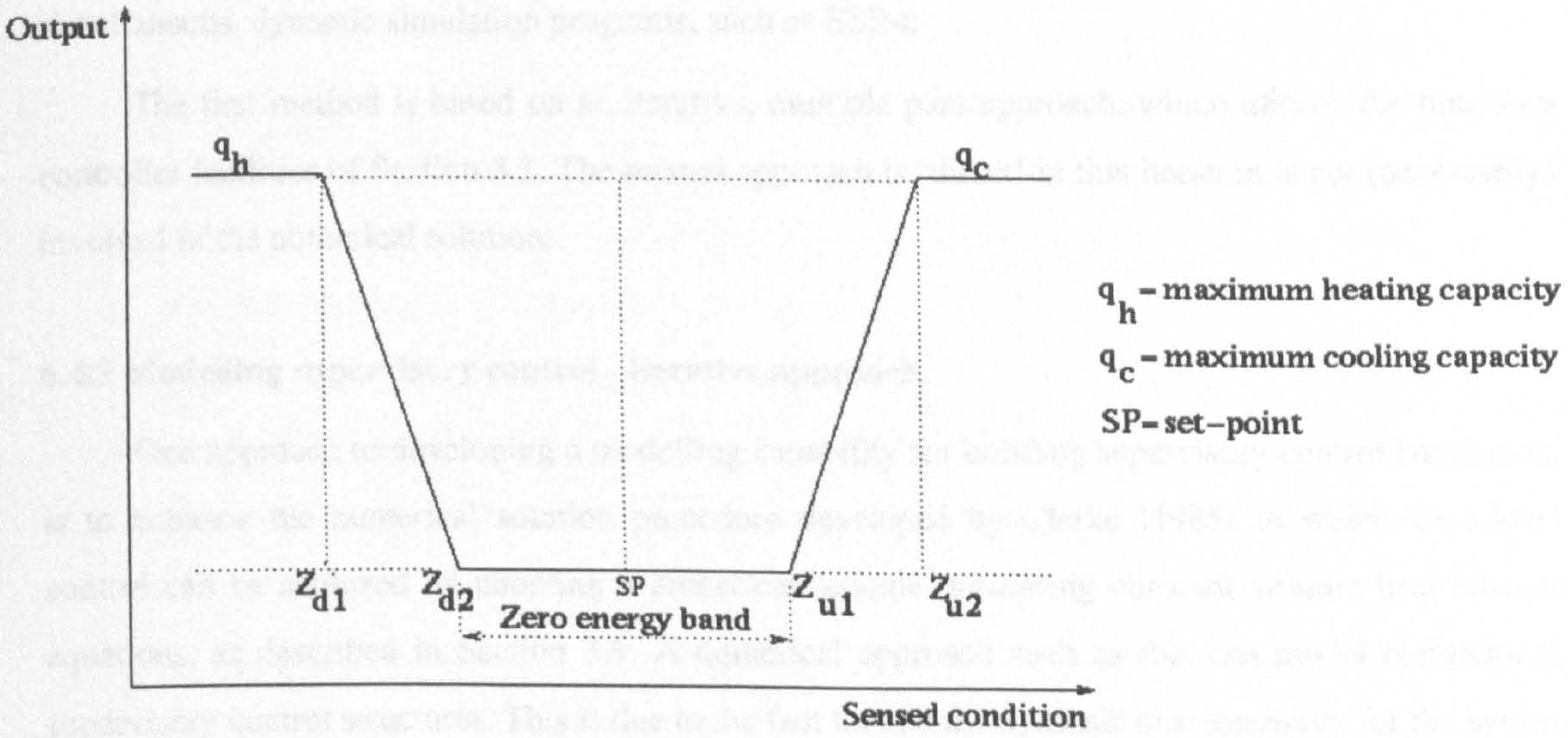


Figure 6.17 Zero energy band energy management function.

6.3.3 FLUID FLOW CONTROL FUNCTIONS.

As elaborated elsewhere [Hensen 1991 and Negrao 1995], fluid flow network components and/or connections may have variables which are subjected to some control strategy. The function now described is used to impose flow-side control function characteristics and constraints on the flow network. Flow functions establish some sensed condition (based on latest computed values), process it according to the active control logic and return the result for processing by the flow-side solvers. The supplementary data items required for the function are listed in Appendix B.

FCL01: Fluid flow controller with hysteresis.

This controller (installed prior to project commencement) acts to linearly modulate fluid flow components or fluid flow connections according to the sensed conditions. User-specified component (valve/damper) hysteresis non-linearity is accounted for in this model, to effectively retard the controller response to the sensed conditions. This controller was enhanced during the course of the project by incorporation of integral and derivative action as described earlier for **BCL05** and BPCL01/2 controllers.

6.4 SYSTEM-LEVEL CONTROL FUNCTIONS.

6.4.1 Modelling approaches.

The modelling approach applied to hierarchical systems is clearly dependent on the program type: simultaneous or sequential, transfer function or numerical methods, and so forth. This section describes two alternative approaches to the modelling of multiple-input, multiple-output (MIMO), hierarchical, cascaded control systems, both of which are suitable for inclusion in discrete time, simultaneous, dynamic simulation programs, such as ESP-r.

The first method is based on an iterative, multiple pass approach, which utilises the time-step controller facilities of Section 5.3. The second approach is 'direct' in that iteration is not (necessarily) involved in the numerical solution.

6.4.2 Modelling supervisory control - iterative approach.

One approach to developing a modelling capability for building supervisory control simulation, is to enhance the numerical solution procedure developed by Clarke [1985] in which zone-level control can be achieved by adopting a numerical scheme processing constant volume heat balance equations, as described in Section 3.4. A numerical approach such as this can model hierarchical, supervisory control structures. This is due to the fact that all the dynamic characteristics for the system are held in the form of building control system equation sets, which provide the means to orchestrate, supervise and optimise the entire system simulation according to a global control logic scheme. One method of numerical matrix processing facilitating such a scheme is now described (Figure 6.18).

Stage 1: Proceed as described in Section 3.4 to reduce, by direct elimination, the construction matrices and, subsequently, the zone matrices to extract the building control system equation set. The unknowns, as before, are solved by introducing a zone-level control strategy (if any) to allow determination of plant flux and zone air/surface/intra-constructional temperature;

Stage 2: The building control system equation set are stored in a system-level matrix for subsequent processing by the system-level control supervisor at *Stage 4*;

Stage 3: The zonal future time-row values produced at Stage 1 are backward substituted in the matrix process to allow determination of all other nodal temperatures;

Stage 4: Once all zones have been processed in this way, and prior to a second pass at the current time-step, *all* building control system equation sets (now held in the system-level matrix) are subjected to supervisory control logic. The system-level supervisor reviews each of the proposed zone-level control states and amends, substitutes and overrides them according to the global control function logic, which may be based on, e.g. time-and-event based control logic, user-defined logic statements, artificial intelligence algorithms, etc.

Stage 5: Once the system-level supervisor has processed *all* building control system equation sets, a simulation time-step controller, *TSCON_8* (Section 5.3.5), is invoked which enables a second pass at the same time-step with identical construction and zone matrices as those at the first pass, i.e. *all* zones are re-processed for a second time at the current simulation time-step.

Stage 6: At the second pass when the building control system equation set is extracted, the unknowns are solved, not using zone-level control logic as was done at the first pass, but by re-calling from memory the control states as determined at *Stage 4* by the control supervisor for the zone currently being processed. These values are then backward substituted in the reduced zone matrices to allow determination of all nodal temperatures.

It is possible to incorporate further iteration into this strategy. For example, if, after a second pass at a given time-step in the simulation, a global control function results in one or more undesirable zonal conditions, then *Stages 4-6* can be repeated until consecutive values of some criteria converge to within some user-defined tolerance.

This numerical technique facilitates the simulation of commonly occurring BEMS system-levels functions such as zone phasing, duty cycling, capacity demand management, time-and-event schedule control, etc., i.e. situations where supervisory controllers act to resolve conflict and prioritise in the event of contention. Algorithms based on the iterative approach outlined above, together with their implementation in ESP-r, are now presented. (Note that definition data items required for these control functions are listed in Appendix B.)

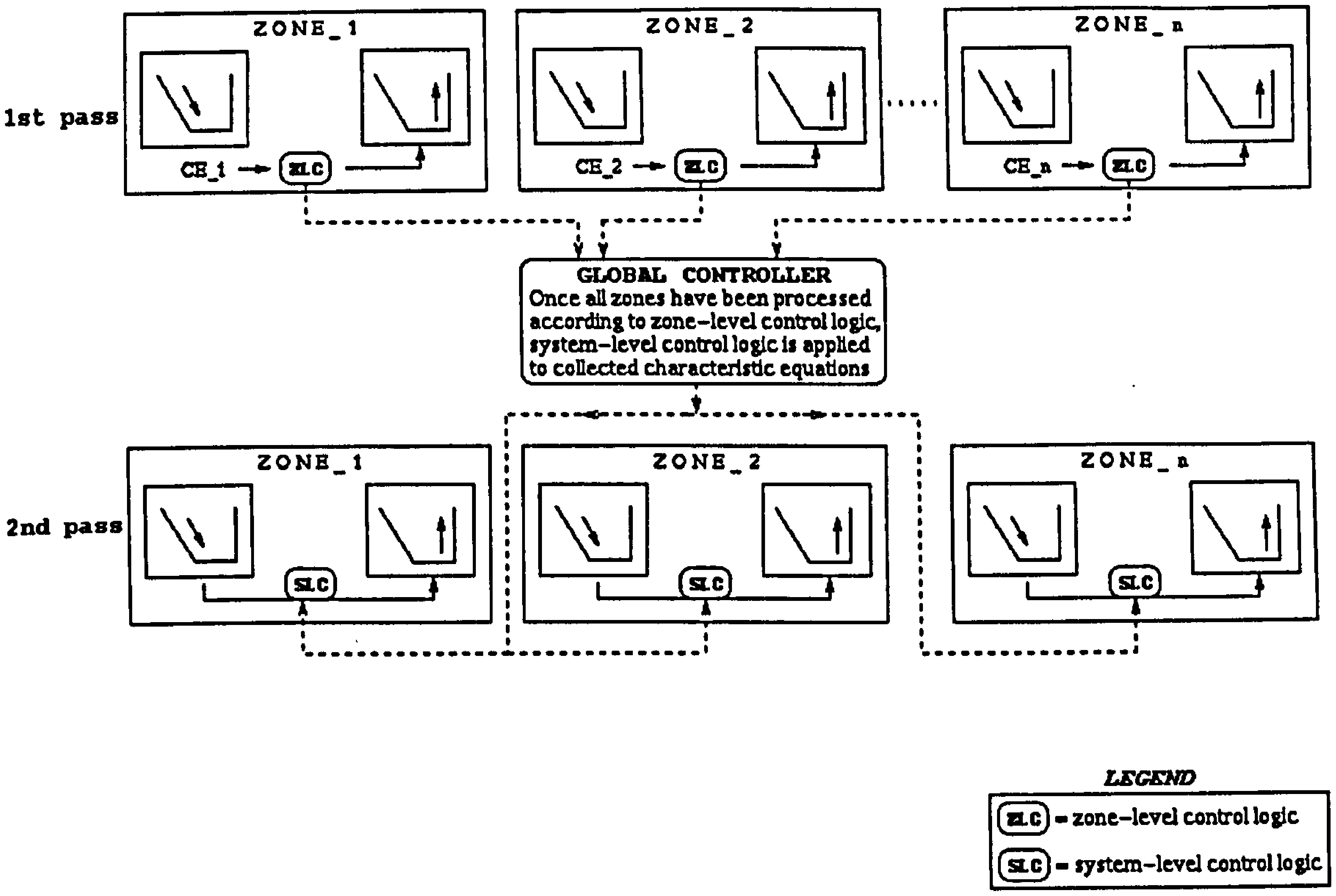


Figure 6.18 Modelling global controller: iterative approach.

6.4.3 Global Control Functions

GCL01: Global on-off controller.

This system-level controller acts to zero individual control loop actuator outputs if:

(mode_1): a user-specified number of control loops have non-zero actuator signals at the first pass;

(mode_2): the sensed condition is greater than the set-point.

For example, consider a 5-zone energy management control loop system with the mode set to '1' and the minimum number of control loops having non-zero actuator signal set to '3'. If at the end of the first pass, the individual control loop status indicates that none, 1 or 2 of the 5 loops have OFF status (i.e. B3 = 0), then this status is maintained and allocated at the 2nd pass at this time-step. If, on the other hand, at the end of the first pass, the individual control loop control status indicates that 3, 4 or all of the 5 loops are OFF, then the actuator output of all five control loops are zeroed at the 2nd pass. In any event, at the end of the 2nd pass, the simulation time-clock is forwarded to the next time-step and the simulation proceeds.

GCL02: Global capacity management controller.

This global controller acts to sequentially zero nominated individual control loop actuator outputs in order to limit the total system flux capacity to within user-defined limits. Again, after the 1st pass at any given simulation time-step, the individual control loop status values are determined in the conventional ESP-r manner. The output of all control loops are summed to obtain the system requirement. If this value is within the specified range, then at the 2nd pass the individual control loop status values, as computed at the 1st pass, are allocated. If, on the other hand, the system requirement is outwith the specified capacity limits, then user-defined control loop actuator outputs are zeroed until the revised system energy requirement is within range.

As an example, consider a 5-loop system. If the user has specified 3 control loops (LOOP_3, LOOP_1 and LOOP_4) which may be shed to satisfy capacity limits, then the actuator signal for these loops will be *sequentially* zeroed until the revised total system output is within capacity limits. If, having sequentially switched off (zeroed) all specified loops, the revised system energy requirement still exceeds capacity limits, then all nominated outputs are zeroed whilst the remaining outputs maintain their status as computed at the 1st pass.

GCL03: Global sequence controller.

This global controller facilitates the simulation of global phasing strategies. An energy demand reduction strategy commonly adopted in a BEMS involves individual control loop actuators being activated with the precondition that nominated control loops have ON status. For example, consider the following 3-loop control scheme. The user-specified number of scheduled loops may be set to '3', with sequence, say: LOOP_3, LOOP_1 and LOOP_2. Thus, LOOP_3 and LOOP_1 output must *both* be non-zero for LOOP_2 to be activated else LOOP_2 will be zeroed (at the 2nd pass) at this time-step. A sample control scheme for the 3-loop example is shown in Table 6.9 and Figure 6.19, where all combinations of sequencing are assessed.

GCL04: Global parameter reset controller.

One of the most common BEMS supervisory control functions is the resetting of local loop controller set-points in an attempt to reduce energy demand. This global controller acts to dynamically reset *any* local zone-level control function (*x_fnc*) miscellaneous data item, (*x_md*) to some user-specified value (*x_reset*). Any miscellaneous data item may be dynamically reset: set-point, integral action time, throttling range, offset, etc. This may be extended to conditional reset according to some sensed variable, as specified by the global sensor definition. The effect of resetting a building control function set-point according to external temperature is shown in Tables 6.10(a) and 6.10(b) and Figures 6.20(a) and 6.20(b) (case *a* for no global control active and case *b* for global parameter reset active). Here, the zone air temperature set-point is reduced from 20 °C to 17 °C in the event of the external air temperature falling below 0 °C.

GCL05: Global scale and offset controller.

This system-level controller acts - according to a range of global logic conditions - to scale and/or offset the zone-level controller outputs evaluated at the first pass. Scaling/offset is active in the event that the (global) sensed condition (mode_1), or rate of change of sensed condition (mode_2), exceeds the user-specified set-point. This controller allows the modelling and appraisal of *centralised trimming* control strategies; for example, this global controller may be set up to reduce all/selected zone-level controller outputs by 30% if the external relative humidity exceeds a given value.

GCL06: Global free-float controller.

This system-level controller should be specified during control periods where *no* global strategy is assumed to be active. No supplementary data items are required.

6.4.4 Modelling system-level controllers - non-iterative approach.

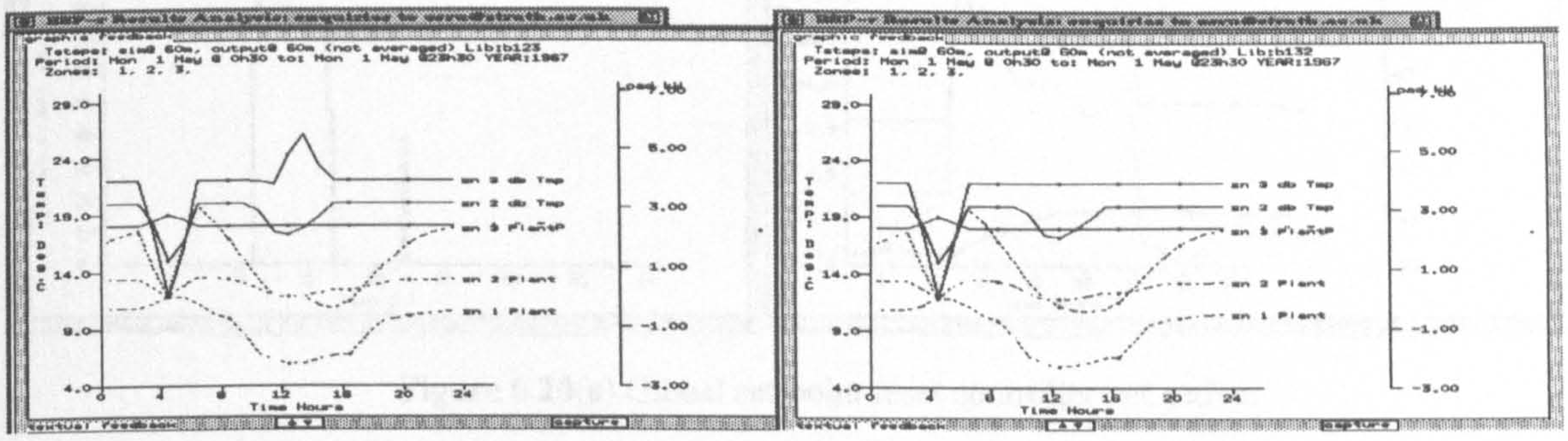
Non-iterative methods for modelling hierarchical MIMO systems are now investigated. An example of how supervisory control is modelled in an non-iterative manner in sequential type energy simulation programs, is the TRNSYS TYPE 99 Supervisory Controller for Air Handling Unit (AHU) and Variable Air Volume (VAV) systems [Corrado and Mazza 1990]. In this supervisory controller model (Figure 6.21), 42 input variables are obtained from sensors and 28 output variables are sent to control devices. Modifiable control algorithms include 12 on-off controllers and 11 PID controllers.

A non-iterative approach to the modelling of hierarchical MIMO systems suitable for the incorporation in the modular, simultaneous, dynamic simulation program, ESP-r, is now presented. As elaborated in Section 3.4, zone-level building-side control functions are processed, at any given time-step, in a sequential manner, each subsystem control function operating on the most recently computed future time-row values. In the non-iterative approach to systems-level controller modelling, all subsystem controller outputs, at each time-step, are continuously fed to the global controller for processing (Figure 6.22). Unlike the iterative approach - in which global control logic is applied only after all zone-level building control functions have been processed at the first pass - this 'direct' method processes all zonal subsystem control functions as they are computed and fed to the global controller at the first pass. In this way, the control functions are processed in much the same way as are *practical,* multiplexed, cascaded BEMS zone-level control functions, i.e. continual resetting of set-points, logic parameters, etc.

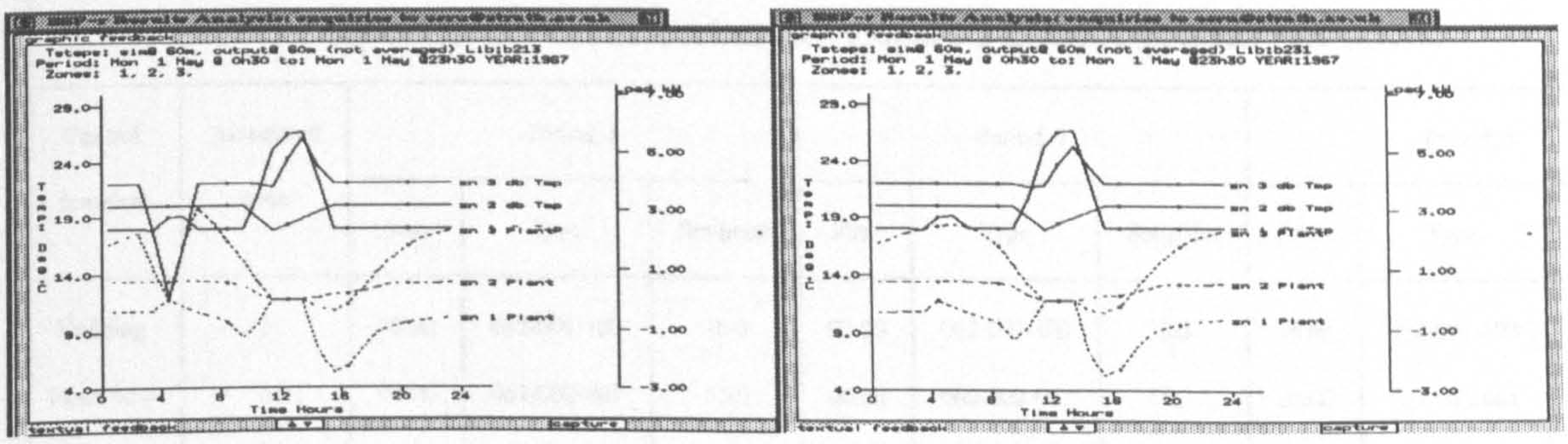
A global controller model based on this approach is now presented.

Table 6.9: Global sequence controller, control schedule.

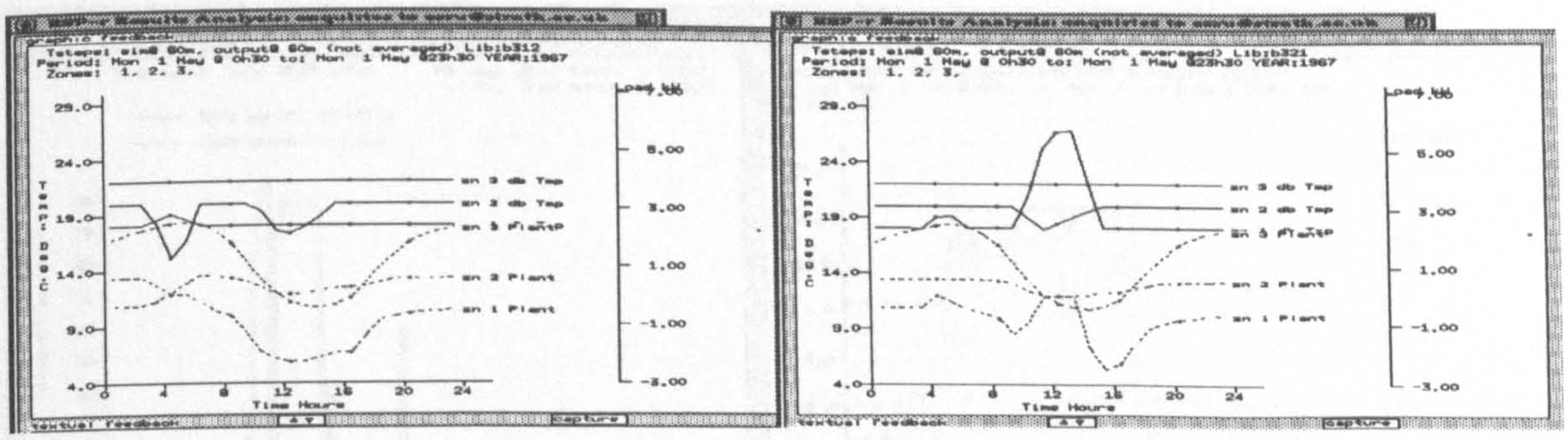
Control function type	Associated zone	Period_1		Period_2		Period_3	
		Start	Law	Start	Law	Start	Law
Building	1	00.000	Ideal	03.00	Free-float	05.00	Ideal
Building	2	00.000	Ideal	10.00	Free-float	14.00	Ideal
Building	3	00.000	Ideal	00.000	Ideal	00.000	Ideal
Global	All	00.000	Sequence	00.000	Sequence	00.000	Sequence



(a) Sequence: 1-2-3 **(b)** Sequence: 1-3-2



(c) Sequence: 2-1-3 **(d)** Sequence: 2-3-1

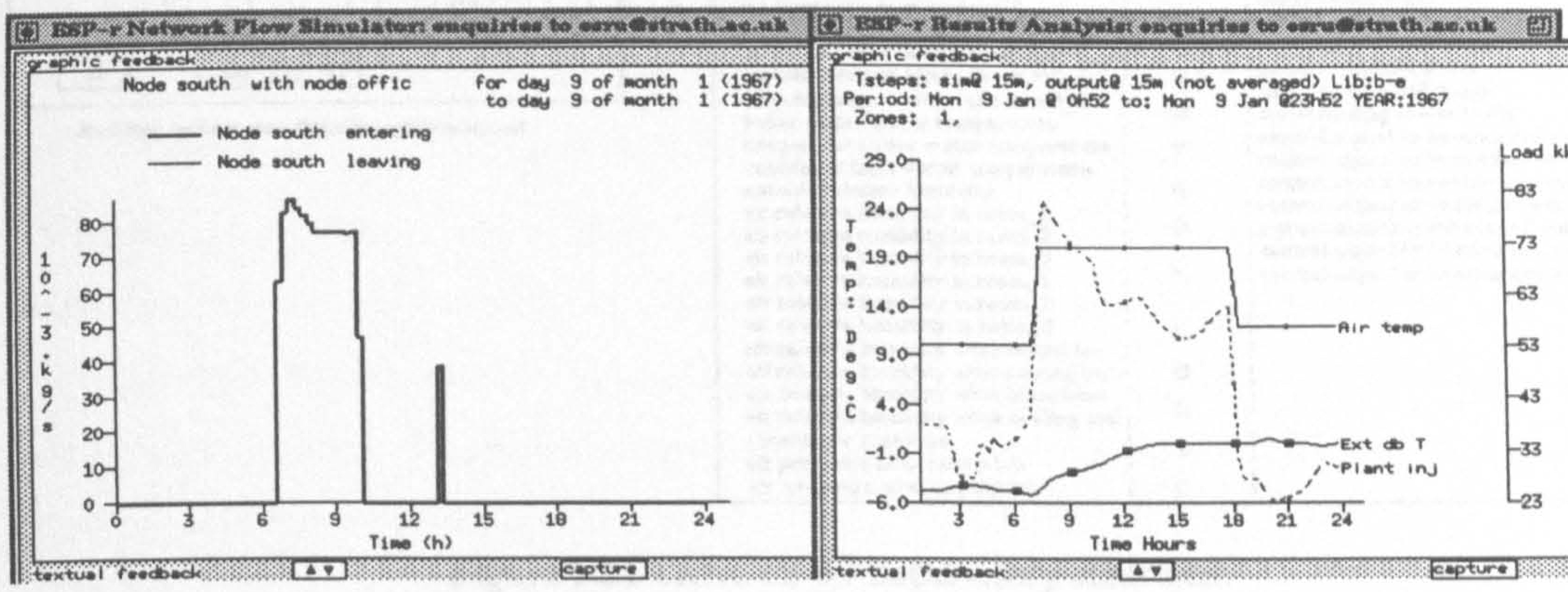


(e) Sequence: 3-1-2 **(f)** Sequence: 3-2-1

Figure 6.19 Global sequence control.

Table 6.10(a): Control schedule - no active global control.

Control function	Assoc. zone	Period_1			Period_2			Period_3		
		Start	Type	Set-point	Start	Type	Set-point	Start	Type	Set-point
Building	1	00.00	062-001-103	10.0	07.00	062-001-110	20.0	18.00	062-001-110	12.0
Fluid flow	1	00.00	062-002-081	15.0	00.00	062-002-081	15.0	00.00	062-002-081	15.0



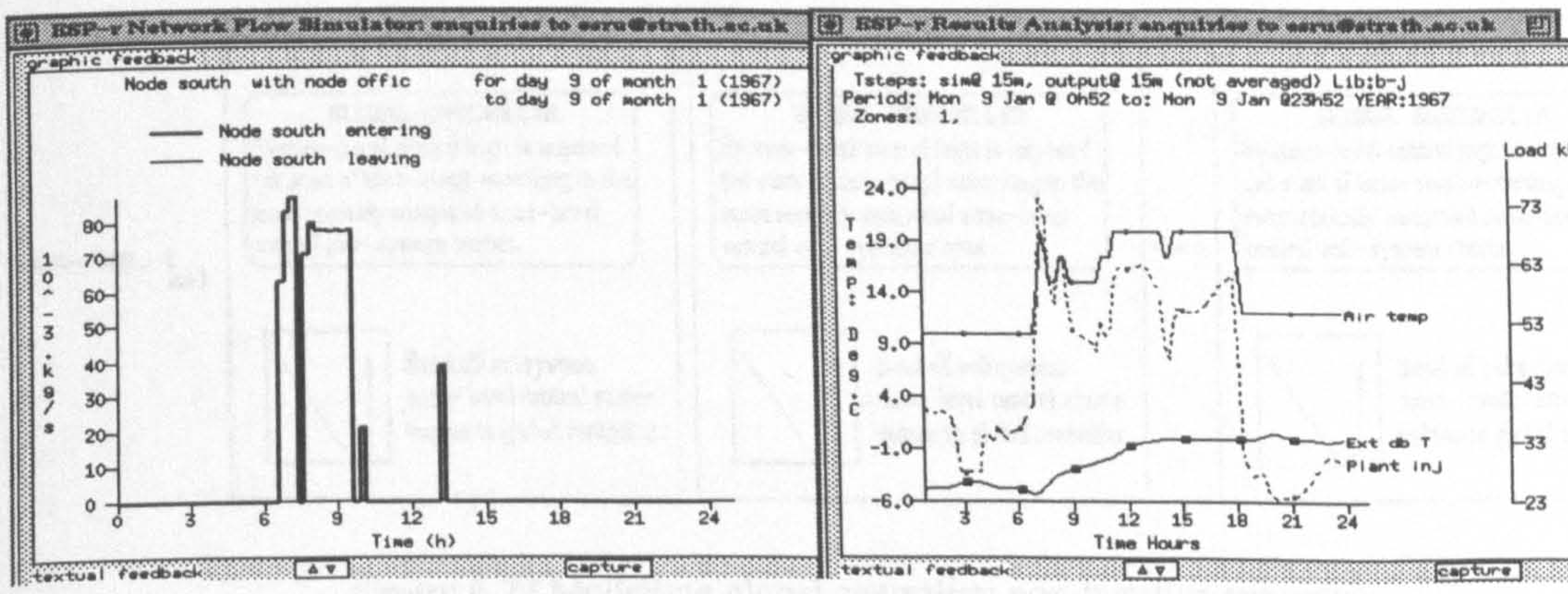
```
Node south  with node offic        for day  9 of month  1 (1967)
                                    to day  9 of month  1 (1967)
```

```
Tsteps: sim@ 15m, output@ 15m (not averaged) Lib:b-e
Period: Mon  9 Jan @ 0h52 to: Mon  9 Jan @23h52 YEAR:1967
Zones:  1,
```

Figure 6.20(a) Global set-point reset controller not active.

Table 6.10(b): Control schedule - global set-point reset controller active.

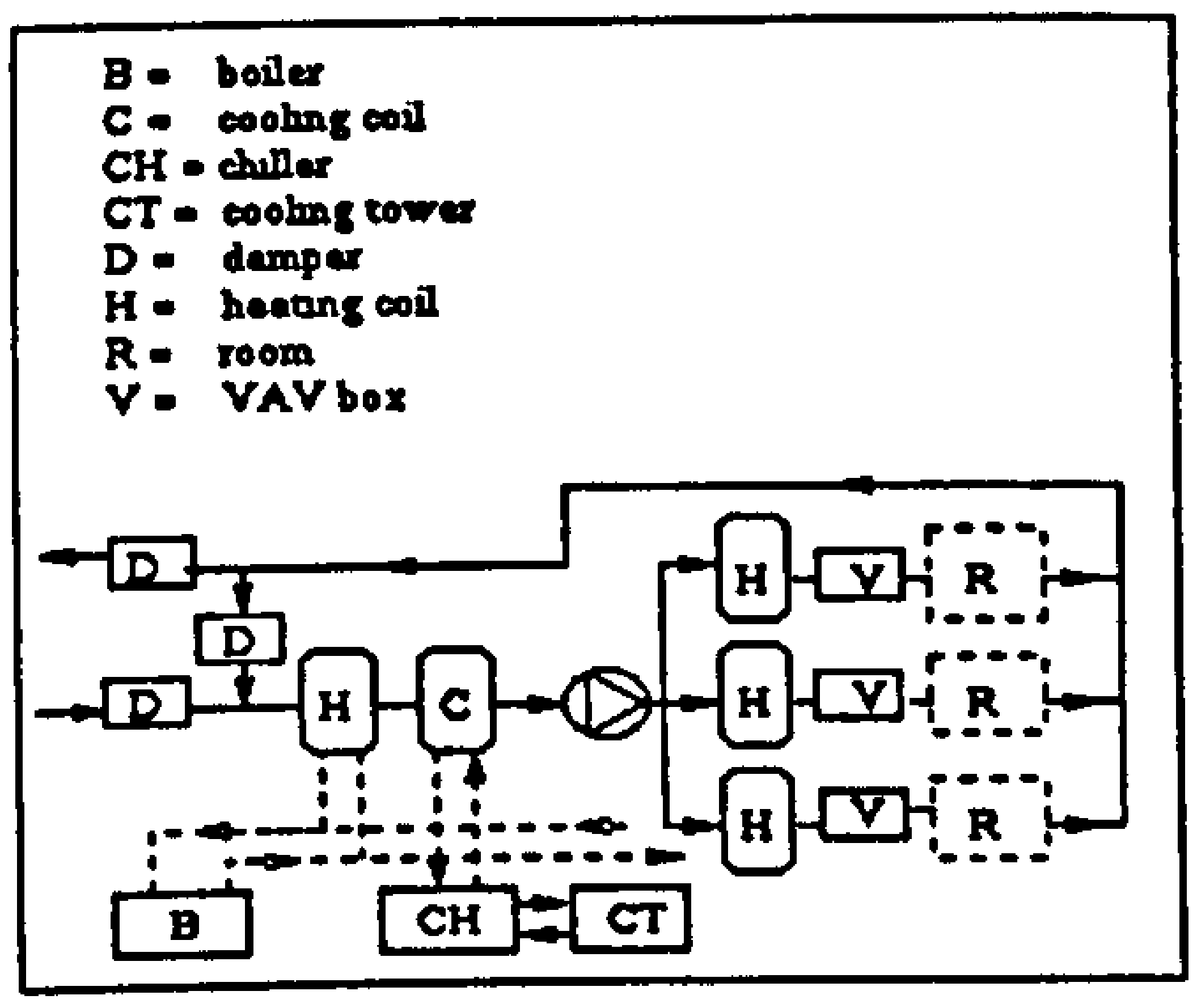
Control function	Associated zone	Period_1			Period_2			Period_3		
		Start	Type	Set-point	Start	Type	Set-point	Start	Type	Set-point
Building	1	00.00	062-001-103	10.0	07.00	062-001-103	20.0	18.00	062-001-103	12.0
Fluid flow	1	00.00	062-002-081	15.0	00.00	062-002-081	15.0	00.00	062-002-081	15.0
Global	All	00.00	Free-float	-	00.07	009-046-161	00.00	18.0	Free-float	-



```
Node south  with node offic        for day  9 of month  1 (1967)
                                    to day  9 of month  1 (1967)
```

```
Tsteps: sim@ 15m, output@ 15m (not averaged) Lib:b-j
Period: Mon  9 Jan @ 0h52 to: Mon  9 Jan @23h52 YEAR:1967
Zones:  1,
```

Figure 6.20(b) Global set-point reset controller active.



Building and air-conditioning system layout.

TRNSYS TYPE 99 - Supervisory controller

Inputs

year
month
day
hour
outside air temperature
air temperature in room_1
air temperature in room_2
air temperature in room_3
air temperature in plenum_1
air temperature in plenum_2
air temperature in plenum_3
extract air temperature
air temperature after return fan
air temperature after mixing box
air temperature after heating coil
air temperature after humidifier
air temperature after cooling coil
air temperature after supply fan
air temperature after duct_1
air temperature after duct_2
air temperature after duct_3
air temperature after reheat coil_1
air temperature after reheat coil_2
air temperature after reheat coil_3
boiler outlet water temperature
evaporator outlet water temperature
condenser inlet water temperature
outside relative humidity
air relative humidity in room_1
air relative humidity in room_2
air relative humidity in room_3
air relative humidity in room_1
air relative humidity in room_2
air relative humidity in room_3
air relative humidity after return fan
air relative humidity after mixing box
air relative humidity after humidifier
air relative humidity after cooling coil
outside air pressure
air pressure after return fan
air pressure after supply fan

SUPERVISORY CONTROL LOGIC

Outputs

on/off plant
on/off supply fan
on/off return fan
on/off boiler
on/off chiller
on/off cooling tower fan
supply fan static pressure
extract/supply flow rate ratio
boiler outlet water temperature set point
cooling tower fan speed control
air mass flow rate through VAV box_1
air mass flow rate through VAV box_2
air mass flow rate through VAV box_3
control signal to mixing box
on/off boiler pump
on/off heating coil pump
on/off reheat coils pump
on/off humidifier pump
on/off cooling coil pump
on/off cooling tower pump
control signal to heating coil valve
control signal to humidifier valve
control signal to cooling coil valve
control signal to cooling tower valve
control signal to reheat coil valve_1
control signal to heating coil valve_2
control signal to heating coil valve_3

Figure 6.21 TRNSYS-99 Supervisory controller.

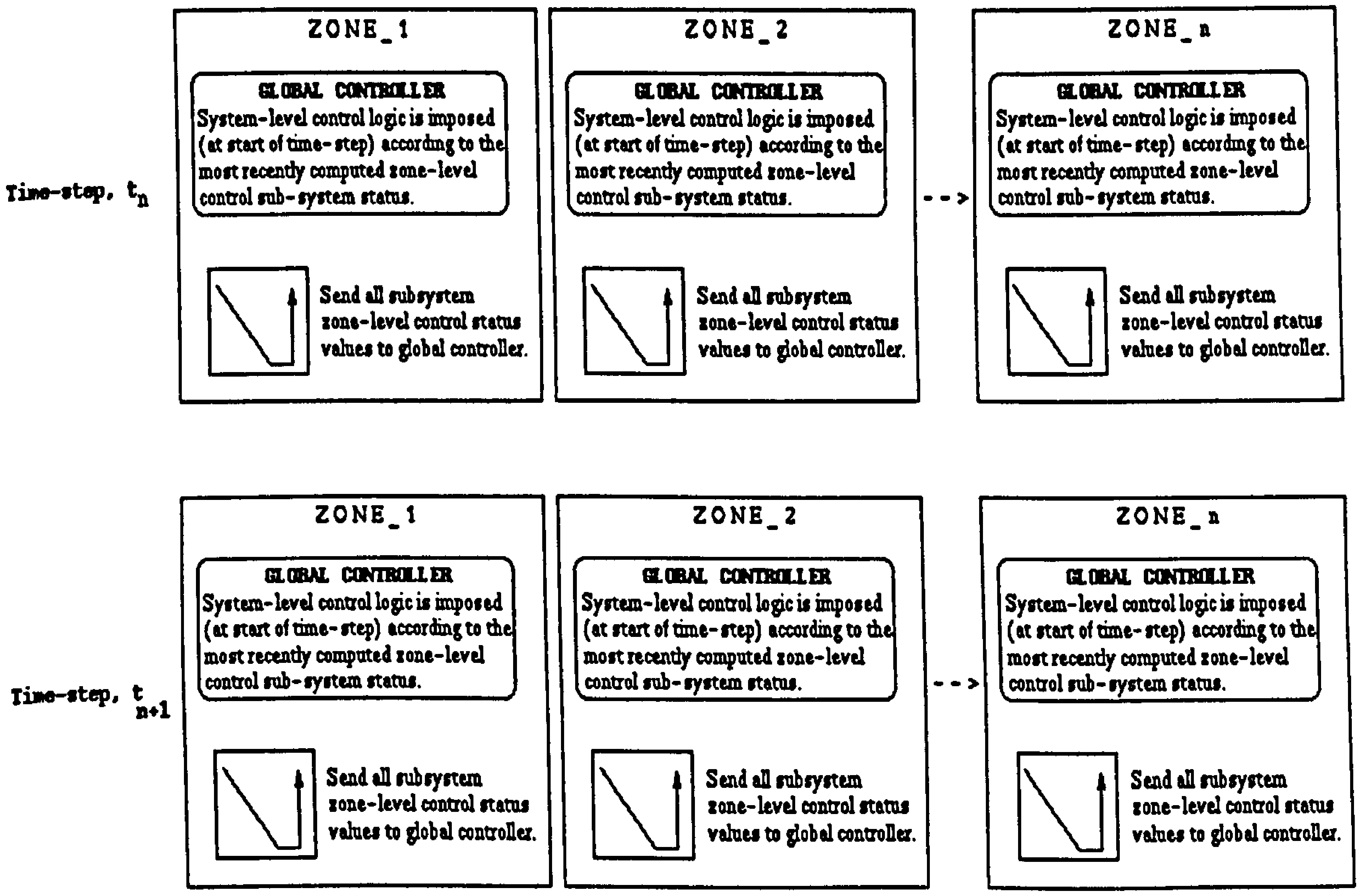


Figure 6.22 Modelling global controller: non-iterative approach.

Discharge global controller.

Discharge control of cooling coil with damper sequencing is one commonly adopted BEMS global control strategy. A schematic diagram of a *Honeywell Chiller Discharge Global Controller* [Honeywell 1989] is shown in Figures 6.23(a) and 6.23(b). The system consists of minimum and maximum outdoor damper air control loops and a cooling valve control loop integrated with an energy management optimum start control loop. Controller elements include PID (split range) together with logical AND elements. The global controller receives inputs from the fan differential pressure sensor, the outside air temperature sensor, the discharge air temperature sensor and the zone air temperature sensor. Global actuation set-points are the return damper, the maximum outside air damper, the minimum outdoor air damper and the chiller control valve.

Sequence of Operation. On a rise in discharge air temperature, the discharge air PID operator modulates the maximum outdoor air damper open in sequence with the chiller valve to maintain the set discharge temperature. The sequencing ranges (Parameters 6,7,8, and 9) are field adjustable parameters. Any time the outdoor temperature exceeds the set point, the maximum outdoor damper closes and the return damper opens.

Optimum start program. When the fan runs (switched on by the optimum start/ occupancy routine, and indicated by the differential pressure signal), the plant/control system is enabled.

Maximum outdoor damper control. The digital output of the logic operator is 1 any time the outdoor air temperature is less than Parameter 2. This signal is *ANDed* with the fan logic signal: a resultant 1 output indicates the damper is under control of the PID operator (top range); a resultant logic 0 sets the damper to a minimum.

Cooling valve control. When the fan is OFF, the differential pressure from the fan sensor is a logic 0, which subsequently closes the chiller valve. When the signal is a logic 1, however, the PID controller (low range) with gain Parameters 3,4 and 5 is in charge of the cooling valve.

Minimum outdoor damper control. The fan signal is *ANDed* with a true (logic 1) from the optimum start/occupancy schedule controller; a resultant logic 1 signal opens the damper.

In ESP-r, the following zone-level control loops are required for the discharge global controller described above.

- One building side controller, *BCL06*, to couple the plant system to the building zone.
- Two fluid flow proportional controllers, *FCL01*, one for the return/ maximum air damper and one for the minimum outside air damper.
- Two plant controllers: *PCLO4* for the plant optimum start routine and *PCLO2* for the PI chiller control.

The zone-level control loop sensed values and actuator outputs are fed, at each time-step, to the global chiller discharge control function, *GCL05*, which orchestrates the control according to the global control logic strategy outlined above by establishing appropriate actuator signals for subsequent processing by the zone-level controllers. Zone-level control loop sensors and actuators are specified as usual (Section 3.5) with regard to element location and operational variables; however, in the case of the customised, 'specific' global controller described here, the actuator outputs for *FCL01* and *PCL02* are established by *GCL05*.

In order to demonstrate system-level discharge global control, consider the test zone controlled according to the schedule listed in Table 6.11. The global function attempts to maintain the zone air point temperature within the range 18-22 °C for the occupancy period, 09.00-18.00 hours. Figure 6.24 shows the global controller input/output signals for a 1-day simulation period run with building-side and plant-side time-steps of 6 minutes and 60 seconds, respectively. Note that scalar offsets on the results plots are used for clarity and also that time-step averaging is disabled.

As expected, prior to the optimum start signal being received, the global controller acts to close both minimum and maximum outdoor air dampers and to disable the PID controller. Upon reaching the predicted start-up time of 05.50 hours, the minimum damper opens fully and the maximum outdoor damper modulates open for a short time until the chiller operates and/or the outdoor dry bulb temperature exceeds the pre-set value of 22.5 °C at which stage it closes as described earlier. The PID controller output (proportional mode only in this case) is oscillatory; this is a function of the simulation time-step and also the specified proportional bands. (It is also due in part to the time-step averaging of results being disabled). Further tuning could expect to achieve smoother profiles. However, the overall performance of the controller is shown to be satisfactory, the (averaged) zone air temperature generally being held within the specified tolerance band during the period of occupancy.

Clearly, the success of such a modelling technique may often be dependent on the simulation time-step. It is likely that, in attempting to model reality and capture the dynamics of practical building/plant/control systems, a (relatively) small time step will often be required for the building and plant-side time-steps; of the order of 6 minutes and 1 minute, respectively, possibly reducing to 1 minute and 6 seconds in some cases, e.g. for heat exchanger control loops. No rigid guidelines/rules can be offered in this respect: often a combination of a knowledge of the expected plant/control system characteristics and behaviour, a simulationist's experience and adoption of iterative, trial-and-error procedures, are required in order to determine suitable time-step values. Possibly the best way of establishing appropriate time-steps is to ascertain the polling rate employed in a practical BEMS. This can, however, prove to be problematic, considering the reluctance that many plant/control system manufacturers have to publishing representative performance data [Aasem 1993].

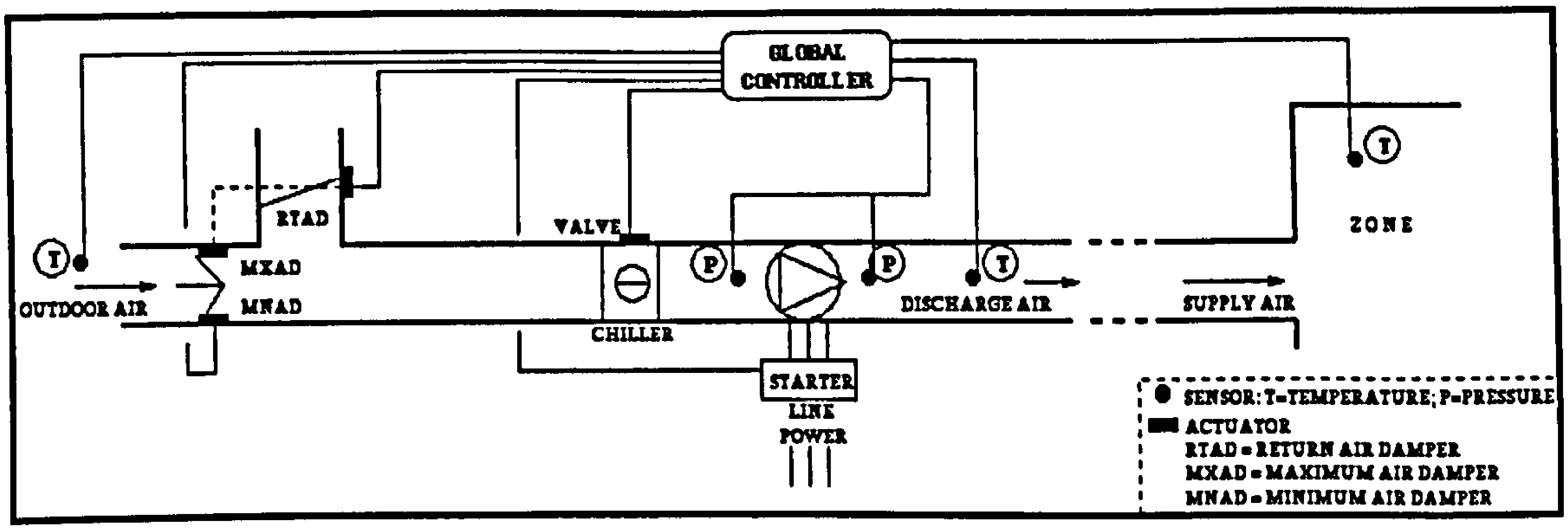
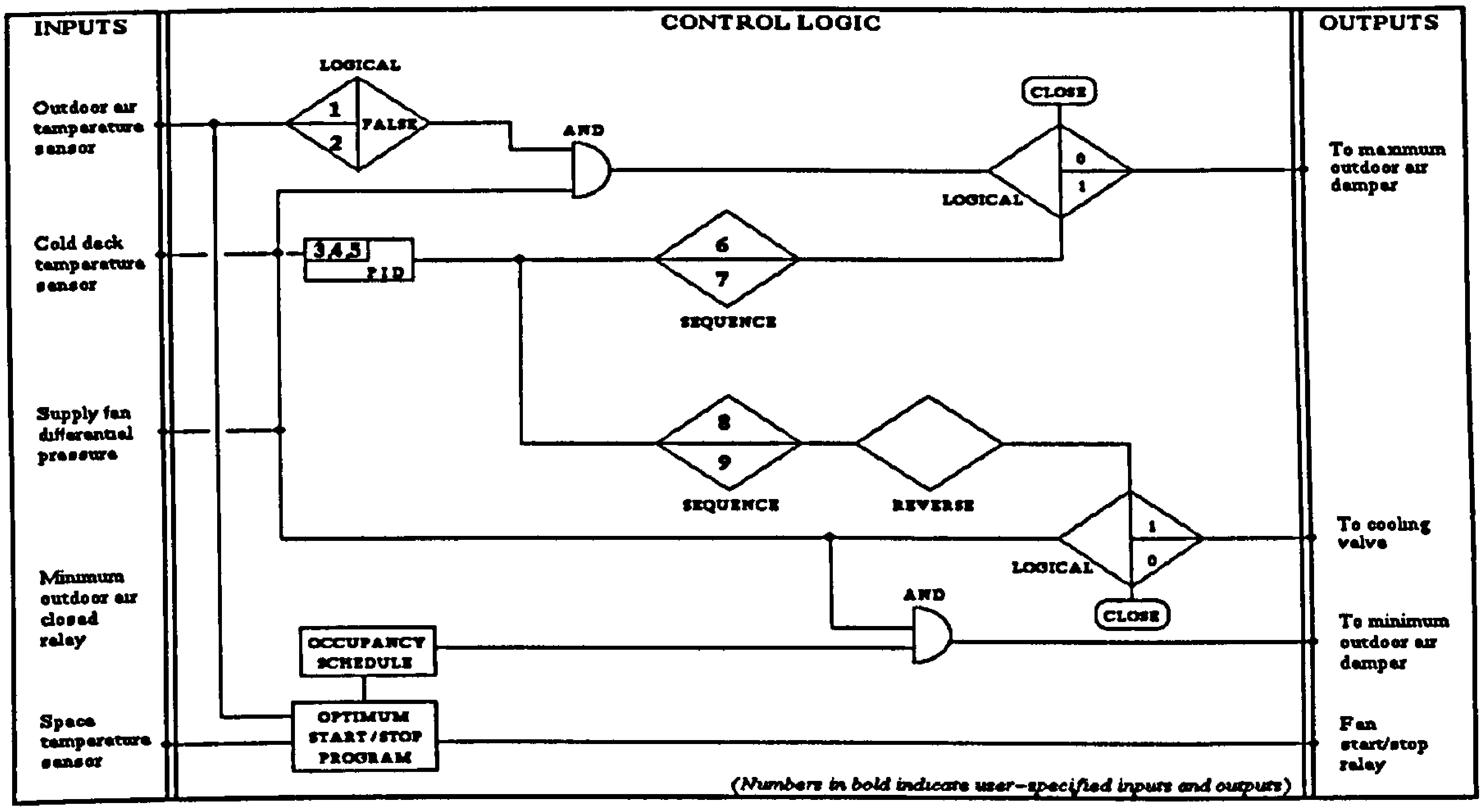


Figure 6.23(a) Chiller discharge global controller schematic [Honeywell, 1989]



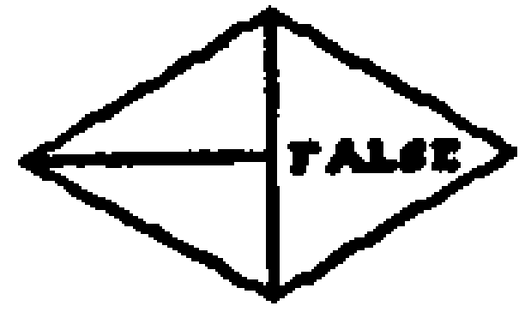
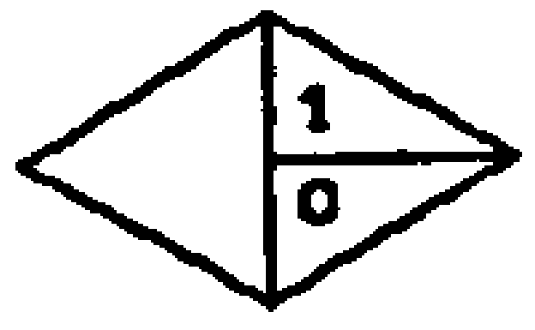
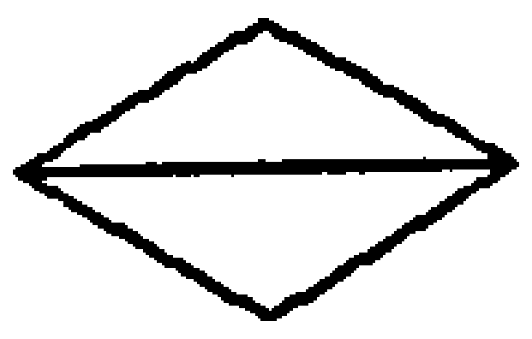
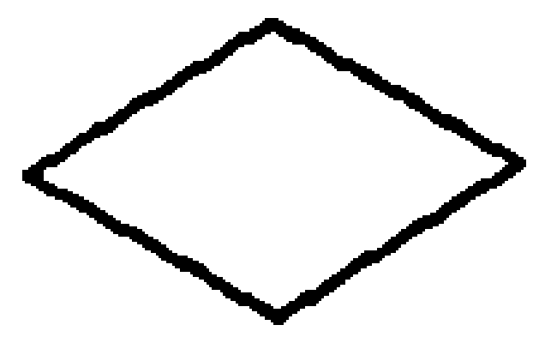
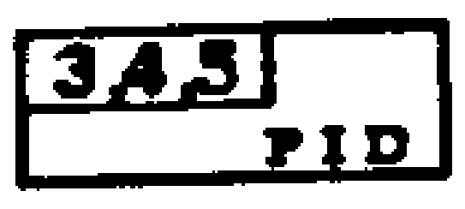
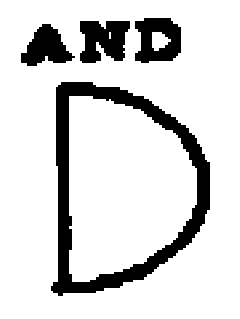
SYMBOL	NAME	DESCRIPTION
	ANALOGUE CONTROLLED DIGITAL OUTPUT	OUTUT SWITCHES BETWEEN DIGITAL STATES AS INPUT VARIES BETWEEN SPECIFIED VALUES
	DIGITALLY CONTROLLED ANALOGUE OUTPUT	OUTPUT CHANGES BETWEEN TWO ANALOGUE INPUTS AS INPUT CHANGES BETWEEN STATES
	SEQUENCE	OUTPUT VARIES 0-100 AS INPUT VARIES BETWEEN SPECIFIED START AND END VALUES
	REVERSE	OUTPUT EQAULS 100 - INPUT
	PID CONTROLLER	PROPORTIONAL+INTEGRAL+DERIVATIVE CONTROLLER
	LOGICAL	OUTPUT IS TRUE IF BOTH INPUTS ARE TRUE

Figure 6.23(b) Chiller discharge global control logic [Honeywell, 1989]

Table 6.11 Global discharge controller: control schedule.

Parameter	1	2	3	4	5	6	7	8	9	Occupancy	Set
(Fig 6.25(b))	Ambient temp. limits		PID gains			Sequence limits				period	point
	22.5 °C	22.5 °C	25.0	0.0	0.0	-20.0	12.0	12.0	40.0	09.00-18.00	18-22 °C

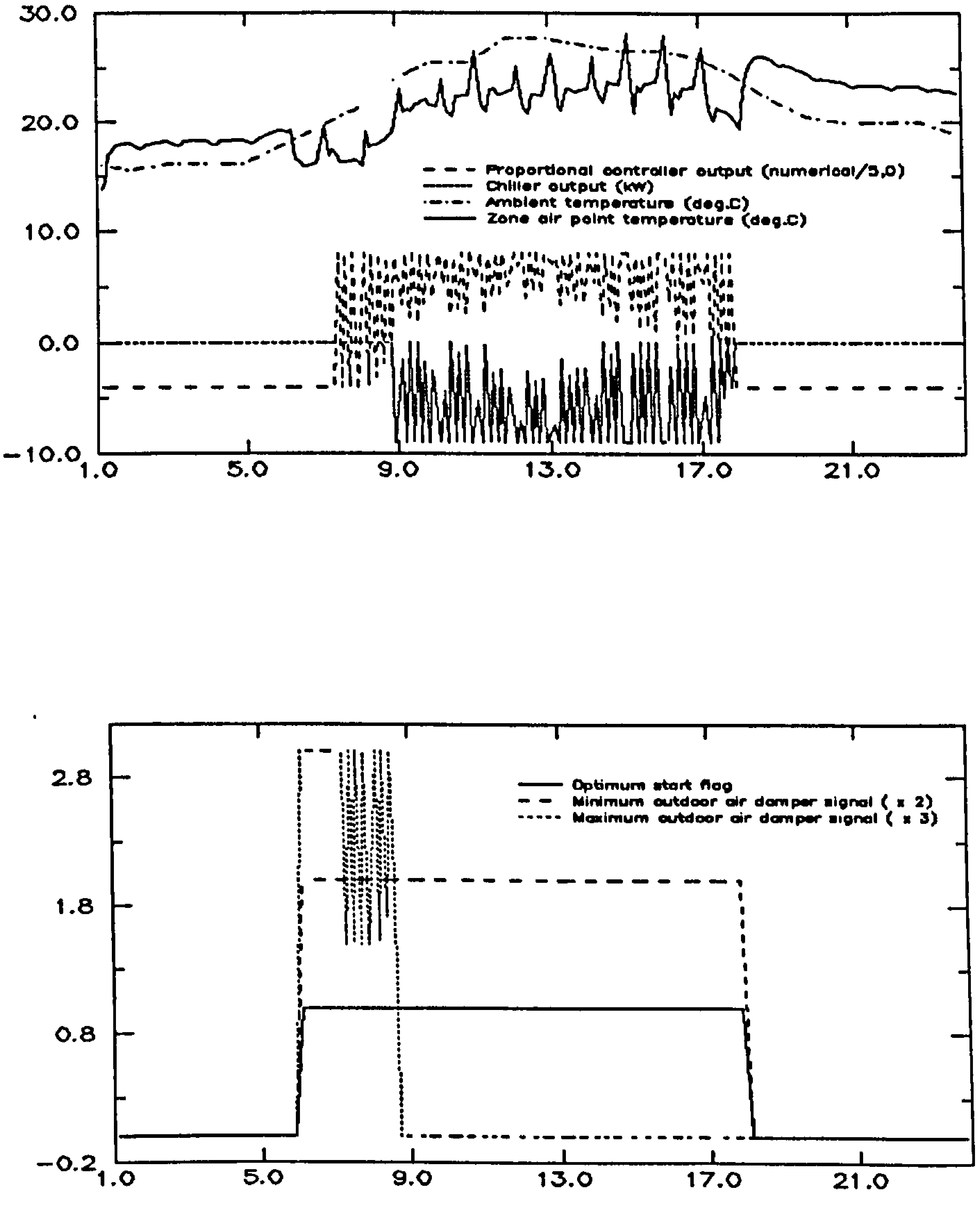


Figure 6.24 Chiller discharge global control: sample results set.

6.5 IMPLEMENTATION OF CONTROL FUNCTIONS IN ESP-r.

The zone-level and system-level controller models installed in ESP-r, and described above, may be supplemented by additional models as the modelling need requires. For this reason, the following set of guidelines for implementation of control functions in ESP-r are now presented. The recommended procedure involves 8 stages (Figure 6.25):

- *Stage 1.* Deciding on the control function (practical or imaginary) to be modelled;
- *Stage 2.* Construction of a flow-chart indicating the main stages in the control logic;
- *Stage 3.* Coding the algorithm in the FORTRAN-77 programming language;
- *Stage 4.* Installing the coded algorithm in the relevant control subsystem module(s);
- *Stage 5.* Possibly updating the module *Makefile*;† to include any subroutines and/or functions contained in new file(s), for subsequent program compilation;
- *Stage 6.* Code checking, debugging and performance testing the coded algorithm to ensure numerical integrity with the entire program system (These issues are elaborated in Chapter 7);
- *Stage 7.* Development of graded tutorial exemplars suitable for subsequent use by a wide group of users, ranging from novice simulationists through to expert users and model developers;
- *Stage 8.* Updating the interface to allow user definition and specification.

The control functions themselves should have the necessary code required to:

- prohibit an incorrect number of controller defining data items being specified;
- provide range checks on the controller defining data items, and thus guard against 'silly' data input;
- prevent division by zero;
- issue warnings should unrealistic control system data be computed.

---

† *make* is a UNIX program which reads a specification (held in a *makefile*) of how the components of a program depend on each other, and how to process them to create an up-to-date version of the program. It checks the times at which the various components were last modified, figures out the minimum amount of recompilation that has to be done to make a consistent new version, then runs the processes.

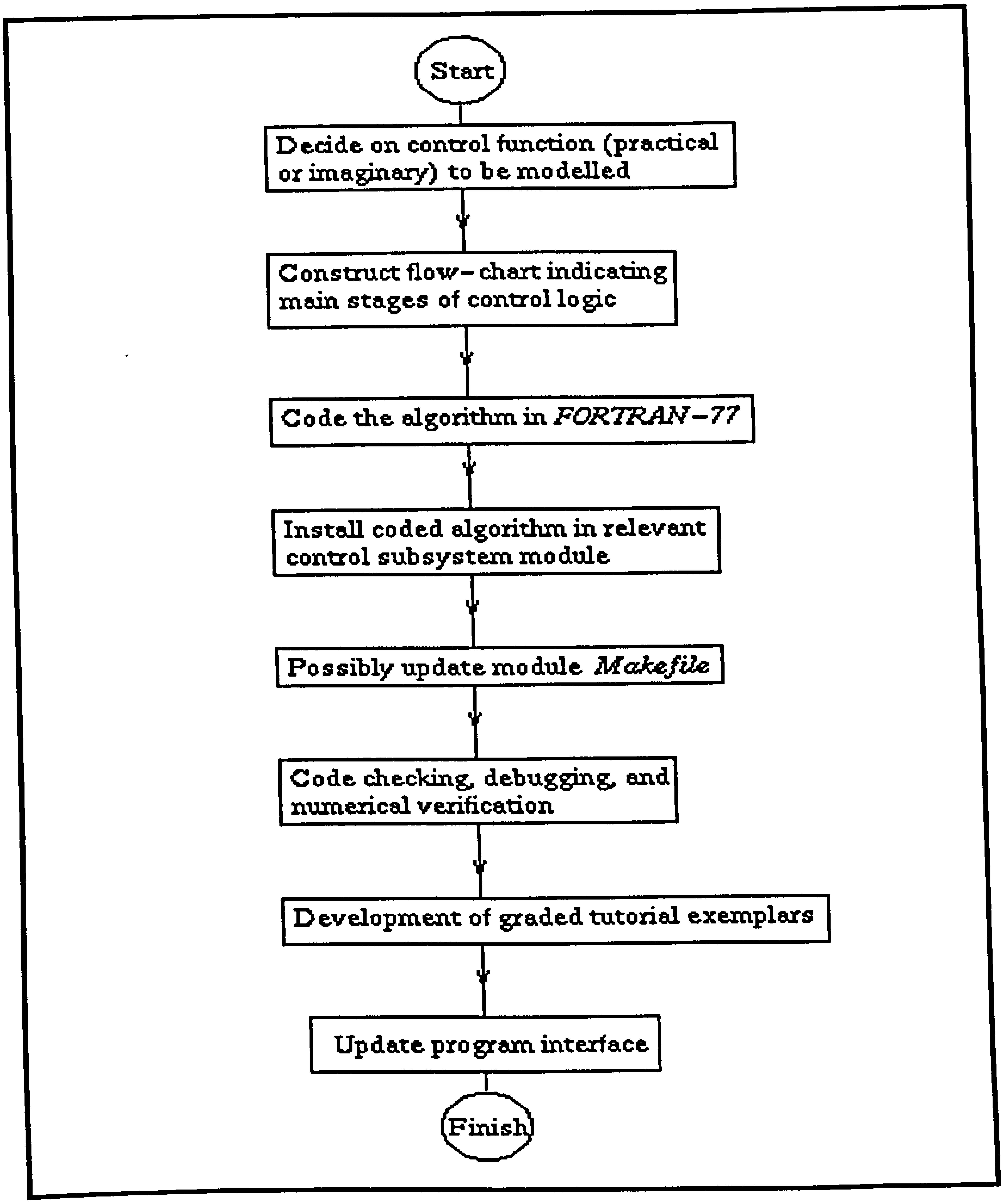


Figure 6.25 Implementation of new control functions in ESP-r.

6.6 SIMULATION ASSISTED CONTROL.

6.6.1 Basic concept.

The zone-level and system-level controller models described above, offer the possibility of modelling a vast range of both practical and highly conceptualised control system types. Simulation, however, need not be restricted to such research and design applications: there exists the very real possibility of extending its use by employing energy simulation programs on-line in BEMS, to act in the role of an intelligent control supervisor.

The notion of marrying the two technologies is supported by BEMS multiplexing techniques which allow rapid, on-line adjustment of control system parameters on the basis of simulated forecasts. Simulation provides a look-ahead capability which facilitates predictions of future reality which can then be used to determine the best possible control action in terms of comfort and energy levels (Figure 6.26). Simulation time-step controllers (described in Section 5.3.4) can then be invoked which enable trial (present) control actions to be simulated in rapid iterative mode until the controller performance is deemed to be satisfactory/optimised (in terms of predicted future outcomes) at which point the simulation proceeds to the next control period. The optimised control system parameters may then be implemented in the BEMS.

As explained in Section 2.2, modern-day practical controllers are often based on a *controller/ system model* structure. The premise implicit with the simulation-assisted control concept is that there is no need for separate system model generation (e.g. by employing identification methods), since in this case the system model is held in the form of system matrix, as described in Chapter 3. Clearly, this results in a simplification of the control system synthesis process, offering, for the first time, the opportunity for building design professionals - not necessarily familiar with highly esoteric control engineering theory - to participate in system design and operation.

The design and operation of practical building control system logical elements requires the following.

(1) A defined objective: control theory concerns itself with the future state of the system. The objective of any control system in every case is connected with the performance of the system over some period of time.

(2) A choice of possible control actions: if no variation of actions is possible, control is not possible since the course cannot be modified.

(3) A means of choosing the correct control strategy. Thus a model of the system is required which is capable of predicting the effect of various control actions on the system state.

The concept of *energy simulation assisted control decision making* (ESAC) offers a means by which these requirements may be met, during both the design and operation of BEMS. The main advantages of a simulation-assisted approach to control design/operation are as follows.

- Any criterion whatever can be used for the decision process, e.g. there is no need to be restricted to, say, quadratic criteria as in conventional optimal control design.
- The difficult and highly specialised problem of control synthesis is avoided.
- Control actions can first be appraised in a software environment before being applied to the real system. This feature offers tremendous potential for the next generation of intelligent buildings and BEMS.

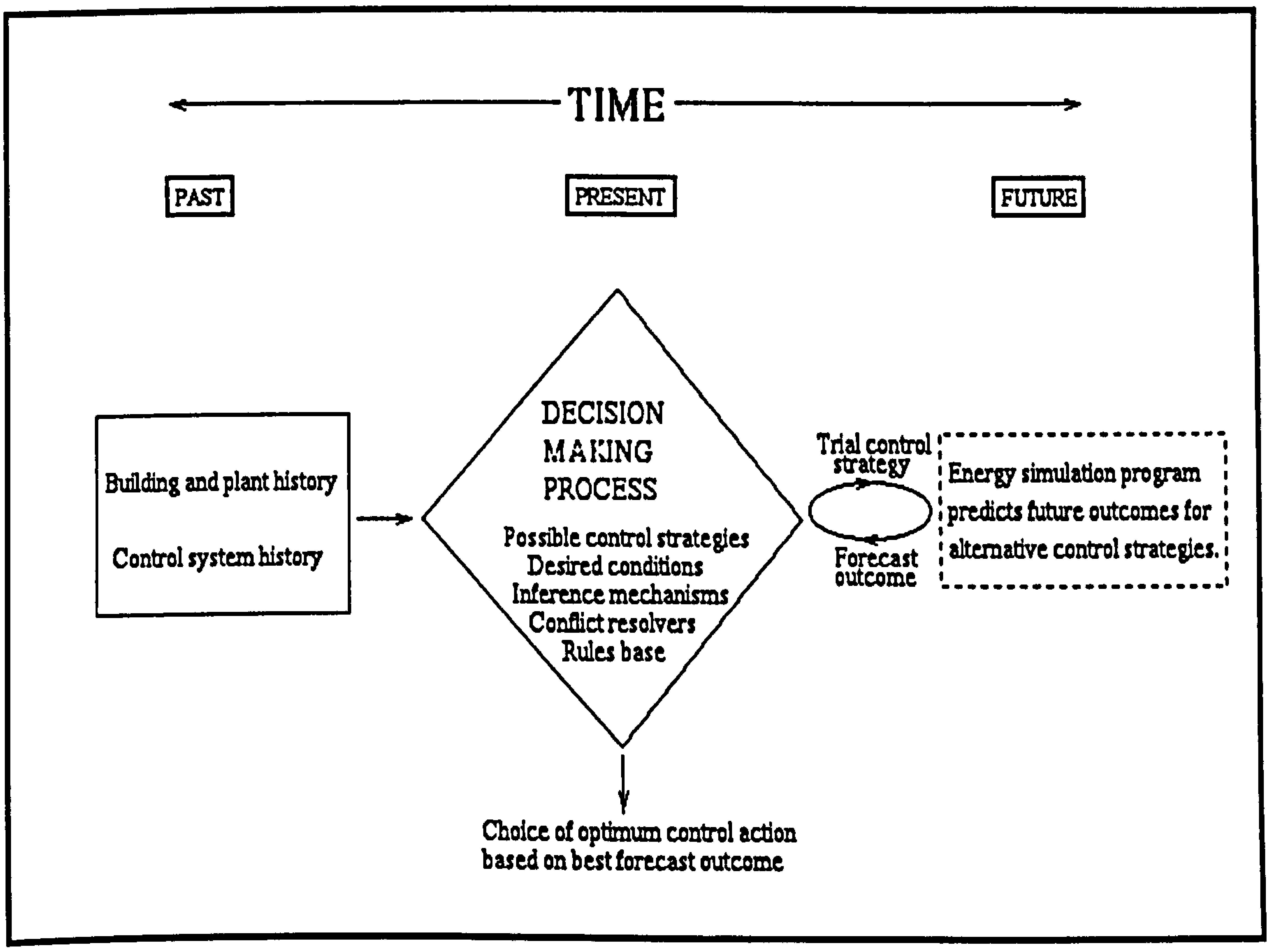


Figure 6.26 Energy simulation assisted control

6.6.2 ESAC algorithms.

Situations where energy managers could employ predictive-iterative simulation schemes are numerous, and include optimisation of:

- plant system start/stop times;
- set-back temperatures;
- sensor/actuator location/variable;
- control mode (fuzzy logic, multi-stage, etc);
- flux injection/extraction levels;
- duty cycled plant components and cycling periods;
- load shedding schema;

- fluid flow network balancing.

The development of ESAC algorithms for such applications are now described. The schemes presented employ the simulation time-step controller (*TSCON_8*), described in Section 5.3.5, to reset the simulation time-clock and thus facilitate iteration.

ESAC01: ESAC optimum start/stop.

Almost all BEMS will have a number of microprocessor-based optimum start/stop control loops available for use. The purpose of the algorithm is to relate the time required for preheat (lead time) to the observed building and/or outside temperatures: equipment is started to ensure the achievement of a comfort level when the first occupant arrives; equipment is stopped when comfort levels can be maintained until the last occupant leaves. Energy savings of up to 40% may be achieved as compared with switch-on by timer [Kohonen, 1984].

There are two main classes of optimum start/stop algorithm: empirical and theoretical. Empirical and semi-empirical optimisers (e.g. the Birtles and John algorithm of the *PCL04* control function, discussed in Section 6.3.2) are based on an observed or assumed relationship between the preheat time and temperatures.

More recently, self-tuning optimum start controllers have been proposed [Murdoch *et al* 1990]. These controllers have their parameters continually updated as the BEMS observes the performance of the controller. The associated algorithms are based on semi-empirically derived relationships between the preheat time and the bulk temperature of the zone to be controlled. Such controllers are claimed not to require any prior knowledge of the thermal characteristics of the heating plant and building. The bulk temperature is based on the variables related to the characteristics of the building and outside temperature as predicted using a first-order model of the room and heating plant. One of the main reasons for serious performance deficiencies in commercially available optimisers is poorly designed optimiser schedules and inefficient self-learning procedures, which are incapable of accurately reflecting the thermal response of buildings [John and Smith 1987].

A proposed new approach for design and/or on-line BEMS applications, is to develop an ESAC algorithm to determine the optimum start-up and optimum shut-down times of the building plant system. Using the numerical method described in Section 3.4, in which the system matrix *is* the building/plant model, simulation can be used in rapid iteration mode to accurately predict the controlled start/stop times. The method is depicted in Figure 6.27. Trial times are predicted and used in the simulation for any specified control period (day, week, month, season, etc.). Zone air temperatures at the 'desired time of arrival/departure' (DTOA/D) can then be predicted. If trial times result in satisfactory air temperatures at the DTOA/D, then the trial times are accepted and the simulation proceeds to the next time-step. If, on the other hand, the trial times are not acceptable, then once all zones have been processed at that time-step, an iterative scheme is activated by which the simulation time-clock is reset to the start of the control period by means of the simulation time-step controller (*TSCON_8*), and the system matrix reconstructed to *exactly* the same coefficients as the previous pass at this time-step. At this point, new trial times are predicted using a binary search algorithm to forward/retard the trial times according to results at the previous pass, and then a further simulation for the control period commences. This prediction-iteration process continues until satisfactory control performance is achieved after which the simulation proceeds to the next control period.

Controller models based on the above approach are installed in ESP-r. Figure 6.28 shows a sample result set for controller *BCL15* applied to a single zone.

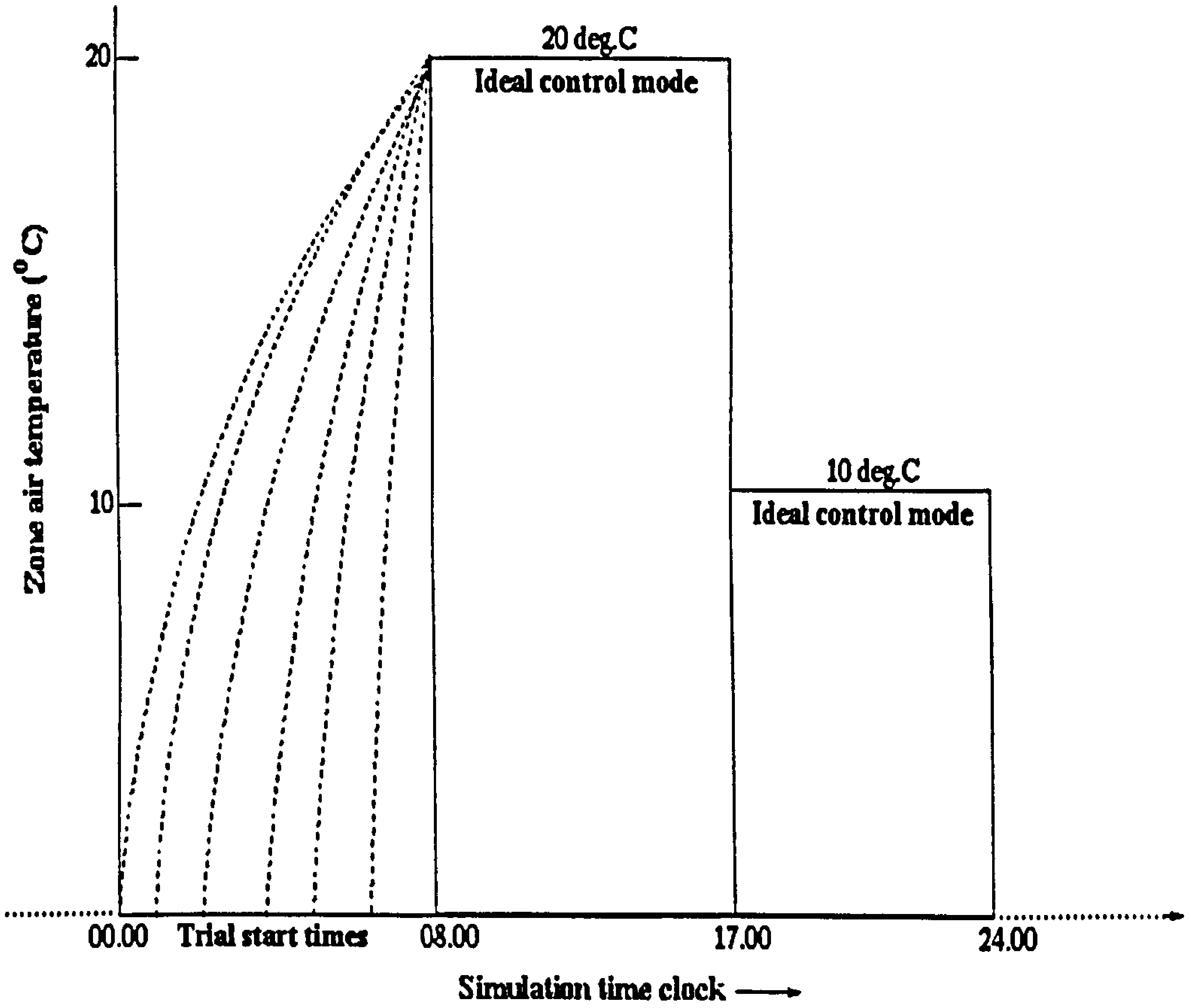
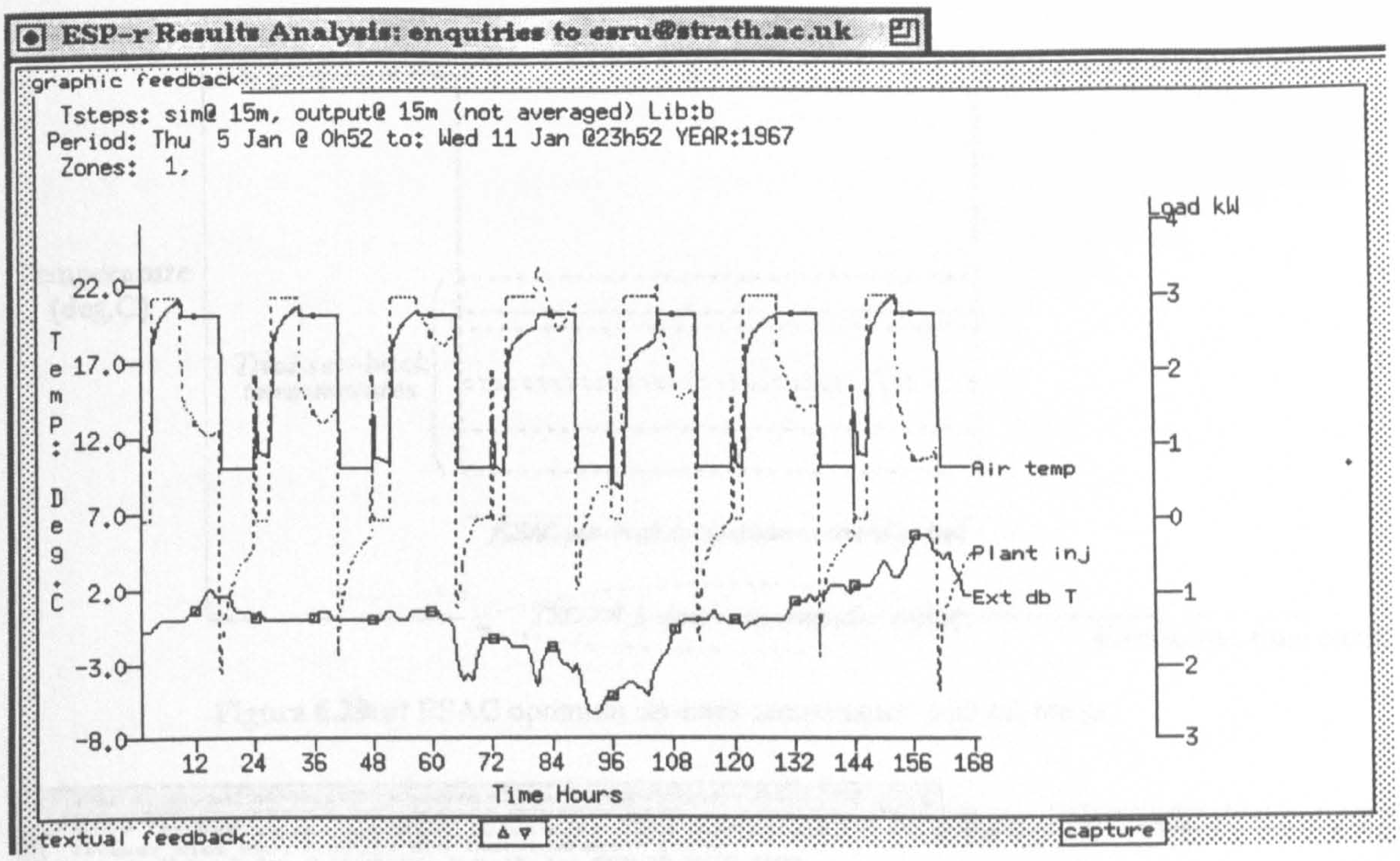


Figure 6.27 ESAC optimum start schedule.



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Tsteps: sim@ 15m, output@ 15m (not averaged) Lib:b
Period: Thu  5 Jan @ 0h52 to: Wed 11 Jan @23h52 YEAR:1967
 Zones:  1,
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Figure 6.28 ESAC optimum start results.

ESAC02: ESAC optimum set-back temperature.

Set-back of temperatures during periods of nonoccupancy is another commonly adopted intermittent heating control scheme. Here, for the period of nonoccupancy, the set-point is decreased to an acceptable minimum; a value determined after taking into account factors such as energy demand and frost protection of building fabric/contents. Typically, this value is fixed for the duration of the control period. Since a fixed set-back temperature for the duration of the control period may not maximise plant system efficiency, it may be deemed more appropriate in some instances to fix the plant capacity and vary the set-back temperature, with some limiting value for frost protection. Simulated-assisted control can be employed to search for the lowest possible set-back temperature, taking due account of any user-specified criterion. This scheme is depicted in Figure 6.29(a).

Consider a single zone controlled according to the following schedule: ideal control (set-point of 21 °C) for the period of occupancy (08.00-01.00 hours); and one period of nonoccupancy (01.00 to 08.00 hours) with the set-back temperature to be determined. During the set-back period, the controller at each simulation time-step iteratively searches for the lowest set-back temperature possible given a limiting period cumulative load capacity constraint, and a minimum frost protection temperature level (10°C). The results for this control scheme for a two week period in early January, are shown in Figure 6.29(b) from which the time-varying temperature set-back levels can be seen. The simulation period iterations are shown in Figure 6.29(c).

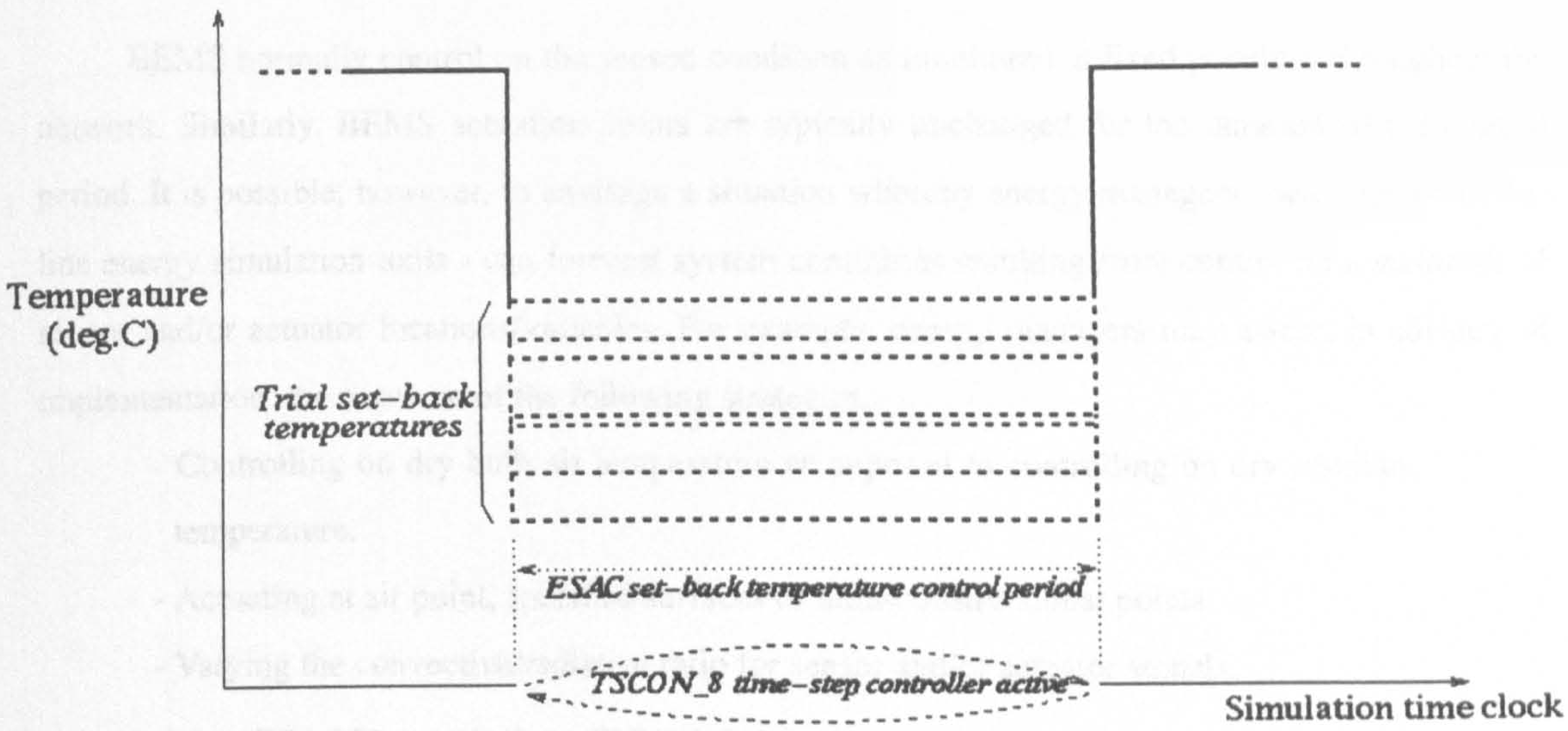
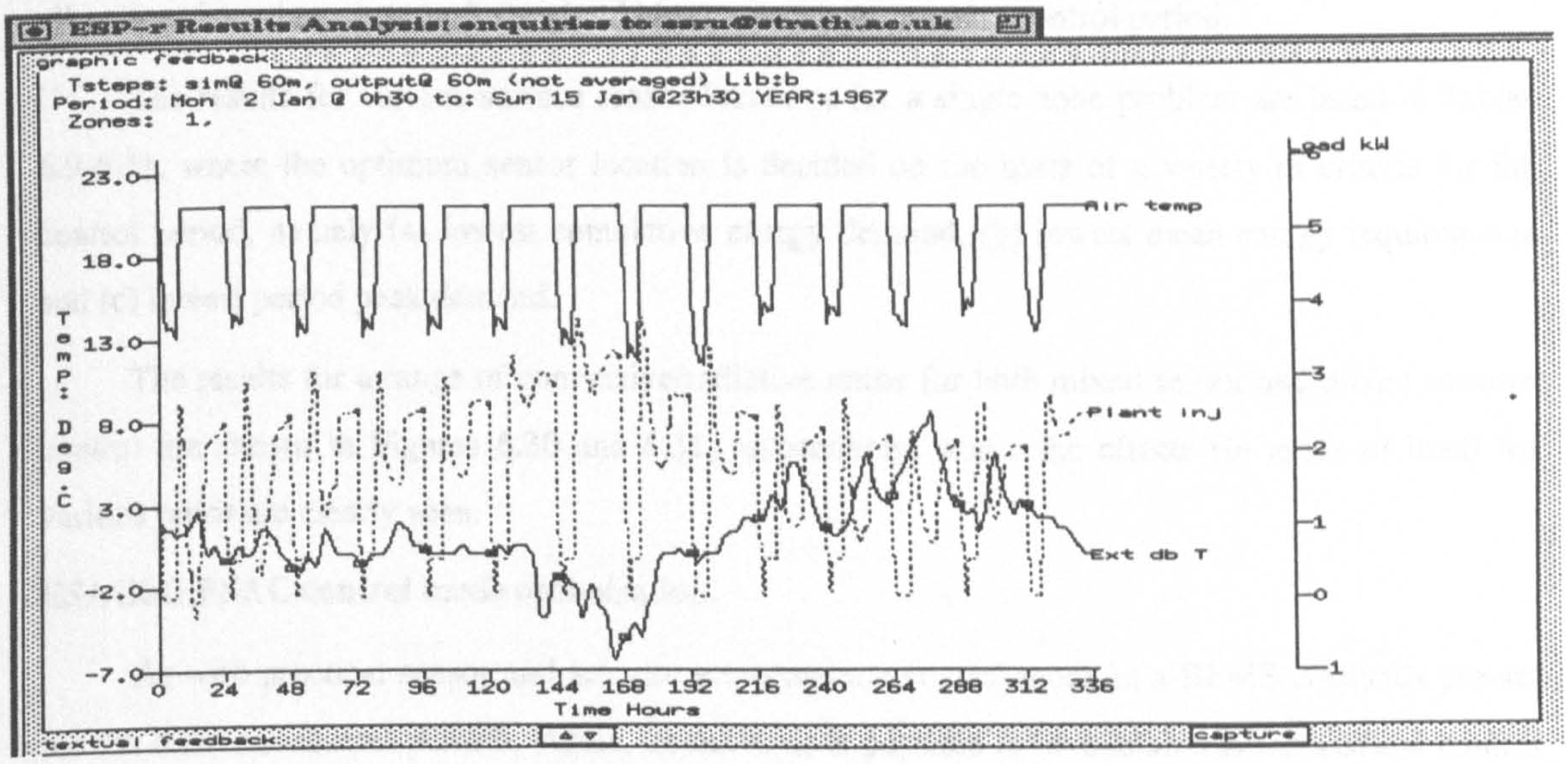


Figure 6.29(a) ESAC optimum set-back temperature: trial set-backs.


ESP-r Results Analysis: enquiries to esru@strath.ac.uk

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Period: Mon  2 Jan @ 0h30 to: Sun 15 Jan @23h30 YEAR:1967
 Zones:  1,
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Figure 6.29(b) ESAC optimum set-back temperature: sample results set.

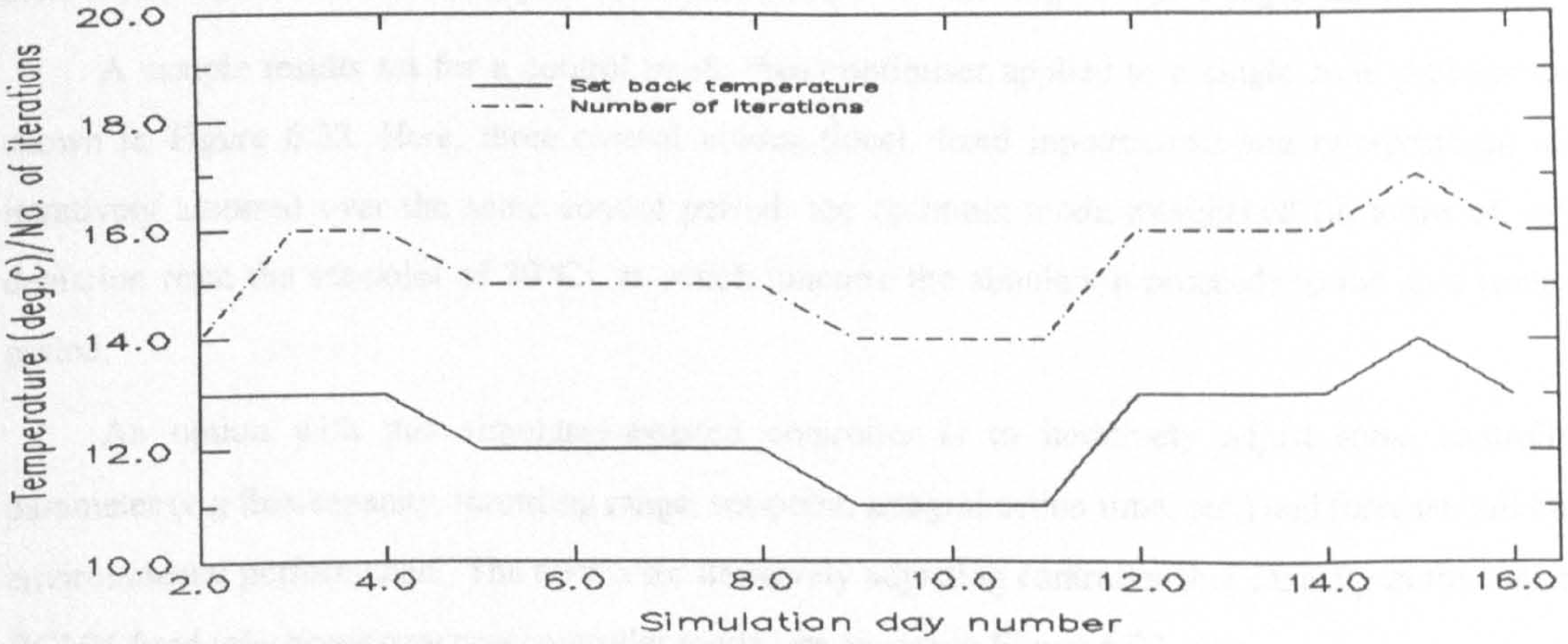

Figure 6.29(c) ESAC optimum set-back temperature: numerical iterations.

ESAC03: ESAC sensor/actuator location.

BEMS normally control on the sensed condition as monitored at fixed positions throughout the network. Similarly, BEMS actuation points are typically unchanged for the duration of the control period. It is possible, however, to envisage a situation whereby energy managers - with the aid of on-line energy simulation tools - can forecast system conditions resulting from control on a *multitude* of sensor and/or actuator locations/variables. For example, energy managers may assess, in advance of implementation, the outcome of the following strategies.

- Controlling on dry bulb air temperature as opposed to controlling on dry resultant temperature.
- Actuating at air point, specified surfaces or intra-constructional points.
- Varying the convective/radiative ratio for sensor and/or actuator signals.

In the ESAC03 controller, *TSCON_8* is utilised to iteratively search for the optimum location/variable in terms of some specified criterion, say energy requirements or comfort levels. Once all options have been assessed, the simulation proceeds to the next control period.

The results for various surface sensor locations for a single zone problem are listed in Tables 6.9-6.11, where the optimum sensor location is decided on the basis of a variety of criteria for the control period, namely (a) lowest cumulative energy demand, (b) lowest mean energy requirements and (c) lowest period peak demand.

The results for a range of convective/radiative ratios for both mixed sensor and mixed actuator control are shown in Figures 6.30 and 6.31, respectively, where the effects (in terms of load) for various ratios are clearly seen.

ESAC04: ESAC control mode optimisation.

As with practical sensor and actuator elements, the control mode in a BEMS is usually pre-set for the different control periods. Again, however, it is possible to invoke simulation-assisted control schema in an attempt to optimise system efficiency, by iteratively searching (using *TSCON_8*) for the control law which offers the best performance in terms of a vast range of operating criteria.

A sample results set for a control mode (law) optimiser applied to a single zone problem are shown in Figure 6.32. Here, three control modes (ideal, fixed input/extract and two-position) are iteratively assessed over the same control period, the optimum mode established (in terms of, say, deviation from the set-point of 20°C), at which juncture the simulation proceeds to the next control period.

An option with this simulated-assisted controller is to iteratively adjust some controller parameter (e.g flux capacity, throttling range, set-point, integral action time, etc.) and forecast building environmental performance. The results for iteratively adjusting controller flux capacity in the case of *BCL04 fixed injection/extraction* controller mode, are shown in Figure 6.33.

Table 6.9: Simulation-assisted sensor location: criterion (a)

Day Number	Energy performance				Control criterion	Optimum location
	Lowest cum. demand	Lowest swing	Min. peak demand	Lowest mean		
1	Surface_3	Surface_3	Surface_4	Surface_4	Lowest cum. demand	Surface_3
2	Surface_4	Surface_4	Surface_3	Surface_4	Lowest cum. demand	Surface_4
3	Surface_1	Surface_1	Surface_4	Surface_4	Lowest cum. demand	Surface_1
4	Surface_3	Surface_3	Surface_2	Surface_4	Lowest cum. demand	Surface_3
5	Surface_1	Surface_1	Surface_4	Surface_4	Lowest cum. demand	Surface_1
6	Surface_3	Surface_3	Surface_2	Surface_4	Lowest cum. demand	Surface_3
7	Surface_2	Surface_2	Surface_3	Surface_4	Lowest cum. demand	Surface_2

Table 6.10: Simulation-assisted sensor location: criterion (b)

Day Number	Energy performance				Control criterion	Optimum location
	Lowest cum. demand	Lowest swing	Min. peak demand	Lowest mean		
1	Surface_3	Surface_3	Surface_4	Surface_4	Lowest mean demand	Surface_3
2	Surface_4	Surface_4	Surface_3	Surface_4	Lowest mean demand	Surface_4
3	Surface_1	Surface_1	Surface_4	Surface_4	Lowest mean demand	Surface_4
4	Surface_4	Surface_3	Surface_2	Surface_4	Lowest mean demand	Surface_4
5	Surface_1	Surface_1	Surface_3	Surface_4	Lowest mean demand	Surface_4
6	Surface_4	Surface_4	Surface_1	Surface_4	Lowest mean demand	Surface_4
7	Surface_4	Surface_4	Surface_1	Surface_4	Lowest mean demand	Surface_4

Table 6.11: Simulation-assisted sensor location: criterion (c)

Day Number	Energy performance				Control criterion	Optimum location
	Lowest cum. demand	Lowest swing	Min. peak demand	Lowest mean		
1	Surface_3	Surface_3	Surface_4	Surface_4	Lowest peak demand	Surface_4
2	Surface_4	Surface_4	Surface_3	Surface_4	Lowest peak demand	Surface_3
3	Surface_1	Surface_1	Surface_3	Surface_4	Lowest peak demand	Surface_3
4	Surface_4	Surface_3	Surface_2	Surface_4	Lowest peak demand	Surface_2
5	Surface_1	Surface_1	Surface_4	Surface_4	Lowest peak demand	Surface_4
6	Surface_3	Surface_3	Surface_2	Surface_4	Lowest peak demand	Surface_2
7	Surface_2	Surface_2	Surface_4	Surface_4	Lowest peak demand	Surface_4

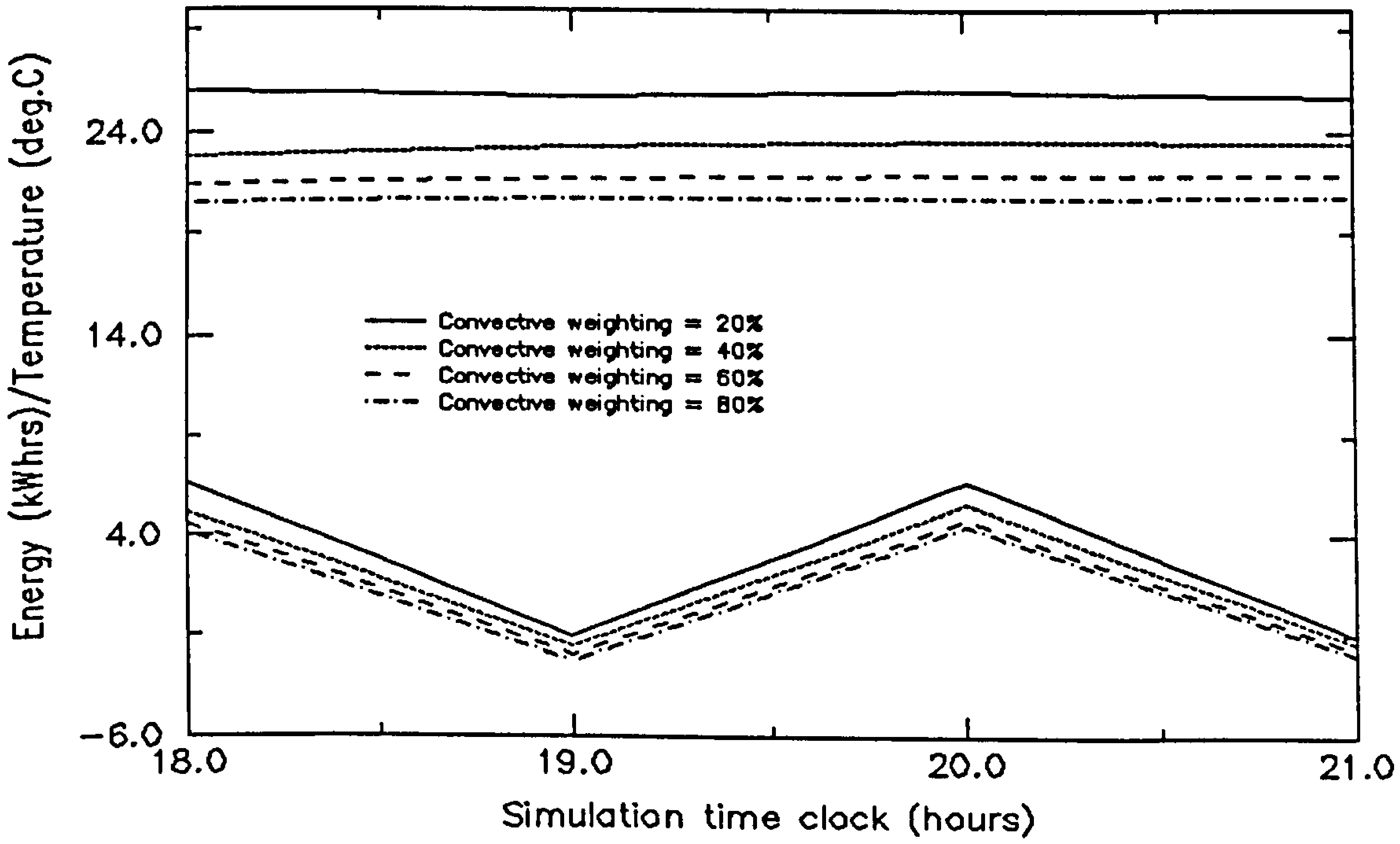

Figure 6.30 ESAC mixed convective-radiative sensor control.

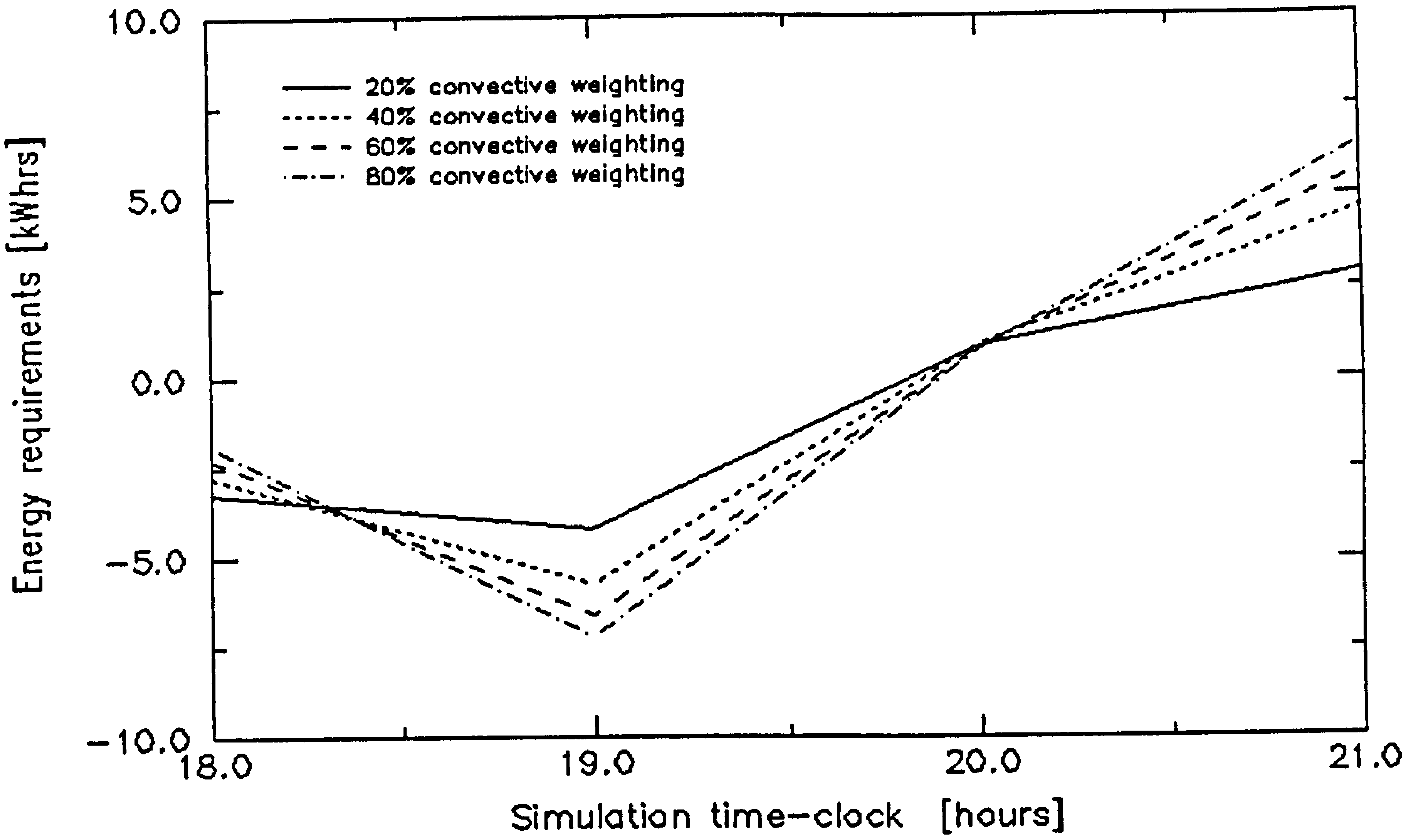

Figure 6.31 ESAC mixed convective-radiative actuator control.

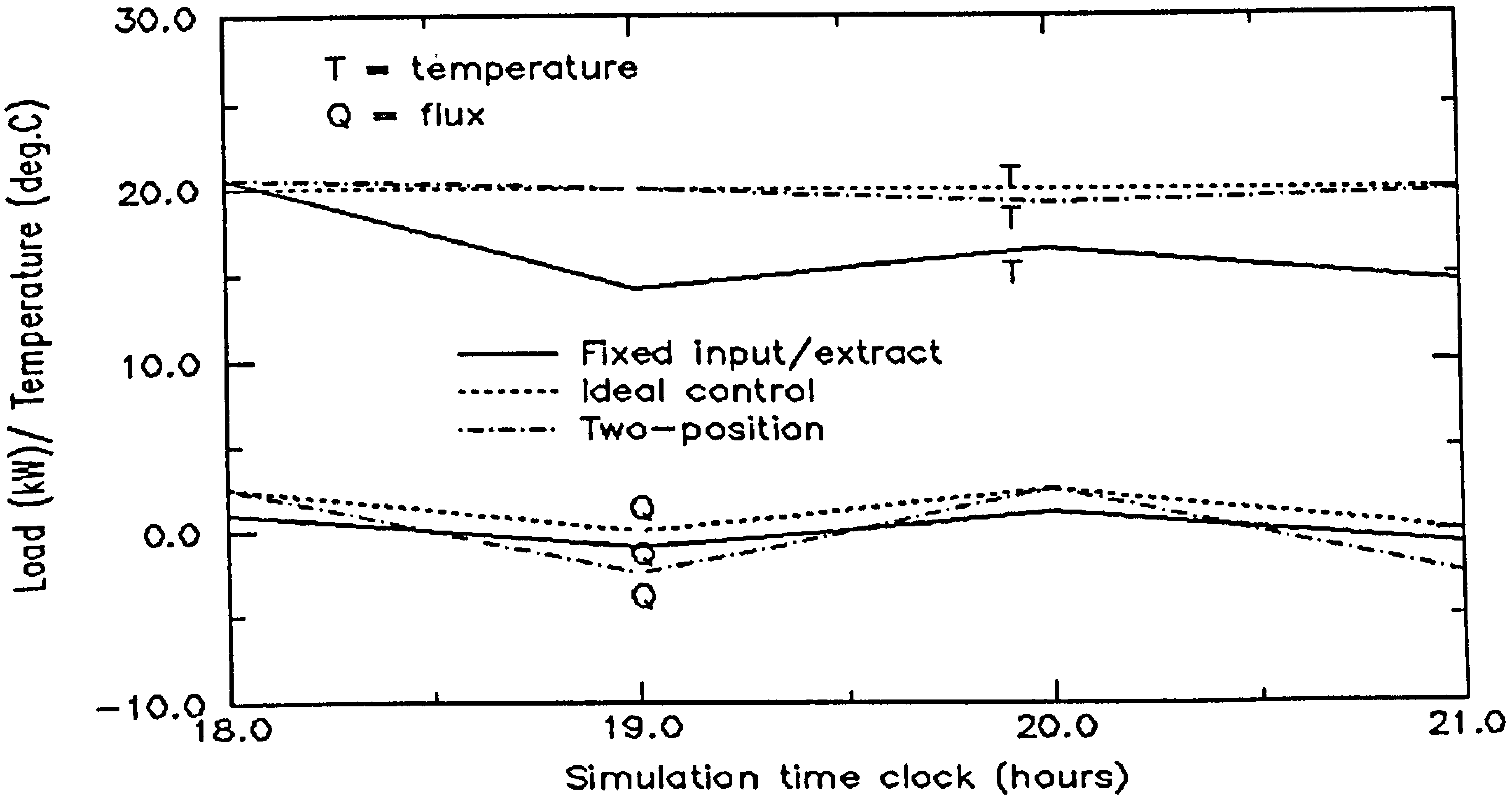

Figure 6.32 ESAC control mode optimiser.

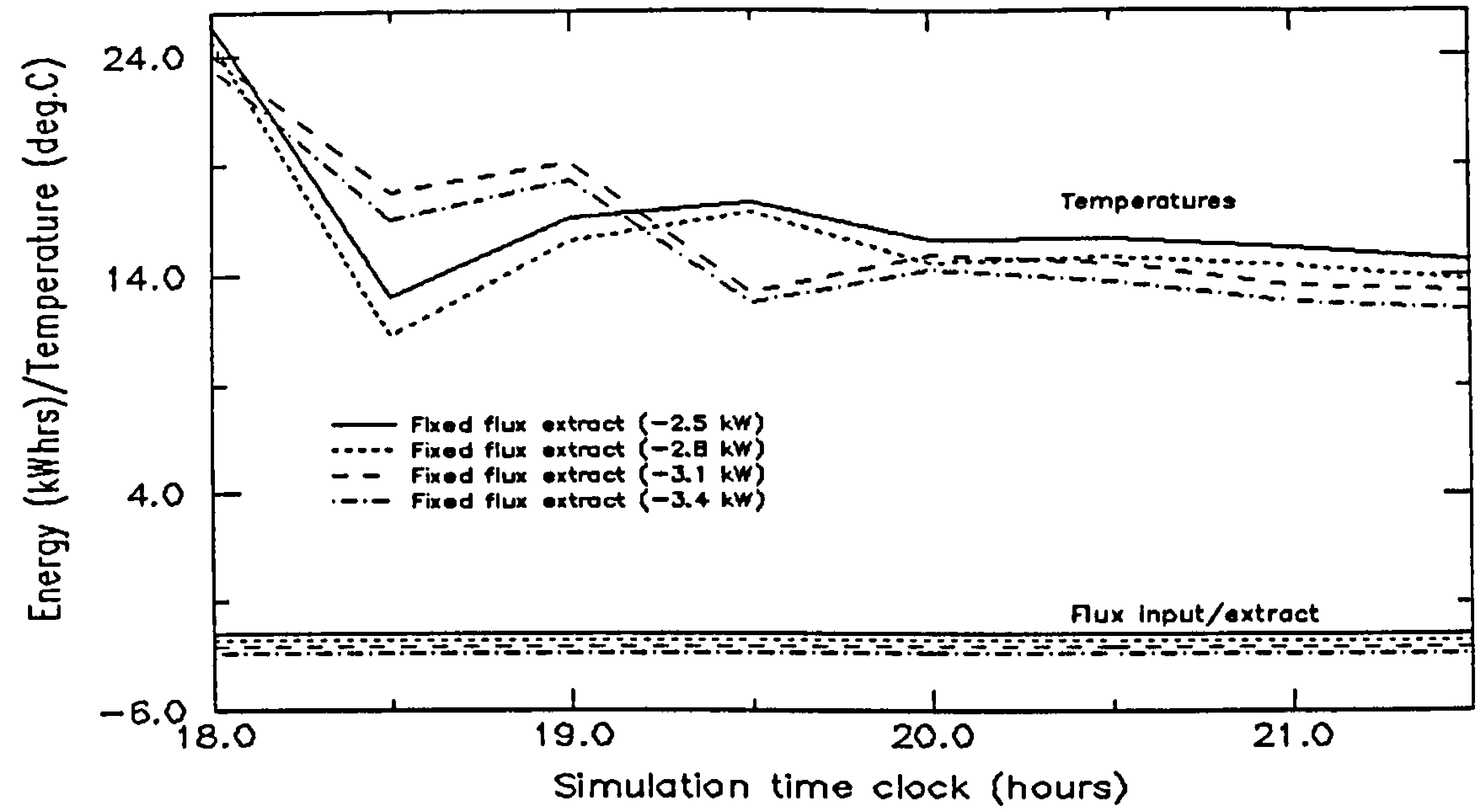

Figure 6.33 ESAC controller output optimiser.

ESAC05: ESAC duty cycling.

Load balancing, by means of duty cycling, is a classical optimisation/allocation problem typically solved using linear programming techniques involving cost functions, constraints, and equalities/inequalities: such problems come within the realms of *Operational Research* [Taffler 1979]. The scheme presented here is a simulation-assisted approach to solving the problem of establishing optimum cycle schedules. (A model for a conventional duty cycle controller, *PCL07*, was described in Section 6.3).

Each plant component is specified in terms of its power rating. The objective function represents the total energy of the system, and the constraints are the minimum and maximum on times for each component. The problem becomes one of minimising the total system energy demand whilst satisfying the specified constraints. Consider the cost function,

$$E = w_1 e_1 + w_2 e_2 + w_3 e_3 \ldots\ldots + w_n e_n \qquad (6.57)$$

where e is the plant energy demand (i.e. power rating x cycle period) and w is the status of plant component (0 = off; 1= on). This objective function may also be liable to constraints. For example, $component_1$ may be subjected to the constraint that it is on for a minimum of 20% and a maximum of 80% of the duty cycle period while $component_2$ may be constrained so that it is on for a minimum of 20% and a maximum of 95% of the duty cycle period. The problem is to minimise E given the constraints on w. A minimisation can be achieved by maximising the negative of the objective function. So-called 'slack variables' are added to turn the inequality constraints into equalities.

A possible procedure is as follows.

Stage 1 Specify power rating for all duty cycled plant, n, P_i, (i = 1 to n)

Stage 2 Specify time base, T.

Stage 3 Evaluate energy from:

$$e_i = P_i T. \tag{6.58}$$

Stage 4 Specify cost function to minimise - in this case the sum of squared plant energies:

$$J = w_1^2 e_1^2 + w_2^2 e_2^2 + w_3^2 e_3^2 + \ldots w_n^2 e_n^2 = \sum_{i=1}^{n} w_i^2 e_i^2 \tag{6.59}$$

where w_1, w_2, etc, represent values of 0 or 1 to indicate if the supply is being used.

Stage 5 (a) Apply quality constraints. For example, the output load at any time-step is required to be Y:

$$\sum_{i=1}^{n} w_i e_i = Y. \tag{6.60}$$

Stage 5(b) Apply inequality constraints. For example, over a time period, N x T (where N is the number of plant-side time-steps per duty cycle period, T) e_i is required to be on for less than $N_{\max}$ time-steps, i.e.

$$\sum_{i=1}^{N} e_i w_i \leq e_{imax} \tag{6.61}$$

where

$$e_{imax} = P_i N_{\max} T. \tag{6.62}$$

This states that e_i must be on for less than $N_{\max}$ time-steps during the last N time-steps. For example, if T is 1 minute, $N_{\max}$ is 30 time-steps and N is 60, then e_i must be on for less than 30 minutes. It may also be the case that e_1 must be on for only (say) 40% of the total load, hence:

$$40\% = \frac{N_{\max}}{N} x100 \tag{6.63}$$

Therefore, if N is 60 minutes, $N_{\max}$ would be 24.

Stage 6 Include in cost functions.

$$J_1 = \sum_{i=1}^{n} (w_i e_i)^2 + \lambda_1 \sum_{i=1}^{n} (w_i e_i - Y) \tag{6.64}$$

$$J_2 = \sum_{k=1}^{N} J_k + \lambda_2 (\sum_{i=1}^{N} (w_i e_i + \alpha_i - e_{imax})) \tag{6.65}$$

where λ is a scalar function of the controlled variables and α_i is a 'slack variable' to allow inequalities to be written as equalities.

At the end of each control period, the simulation has established on-off periods for each plant item based on the specified constraints. However, in order to find the optimum duty cycling scheme, in terms of which plant to cycle and under what restraints, the simulation time clock can be reset (by means of *TSCON_8*) to the start of the control period, and a new minimum energy demand calculated for a different set of plant items and/or constraints.

ESAC06: ESAC load shedding algorithm.

Unlike most other BEMS functions, load management by load shedding, is designed *not* to reduce energy consumption but to reduce maximum demand penalty charges and to alleviate the peak demand on utilities. If the kW electrical demand goes too high in any half-hour in the month, then the user has to pay for this worst half-hour in the month. It is therefore worthwhile to keep the maximum demand at a low and steady level. Various methods of load shedding are discussed by Levermore [1992].

The ESAC algorithm, described below and depicted in Figures 6.34 and 6.35, monitors the cumulative demand for any specified demand interval and compares the forecast demand to the allowable value and, if necessary, shed loads on either a time or size basis.

The procedure is as follows.

Stage 1 At the start of each demand interval (DI), the cumulative consumption (DCC) is re-initialised to zero.

Stage 2 At the end of the DI, the DCC is compared with the target cumulative consumption (TCC). If the DCC is less than, or equal to, the TCC then simulation proceeds to the next DI. If, on the other hand, the DCC is greater than the TCC then the following predictive-iterative procedure is invoked.

Stage 3 Time-step controller *TSCON_8* is invoked to reset the simulation time clock to the start of the DI.

Stage 4 Loads are shed according to the specified priority criteria.

Stage 5 A further simulation is run using the revised plant group on/off status values;

Stage 6 Stages 3-5 are repeated until DCC is less than, or equal to, TCC.

With the *ESAC06* controller, shedding can be done on either a group or a time-step priority basis. If the former, then at each reset operation and at the same simulation time-step, group loads are shed in increasing number. If the DCC is still too high when all specified groups have been shed, then the simulation time-step is decremented by unity, and groups are shed in increasing number at this simulation time-step; and so on until the DCC is within the required range. If, on the other hand, the shedding process is on a time-step basis, then the number of groups shed is fixed for each simulation reset as each DI time-step is passed through. If the simulation time-step has reached as far back as the first time-step and the DCC is still too high, then the groups shed are incremented by one group and the simulation time-step backward stepped at subsequent simulations.

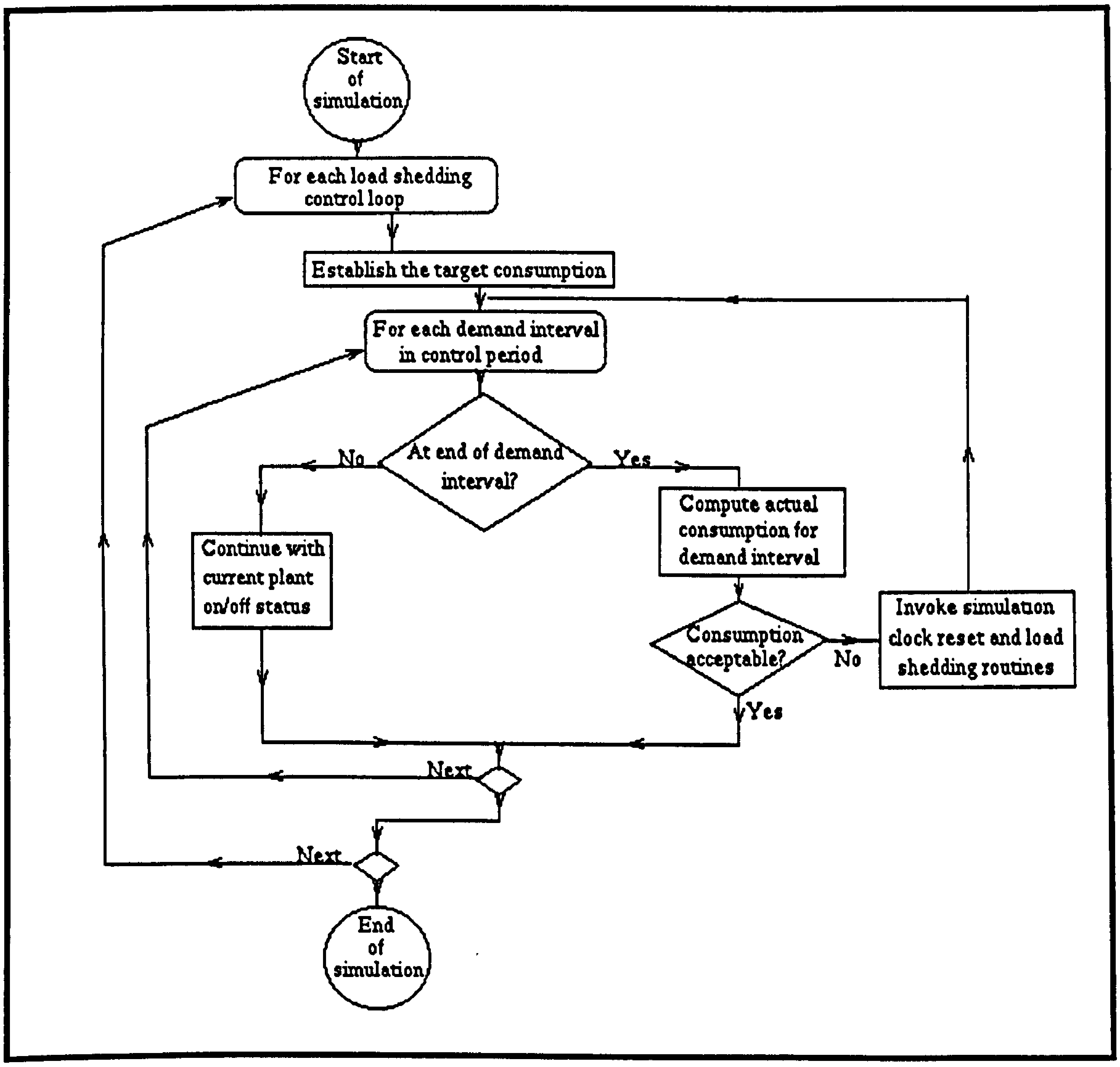

Figure 6.34 ESAC load shedding algorithm flow chart.

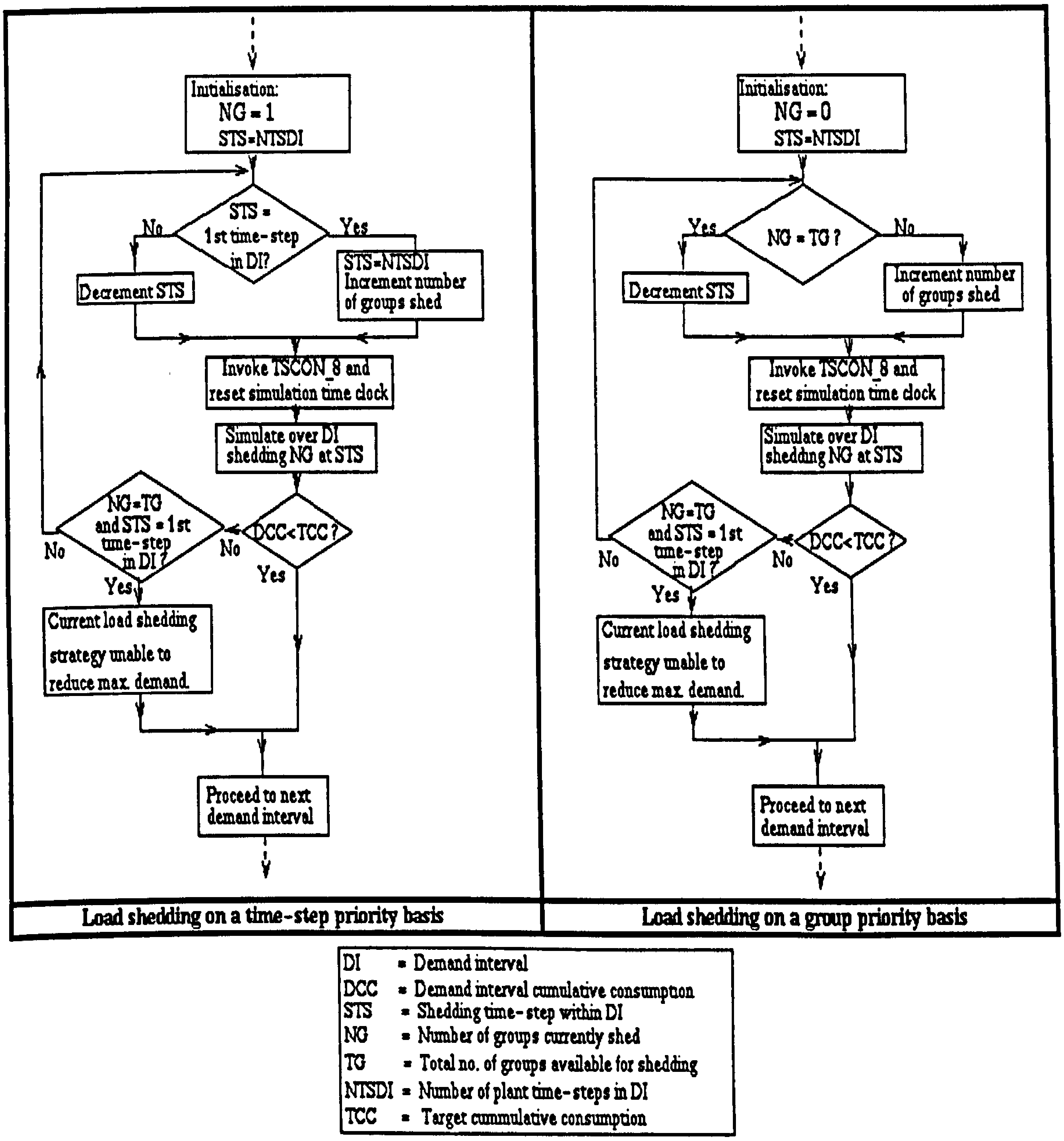

Figure 6.35 ESAC load shedding algorithm: shedding priority.

ESAC07: ESAC balancing controller.

Tuning and commissioning controllers is as problematic in simulation as it is in practice. BEMS suppliers are increasingly using sophisticated software tools to speed up and improve the quality of system design and commissioning. This section describes how simulation can assist the commissioning of fluid flow networks.

Design engineers aim to balance the fluid flow circuits at the design stage of a project so that, when the systems are brought into operation, each outlet or unit will operate at the design flow rate, within specified tolerances. Devices for regulating the flow in the ductwork and pipework systems then exist to allow on-site balancing such that each outlet or unit receives its rated flow rate. However, in practice, many systems are operated in either an unbalanced state, with the resulting loss of plant system efficiency, uncomfortable zonal air movement patterns, and incorrect temperature and humidity conditions. Several studies have shown the importance of good commissioning procedures for building energy performance. For example, a study of the benefits of retrofitting BEMS in existing buildings [John and Smith, 1987] revealed that most of the considerable savings were found to be attributable to the recommissioning of the HVAC plant control systems.

Poorly commissioned plant is due, in part, to the fact that balancing a flow system typically involves very time-consuming and tedious trial and error commissioning procedures. This is particularly so in cases where the valve/damper sets are physically remote from one another (e.g. on different floors), often requiring the commissioning engineers to cover large distances between trial adjustments. Consequently, such procedures are often neglected or carried out in an unsatisfactory manner.

One way of addressing this problem is to use fluid flow simulation to predict the optimum valve/damper settings for the flow network branches such that a balanced system exists. The ESAC flow network balancing algorithm now described is based on the balancing method proposed by Harrison and Gibbard [1965] and adopted by the CIBSE Commissioning Codes for air and water distribution systems (Series A [1971] and Series W [1989], respectively).

The procedure (which may be carried out at all/selected time-steps) is as follows.

Stage 1: Preliminary checks are made in the program to ensure that all valves/dampers in all the specified branches are set to 100% open.

Stage 2: The ratio of measured flow rate to the design flow rate, R, is computed for each branch.

Stage 3: The index line (i.e. the branch having the smallest R ratio in any group of outlets served by a branch) is established for each branch with all valve/dampers open.

Stage 4: Each branch line valve/damper is (iteratively) adjusted in order of increasing R ratio, such that all the lines receive their correct *proportion* of the total flow rate.

Stage 5: Design branch flow rates at Stage 4 are unlikely, and branch fan/pump and/or supply valve/damper adjustment is usually necessary to ensure that the branches receive their design flow rates within a specified tolerance of balance.

This procedure, then, may be employed (on-line on a BEMS) to give a time-series of percentage valve openings as required for balanced flow networks.

A number of schemes for modelling building control systems logical elements have been presented in this chapter including zone-based and systems-level control structures and also the concept of simulation-assisted control. The following chapter proceeds to discuss issues relating to validation of the developed schemes.

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Chapter 7

VALIDATION.

This Chapter deals with the issue of software verification of the schemes developed as part of this project and described in earlier chapters. The main sources of modelling error and methods for the validation of the developed schemes are discussed.

7.1 INTRODUCTION.

7.1.1 The need.

During the modelling and program development process, many assumptions and compromises are inevitably made and, as a result, the exact replication of reality is not achieved. Thus, industrialists, model developers, practitioners and researchers all have to concern themselves with issues of accuracy and applicability. As the use of simulation programs has grown over the past 15 years, so designers have come to rely on them to provide accurate results. In trying to guarantee acceptable performance, designers are being expected to carry out performance assessments which are beyond the capacity of traditional manual techniques. It is vital, therefore, that designers can trust a program's results and, whilst it is accepted that the *perfect* simulation model is unattainable, it is nevertheless important that programs are at least accurate enough for the results to fall within an acceptable margin of error.

7.1.2 Sources of error.

The overall accuracy of simulation programs depends on many factors. Judkoff *et al* [1983] identified the main sources of inaccurate predictions in building simulation programs:

- differences between actual and assumed weather conditions;
- differences between actual and assumed occupancy behaviour;
- user error in creating simulation input files;
- differences between actual and assumed thermophysical material properties;
- differences between the actual heat and mass transfer mechanisms and the algorithmic representation of those mechanisms in the program;
- incorrect software implementation.

Accepting this categorisation of error sources, the first four may be considered as *external* sources of errors as they are independent of the working performance of the program. The other two categories are classified as *internal* sources since they are under control of the developer and are directly responsible for the internal program operation. Some of the external sources of errors can be eliminated by the use of a knowledge-based interface which checks that the input parameters are within a legal range and supplies intelligent defaults. However, most errors are outwith the developer's control and depend on the user's judgment, skill and experience in selecting, for example, boundary conditions. The assumptions made in the running of the program are clearly vital and any shortcomings in the data input will compromise the accuracy of the simulation. In this respect, it helps if a user has some hypothesis about the results prior to running the program.

Bowman and Lomas [1985] and Lomas *et al* [1994], identify some specific examples of internal sources of error: physical phenomena not included in the modelling because they are thought (incorrectly) to be unimportant; approximation of relevant complex phenomena; simplification of physical processes to ease or speed up calculations. Errors on the model derivation, such as unit conversions, can be added to this list. Simplification involves the adoption of a computer model which may not be appropriate for the representation of the mathematical devices (such as discretisation techniques, relaxation factors, linear equation solvers, etc.), although they may be the best approaches possible.

7.1.3 Approaches to validation.

Practitioners are mainly concerned with *overall* program simulation result accuracy. Researchers, model developers, and program authors, on the other hand, are usually also concerned with the integrity of individual component, subsystem, and system models (the model validation process being simpler at component or sub-component level than at whole system level [Chow 1995]). In any case, quality of prediction tools can be improved via three main approaches. First, by developing new mathematical models for the better representation of the heat and mass transfers and the control system characteristics occurring within the building/plant system. Second, by increasing the simulation resolution in order to reduce the number of simplifying assumptions. Third, by elaborating a comprehensive validation methodology which includes all the stages of program development and which may subsequently be deployed in order to determine the range, validity and the uncertainty of building energy simulation programs. In order to increase the modelling confidence, it is now widely recognised by researchers that this can only be achieved by repeated application of a validation methodology by which the programs are exercised in ways which represent the expected range of application and which are appropriate to the domain of its intended use [Irving, 1988]. One complete validation procedure was developed within the PASSYS project [Jensen 1994] and comprises the following steps.

- critical evaluation of the theory;
- checking of the source code;
- sensitivity and statistical analysis;
- analytical validation;
- inter-program comparison;
- empirical validation.

Review of theory serves two important purposes: firstly, to understand the scope of an algorithm; and secondly, to check its coding implementation. As regards source code verification, during the developments reported here, the code was created using CASE tools (for syntax error trapping) and debugging tools (for logic error trapping):

forchk is a Fortran program development aid developed at Leiden University. It verifies the syntax, composes cross reference tables of constants, labels, variables, arrays, referenced subprograms, and indicates how these items are used. As an option, **forchk** validates the syntax for conformance with the ANSI Fortran 77 standard. The reference structure of subprograms can be presented, and cross reference tables of subprograms, commons, input/output and include files are composed. Arguments of referenced subprograms and common blocks are checked for consistency. Cross reference tables of all elements of each common block can be generated.

dbx is an interactive, line-orientated, source-level, symbolic debugger. It allows the user to determine where the program crashed, to view variables and expressions, set breakpoints in the code, and run and trace a program. In addition, machine-level and other commands are available to help debug the code. **dbxtool** is a window-based interface to **dbx** for use on *SUN* workstations allowing a more convenient interface. Debugging is easier because the mouse can be used to enter commands from redefinable buttons on the screen.

A sensitivity analysis is usually concerned with the influence of input parameter variations on simulation predictions. This is rarely a trivial exercise: for example, the ESP-r system contains hundreds of variables and parameters which make it virtually impossible to rigorously test the effect of changing each parameter in a particular situation.

The analytical solution is usually free of uncertainties but its application is restricted to simple cases. In such cases, it is the most suitable for validating codes related to the specific processes in isolation since acceptable overall simulation accuracy does not necessarily mean acceptable accuracy for all processes in isolation. Analytical tests may be used to measure the effect of discretisation and roundoff errors on the algorithm and its boundary conditions. The *overall* potential of the model under investigation cannot, then, be checked using analytical validation because only tests for simplified sub-sets can be analysed. However, these are usually the only *truth* standard available to corroborate simulation predictions.

In the inter-program comparison approach, a component or system is modelled using different simulation programs and their predictions compared. Any level of complexity can be tested and no input uncertainties are present. However, a standard of absolute correctness cannot be identified and the method fails to give an indication about either the accuracy of a given model or the possible source(s) of the observed differences.

From a researcher's point of view, empirical validation is often considered to be the bottom-line test [Bunn 1995]. Traditionally, this procedure is enacted by comparing the predictions from the program with corresponding monitored data. Higher accuracy and reliability can be expected provided that the measurements are accurate. However, application difficulties are often encountered including the complexities and costs associated with monitoring and extrapolating from specific test conditions to more realistic cases.

The following sections describe a series of analytical, inter-model and empirical validation tests carried out in order to verify the control system models installed in ESP-r during the course of this project.

7.2 VALIDATION TESTS.

7.2.1 Introduction.

It is not possible, given the time constraints of the present work, to test and verify *all* the developed schemes described in earlier chapters, and thus a selection of representative cases will be considered. In the validation tests reported here, zone-level building, plant-side and global controller models are assessed. Actuator and sensor delay models are also examined. Table 7.2.1 summarises the validation test series.

Table 7.2.1 Validation exercises: summary of test series.

Reference	Method	Controlled system	Disturbance	Control mode	Control functio
A1	Analytical	Zonal convective heating	set-point change	Modulating (PID)	Building: *BCL05*
A2	Analytical	DHW calorifier	Load & set-point change	Modulating (PID)	Plant: *PCL01*
B1	Inter-model	Zonal convective heating	set-point change	Intermittent (2-position)	Building: *BCL10*
B2	Inter-model	DHW calorifier	Load & set-point change	Intermittent (2-position)	Plant: *PCL08*
B3	Inter-model	Zonal convective heating	set-point change	Intermittent (Supervisory)	Global: *GCL03*
C1	Empirical	AHU chiller	set-point change	Modulating (PI)	Plant: *PCL02*

7.2.2 Validation test A.1: Analytical validation of building-side controller.

Validation test series A1 involves the analytical validation of the ESP-r building-side proportional+integral (PI) flux/temperature controller function, *BCL05*. The simulated results for a controlled convective heating system are compared to a results set established by means of an analytical procedure. The convective heating system is depicted in Figure 7.1.

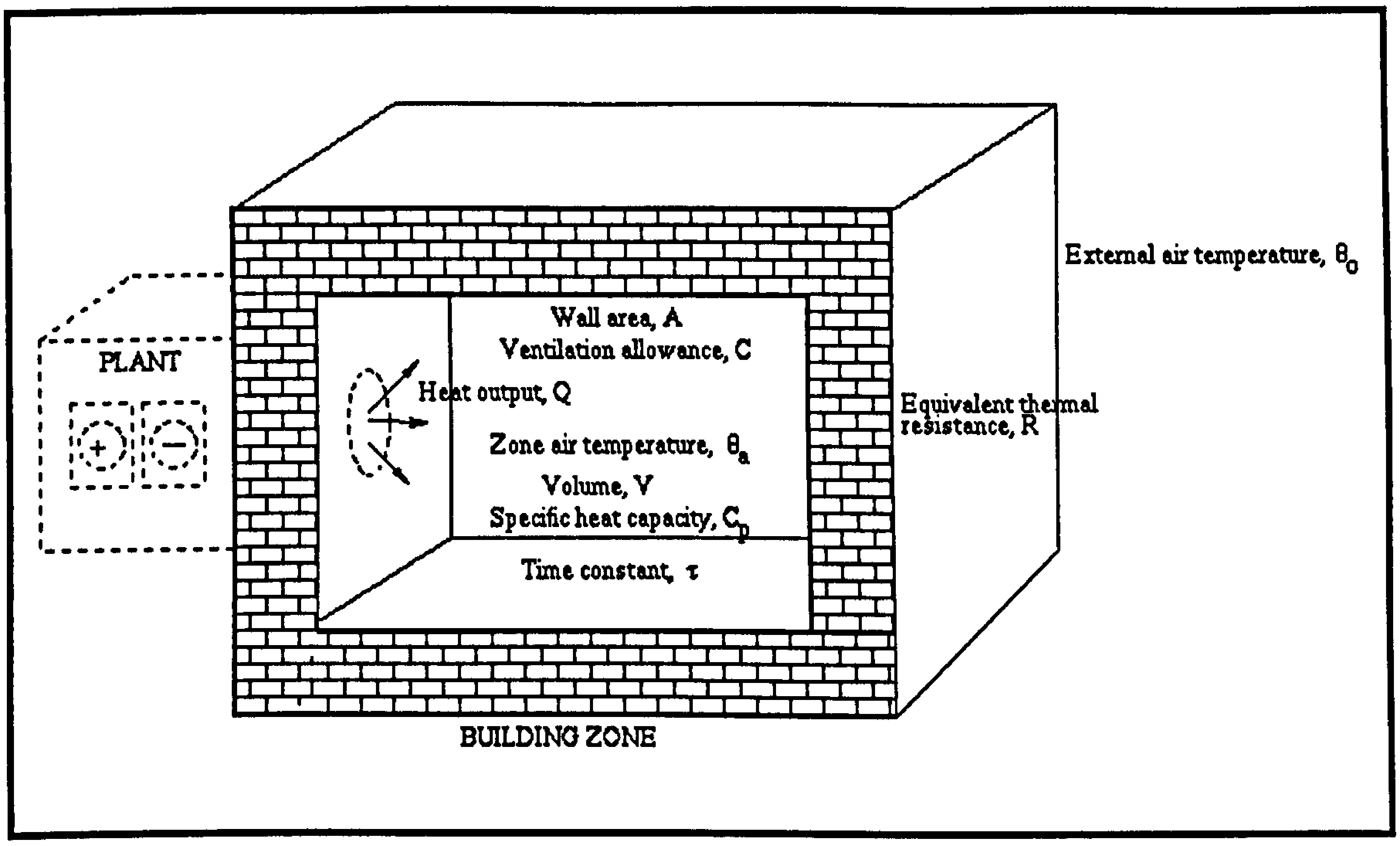


Figure 7.1 Validation test series A1: convective heating system schematic.

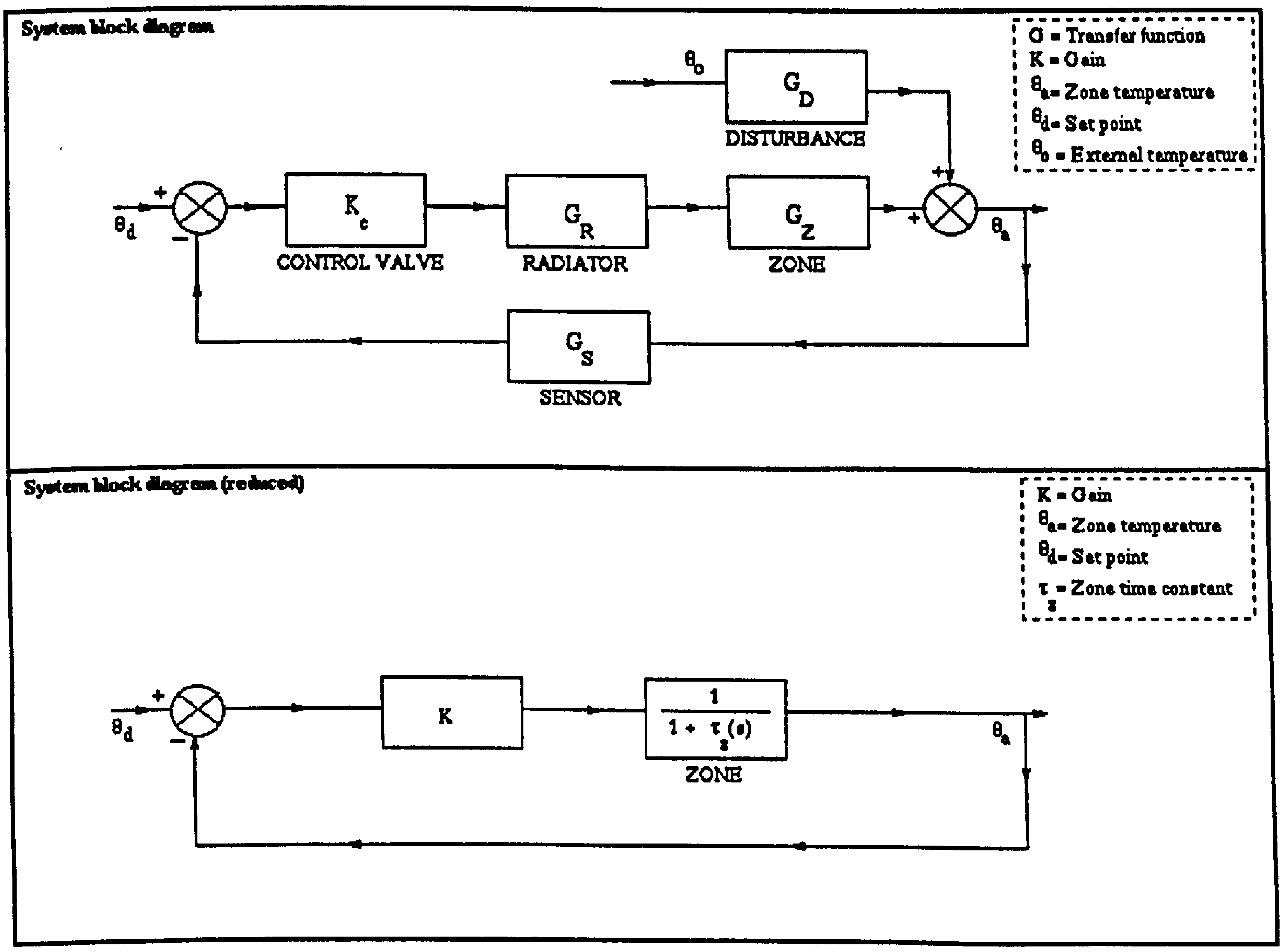


Figure 7.2 Validation test series A1: convective heating system block diagram.

For the control loop to be analysed it is necessary to assign a transfer function to each element within the loop (Figure 7.2). The elements of an air conditioning zone may be modelled by a simple first order model [Hanby 1976]:

$$G(s) = \frac{K}{1+\tau s} \tag{7.1}$$

where K is the element gain and τ is the element time constant (s).

The response of the zone air temperature to a step change disturbance in load and/or set-point is dependent on the mode of heating. Prediction of the response using continuity equations and neglecting thermal capacitance effects [Zermuehlen and Harrison 1965] leads to a system with a time constant τ_z given by:

$$\tau_z = \frac{VC}{\Sigma UA + C_v} \tag{7.2}$$

where V is the zone volume (m^3), C is the volumetric specific heat of air ($J.K^{-1}m^{-3}$), U is the construction U-value ($Wm^{-2}K^{-1}$), A is the zone surface area (m^2 and C_v is the ventilation allowance for heat loss (WK^{-1}).

The zone transfer function may then be written as:

$$G_z(s) = \frac{K_z}{1+\tau_z(s)} \tag{7.3}$$

where G is a transfer function.

The heat loss coefficient for the zone is given by:

$$\Sigma UA + C_v(W/°C) \tag{7.4}$$

hence the zone gain, K_z is:

$$K_z = \frac{1}{\Sigma UA + C_v}(°C/W). \tag{7.5}$$

For the building-side controller model under consideration here (*BCL05*), the *ideal* plant may be combined with the controller element gain, giving an combined plant/controller gain, K_c.

The total system gain is the product of the individual element gains. Therefore the total system gain is:

$$K = \frac{K_c}{\Sigma UA + C_v}. \tag{7.6}$$

Table 7.2.2 (a). Analytical validation test series A.1: convective heating system parameters.

Element	Parameter	Assigned value
Zone	Volumetric specific heat of air, C	1020 $J.K^{-1}m^{-3}$
	Ventilation allowance, C_v	10.7 (W.K^{-1})
	Zone surface area, A	16 m^2
	Construction U-value, U	0.237
	Zone volume, V	64 m^3
Controller	Proportional gain, K_p	150 W/°C
	Integral action time, T_i	300.0 seconds
	Transport delay, T	60 seconds

Table 7.2.2 (b). Analytical validation test series A.1: convective heating system equations.

Test reference	Control mode	$\Delta\theta_d$ (°C)	Sensor delay (s)	$\Delta\theta_a(t)$ (°C)
A.1(i)	P	Step (+1.0)	0.0	$0.91-(0.91exp(-0.0025t))$
A.1(ii)	PI	Step (+1.0)	0.0	$1.0+(0.42exp(-0.0013t)sin(0.0025t))$ $-(1.0exp(-0.0013t)cos(0.0025t))$
A.1(iii)	PI	Step (+1.0)	60.0	$1.0+(0.16exp(-0.05t)cos(0.019t))$ $+(0.42exp(-0.05t)sin(0.019t))$ $-(1.16exp(-0.0012t)cos(0.0027t))$ $+(0.38exp(-0.0012t)sin(0.003t))$

For analysis of the response of the building-side controller to a step change in set-point (θd), the load (θ_o) can be assumed to be constant. For the case of an ideal sensing element in the system shown in Figure 7.2, the zone air temperature is given by

$$\theta_a = K_c \frac{G_z}{1 + K_c G_z} \theta_d \tag{7.7}$$

where G_z is the transfer function for the zone and K_c is the controller gain. Note that for proportional control, K_c is a simple proportional gain, K_p. For proportional plus integral control, an extra parameter, the integral action time (T_i), is introduced in which case the controller transfer function, K_c, is then taken to be K_p ($1 + 1/T_i s$) appropriate for a PI controller.

The modelling of a transport delay can be facilitated by including a delay function, e^{sT}, (where T is the time delay in seconds) in the feedback path (Figure 7.2). Using the Pade approximation of

$$exp(-sT) = \frac{2 - sT}{2 + sT} \tag{7.8}$$

[Liptak 1995] allows Equations (7.7) to be re-written to take account of a transport delay:

$$\theta_a = K \frac{G_z}{1 + K G_z} \theta_d \tag{7.9}$$

where

$$K = K_c \frac{2 - sT}{2 + sT}. \tag{7.10}$$

Using the controlled system parameter values listed in Table 7.2.2 (a), Equations (7.7), (7.9) may be solved analytically for controlled system response to a set-point disturbance with the aid of CAL (Computer Aided Learning) tools such as XMAPLE [Bruce 1991] which formulate the solution for complex differential equations. The solution in the time domain for P, PI and PI (with transport delay) control modes in response to a step change in set-point are listed in Table 7.2.2 (b).

The zone control was modelled in ESP-r by employing a *BCL05* modulating positional proportional+integral (PI) control function with assigned values as listed in Table 7.2.2 (a). All simulations were run for a 1-day period with a fixed time-step of 1-minute.

The results for the ESP-r simulations for the cases of proportional only, full PI control and PI with transport delay, are compared with the analytical set in Figure 7.3, from which it is clear that there is a close correlation between analytic and simulated predictions.

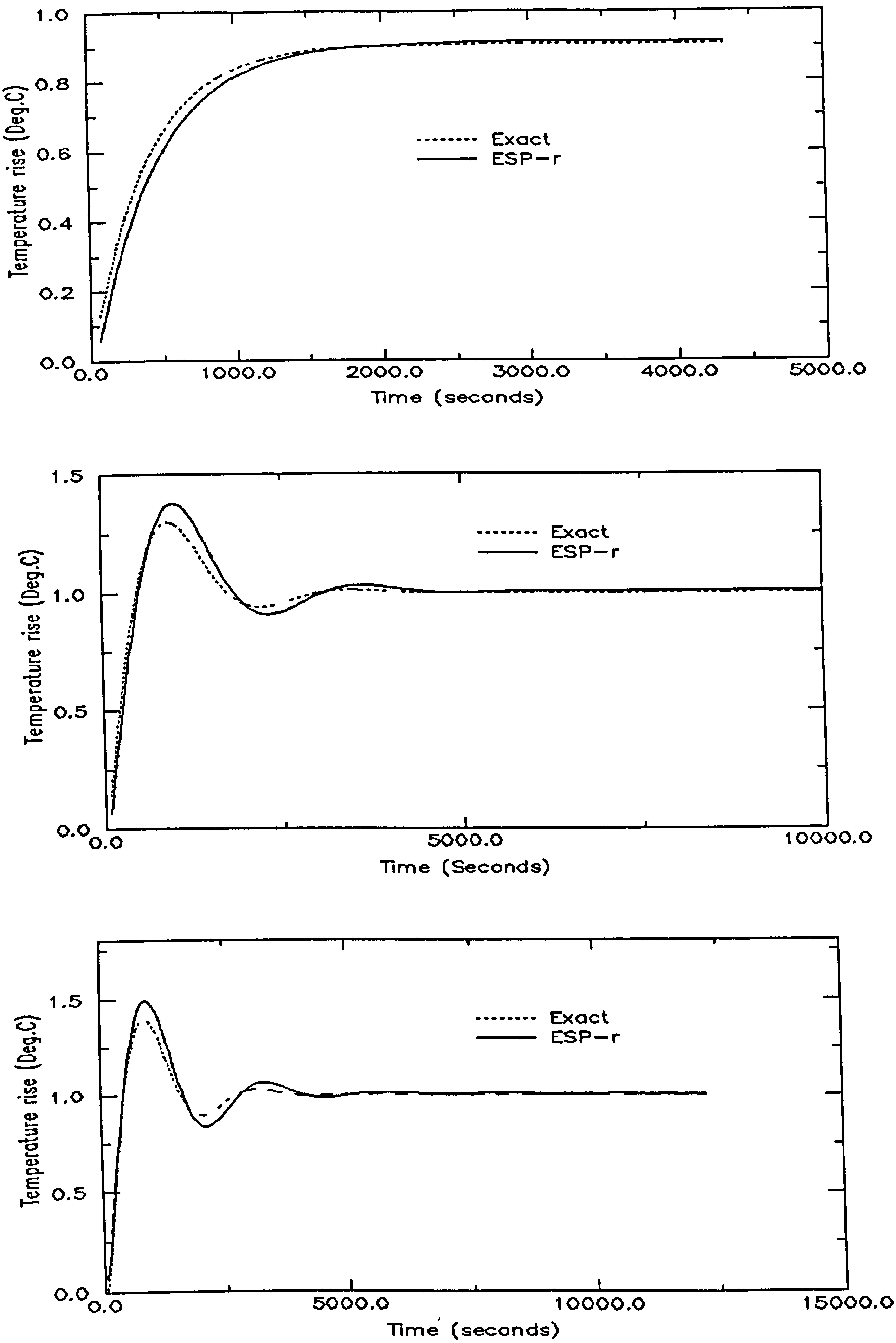


Figure 7.3 Analytical validation: Proportional (top), PI (centre) and PI with actuator delay (bottom).

7.2.3 Validation test A.2: Analytical validation of plant-side controller.

This test involves the analytical validation of the ESP-r plant-side positional proportional+integral+derivative (PID) flux/temperature controller function, *PCL01*. The analytical and simulated results for a controlled domestic hot water (DHW) calorifier are compared. The DHW calorifier system is depicted in Figure 7.4.

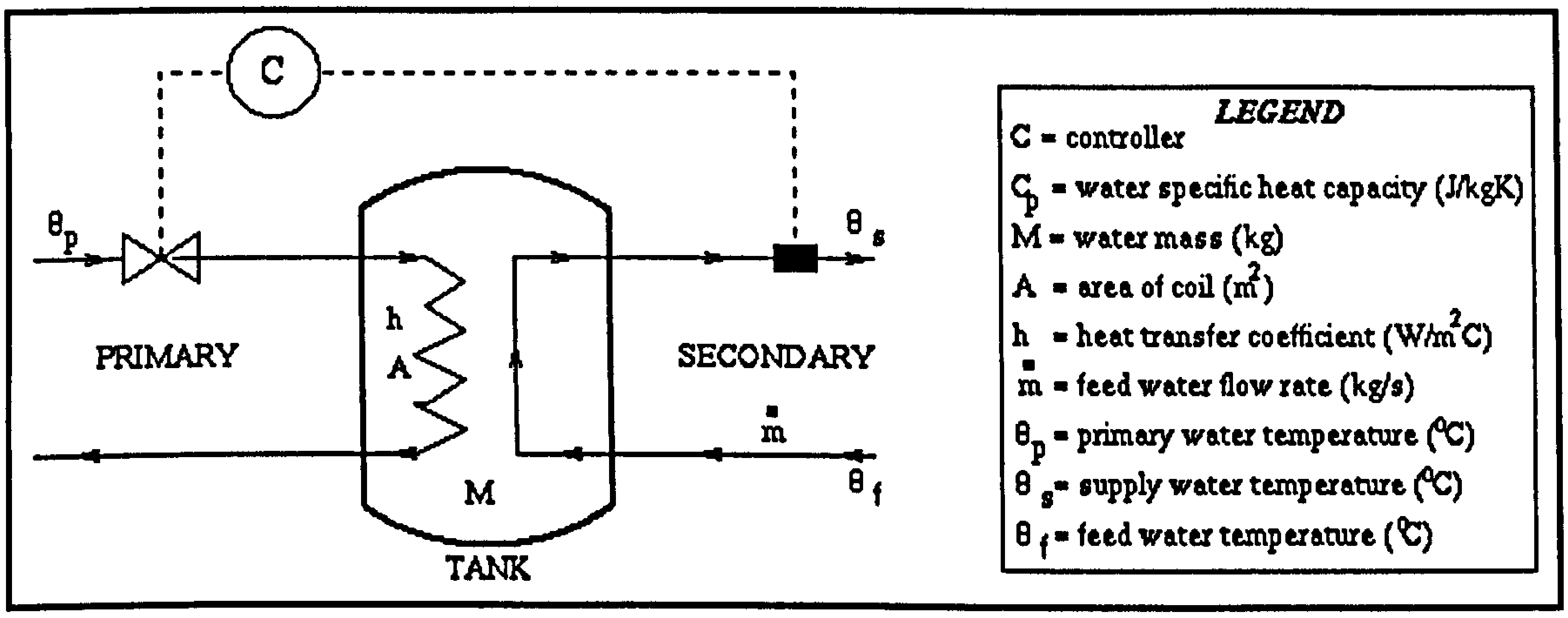


Figure 7.4 Validation test series A2: calorifier system schematic diagram.

Writing a heat balance equation for the calorifier gives:

Rate of heat storage in secondary + rate of heat loss from secondary = rate of energy supply from primary.

The governing differential equation is then

$$MC_p(d\theta_s/dt) + \dot{m}C_p(\theta_s - \theta_f) = hA(\theta_p - \theta_s) \tag{7.11}$$

where M is the mass of water in the tank (kg), C_p is the specific heat capacity of the feed water ($Jkg^{-1}K^{-1}$), θ_s is the supply water temperature (°C), $\dot{m}$ is the mass flow rate of feed water (kg/s), θ_f is the feed water temperature (°C) and θ_p is the primary water temperature (°C).

Equation (7.11) may be written as

$$\theta_s(s) = \frac{\theta_f(s)}{\phi(1+\phi\tau(s))} + (\phi - 1)\frac{\theta_f(s)}{\phi(1+\phi\tau(s))} \tag{7.12}$$

where $\phi = 1 + \frac{\dot{m}C_p}{hA}$ and $\tau = \frac{MC_p}{hA}$.

A controller may be added to this system in an attempt to hold the supply water temperature, θ_s, within prescribed limits regardless of any disturbances to the feed water temperature, θ_f, and/or desired value, θ_d. Control is achieved by means of P, PI, PID control action on the manipulated variable (the primary water temperature). A block diagram representation of the system incorporating a controller is depicted in Figure 7.5. This system may be described in the *s*-domain (Section 2.2) by

$$\theta_s(s) = K_c \frac{\theta_d}{\phi(1+\phi\tau(s))+K_c} + \frac{(\phi-1)}{\phi(1+\phi\tau(s))+K_c} \qquad (7.13)$$

where K_c is the controller gain. For proportional control, K_c is a simple proportional gain, K_p. For proportional plus integral control, an extra parameter, the integral action time (T_i), is introduced in which case the controller transfer function, K_c, is then taken to be K_p $(1 + 1/T_i s)$ appropriate for a PI controller. A block diagram representation of the Equation (7.13) is depicted in Figure 7.6.

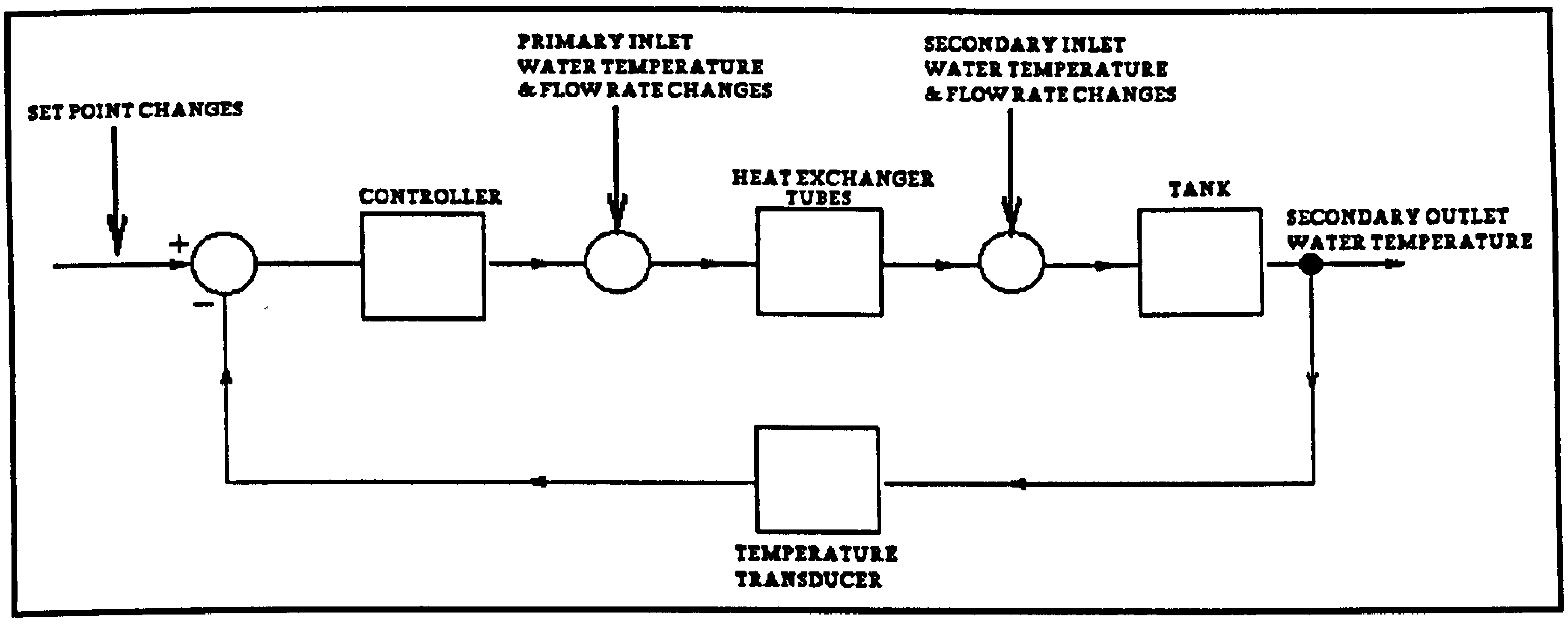


Figure 7.5 Validation test series A2: calorifier block diagram.

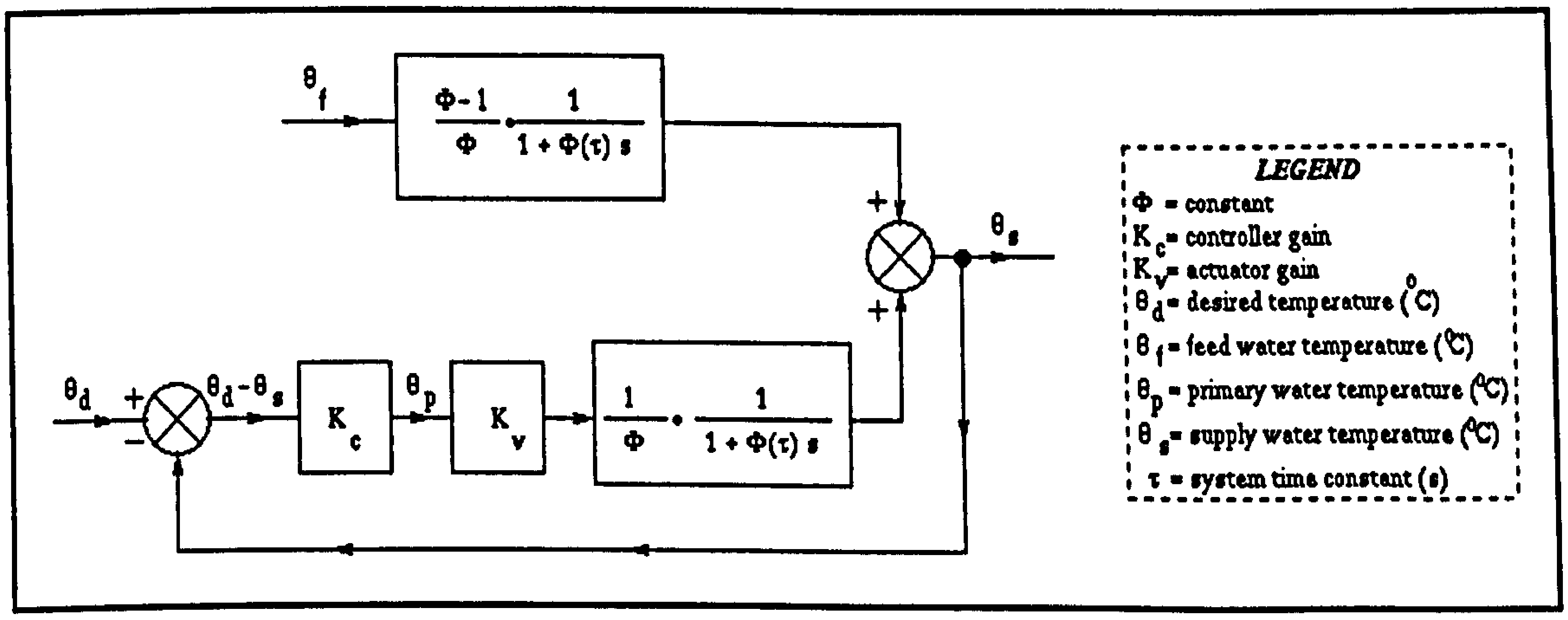


Figure 7.6 Validation test series A2: calorifier equation block diagram.

In order to compare the system response to a load change, it is assumed that there is zero change in the set-point, θ_d. For this case (assuming no actuator delay), Equation (7.13) reduces to:

$$\theta_s(s) = (\phi - 1)\frac{\theta_f(s)}{\phi(1+\phi\tau(s)) + K_c}. \tag{7.14}$$

Alternatively, to compare the system response to a set-point change, it is assumed that there is zero change in the load, θ_f, in which case (assuming no actuator delay), Equation (7.13) reduces to:

$$\theta_s(s) = K_c\frac{\theta_d(s)}{\phi(1+\phi\tau(s)) + K_c}. \tag{7.15}$$

An actuator delay can be modelled by including a time delay function, e^{sT} (where T is the time delay in seconds), in series with the controller gain, K_c as depicted in Figure 7.6. Using the Pade approximation of

$$K_v = exp(-sT) = \frac{2-sT}{2+sT} \tag{7.16}$$

[Liptak 1995] allows Equations (7.14) and (7.15) to be re-written as Equations (7.17) and (7.18), respectively, to take account of actuator time delay:

$$\theta_s(s) = (\phi - 1)\frac{\theta_f(s)}{\phi(1+\phi\tau(s)) + K} \tag{7.17}$$

and

$$\theta_s(s) = K\frac{\theta_d}{\phi(1+\phi\tau(s)) + K} \tag{7.18}$$

where

$$K = K_c K_v. \tag{7.19}$$

Using the system parameter values listed in Table 7.2.3 (a), Equations (7.14, 7.15, 7.17 and 7.18) may be solved analytically for various load and set-point disturbances with the aid of the XMAPLE program. The solution in the time domain for various system disturbances and control modes are listed in Table 7.2.3 (b).

In ESP-r, the calorifier system was modelled using a *type 50* 2-node calorifier component, two *type 24* temperature source components, two *type 15* pump components and a plant-side control loop configured as depicted in Figure 7.7. Simulations were run according to the test schedule listed in Table 7.2.3 (b) using a 3 second time-step unless otherwise stated.

It is clear from the simulation results sets (Figures 7.8 - 7.12) that the degree of correlation between ESP-r is acceptable. Figure 7.10 indicates that the degree of correlation increases with decreasing time-step.

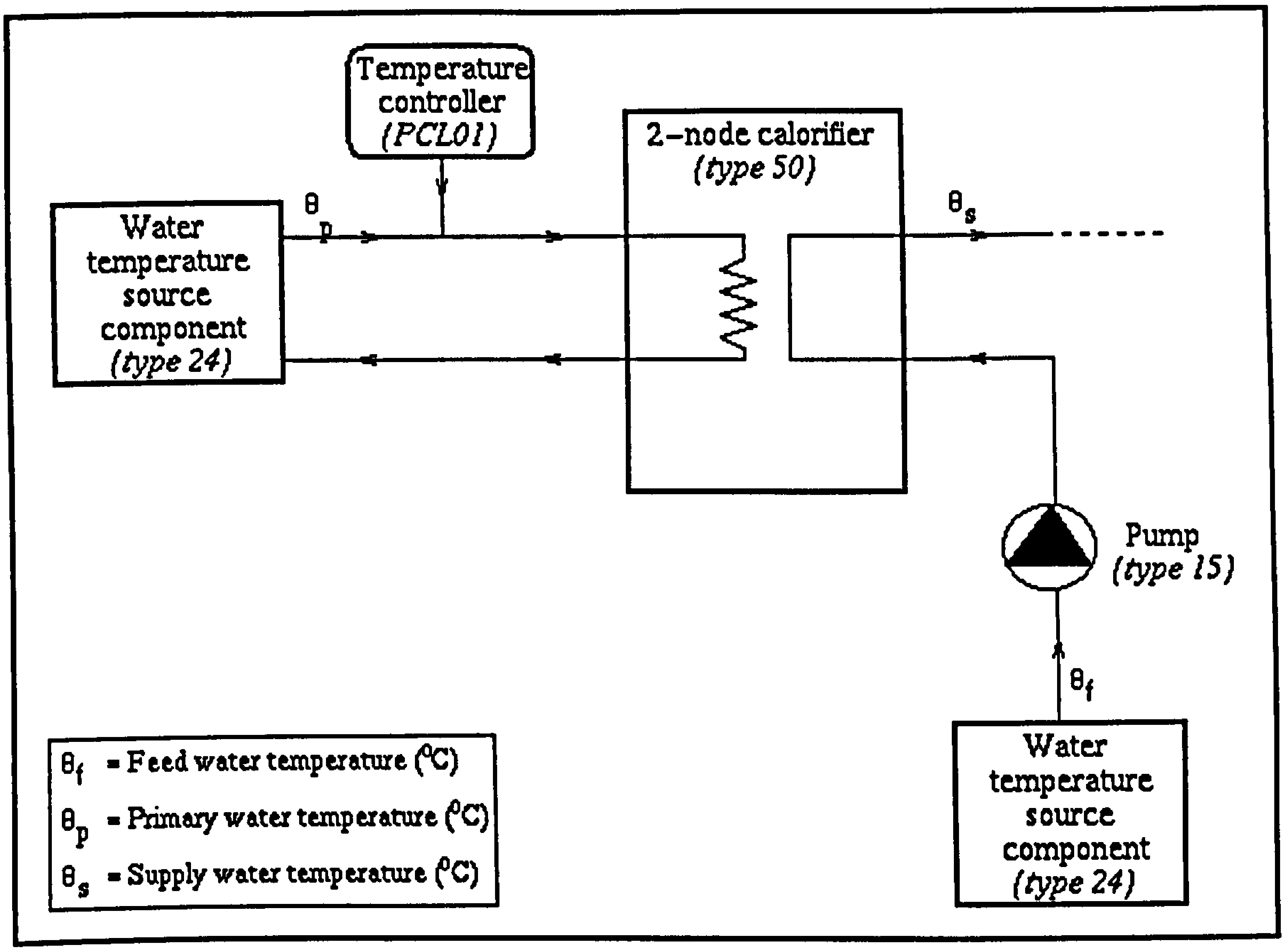


Figure 7.7 Validation test series A2: ESP-r calorifier system configuration.

Table 7.2.3 (a). Analytical validation test series A.2: calorifier system parameters.

Element	Parameter	Assigned value
Calorifier	Primary water temperature, θ_p	80 °C
	Specific heat capacity of water, C_p	4180 J/(kg.K)
	Feed water flow rate, $\dot{m}$	0.3 kg/s
	Heat transfer coefficient, h	600 W/(m^2K)
	System mass, M	100kg
	Coil area, A	0.75 m^2
	ϕ	3.247
Controller	Proportional gain	16.7 % per °C
	Integral action time	10.0 seconds
	Derivative action time	5 seconds

Table 7.2.3 (b). Analytical validation test series A.2: calorifier system equations.

Test ref.	Control mode	$\Delta\theta_f$ (°C)	$\Delta\theta_d$ (°C)	Actuator delay (s)	$\Delta\theta_s(t)$ (°C)
A.2(i)	P	Step (+5.0)	0.0	0.0	$1.36exp(-0.011t) + 1.362$
A.2(ii)	PID	Step (+5.0)	0.0	0.0	$0.584exp(-0.005t)sin(0.026t)$
A.2(iii)	PID	Step (+5.0)	0.0	10.0	$-0.0011exp(-0.701t)) + (0.0011exp(-0.0044t)$ $+cos(0.0252t)) + (0.584exp(-0.0044t)sin(0.0257t)$
A.2(iv)	PID	0.0	Step (+0.6)	0.0	$0.6 + (0.0278exp(-0.0055t)sin(0.025t))$ $-(0.6exp(-0.0055t)cos(0.025t))$
A.2(v)	PI	sine wave +/- 5	0.0	0.0	$-0.003exp(-0.005t)sin(0.025t)$ $-0.013exp(-0.005t)cos(0.025t) + 0.013cos(0.0006t)$
A.2(vi)	PI	0.0	Step (+0.6)	0.0	$0.6 + (0.03exp(-0.005t)sin(0.02t))$ $-(0.6exp(-0.005t)cos(0.02t))$

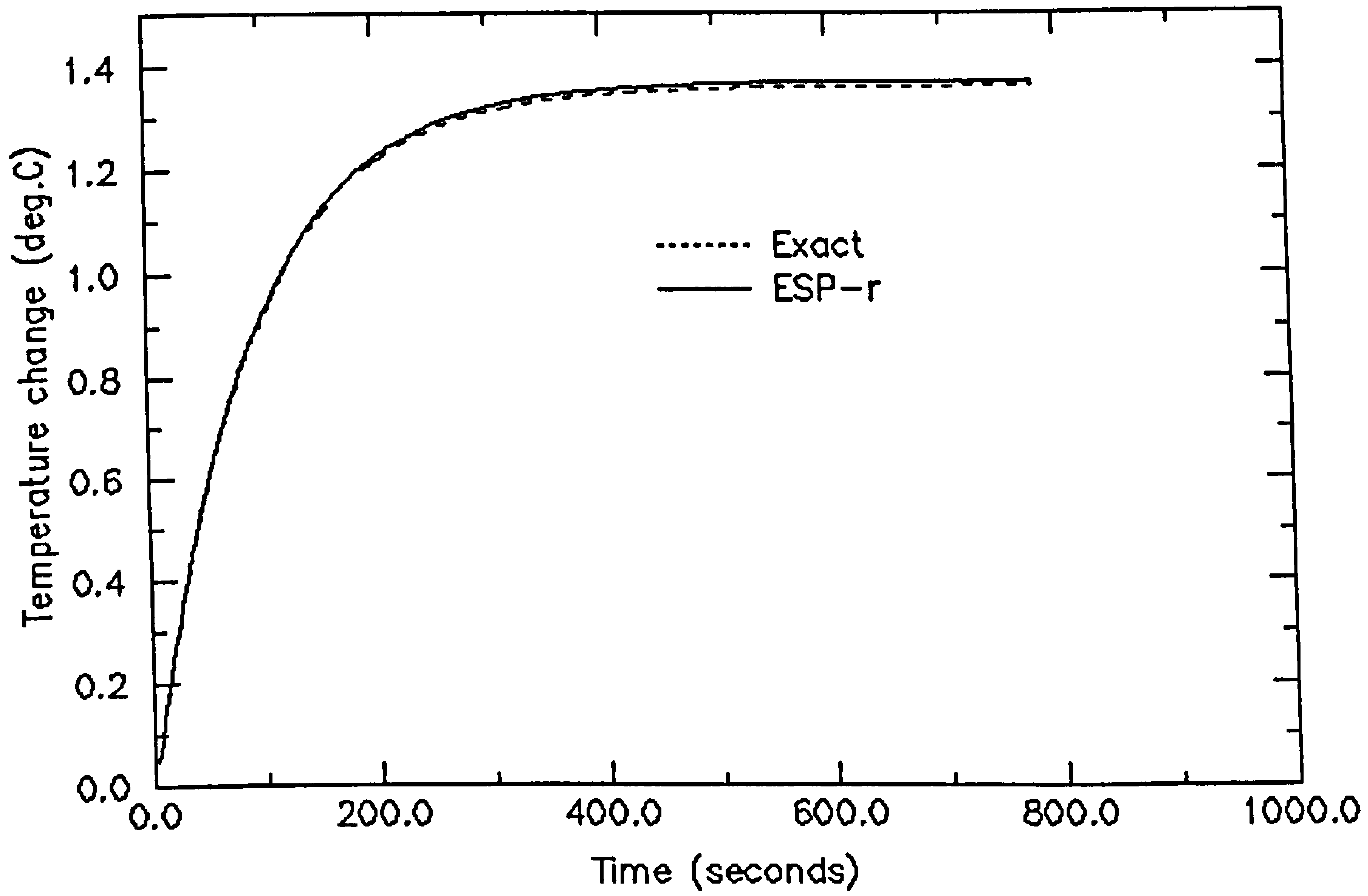


Figure 7.8 Analytical validation test series A.2: Proportional control (step change in load).

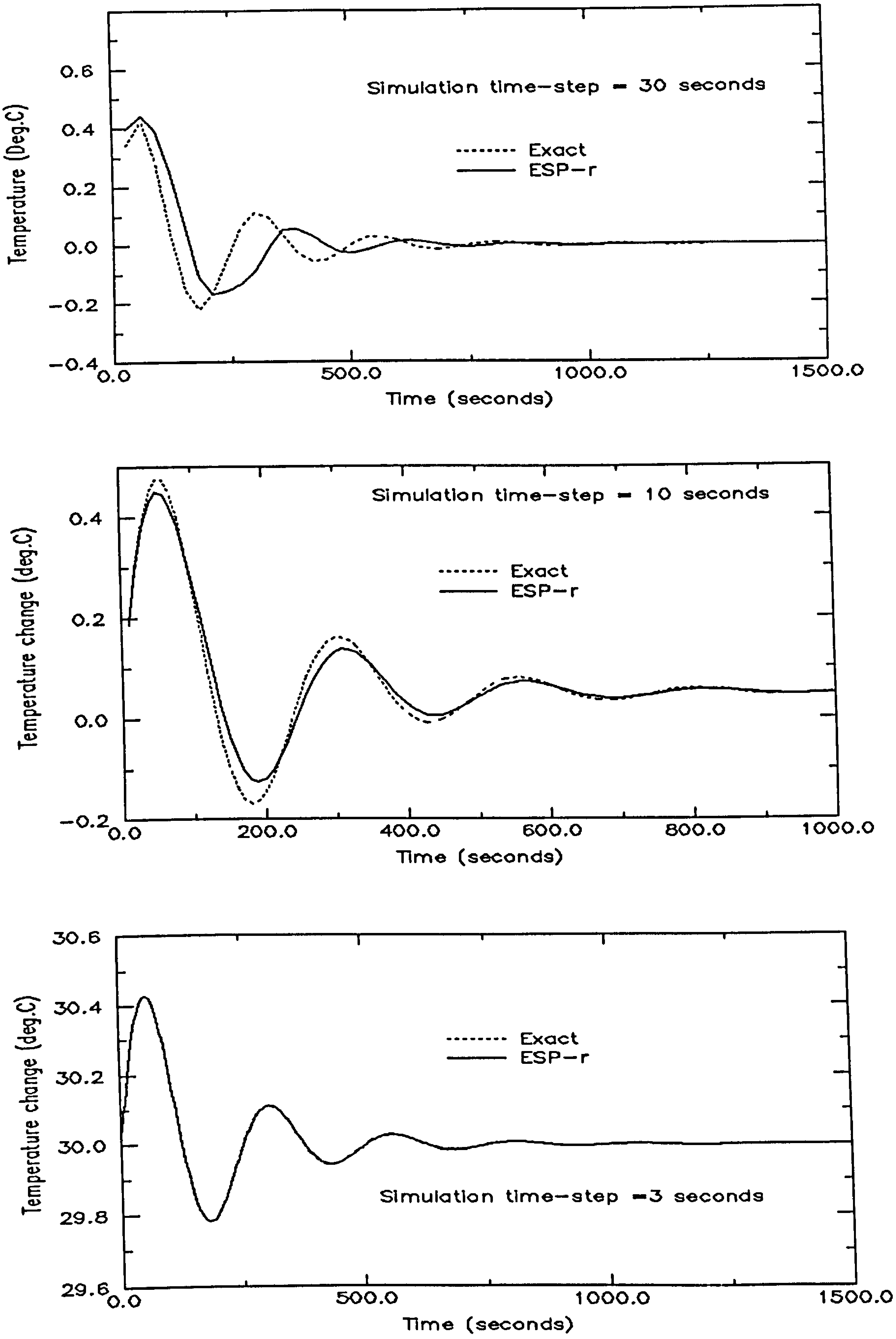
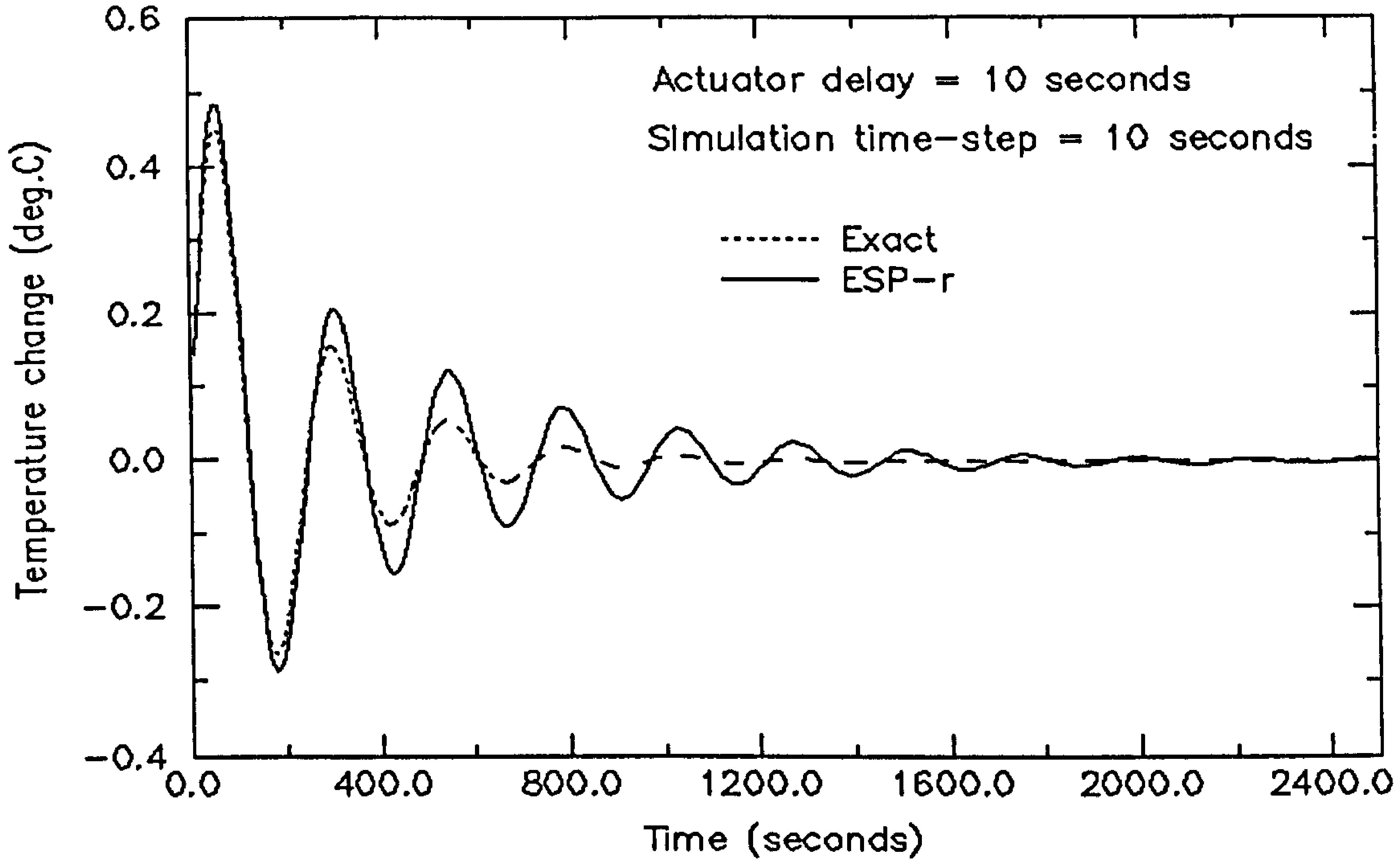


Figure 7.9 Analytical validation test series A.2: PID control (step change in load).



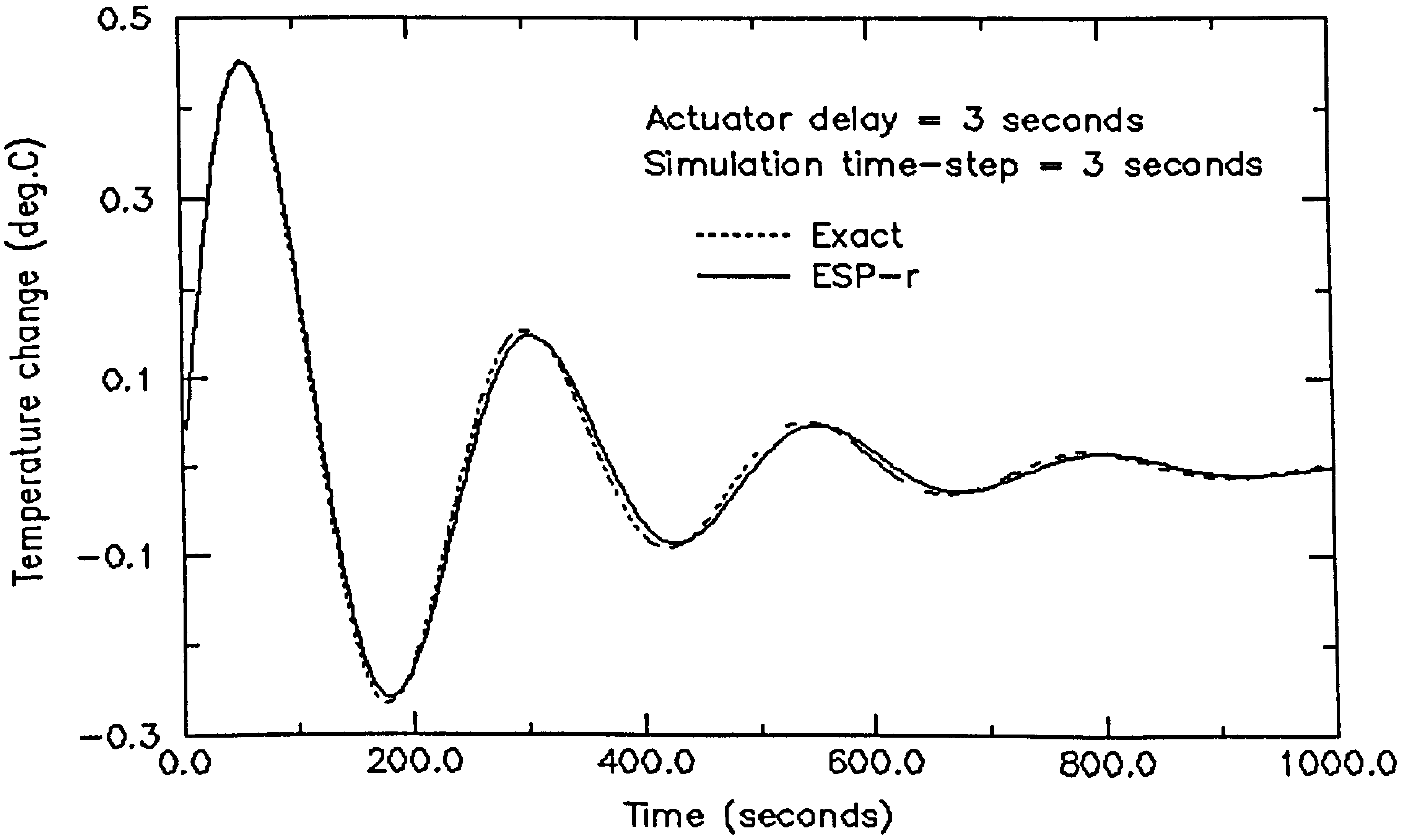


Figure 7.10 Analytical validation test A.2: PID control with delay (step change in load).

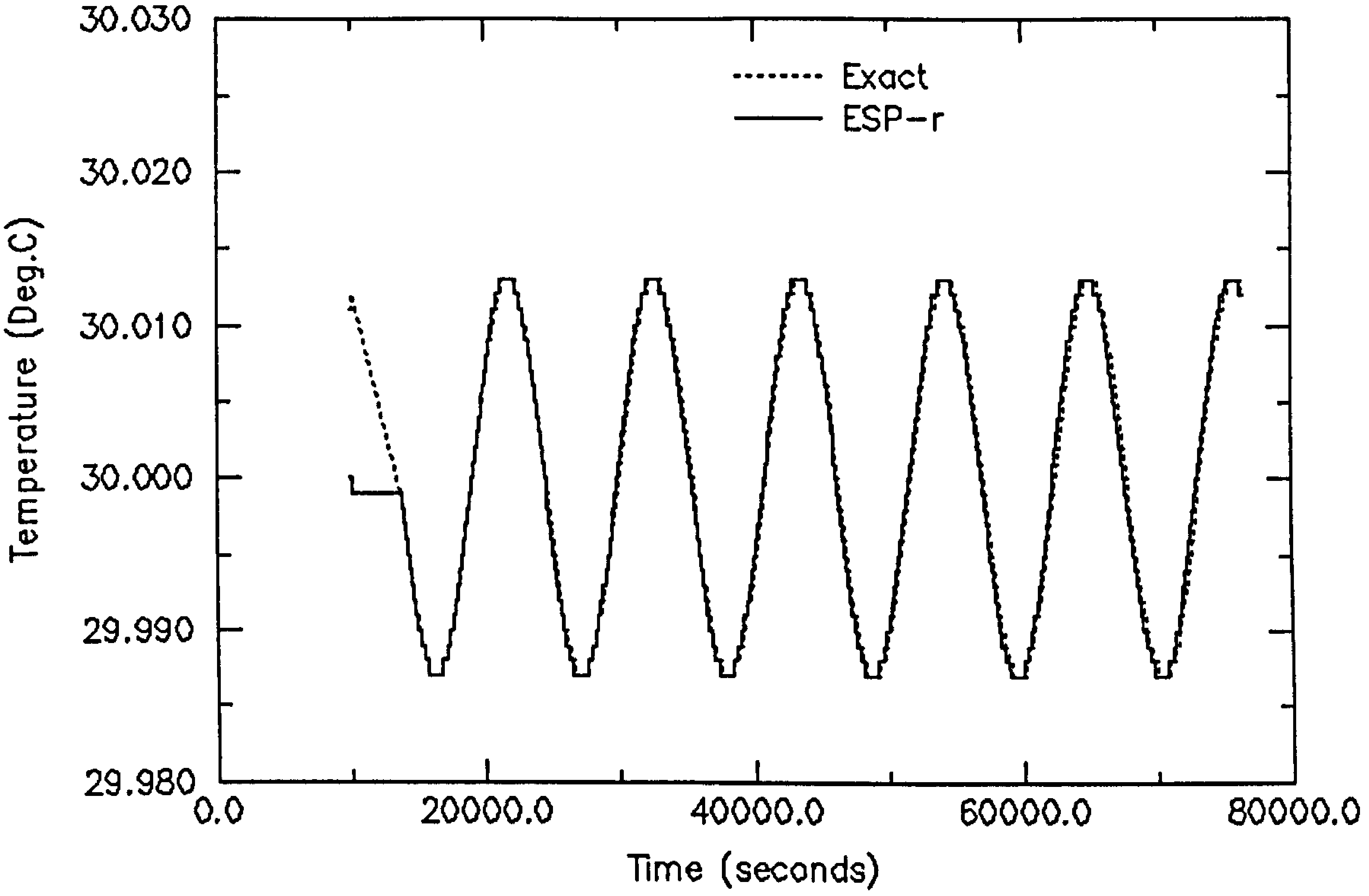


Figure 7.11 Analytical validation test A.2: PID control (sinusoidal change in load).

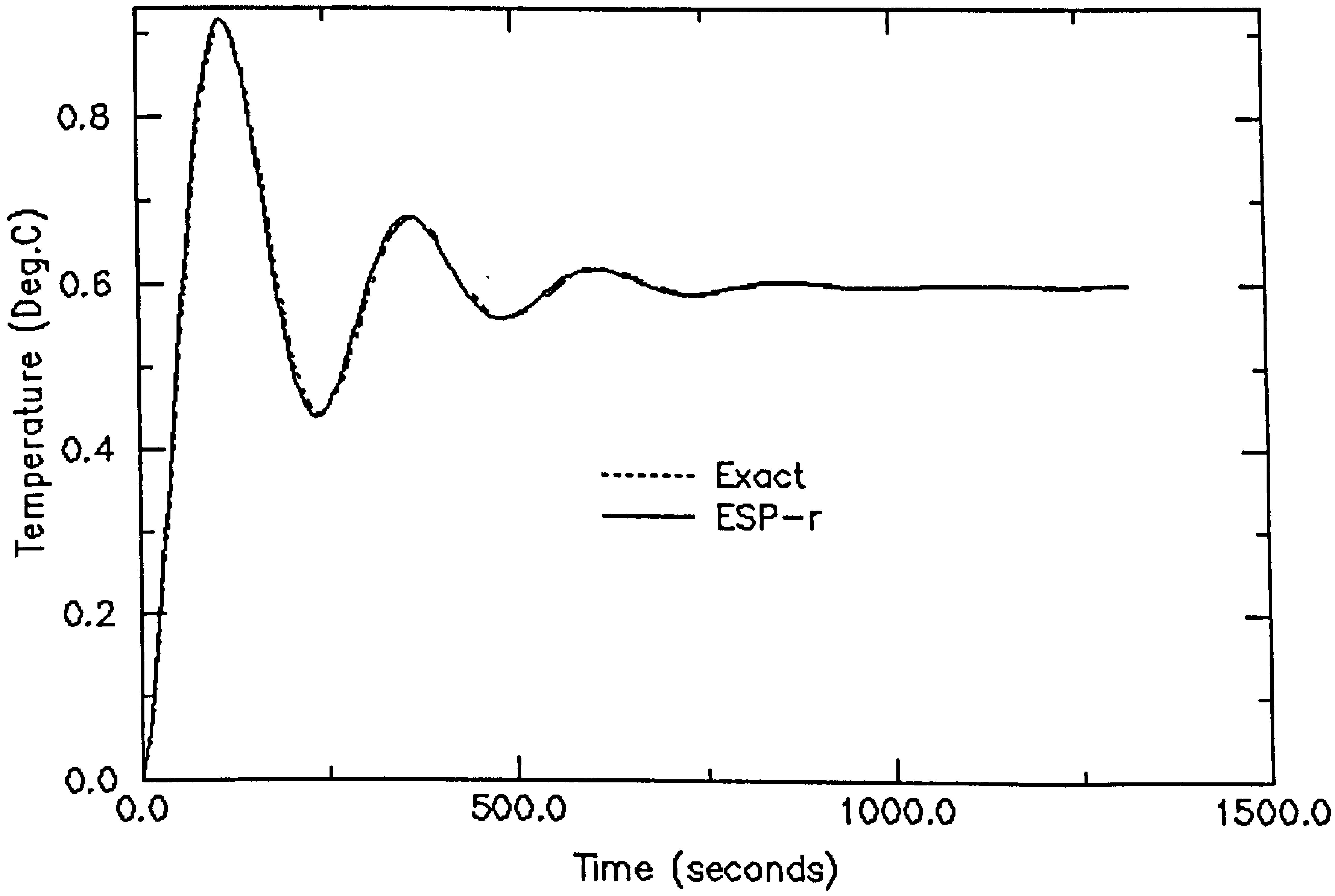


Figure 7.12 Analytical validation test A.2: PID control (step change in set-point).

7.2.4 Validation test B.1: Inter-model validation of building-side and global controllers.

The purpose of this test series is to validate building-side, global and plant-side two-position multi-sensor controllers (*BCL10, GCL03* and *PCL08* respectively). The response of the control system as modelled by the ESP-r controllers is compared to the response as predicted by a general purpose simulation program called TUTSIM. For a thorough explanation of TUTSIM, the reader should refer to the System Manual [Walter and Jiner 1990]. Briefly stated, TUTSIM is particularly suited for the simulation of continuous dynamic systems represented by differential equations as is the case with ESP-r. TUTSIM can be regarded as a toolbox with a large number of elementary functions pre-programmed. Each elementary function may be represented as a block so that interconnections between blocks complete the object system being modelled.

In the first test, the ESP-r building-side two-position multi-sensor control function, *BCL10,* is used to model the zone-level intermittent control action applied to a 3-zone convective heating system subjected to a system disturbance (i.e. a change in controller set-point), and the results compared to a results set generated by a TUTSIM simulation of the same problem. The TUTSIM model of the combined zone and (idealised) plant system is based on a first-order model of the zone and the heating plant (Florez and Barney 1984). It is assumed that the thermal time constants associated with the heating plant and the internal air space and its contents are negligible compared to that of the building structure. The differential equation governing the time variation in the zone temperature (θ_r) is:

$$\tau d \frac{\theta_z(t)}{dt} + \theta_z(t) = RQ_h(t) + \theta_o(t) \qquad (7.20)$$

where θ_z (t) is the zone air temperature (°C), Q_h (t) is the heat output of the heating system (W) and θ_o (t) is the external dry bulb air temperature (°C).

The TUTSIM configuration for a single zone is depicted in Figure 7.13. The zone air point temperature time derivative, $d\theta_z$, is obtained by using gain (GAI) functions to sum the appropriate quantities and then using an Euler (EUL) function to integrate the time derivative. It should be noted that an INT function is normally used for integration purposes when using TUTSIM. However, the TUTSIM manual recommends specification of the EUL integrating function for the modelling of *discontinuous* control action otherwise inaccuracies may occur in the prediction of the controlled variable. This was verified during the course of these validation exercises when the replacement of the EUL function by the INT function resulted in a significant phase shift between ESP-R and TUTSIM predictions.

The zone and plant system parameters are those listed in Table 7.2.2 (a) for the analytical test series A.1 and were defined by employing constant (CON) functions. All three zones had identical parameters specified with the exception of controller set-points (listed in Table 7.2.4). The controlled system was modelled by specifying REL (relay) and IFE (logic) functions were used to initiate a step change in controller set-point and to model controller relay switching action.

A series of TUTSIM simulations were carried out using a 1-minute time-step for the 3-zone configuration shown in Figure 7.14 but with the global controller function disabled. Similarly, a corresponding series of ESP-r simulations (employing the *BCL10* controller function) were processed using a similar simulation time-step. The results for the zone-level controller test are shown in Figure 7.15, from which it is evident that there is good agreement between program predictions.

The second test in this series involves validation of the ESP-r two-position global controller, *GCL03*. Here, GCL03 is used to supervise the three zone-level controllers of the previous test. The global control schedule imposed on the zone-level control strategy is that listed in Table 7.2.4, i.e. zone_B heating is ON only if zone_C heating is ON which in turn is ON only if zone_A heating is ON. The global control was modelled in TUTSIM by the inclusion of REL and IFE logic functions as depicted in Figure 7.14, which act to switch the zone-level controllers according to the supervisory logic. The results for this test are shown in Figure 7.16 where it clear that there is a close correlation between TUTSIM and ESP-r predictions.

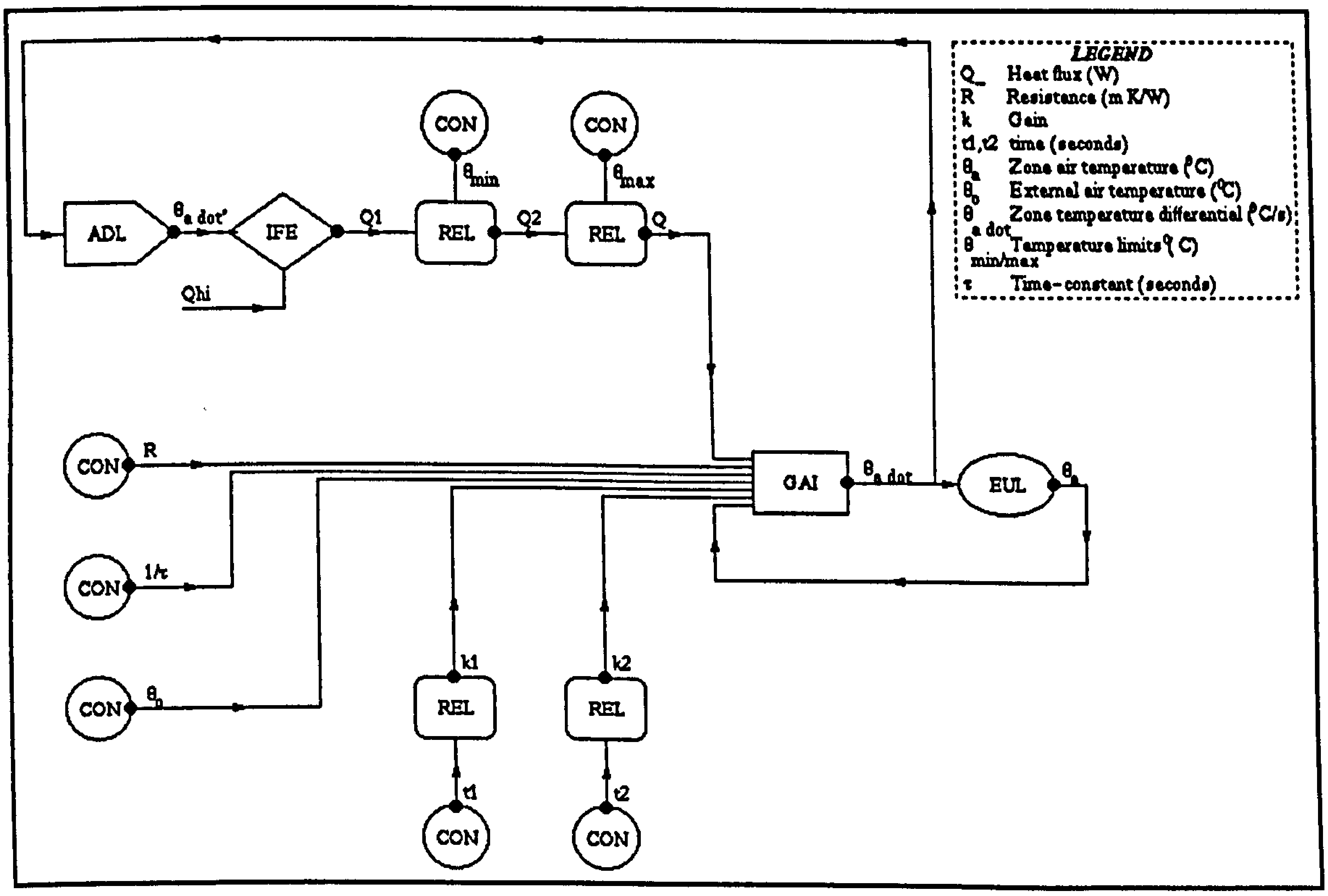


Figure 7.13 Validation test B.1: TUTSIM configuration of 1-zone heating system.

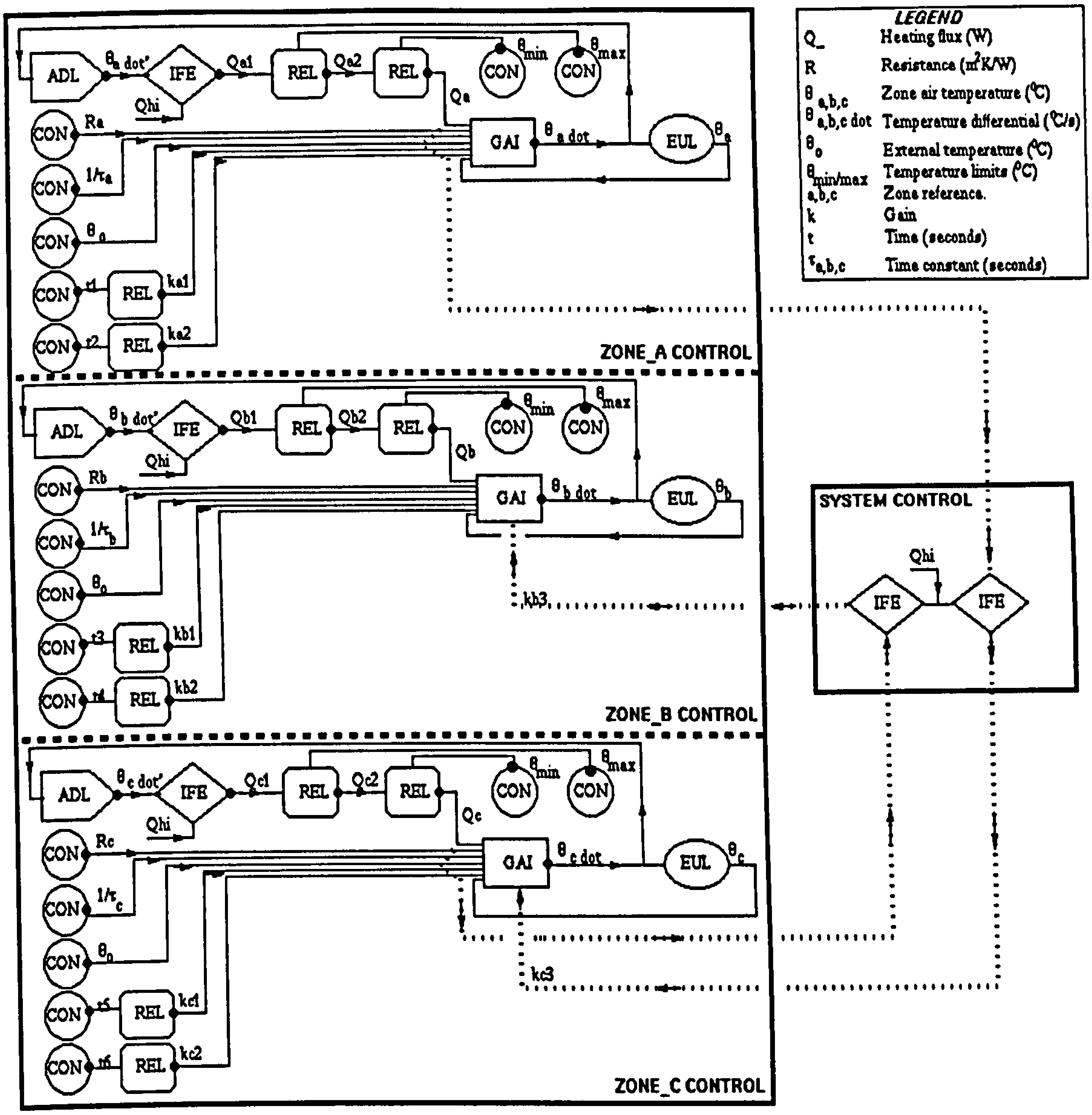


Figure 7.14 Validation test B.1: TUTSIM configuration of 3-zone heating system.

Table 7.2.4. Inter-model validation test series B.1: control schedule.							
Control function	Coupled zone	Period_1		Period_2		Period_3	
		Start	set-point (°C)	Start	set-point (°C)	Start	set-point (°C)
BCL10	A	00.00	15.0	12.00	16.0-17.0	21.00	15.0
BCL10	B	00.00	15.0	15.00	16.0-17.0	23.00	15.0
BCL10	C	00.00	15.0	10.00	16.0-17.0	18.00	15.0
GCL03	All	00.00	Sequence: A-C-B	(00.00)	Sequence: A-C-B	(00.00)Sequence: A-C-B	

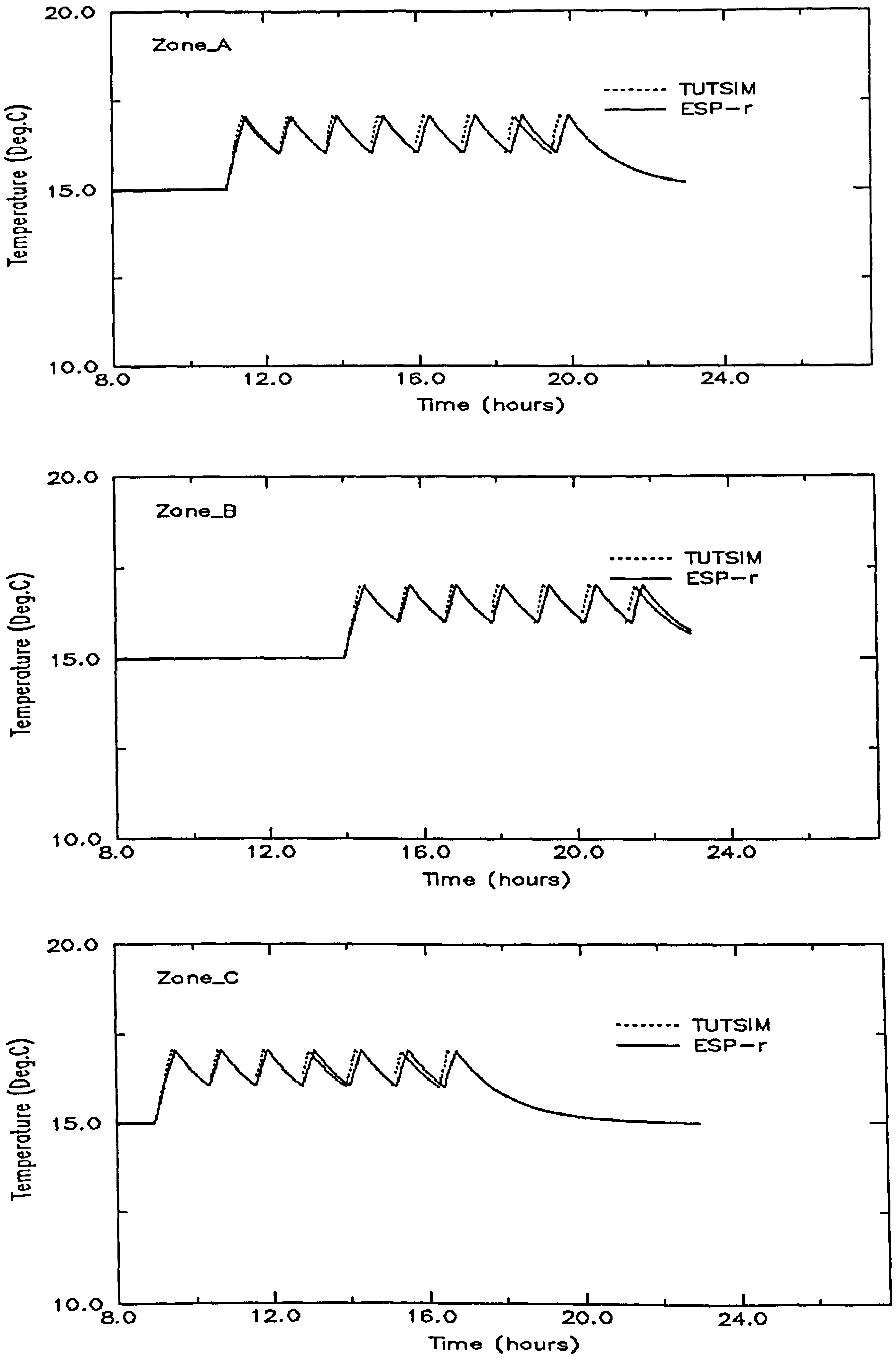


Figure 7.15 Inter-model validation test B.1: Two-position zone-level control.

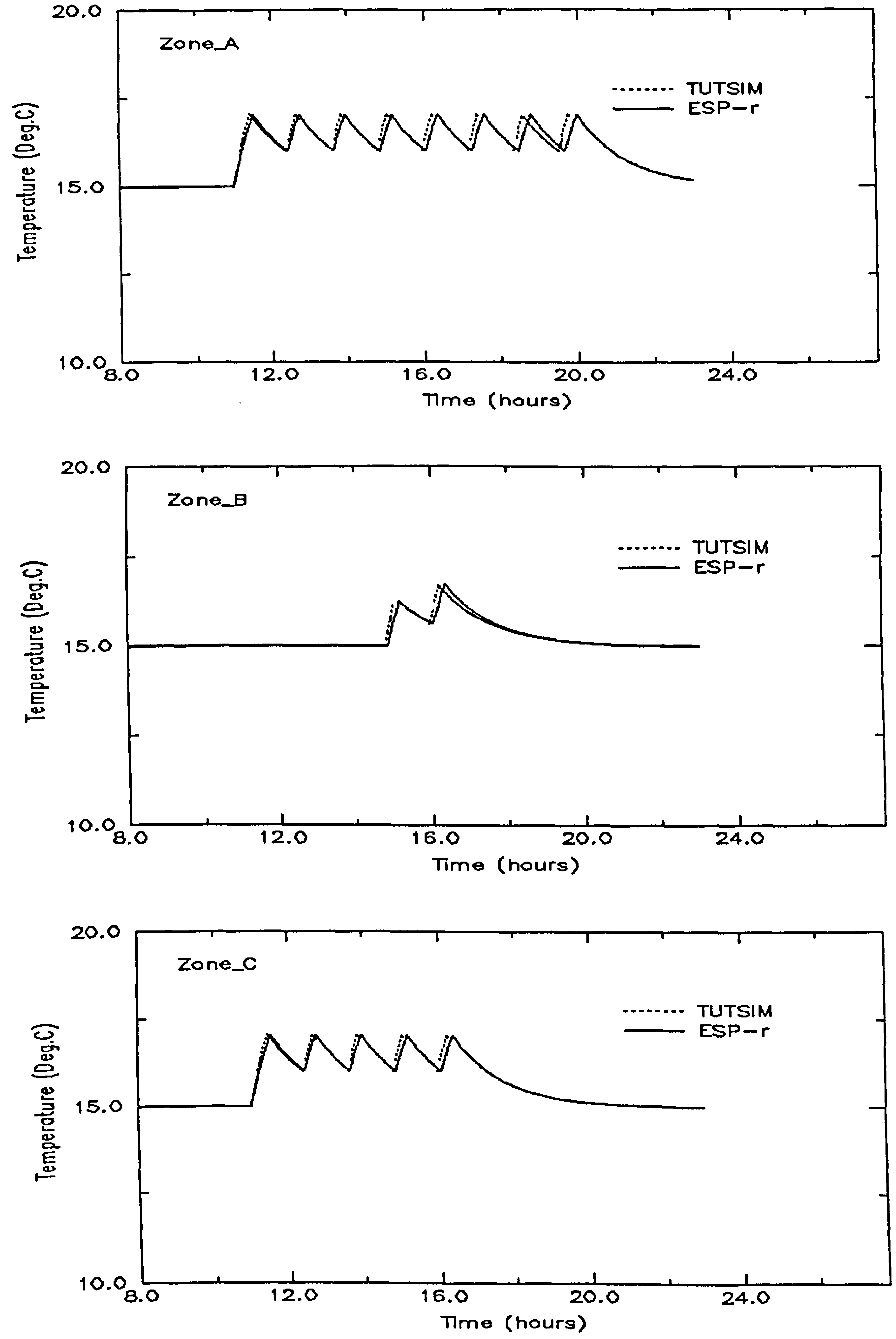


Figure 7.16 Inter-model validation test B.1: Two-position system-level control.

7.2.5 Validation test B.2: Inter-model validation of plant-side controller.

The test series B.2 involves the validation of the ESP-r two-position controller, *PCL08*. The controller is applied to the calorifier system of Section 7.3 to obtain intermittent control action on the primary water supply, θ_p, in attempt to hold the supply temperature, θ_s, constant irrespective of system disturbances. The control system response to two types of system disturbance are modelled: firstly, a step set-point change in the supply water temperature; and secondly, a step load change in the feed water temperature θ_f. In both cases, the controller acts to maintain the controlled variable, θ_s, within prescribed limits by means of two-position control action on the manipulated variable, θ_p, i.e., from Equation 7.11, setting θ_p equal to θ_s effectively zeros the heat transfer from primary to secondary lines.

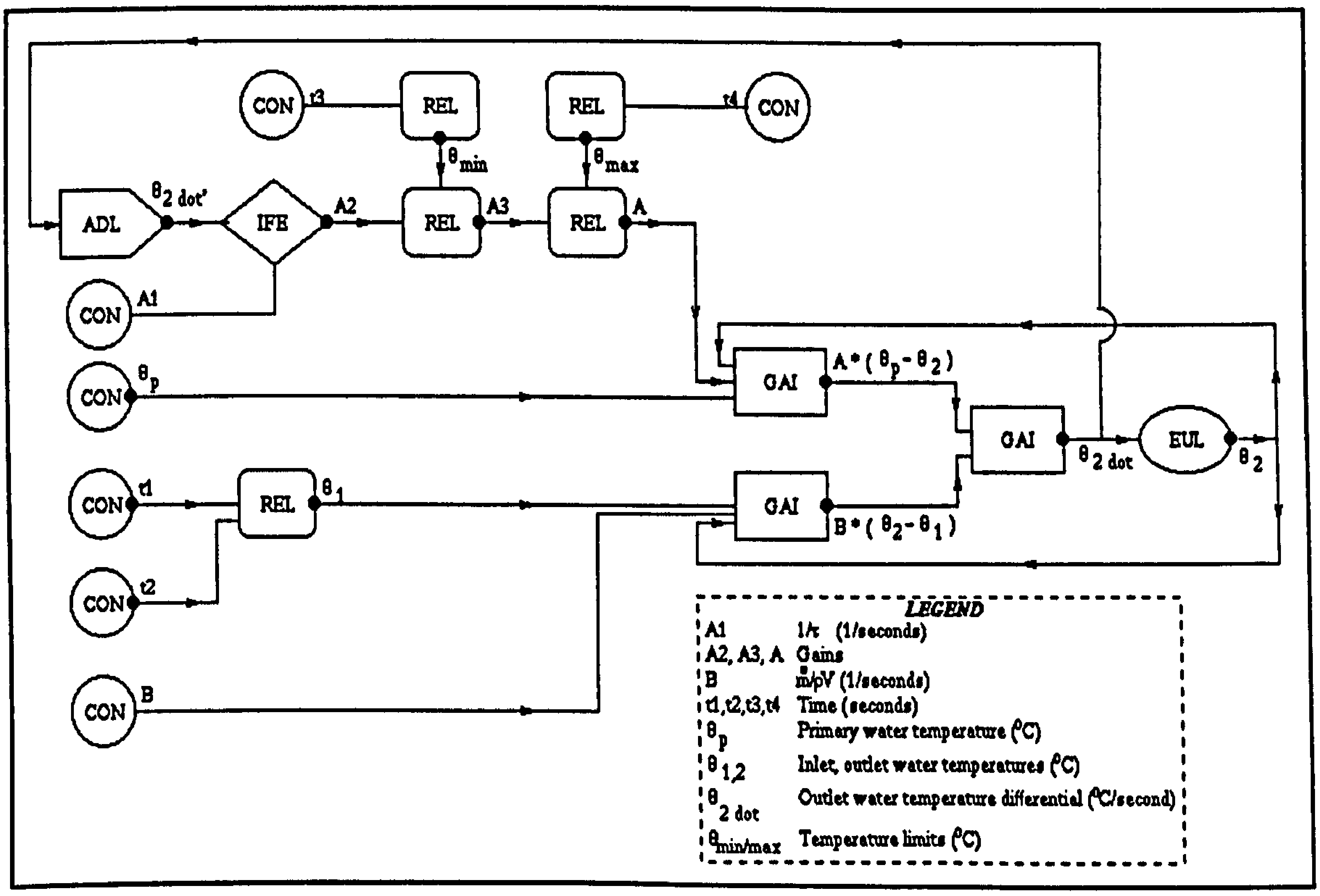


Figure 7.17 Inter-model validation test B.2: TUTSIM calorifier system representation.

The TUTSIM configuration of the controlled calorifier system is depicted in Figure 7.17. The fixed parameters relating to the calorifier (i.e. those listed in Table 7.2.3 (a) for the analytical test series A.2) were defined by employing constant (CON) functions. The supply water temperature (θ_s) was obtained by using gain (GAI) functions to sum the appropriate quantities of Equation (7.11) and then using an Euler (EUL) function to integrate the time derivative.

The control system is modelled by employing relay (REL) and conditional (IFE) function blocks to model controller relay switching logic. REL functions were used to initiate a step load change in the feed water temperature (θ_f) of 10 °C at 10.00 hours and a step change in throttling range of 3 °C at 20.00 hours. (Note that $d\theta_s$ used as the input to the IFE block can only be calculated if θ_s is known and hence an ADL (algebraic delay block is required for use at the first simulation time-step.). TUTSIM was then instructed to commence a 1-day simulation using a time-step of 3 seconds.

The calorifier system was modelled in ESP-r in a similar manner to that described in Section 7.2.3 for the analytical test series A.2, only in this test the control function used is the plant-side control function, *PCL08* (Figure 7.18). Simulations were then run for a 1-day period using a 3 second time-step, according to the schedule listed in Table 7.2.5.

As indicated by Figure 7.19, good agreement was obtained between ESP-r predictions and TUTSIM simulations, indicating that the control signals established by the models installed in the ESP-r plant controller library and the subsequent solution of the nodal equations is accurate. It can also be concluded that the TUTSIM program offers a useful and powerful means of modelling systems described by continuous differential equations. It thus facilitates the verification of controller modelling strategies based on the complex manipulation of differential equations.

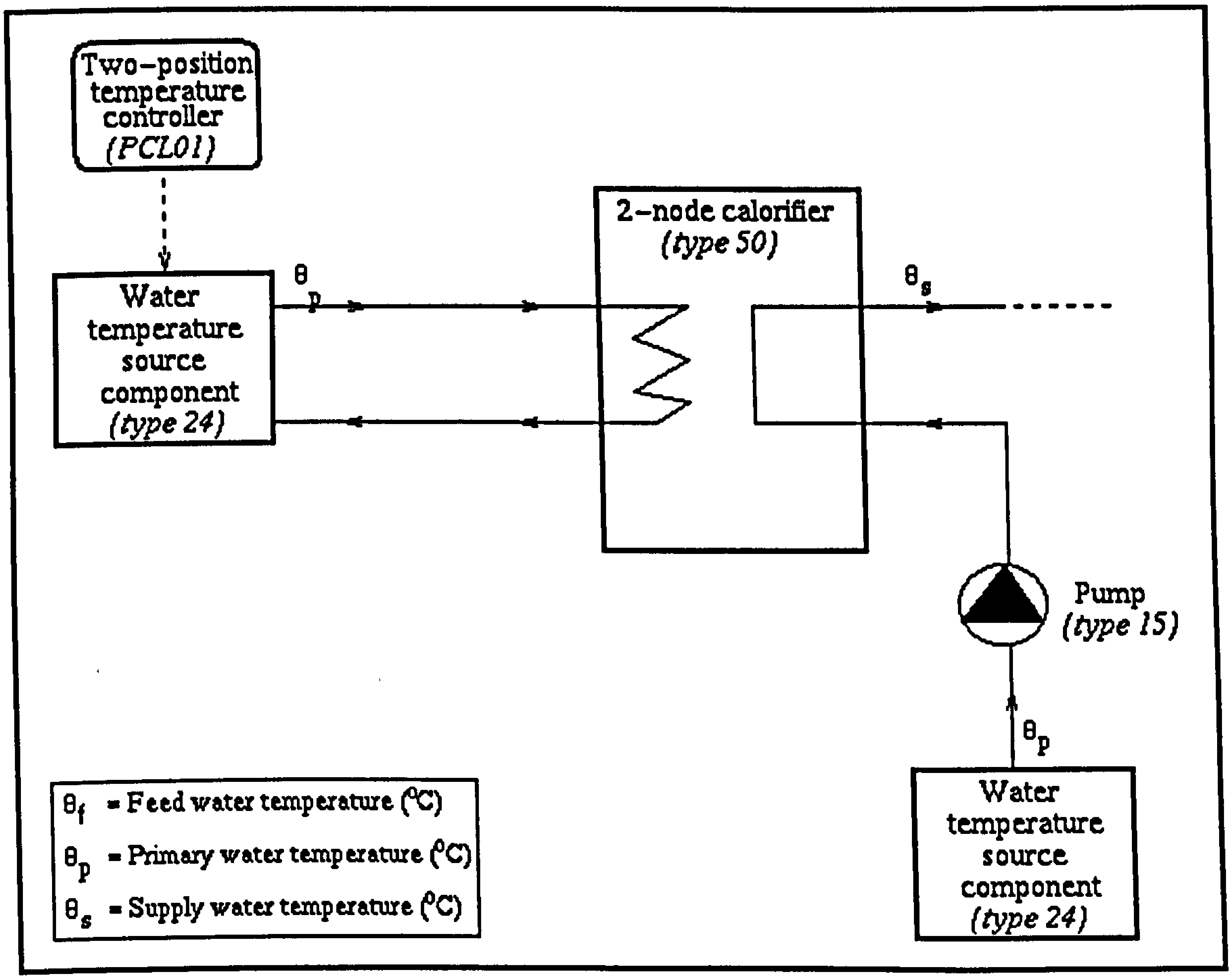


Figure 7.18 Inter-model validation test B.2: ESP-r calorifier system configuration.

Table 7.2.5. Inter-model validation test series B.2: control schedule.

Control function	Period_1		Period_2	
	Start	Throttling range (°C)	Start	Throttling range (°C)
PCL08	00.00	31.5-31.6	20.00	33.5-36.5

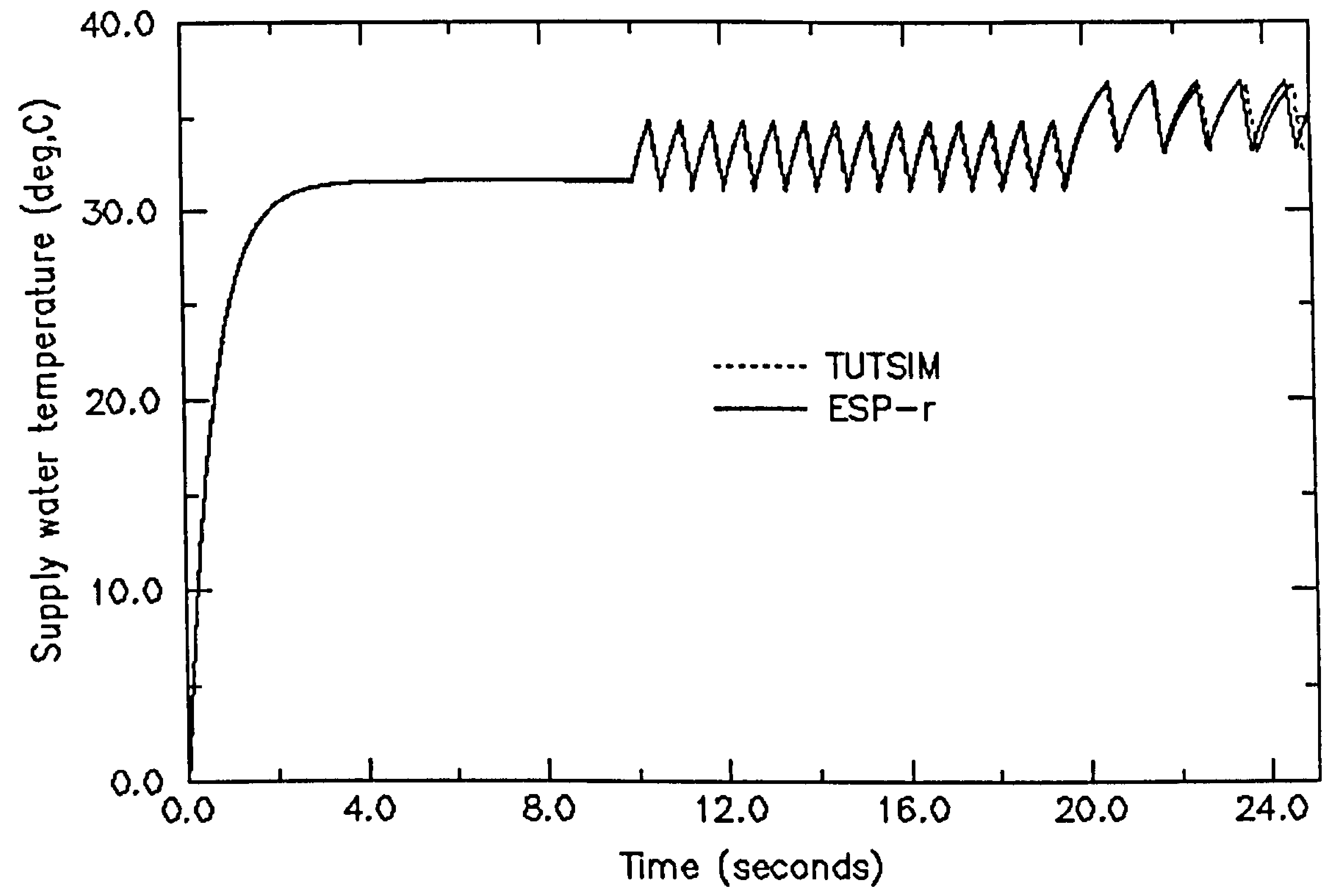


Figure 7.19 Inter-model validation test B.2: Calorifier controller response.

7.2.6 Validation test C: Empirical validation of plant-side controller.

The system modelled is a cooling coil modulating proportional-integral (PI) flow rate controller which attempts to maintain the chiller discharge air temperature at a prescribed level irrespective of any system disturbances, by means of modulating the cold water supply to the cooling coil in the air stream. This system was modelled by ESP-r as depicted in Figure 7.20, with controlled system parameters as listed in Table 7.2.6. The predicted and measured discharge air temperature values are shown in Figure 7.21, for a step change in set point (from 27 °C to 15 °C) from which it is clear that although the final steady state values for both controllers are similar, it is observed that there are discrepancies during the transient response phase. These observed discrepancies can be attributed in part to the modelling resolution (2 node) used to model the thermodynamic response of the chiller component, and also to the operating characteristics affecting the system dynamics for which data was unavailable and therefore not taken into account during the modelling process, including:

- Non-ideal characteristics of the control elements, e.g. preload;
- Disturbances other than set point change, e.g. fluctuation in flow rates;
- Experimental error.

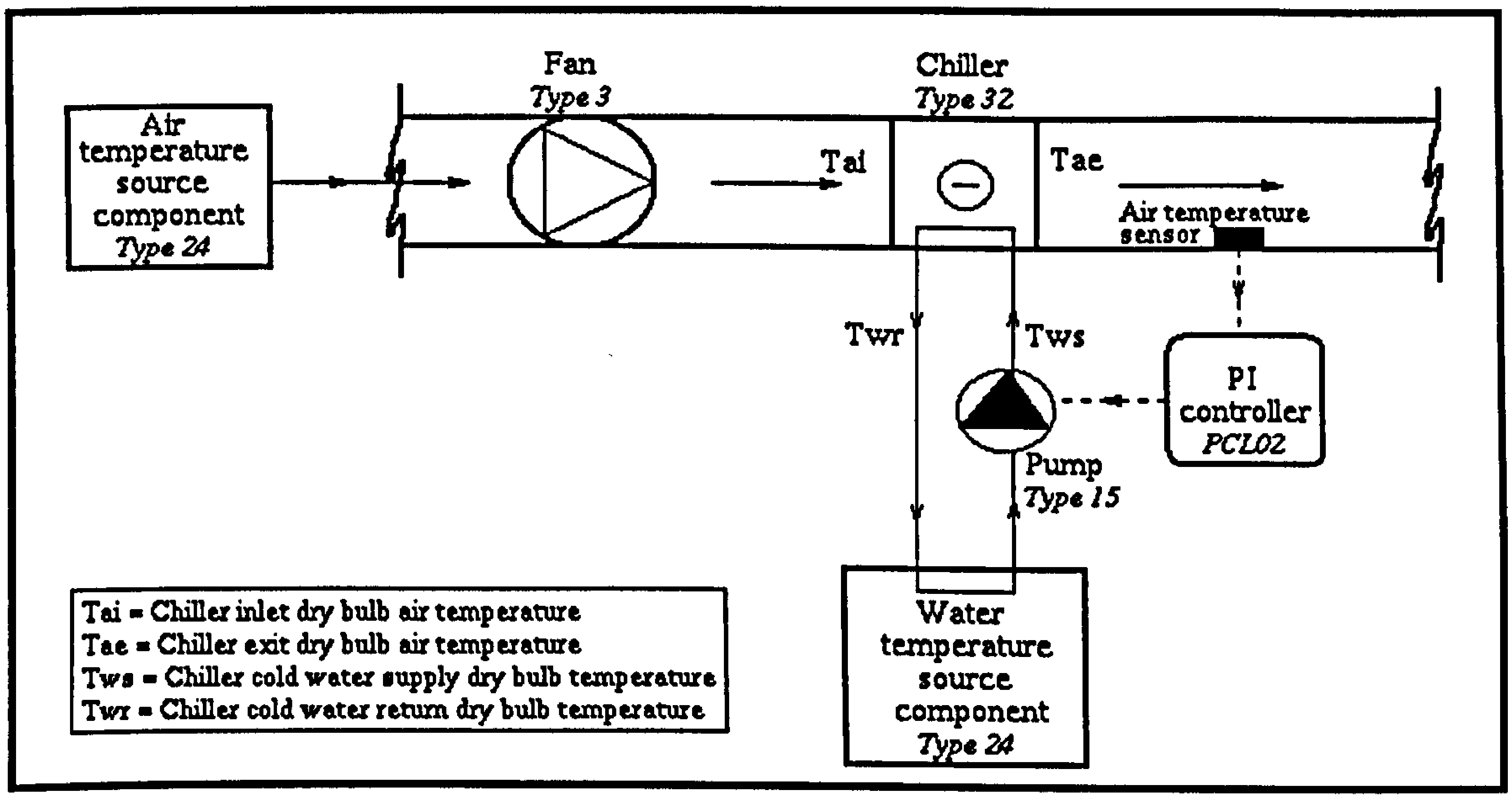


Figure 7.20 Empirical validation test: ESP-r model configuration of chiller system.

Table 7.2.6. Analytical validation test series C: chiller system parameters.

Element	Parameter	Assigned value
Chiller	Number of tube rows	4
	Face area, A	0.46 m^2
	Face velocity	2.0 ms^{-1}
	Rated water flow rate	0.001 m^3s^{-1}
	Inlet water temperature	7.6 °C
	Exit water temperature	12.8 °C
	Inlet air temperature	27.0 °C
	Exit air temperature	15.0 °C
Controller	Proportional gain	30
	Integral gain	0.5 s^{-1}
	Set-point	15 °C

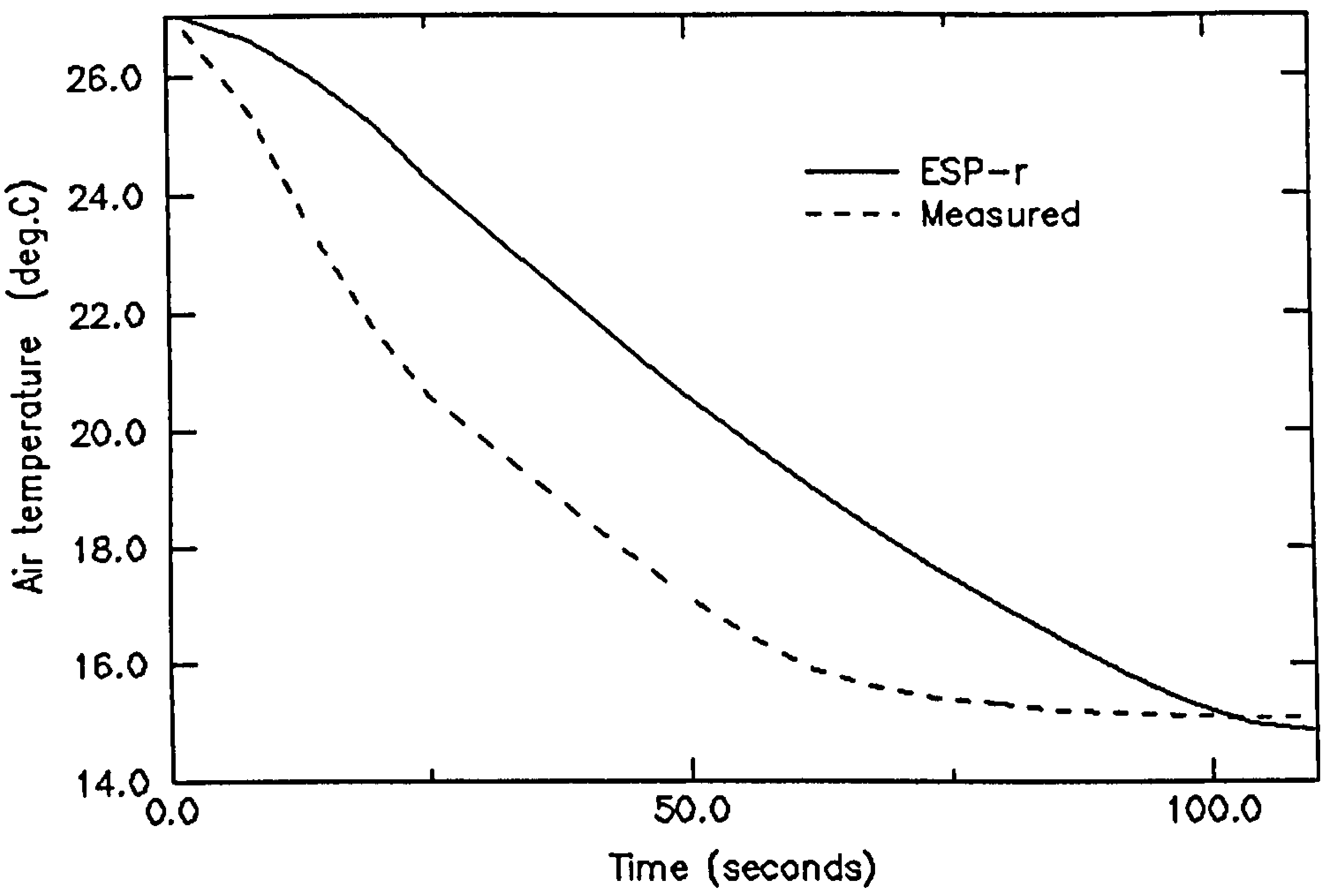


Figure 7.21 Empirical validation test: Chiller system PI controller response.

Comment.

In conclusion, the validation tests reported above have verified the installation procedures and the accuracy of the developed control system modelling strategies based on the manipulation of ESP-r numerical solvers. For all the representative cases considered, there was good agreement between result sets, the degree of correlation increasing with decreasing simulation time-step. Such good agreement is not surprising in the case of control system simulation where ‘correct‘ answers may realistically be expected *providing the installation procedures themselves are correct.*

The verification of several representative schemes has been reported in this chapter. Techniques employed included critical evaluation of the theory and checking of source code together with analytical, inter-model and empirical validation tests. The following chapter proceeds to discuss issues relating to the applicability of the developed schemes.

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Chapter 8

APPLICABILITY.

This chapter identifies the main categories of control system program users. The control system modelling features developed in the present work are assessed in terms of their applicability. Finally, future developments in the areas of applicability are discussed.

8.1 APPLICABILITY.

8.1.1 Levels of abstraction and applicability.

Different stages in the building design process do not require the same level of modelling abstraction. Members of the design team will look to simulation for answers to questions pertinent to their particular areas of expertise. Building design itself is a fluid, amorphous process; yet broad categories and classification of simulation user types may still be identified. The following levels of abstraction, areas of application and types of user for building control systems modelling programs may be identified (Figure 8.1).

Category 1: Initial design stage appraisal studies involving architects and their clients. Often, at this stage, no decision will have been taken regarding the systems regulation, and idealised plant systems and control schema are often sufficient. At this stage architects may wish to assess, for example, the effect of varying boundary (climatic) conditions and site orientation in terms of predicted energy consumption, or the predicted seasonal comfort levels [Clarke and Maver 1991].

Category 2: Focused, in-depth studies of building system operating strategies, as required by practicing HVAC and BEMS engineers, to ascertain optimum configuration for the plant [Crawley and Nall 1983]. Professionals at this stage will be more concerned with establishing appropriate set-back temperatures, analysing the response time of the sensing and actuating elements, or assessing the relationship between thermal and visual control parameters than with issues such as orientation or office depth [Leaman 1993].

Category 3: Research and development work carried out in order to progress new methods and techniques relating to sophisticated, 'smart' controllers [Clarke and Emslie 1988]. This includes applications of on-line BEMS simulation-based predictive-iterative controllers.

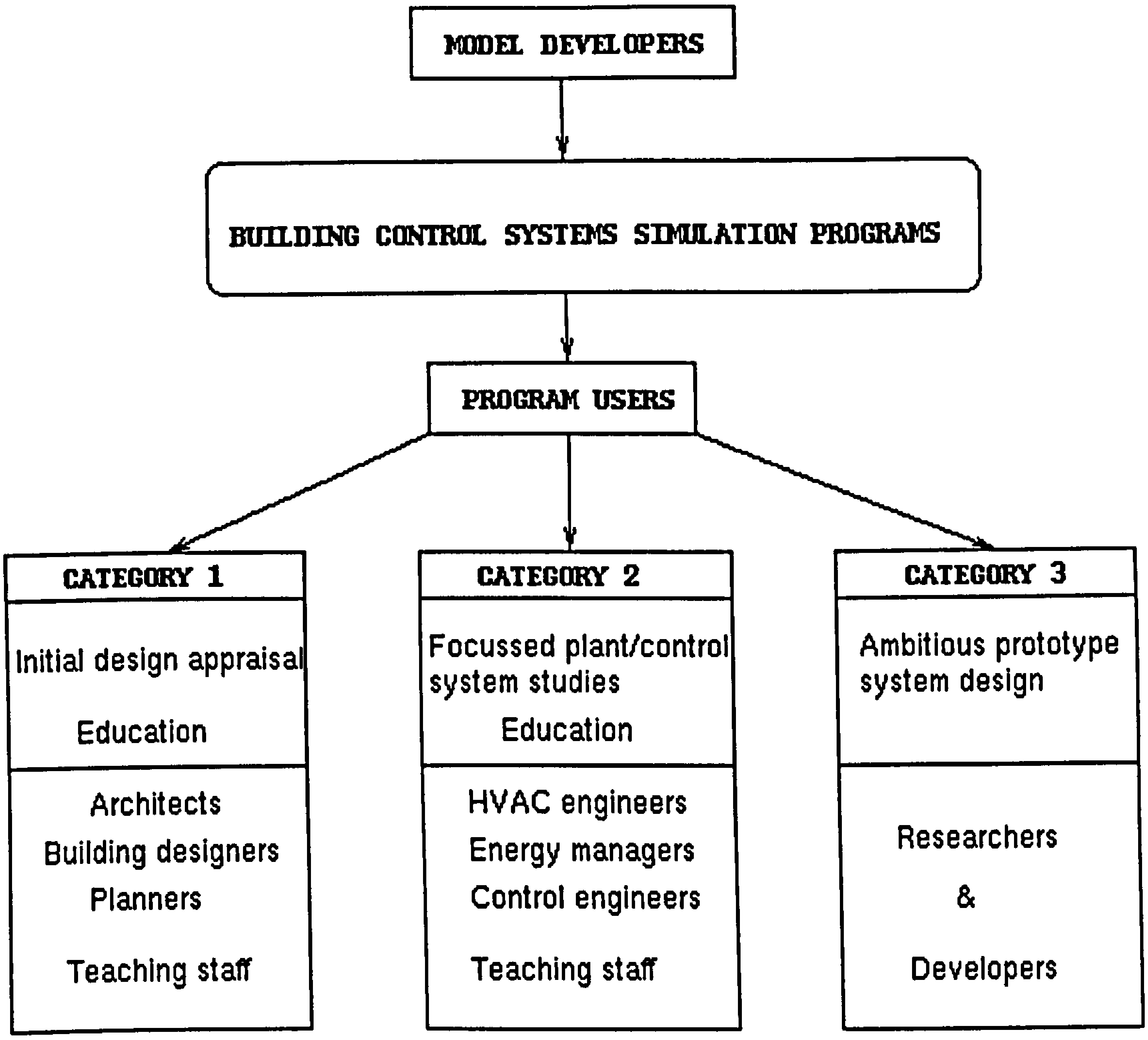


Figure 8.1 Application: user categories

8.1.2 Case studies.

The use of ESP-r in a building performance evaluation context and its suitability to the three main areas of application identified above, is demonstrated in the form of three case studies.

- An initial design stage case study involving a multi-zone house situated in rural Scotland.
- An in-depth study of a commercial building's integrated zone, event, flow, global and plant control system.
- Advanced control system design specification for a municipal building, which includes a simulated-assisted predictive-iterative thermal control scheme.

These case studies are described with particular reference to the control system's spatial, temporal and logical element modelling features as described in previous chapters. Here, the focus is on these elements when integrated in complete control systems.

8.1.2.1 Application Category 1: Initial design stage control appraisal.

This case study is presented to exemplify initial stage design, where control system dynamics are *not* the main focus, but where the design team may be concerned with indicative comfort levels and energy demands. Typically, the exact form of the plant system will not be known, and only indicative data is available on the expected mode of control. Operating set-points, throttling ranges and so forth, will not be available because the plant system is assumed to be ideal, and thus no explicit description is required.

House: problem description.

The house is situated on a remote Scottish island in a high wind location. The provision of an unheated buffer space for inclement weather protection is part of the design brief. Because of site constraints, the lounge faces south-west. The model contains ten thermal zones (Figure 8.2):

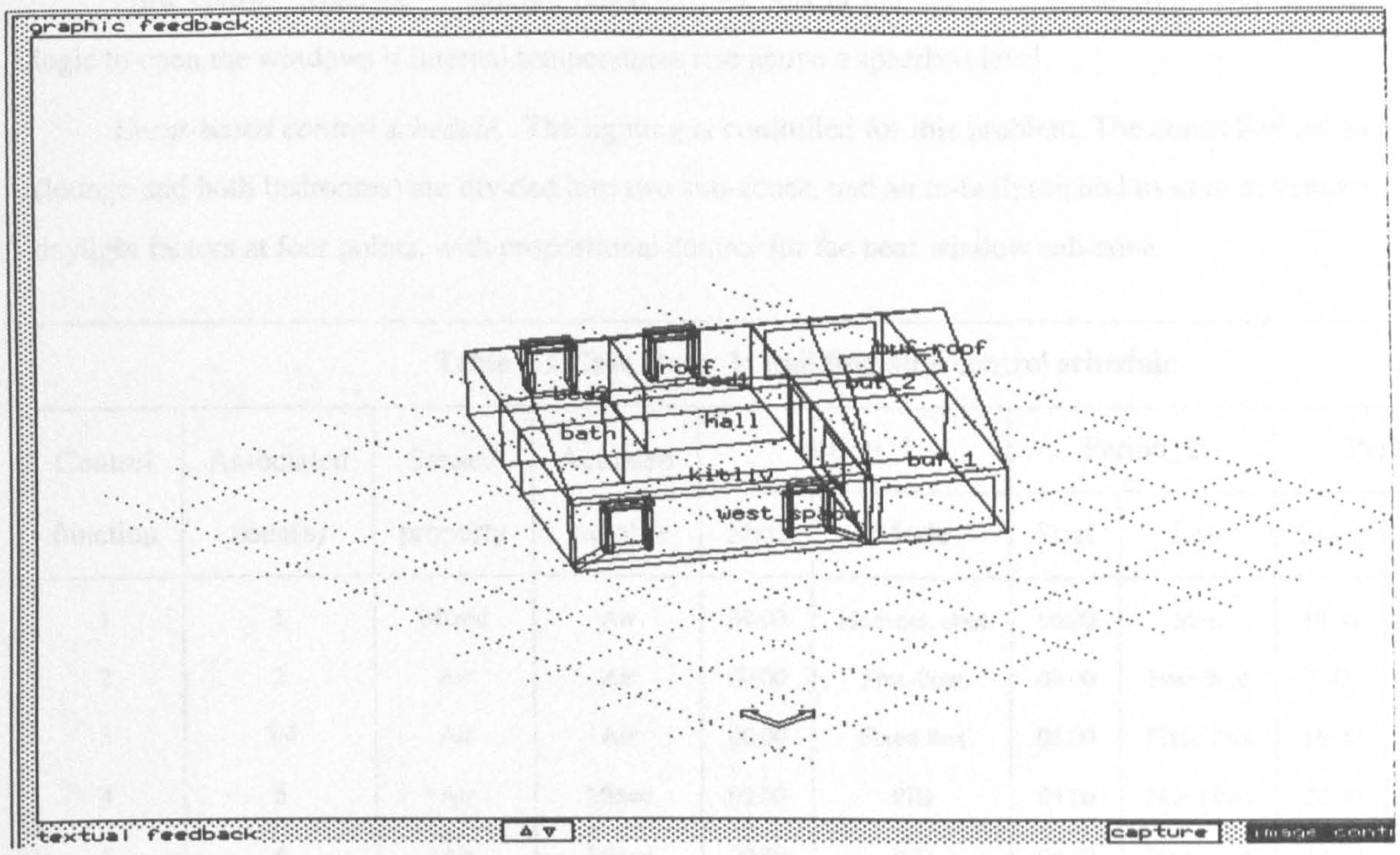
1) combined kitchen and lounge (kitliv)
2) hollow south-west wall (west_space)
3) passage (hall)
4) bathroom (bath)
5) bedroom (bed1)
6) bedroom (bed2)
7) buffer south-west portion (buf_1)
8) buffer north-east portion (buf_2)
9) upper buffer (buf_roof)
10) roof over occupied space (roof)

The model employs seasonally adjusted air flow networks to represent air movement. The subdivision of the sun-space into 3 thermal zones allows the buoyancy force to be represented.

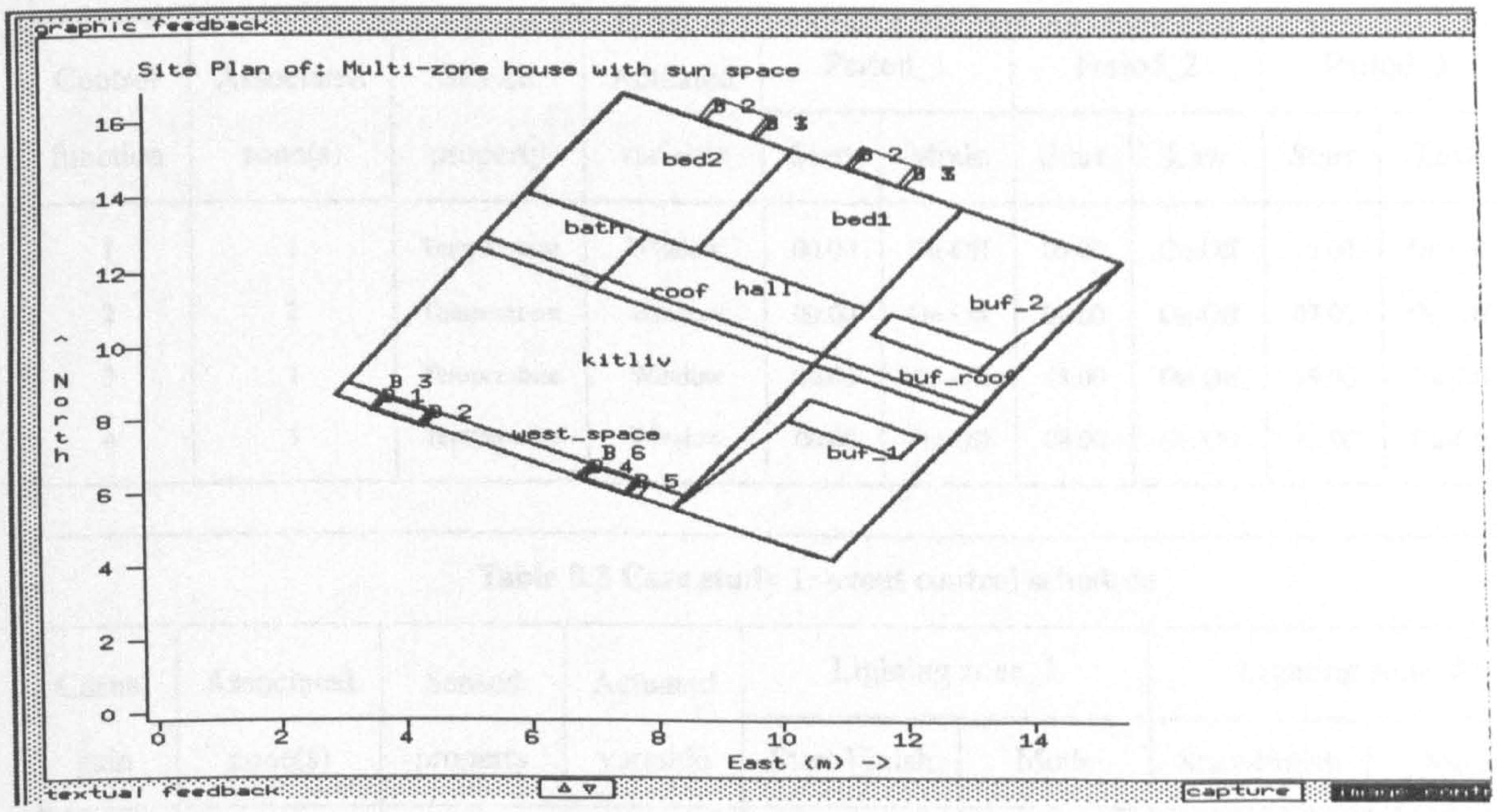
House: control specification.

Zone-level, flow and event-based control schedules are defined for this problem. The control schedules are summarised in Tables 8.1-8.3.

Zone-level control schedule. There are 6 zone-level control functions mapped to the various zones, with the exception of Zone_2 (west_space), which is specified as free-floating for all control periods comprising the simulation period. A variety of control modes are active: ideal control for the lounge; PID control for the bedrooms; fixed flux input/extract for the hall and bathroom; two-position for the buffer zones; free-floating for the *'west_space'*; and multi-sensor discriminating pro-rata control holding the roof internal surface temperature at the lowest of the hall temperature and the bedroom ceiling temperatures. Similarly, sensor and actuator types vary: e.g mixed convective-radiative sensor (modelling comfort control), and mixed convective-radiative actuators (modelling a radiative heating system) for the lounge and bedrooms. Since no plant system configuration file is defined, the energy input/extract is by means of 'idealised' plant equipment.



(a)



(b)

Figure 8.2 Multi-zone house: (a) perspective; (b) plan view

Flow control schedule. There are timed extract fans in the kitchen and bathroom and control logic to open the windows if internal temperatures rise above a specified level.

Event-based control schedule. The lighting is controlled for this problem. The controlled zones (lounge and both bedrooms) are divided into two sub-zones, and an in-built method used to determine daylight factors at four points, with proportional control for the near window sub-zone.

Table 8.1 Case study 1: building-side control schedule

Control function	Associated zone(s)	Sensed property	Actuated variable	Period_1		Period_2		Period_3	
				Start	Mode	Start	Law	Start	Law
1	1	Mixed	Air	00.00	Ideal opt. start	06.00	Ideal	18.00	Ideal
2	2	Air	Air	00.00	Free-float	09.00	Free-float	22.00	Free-float
3	3,4	Air	Air	00.00	Fixed flux	06.00	Fixed flux	18.00	Fixed flux
4	5	Air	Mixed	00.00	PID	09.00	Fixed flux	22.00	PID
5	6	Air	Mixed	00.00	PID	09.00	Fixed flux	22.00	PID
6	7,8,9	Air	Air	00.00	On-Off	09.00	On-Off	22.00	On-Off
7	10	Surface	Surface	00.00	Pro-rata	09.00	On-Off	22.00	On-Off

Table 8.2 Case study 1: flow control schedule

Control function	Associated zone(s)	Sensed property	Actuated variable	Period_1		Period_2		Period_3	
				Start	Mode	Start	Law	Start	Law
1	1	Temperature	Window	00.00	On-Off	03.00	On-Off	5.00	On-Off
2	2	Temperature	Window	00.00	On-Off	06.00	On-Off	07.00	On-Off
3	1	Temperature	Window	00.00	On-Off	18.00	On-Off	19.00	On-Off
4	1	Temperature	Window	00.00	On-Off	08.00	On-Off	18.00	On-Off

Table 8.3 Case study 1: event control schedule

Casual gain	Associated zone(s)	Sensed property	Actuated variable	Lighting zone_1		Lighting zone_2	
				Start-Finish	Mode	Start-Finish	Mode
Lighting	1	Illuminance	Flux	08.00-24.00	Proportional	08.00-24.00	Proportional
Lighting	5	Illuminance	Flux	08.00-24.00	Top-up	08.00-24.00	Top-up
Lighting	6	Illuminance	Flux	08.00-24.00	Top-up	08.00-24.00	Top-up

House: simulation diagnostics.

A simulation was run, using an hourly time-step and the Kew 1967 boundary condition climate file, over a spring week (12th - 18th April). The air flow network predictions and temperature/comfort profiles for the living room are shown in Figures 8.3 and 8.4 respectively, and those for the bedrooms are shown in Figure 8.5 and 8.5. Comfort conditions during the ideal temperature control period are considered acceptable for both living room and bedrooms.

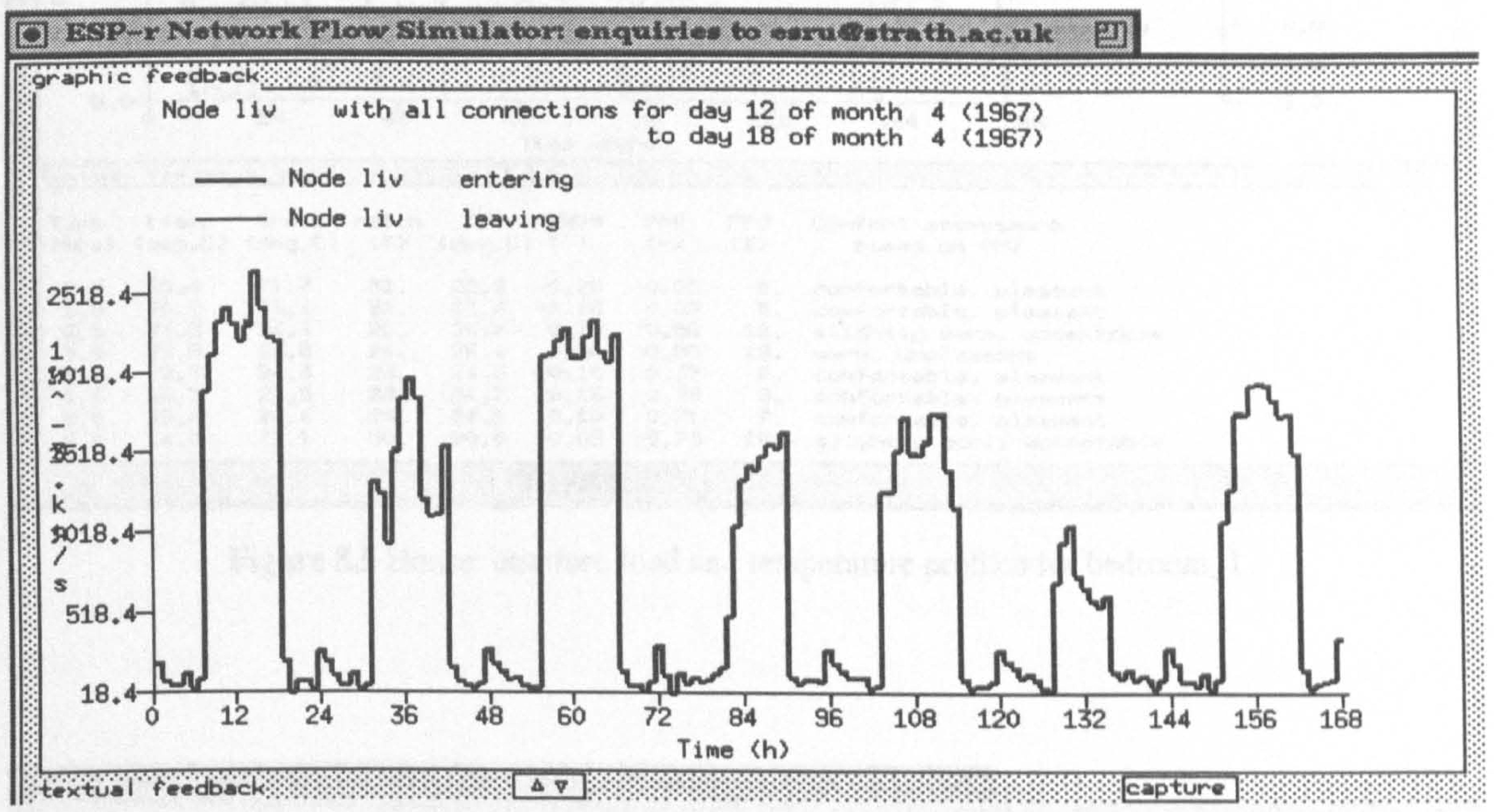
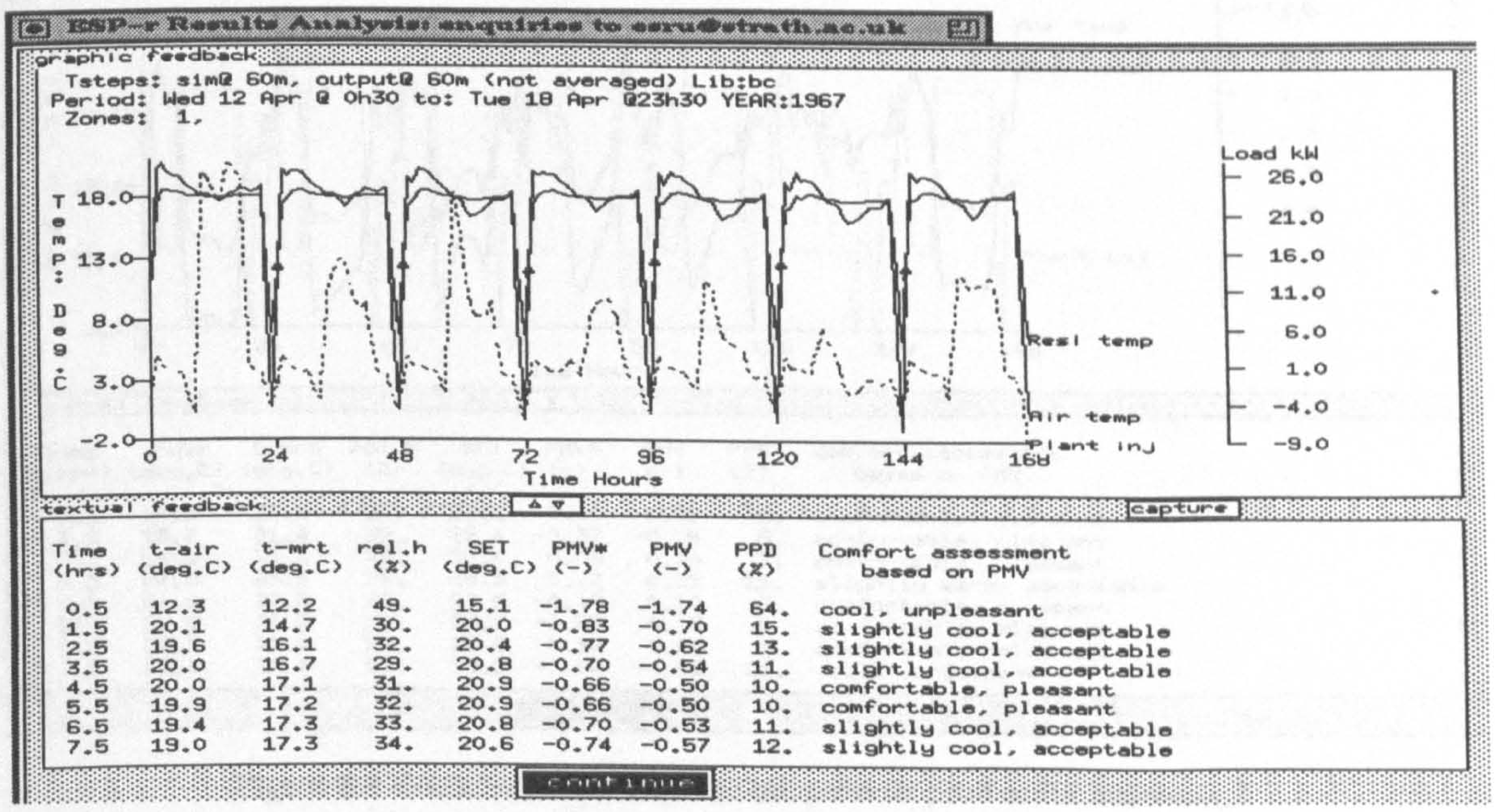


Figure 8.3 House: mass flow rate profile for lounge

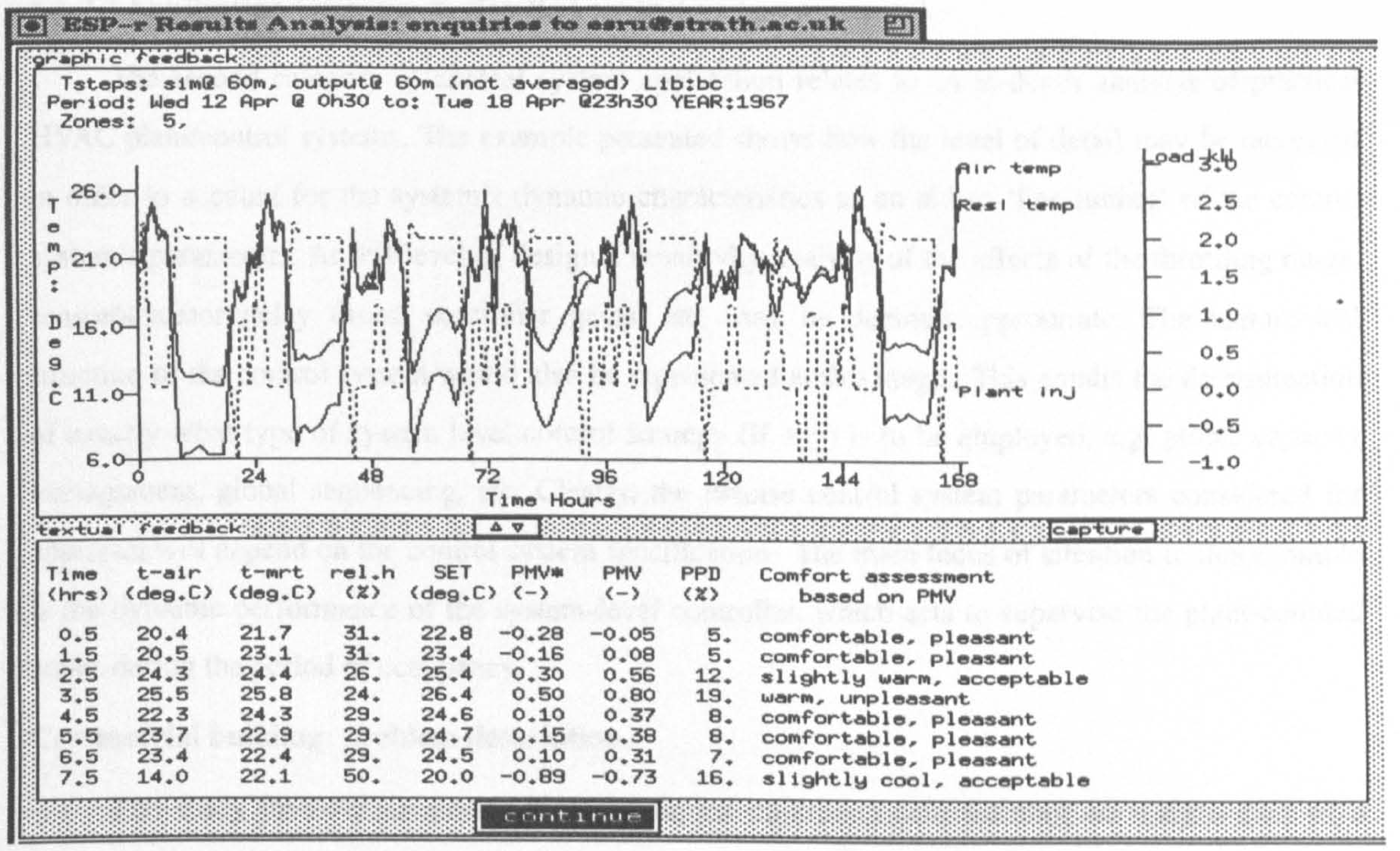


```
 Tsteps: sim@ 60m, output@ 60m (not averaged) Lib:bc
Period: Wed 12 Apr @ 0h30 to: Tue 18 Apr @23h30 YEAR:1967
 Zones:  1,
```

```
Time    t-air    t-mrt    rel.h    SET    PMV*    PMV    PPD   Comfort assessment
(hrs)  (deg.C)  (deg.C)   (%)   (deg.C)  (-)     (-)    (%)      based on PMV

 0.5   12.3     12.2     49.    15.1   -1.78   -1.74    64.   cool, unpleasant
 1.5   20.1     14.7     30.    20.0   -0.83   -0.70    15.   slightly cool, acceptable
 2.5   19.6     16.1     32.    20.4   -0.77   -0.62    13.   slightly cool, acceptable
 3.5   20.0     16.7     29.    20.8   -0.70   -0.54    11.   slightly cool, acceptable
 4.5   20.0     17.1     31.    20.9   -0.66   -0.50    10.   comfortable, pleasant
 5.5   19.9     17.2     32.    20.9   -0.66   -0.50    10.   comfortable, pleasant
 6.5   19.4     17.3     33.    20.8   -0.70   -0.53    11.   slightly cool, acceptable
 7.5   19.0     17.3     34.    20.6   -0.74   -0.57    12.   slightly cool, acceptable
```

Figure 8.4 House: comfort, load and temperature profiles for lounge

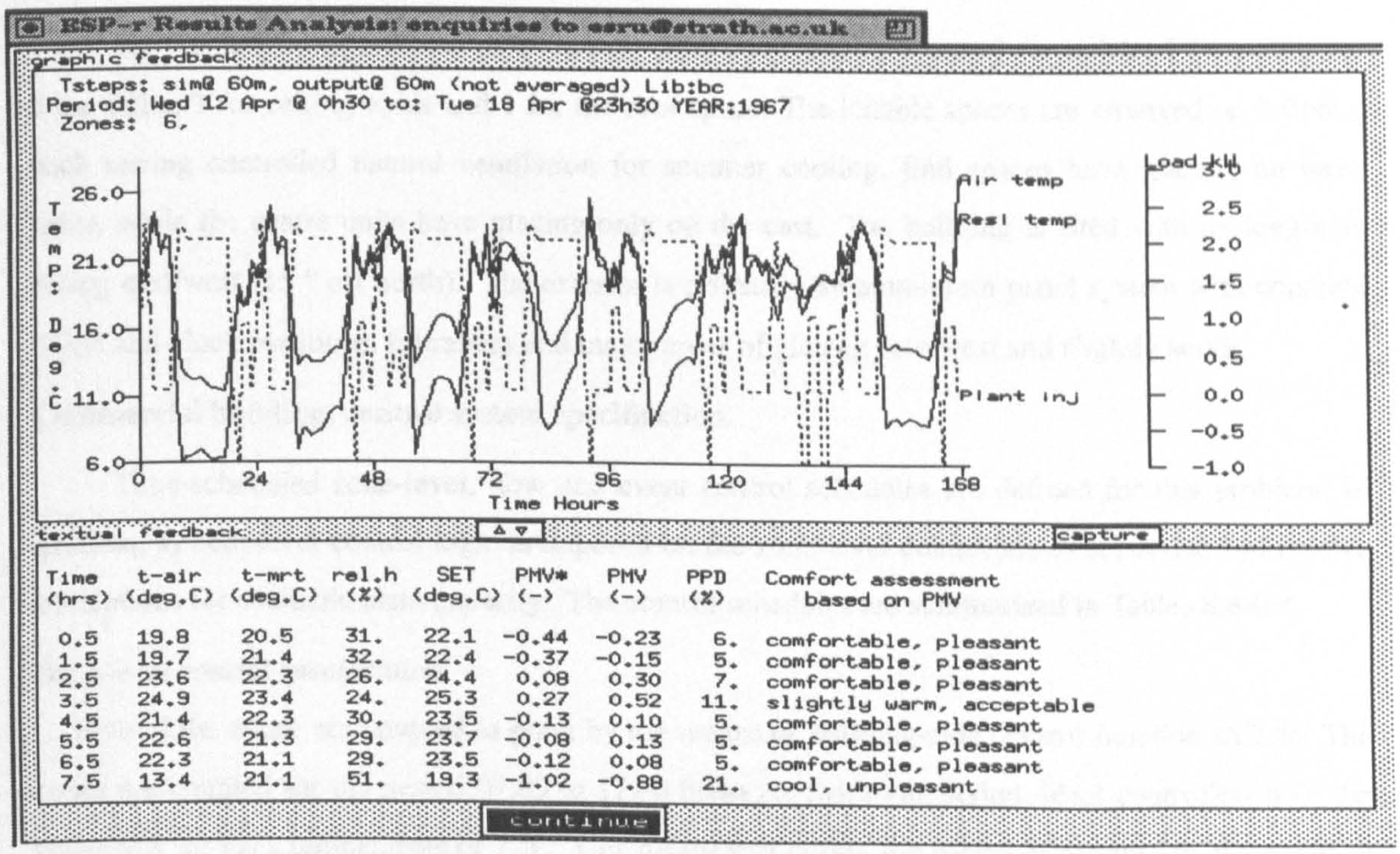


```
 Tsteps: sim@ 60m, output@ 60m (not averaged) Lib:bc
Period: Wed 12 Apr @ 0h30 to: Tue 18 Apr @23h30 YEAR:1967
 Zones:  5,
```

```
Time    t-air    t-mrt   rel.h    SET    PMV*    PMV    PPD   Comfort assessment
(hrs) (deg.C) (deg.C)    (%)   (deg.C)  (-)     (-)    (%)      based on PMV

 0.5   20.4     21.7     31.    22.8   -0.28   -0.05     5.   comfortable, pleasant
 1.5   20.5     23.1     31.    23.4   -0.16    0.08     5.   comfortable, pleasant
 2.5   24.3     24.4     26.    25.4    0.30    0.56    12.   slightly warm, acceptable
 3.5   25.5     25.8     24.    26.4    0.50    0.80    19.   warm, unpleasant
 4.5   22.3     24.3     29.    24.6    0.10    0.37     8.   comfortable, pleasant
 5.5   23.7     22.9     29.    24.7    0.15    0.38     8.   comfortable, pleasant
 6.5   23.4     22.4     29.    24.5    0.10    0.31     7.   comfortable, pleasant
 7.5   14.0     22.1     50.    20.0   -0.89   -0.73    16.   slightly cool, acceptable
```

Figure 8.5 House: comfort, load and temperature profiles for bedroom_1



```
 Tsteps: sim@ 60m, output@ 60m (not averaged) Lib:bc
Period: Wed 12 Apr @ 0h30 to: Tue 18 Apr @23h30 YEAR:1967
 Zones:  6,
```

```
Time    t-air    t-mrt   rel.h    SET    PMV*    PMV    PPD   Comfort assessment
(hrs) (deg.C) (deg.C)    (%)   (deg.C)  (-)     (-)    (%)      based on PMV

 0.5   19.8     20.5     31.    22.1   -0.44   -0.23     6.   comfortable, pleasant
 1.5   19.7     21.4     32.    22.4   -0.37   -0.15     5.   comfortable, pleasant
 2.5   23.6     22.3     26.    24.4    0.08    0.30     7.   comfortable, pleasant
 3.5   24.9     23.4     24.    25.3    0.27    0.52    11.   slightly warm, acceptable
 4.5   21.4     22.3     30.    23.5   -0.13    0.10     5.   comfortable, pleasant
 5.5   22.6     21.3     29.    23.7   -0.08    0.13     5.   comfortable, pleasant
 6.5   22.3     21.1     29.    23.5   -0.12    0.08     5.   comfortable, pleasant
 7.5   13.4     21.1     51.    19.3   -1.02   -0.88    21.   cool, unpleasant
```

Figure 8.6 House: comfort, load and temperature profiles for bedroom_2

8.1.2.2 Application Category 2: Detailed control system appraisal.

The second category of control system application relates to an in-depth analysis of practical HVAC plant/control systems. The example presented shows how the level of detail may be increased in order to account for the system's dynamic characteristics as an aid to 'fine-tuning' of the control system's parameters. At this level of design a sensitivity analysis of the effects of the throttling range, sensor/actuator delay times, controller gains, etc, may be deemed appropriate. The hierarchical structure of the control system would also be represented at this stage. This entails the determination of exactly what type of system level control strategy (if any) is to be employed, e.g. global capacity management, global sequencing, etc. Clearly, the precise control system parameters considered for appraisal will depend on the control system specification. The main focus of attention in this example is the dynamic performance of the system-level controller, which acts to supervise the plant-coupled zones during the period of occupancy.

Commercial building: problem description.

The study involves an analysis of a complex control system forming an integral part of a commercial building's HVAC and lighting control system. The building is situated in North East Scotland, with a layout suitable for high-tech companies (Figure 8.7). The HVAC system is a dual-duct system supplied from central boiler/chiller plant (Figure 8.8). The hot and cold duct flow rates are controlled by dampers.

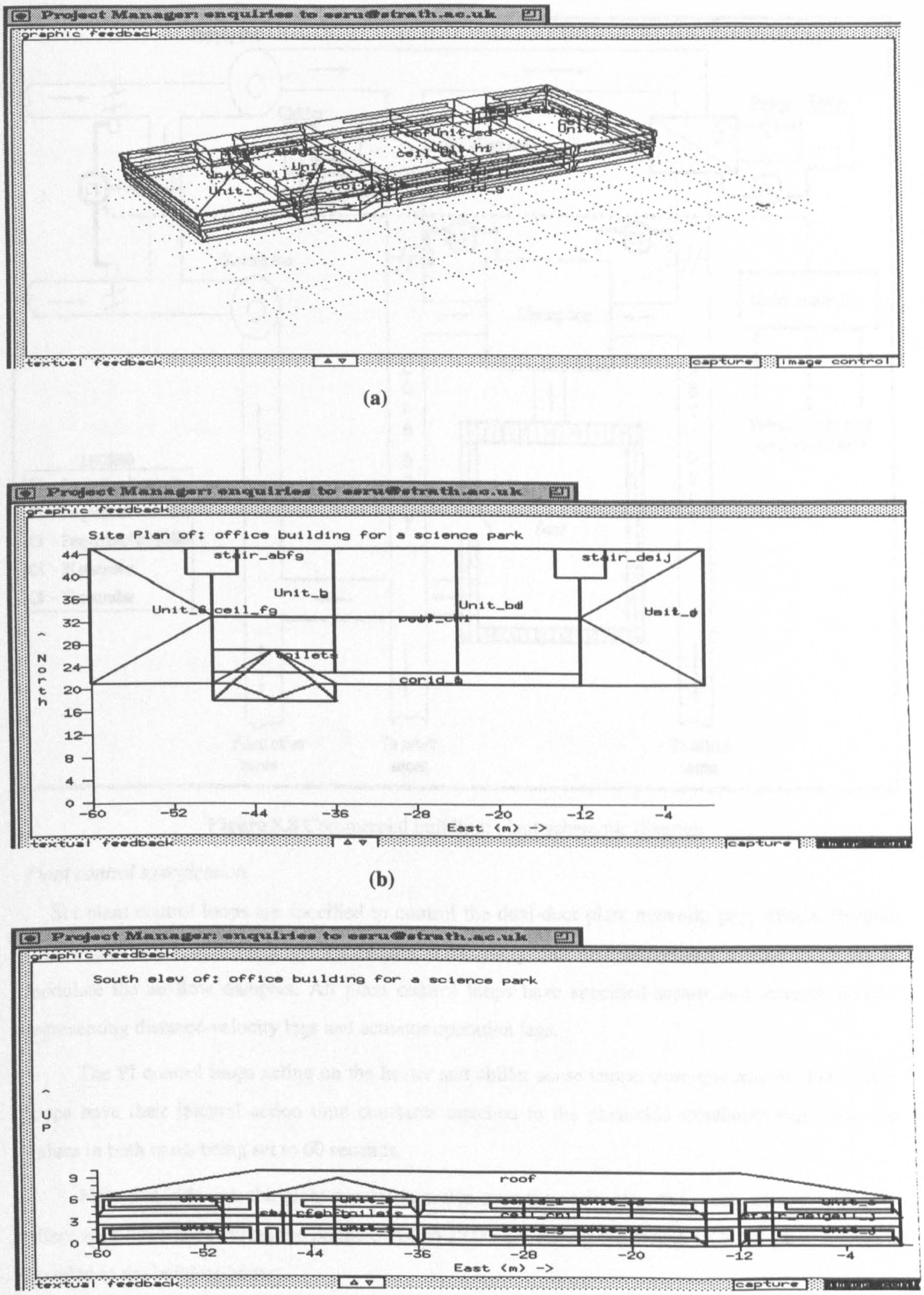
The building is represented as 21 zones - 1 for each lettable space, 1 for toilets, 3 for entrances, 3 for stairs, 3 for ceiling voids and 1 for the roof space. The lettable spaces are arranged on 2 floors, each having controlled natural ventilation for summer cooling. End spaces have glazing on three sides, while the centre units have glazing only on the east. The building is sited with its long axis facing east/west (15 ° off north). The exterior is primarily an aluminium panel system with concrete floors and block partitions. Entrances and major areas of glazing face west and slightly south.

Commercial building: control system specification.

Time-scheduled zone-level, flow and event control schedules are defined for this problem. In addition, system-level control logic is imposed on the zone-level controllers to supervise and resolve contentions for available plant capacity. The control schedules are summarised in Tables 8.4-8.8.

Zone-level control specification.

Five of the zones are coupled to plant by the means of building-side control function *BCL06*. The zones are coupled for the period 07.00 to 17.00 hours; outwith this period, ideal controllers hold the zones at a set-back temperature of 7 °C. This means that during the period of occupancy, the practical system dynamics such as time lags associated with the heater and chiller are accounted for in full. The remaining (uncontrolled) zones free-float under the influence of boundary and adjacent zone conditions. This demonstrates the applicability of building-side control functions for *all* categories of control system simulation, i.e. at both initial and advanced design stages.



Project Manager: enquiries to esru@strath.ac.uk

(a)

Project Manager: enquiries to esru@strath.ac.uk

Site Plan of: office building for a science park

(b)

Project Manager: enquiries to esru@strath.ac.uk

South elev of: office building for a science park

(c)

Figure 8.7 Commercial building: (a) perspective (b) plan (c) south elevation.

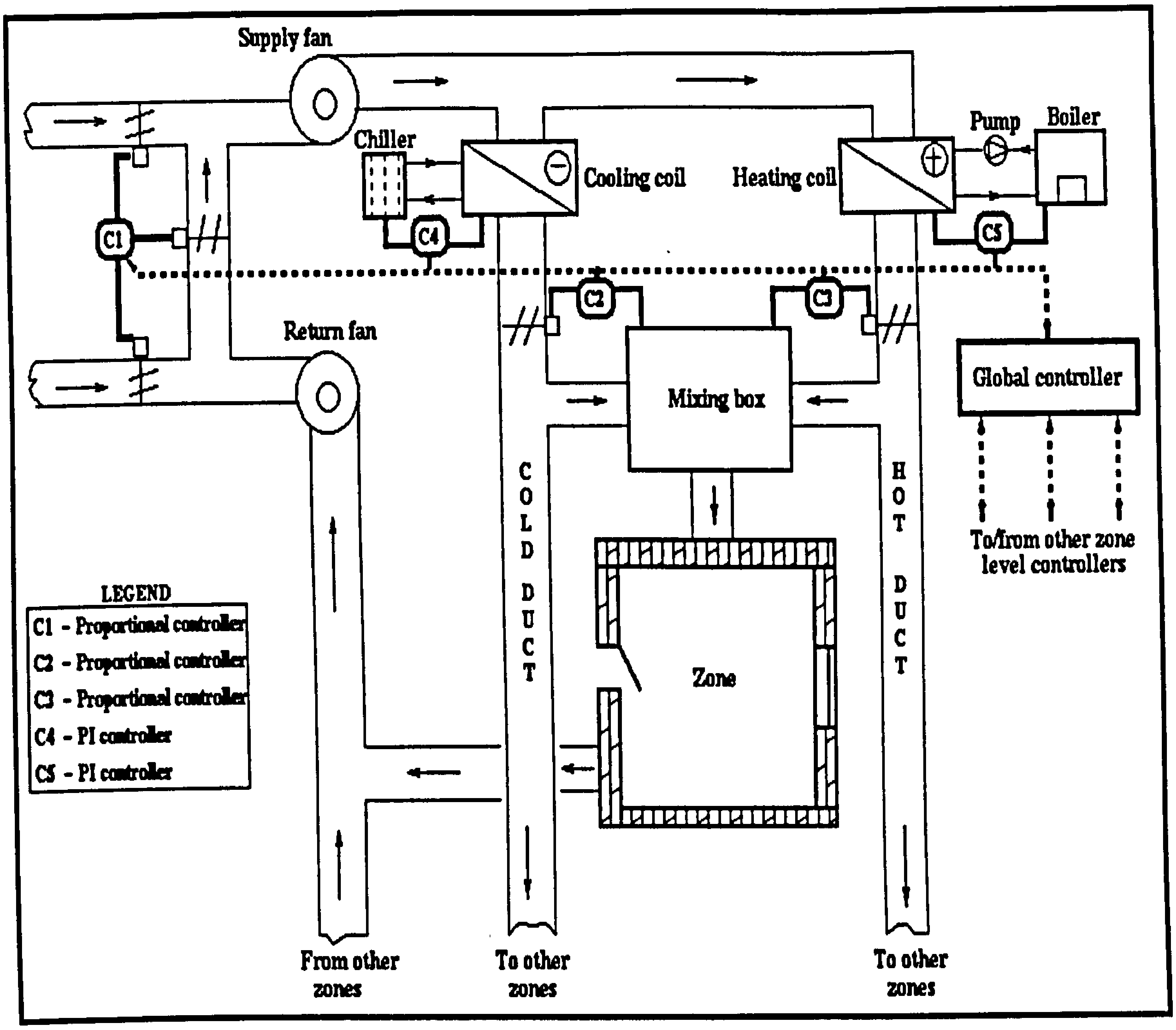


Figure 8.8 Commercial building: plant schematic diagram.

Plant control specification.

Six plant control loops are specified to control the dual-duct plant network; proportional-integral (PI) control loops act to modulate the heating and cooling coils and proportional control loops act to modulate the air-flow dampers. All plant control loops have specified sensor and actuator delays, representing distance-velocity lags and actuator operation lags.

The PI control loops acting on the heater and chiller sense temperature and actuate flux. These loops have their integral action time constants matched to the plant-side simulation time-step, the values in both cases being set to 60 seconds.

Note that although the plant control is active over the entire day, the plant network will only affect zone conditions during the period 07.00 to 17.00, i.e. during the period when the plant system is coupled to the building zones.

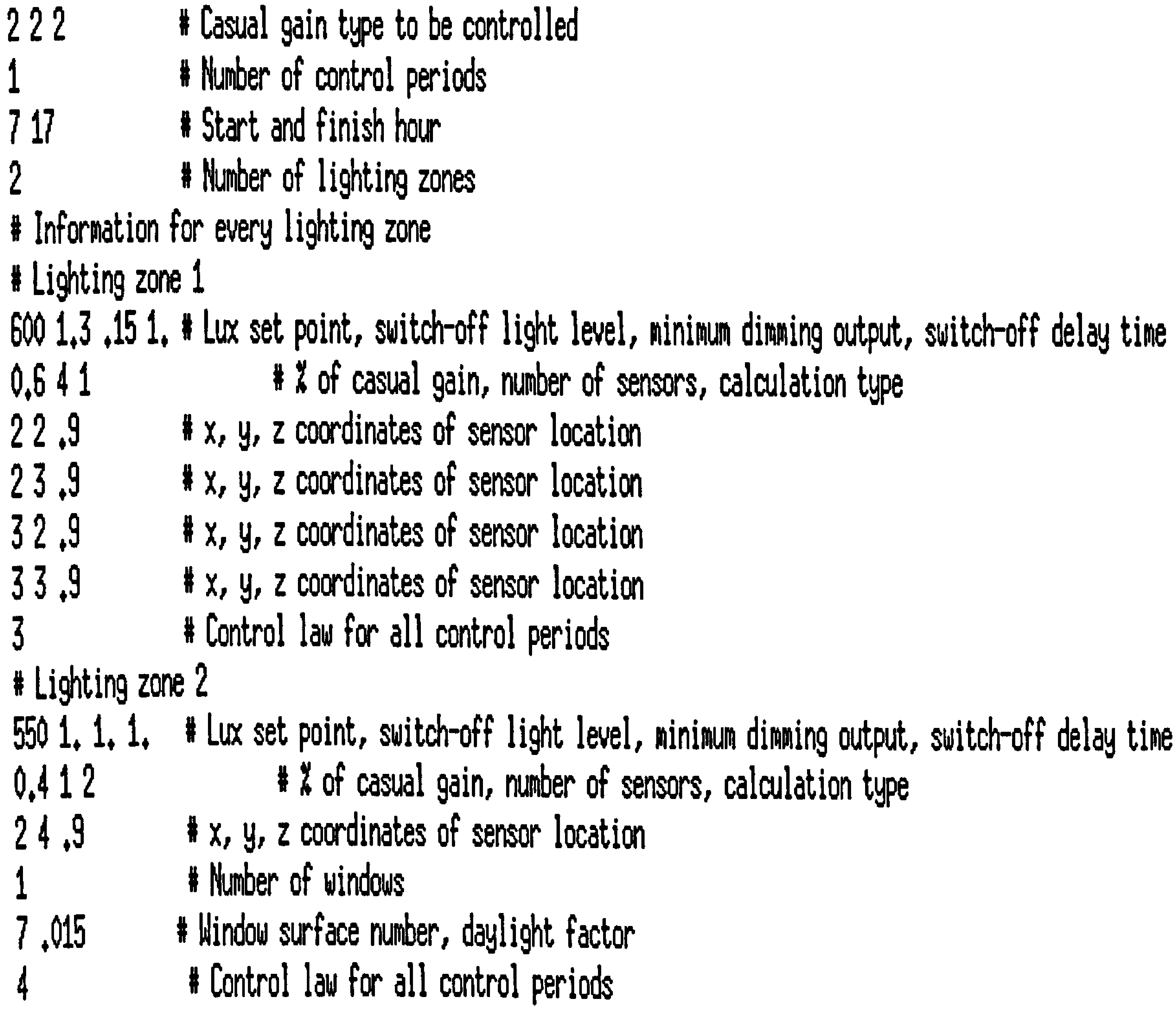
Flow control specification.

There are timed ventilation controllers for all office units which operate when the internal temperatures rise above the specified levels (e.g. 10 °C).

Event control specification.

Event control for this case study is of a more complex nature than for the house exemplar, representing the more detailed analysis normally required by lighting engineers at the detailed stage of design. Here, control is in the form of a lighting manipulator with both single *and* multiple point illuminance sensing control schemes active. The *casual gain control* file for this problem is shown in Figure 8.9.

The casual gain type "2" indicates Weekdays, Saturday and Sunday control. Only one control period is defined. This is usually adequate for most lighting control applications. The start and finish hours are 07.00 and 17.00 covering the period of occupancy. Two lighting zones are defined: the first represents the back portion of the room and has a multi-point sensor feeding a proportional dimming function; the second lighting zone represents the front portion of the zone and has a single-point sensor effecting control on the basis of a probability function to model stochastic occupant behaviour.



```
2 2 2           # Casual gain type to be controlled
1               # Number of control periods
7 17            # Start and finish hour
2               # Number of lighting zones
# Information for every lighting zone
# Lighting zone 1
600 1.3 .15 1.  # Lux set point, switch-off light level, minimum dimming output, switch-off delay time
0.6 4 1                 # % of casual gain, number of sensors, calculation type
2 2 .9          # x, y, z coordinates of sensor location
2 3 .9          # x, y, z coordinates of sensor location
3 2 .9          # x, y, z coordinates of sensor location
3 3 .9          # x, y, z coordinates of sensor location
3               # Control law for all control periods
# Lighting zone 2
550 1. 1. 1.    # Lux set point, switch-off light level, minimum dimming output, switch-off delay time
0.4 1 2                 # % of casual gain, number of sensors, calculation type
2 4 .9          # x, y, z coordinates of sensor location
1               # Number of windows
7 .015          # Window surface number, daylight factor
4               # Control law for all control periods
```

Figure 8.9 Commercial building: casual gain control file.

As can be seen from the information defining the first lighting zone, a reference light level (set-point) has been set to 600 lux. The switch-off light level is 130% of the reference light level and the minimum dimming light output is set to 15% (i.e. the dimming range is 100% - 15%). The switch-off delay time is set to 1 hour.

The first lighting zone controls 60% of the total zone lighting casual gain. The number of sensors is set to 4 and the calculation type to 1, which calls for ESP-r's internal daylight factor preprocessor, as opposed to an external call to RADIANCE. Multiple lighting sensors are used to account for a variance in illuminance within the space in terms of what the ceiling mounted photocells would detect. The average of these sensors is used within the simulation. Finally, the control law identifier is set to 3, representing proportional dimming control.

The second lighting zone controls 40% of the total zone controlled casual gain. The reference light level is 550 lux, with the switch-off light level and minimum dimming light output set to 100% which is adequate for a simple on-off control. For this case only one sensor is specified and the calculation type is set to 2, which calls for user specified daylight factors. For this type of calculation additional data are required. These include the number of windows, in this case 1, the window surface identifier, here 7, and the list of daylight factors, here only one, set at 1.5%. Finally, the Hunt probability switching control function, type 4, is selected.

System level control specification.

A number of BEMS global control schemes are assessed in this case study in order to demonstrate system-level control. Firstly, the zones are under zone-level control only, i.e. no global supervisory control is active. The simulation is then repeated, this time with global capacity management control (*GCL01*) active where zone-level controllers are switched according to ambient conditions. A third simulation is then run, this time with global scheduling control (*GCL02*) where zone-level controllers are sequentially shed, in accordance with the global controller schedule, until the total energy requirement is within the specified available system capacity limits.

Table 8.4 Case study 2: building control schedule

Control function	Associated zone(s)	Sensed property	Actuated variable	Period_1		Period_2		Period_3	
				Start	Mode	Start	Law	Start	Law
1	3	Air	Air	00.00	Ideal fixed	07.00	Plant coupled	17.00	Ideal fixed
2	4	Air	Air	00.00	Ideal fixed	07.00	Plant coupled	17.00	Ideal fixed
3	5	Air	Air	00.00	Ideal fixed	07.00	Plant coupled	17.00	Ideal fixed
4	6	Air	Air	00.00	Ideal fixed	07.00	Plant coupled	17.00	Ideal fixed
5	8	Air	Air	00.00	Ideal fixed	07.00	Plant coupled	17.00	Ideal fixed

Table 8.5 Case study 2: flow control schedule

Control function	Associated zone(s)	Sensor property	Actuated variable	Period_1		Period_2		Period_3	
				Start	Mode	Start	Law	Start	Law
1	3,4,5,6,7,8,9,10	Temperature	Window	00.00	On-Off	07.00	On-Off	17.00	On-Off
2	3,4,5,6,7,8,9	Temperature	Door	00.00	On-Off	07.00	On-Off	17.00	On-Off

Table 8.6 Case study 2: plant control schedule

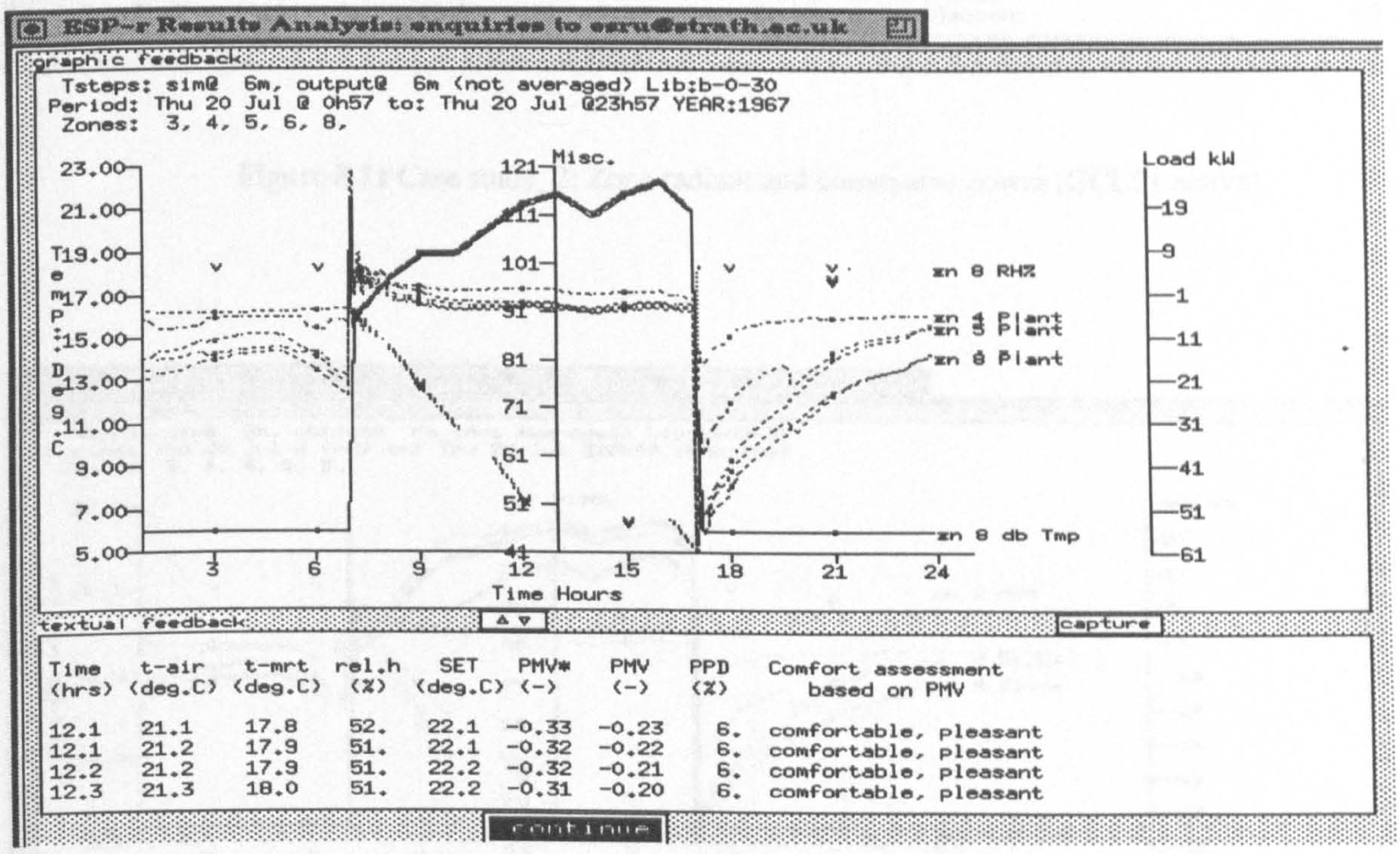
Control function	Sensed property	Actuated variable	Period_1	
			Start	Mode
1	External temperature	Flow diversion ratio	00.00	Proportional
2	External temperature	Flow diversion ratio	00.00	Proportional
3	External temperature	Flow diversion ratio	00.00	Proportional
4	External temperature	Flow diversion ratio	00.00	Proportional
5	Plant component temperature	Flow rate	00.00	Proportional+integral
6	Plant component temperature	Flow rate	00.00	Proportional+integral

Table 8.7 Case study 2: event control schedule

Casual gain	Associated zone(s)	Sensor property	Actuated variable	Lighting zone_1		Lighting zone_2	
				Start-Finish	Mode	Start-Finish	
Lighting	3	Illuminance	Flux	07.00-17.00	Proportional	07.00-17.00	Probability switching
Lighting	4	Illuminance	Flux	07.00-17.00	Proportional	07.00-17.00	Probability switching
Lighting	5	Illuminance	Flux	07.00-17.00	Proportional	07.00-17.00	Probability switching
Lighting	6	Illuminance	Flux	07.00-17.00	Proportional	07.00-17.00	Probability switching
Lighting	8	Illuminance	Flux	07.00-17.00	Proportional	07.00-17.00	Probability switching
Lighting	9	Illuminance	Flux	07.00-17.00	Proportional	07.00-17.00	Probability switching
Lighting	14	Illuminance	Flux	07.00-17.00	Proportional	07.00-17.00	Probability switching
Lighting	15	Illuminance	Flux	07.00-17.00	Proportional	07.00-17.00	Probability switching
Lighting	16	Illuminance	Flux	07.00-17.00	Proportional	07.00-17.00	Probability switching
Lighting	17	Illuminance	Flux	07.00-17.00	Proportional	07.00-17.00	Probability switching

Table 8.8 Case study 2: system control schedule

Control scheme	Associated zone(s)	Sensed property	Actuated variable	Period_1		Period_2		Period_3	
				Start	Mode	Start	Law	Start	Law
Scheme_1	All	External temperature	Numerical	00.00	Free-float	07.00	Global on-off	17.00	Free-float
Scheme_2	All	Not required	Numerical	00.00	Free-float	07.00	Global management	17.00	Free-float

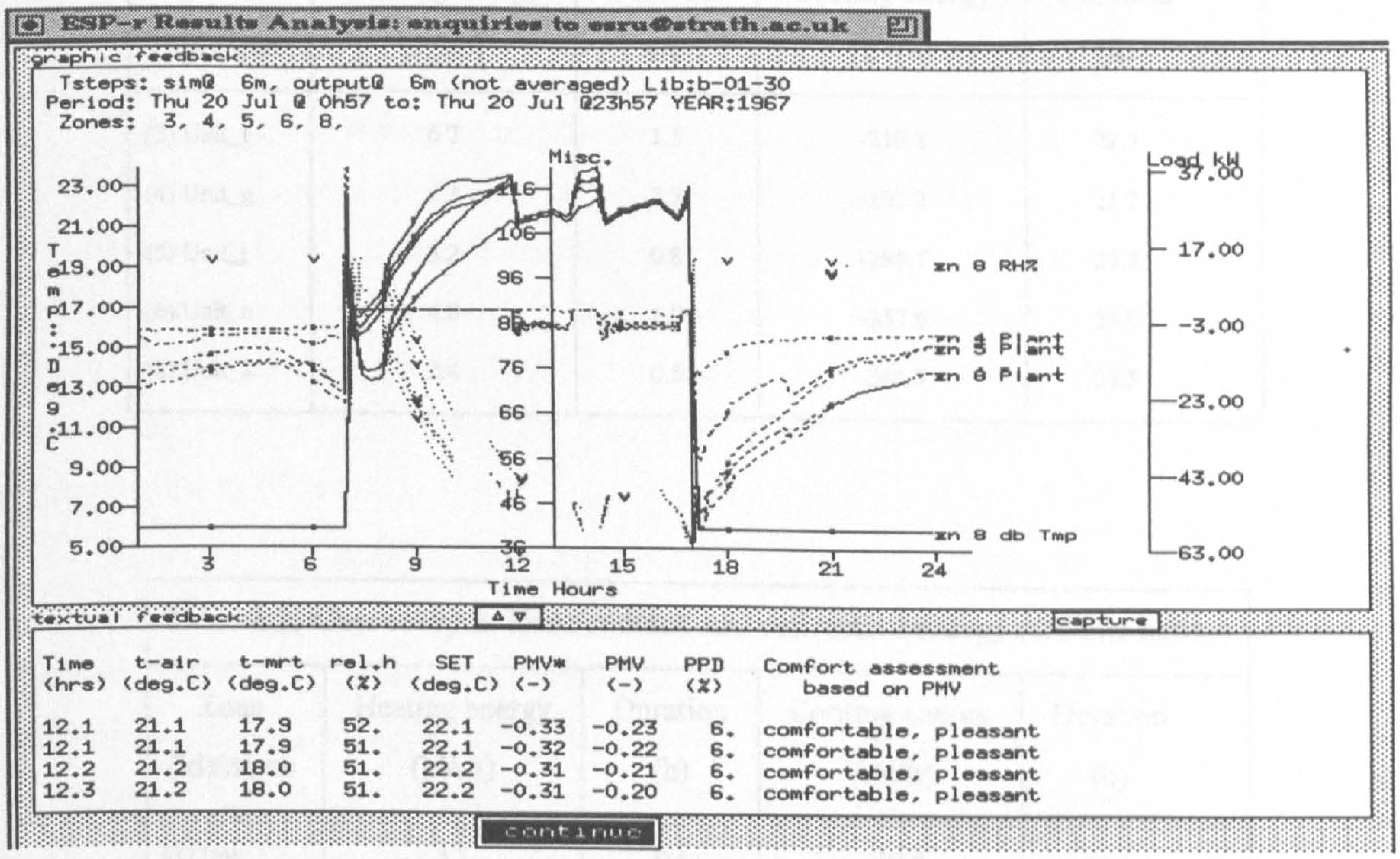


```
 Tsteps: sim@  6m, output@  6m (not averaged) Lib:b-0-30
Period: Thu 20 Jul @ 0h57 to: Thu 20 Jul @23h57 YEAR:1967
 Zones:  3, 4, 5, 6, 8,
```

```
Time   t-air   t-mrt   rel.h   SET    PMV*    PMV   PPD  Comfort assessment
(hrs) (deg.C) (deg.C)  (%)   (deg.C) (-)     (-)   (%)     based on PMV

12.1   21.1    17.8    52.    22.1  -0.33  -0.23    6.  comfortable, pleasant
12.1   21.2    17.9    51.    22.1  -0.32  -0.22    6.  comfortable, pleasant
12.2   21.2    17.9    51.    22.2  -0.32  -0.21    6.  comfortable, pleasant
12.3   21.3    18.0    51.    22.2  -0.31  -0.20    6.  comfortable, pleasant
```

Figure 8.10 Case study_2: Zone radiant and convective power (no global control).

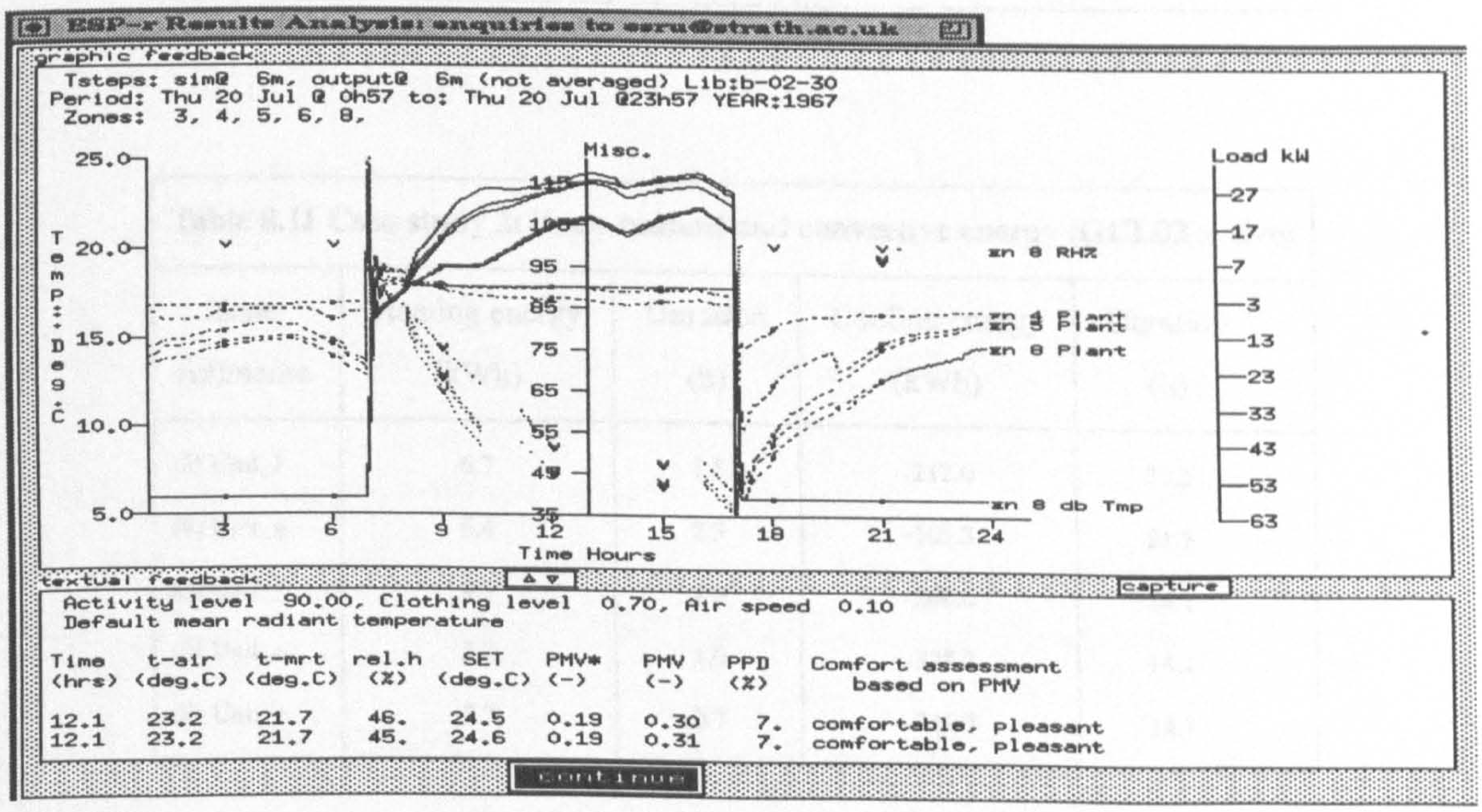


```
Tsteps: sim@  6m, output@  6m (not averaged) Lib:b-01-30
Period: Thu 20 Jul @ 0h57 to: Thu 20 Jul @23h57 YEAR:1967
 Zones:  3, 4, 5, 6, 8,
```

```
Time    t-air    t-mrt   rel.h    SET    PMV*    PMV    PPD    Comfort assessment
(hrs) (deg.C) (deg.C)   (%)   (deg.C) (-)     (-)    (%)       based on PMV

12.1    21.1     17.9    52.    22.1  -0.33  -0.23     6.   comfortable, pleasant
12.1    21.1     17.9    51.    22.1  -0.32  -0.22     6.   comfortable, pleasant
12.2    21.2     18.0    51.    22.2  -0.31  -0.21     6.   comfortable, pleasant
12.3    21.2     18.0    51.    22.2  -0.31  -0.20     6.   comfortable, pleasant
```

Figure 8.11 Case study_2: Zone radiant and convective power (GCL01 active).



```
Tsteps: sim@  6m, output@  6m (not averaged) Lib:b-02-30
Period: Thu 20 Jul @ 0h57 to: Thu 20 Jul @23h57 YEAR:1967
 Zones:  3, 4, 5, 6, 8,
```

```
Activity level  90.00, Clothing level  0.70, Air speed  0.10
Default mean radiant temperature

Time    t-air    t-mrt   rel.h    SET    PMV*    PMV    PPD    Comfort assessment
(hrs) (deg.C) (deg.C)   (%)   (deg.C) (-)     (-)    (%)       based on PMV

12.1    23.2     21.7    46.    24.5   0.19   0.30     7.   comfortable, pleasant
12.1    23.2     21.7    45.    24.6   0.19   0.31     7.   comfortable, pleasant
```

Figure 8.12 Case study_2: Zone radiant and convective power (GCL02 active).

Table 8.9 Case study 2: Zone radiant and convective energy (no global control).

Zone (id)/name	Heating energy (kWh)	Duration (h)	Cooling energy (kWh)	Duration (h)
(3) Unit_f	6.7	1.5	-210.8	22.5
(4) Unit_g	6.3	2.3	-102.2	21.7
(5) Unit_j	3.2	0.8	-298.7	23.2
(6) Unit_a	4.0	1.0	-357.6	23.0
(8) Unit_e	2.4	0.5	-381.7	23.5

Table 8.10 Case study 2: Zone radiant and convective energy (GCL01 active)

Zone (id)/name	Heating energy (kWh)	Duration (h)	Cooling energy (kWh)	Duration (h)
(3) Unit_f	3.8	0.1	-199.6	18.1
(4) Unit_g	2.8	0.1	-100.3	18.1
(5) Unit_j	3.0	0.1	-281.5	18.1
(6) Unit_a	3.1	0.1	-341.3	18.1
(8) Unit_e	2.9	0.1	-362.2	18.1

Table 8.11 Case study 2: Zone radiant and convective energy (GCL02 active)

Zone (id)/name	Heating energy (kWh)	Duration (h)	Cooling energy (kWh)	Duration (h)
(3) Unit_f	6.7	1.5	-212.0	22.5
(4) Unit_g	6.4	2.3	-103.3	21.7
(5) Unit_j	4.3	1.0	-268.0	14.1
(6) Unit_a	5.2	1.0	-325.3	14.1
(8) Unit_e	3.3	0.7	-346.7	14.1

Commercial building: simulation diagnostics.

All simulations were performed using the Kew 1967 climate for a typical summer day (20th August) with a pre-conditioning period (to overcome effects of initial assumptions) of 12 days. The building and plant-side time-steps are 6 minutes and 1 minute, respectively.

The temperature and load requirements for these simulation runs are as shown in Figures 8.10-8.12, and the energy requirements listed in Tables 8.9-8.11 for the cases of (1) no global level control imposed, (2) global on-off switching according to prevailing ambient conditions and (3) global capacity management control with load shedding. Figure 8.11 and Table 8.10 show how the global switching operates to zeroise the zone-level controllers when the ambient dry bulb air temperature exceeds the global set point (21 °C); the reduction in energy requirement being achieved without compromising comfort levels.

Figure 8.12 and Table 8.11 show the effect of global load shedding switching in order to limit the zone-level energy requirements. Here, zones (in the order 3,4,5,6 and 8) are selected for shedding until the total system requirement is less than the prescribed limit (1300 kWh). A comfort analysis for the three control schemes is also listed, the comfort assessment being based on an activity level of 90, a clo value of 0.70, and an air speed of 0.01 m/s. The results indicate that the global control strategies, whilst reducing cooling demand and increasing zone air temperatures, do not compromise comfort conditions.

This case study demonstrates the type of analysis that practising control engineers could carry out: for example, to establish how far back the heating/cooling inputs can be cut without compromising comfort conditions.

8.1.2.3 Application Category 3: Advanced control system design.

The final case study demonstrates the use of control system simulation in a research and development context. Here, the attention is focused on modelling highly advanced control systems. The case study is a public office building situated in central Scotland. The control specification is ambitious with a mix of the spatial, temporal and logical elements as discussed earlier.

Municipal building: problem description.

The building consists of 13 zones, representing 12 office spaces and a corridor (Figure 8.13). A packaged air-conditioning system is specified to service the complex (Figure 8.14).

Multi-zone municipal building: control system specification.

Time-scheduled zone and plant schedules are defined. Four control periods are specified: 00.00-08.00, 08.00-14.00, 14.00-20.00 and 20.00-24.00. The control schedules are summarised in Tables 8.12 and 8.13. Attention is focused on three advanced modelling features:

- the performance of a fuzzy logic controller;
- relative humidity control;
- ESAC optimum start.

Zone control specification.

Different zone controllers are active during the 4 specified control periods. An optimum start controller is active for the period 00.00-08.00. For the period 08.00-14.00 hours, all zones are controlled by a fuzzy logic controller *BCL17*; while, for the period 14.00-20.00, all zones are coupled to the packaged air-conditioning unit. Finally, during the set-back period, the 12 office zones are controlled by means of a fixed heat input controller *BCL04*.

Plant control specification.

Four control loops are specified to control the air-conditioning plant (Figure 8.14): proportional-integral (PI) control loops act to modulate the pre-heating and re-heating batteries, the cooling coil and the spray humidifier. The pre-heater and re-heater controllers sense duct air temperature and actuate heating flux; the humidifier controller senses relative humidity and actuates water flow rate; and the chiller controller senses relative humidity and actuates flux. The plant system is coupled to the building zones by means of the building control functions *BCL06* for the period 14.00-20.00 hours.

Table 8.12 Case study 3: building control schedule

Control function	Mapped zone(s)	Sensed property	Actuated variable	Period_1		Period_2		Period_3		Period_4	
				Start	Law	Start	Law	Start	Law	Start	Law
1	All	Air	Air	00.00	Optimum start	08.00	Fuzzy logic	14.00	Plant coupled	20.00	Night set-back

Table 8.13 Case study 3: plant control schedule

Control function	Sensed property	Actuated variable	Period_1	
			Start	Mode
1	Duct air temperature	Heating flux	00.00	Proportional+integral
2	Relative humidity	Flow rate	00.00	Proportional+integral
3	Duct air temperature	Cooling flux	00.00	Proportional+integral
4	Relative humidity	Heating flux	00.00	Proportional+integral

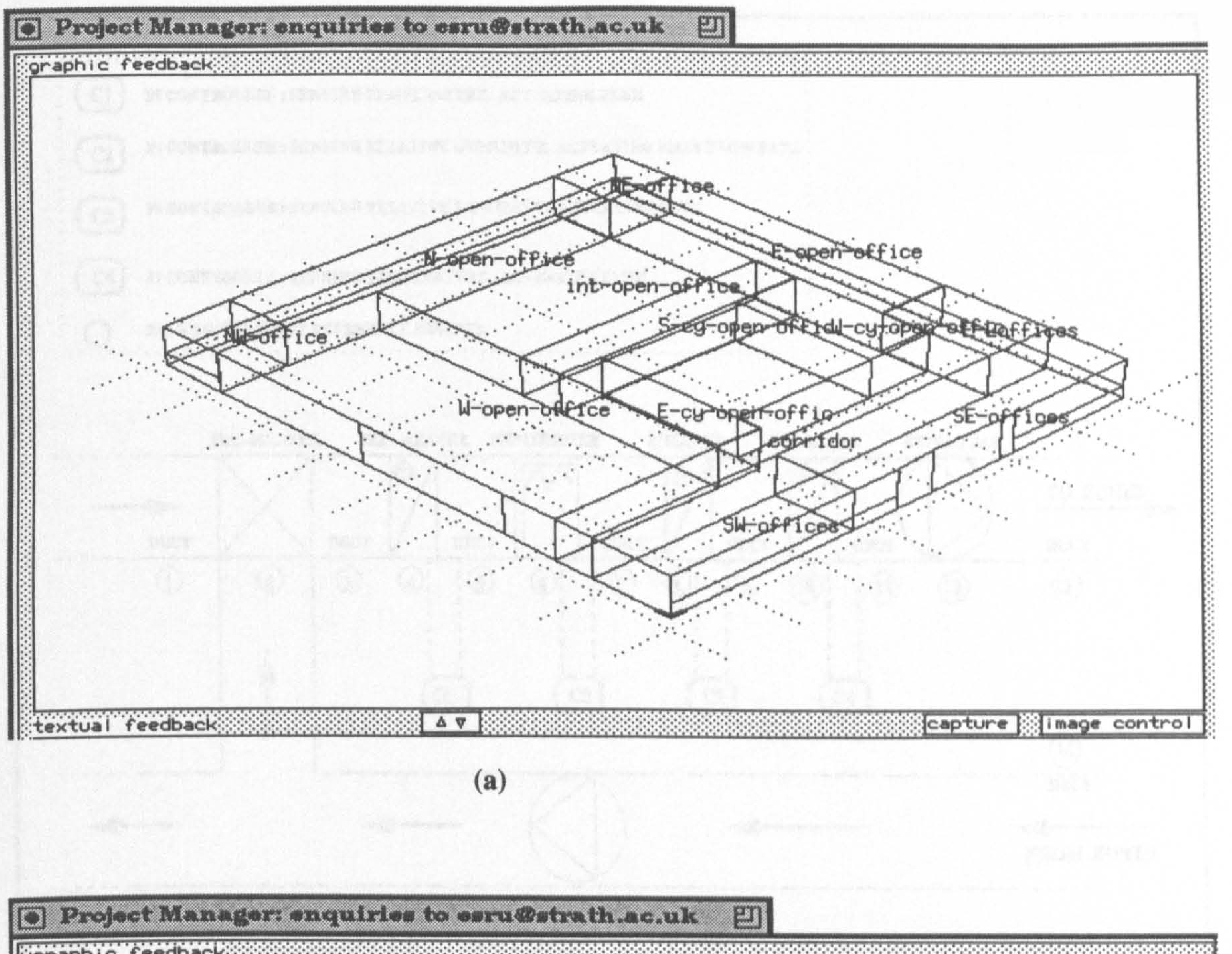


Figure 8.13 Municipal building: (a) perspective view, (b) plan view.

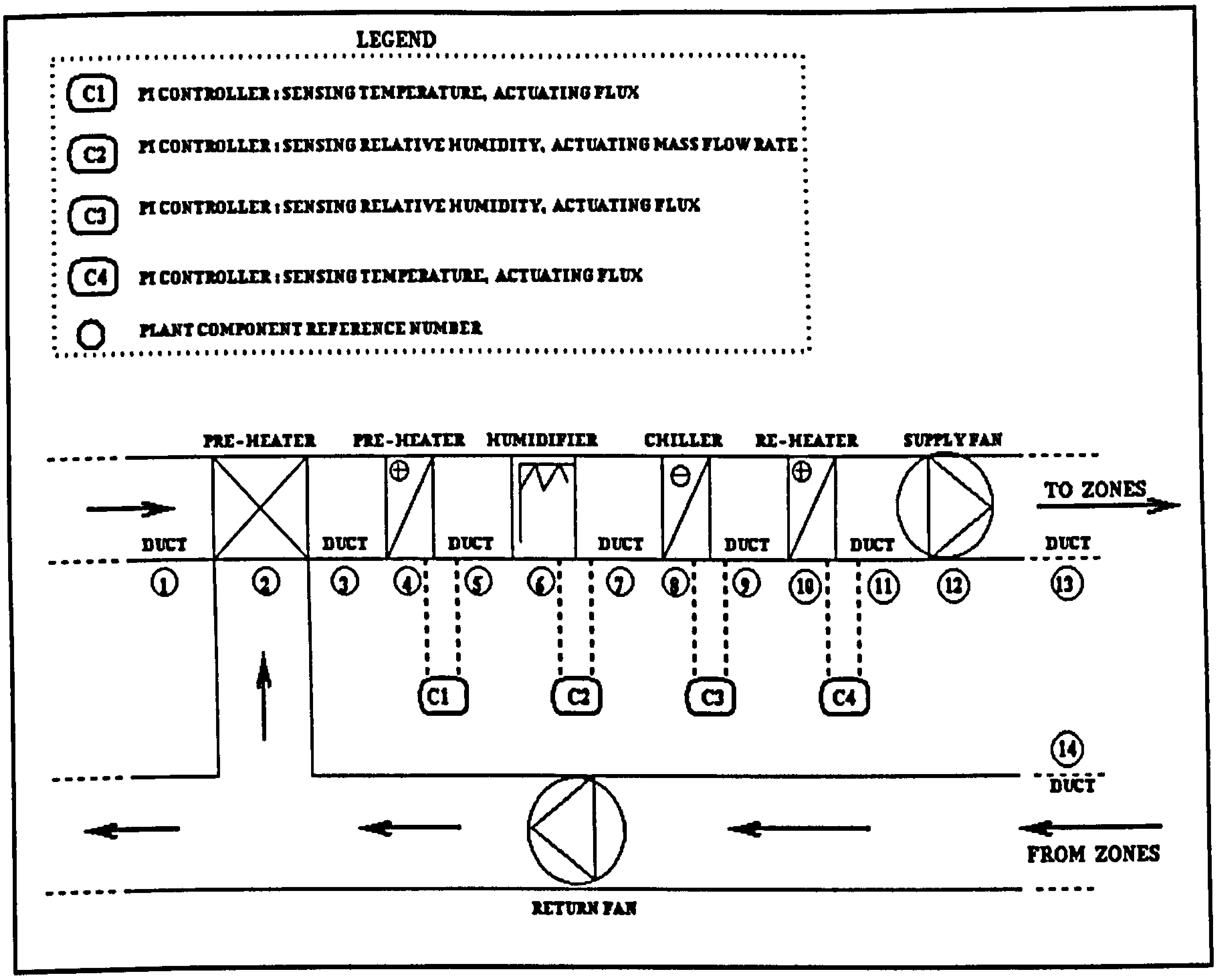


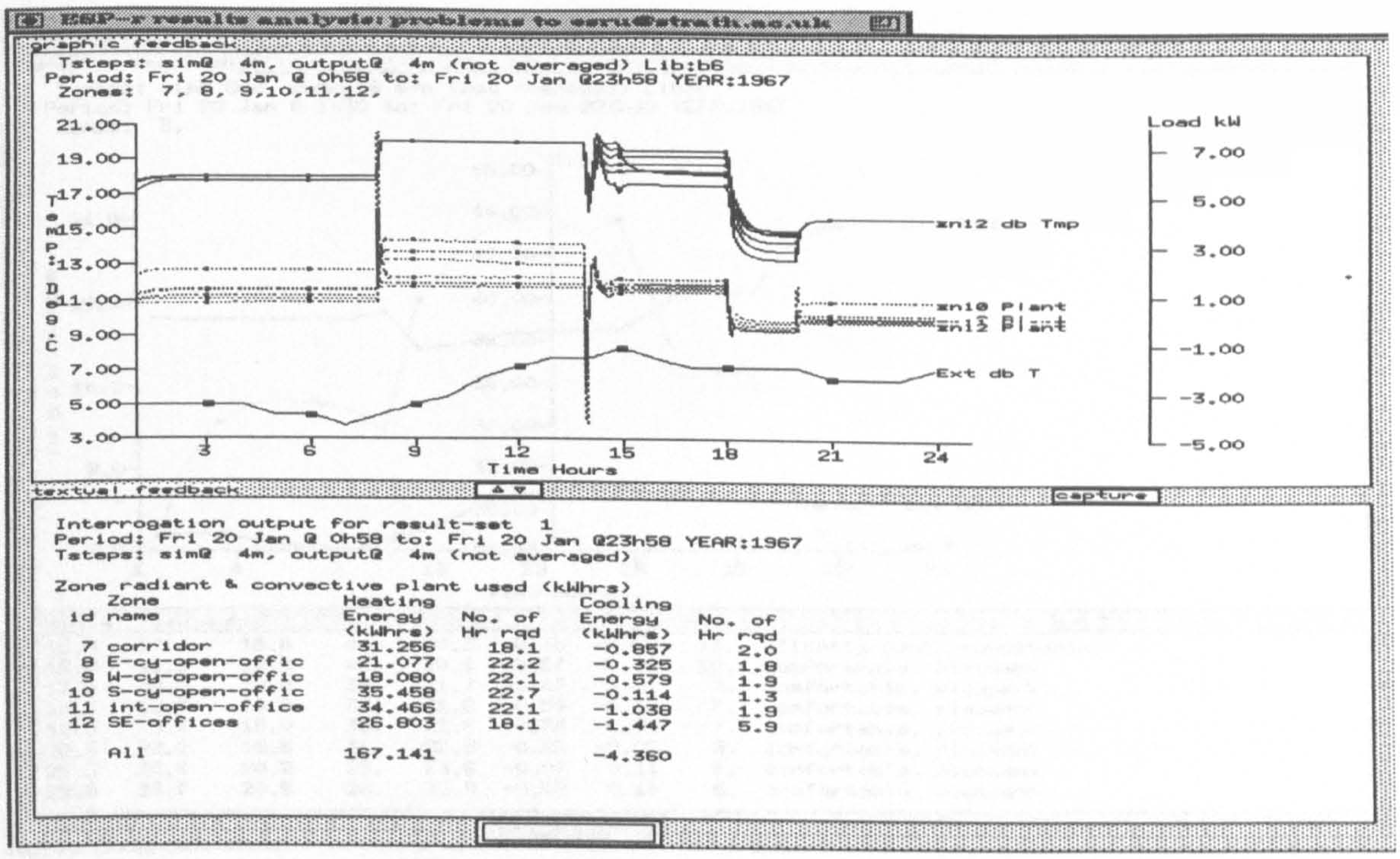
Figure 8.14 Municipal building: year-round air conditioning plant.

Municipal building: simulation diagnostics.

All simulations were run using the Kew 1967 climate for a winter day (20th January). The building and plant time-steps were specified as 4 minutes and 1 minute, respectively.

The first simulation is used to compare the temperature and energy profiles for the cases of fuzzy logic control and ideal control being active for the 3rd control period, 08.00-14.00, both with a set-point of 20 °C. In the former case, the zone air temperature is held within the range 18.5 - 20.5 °C, normally deemed adequate for such an application (Figure 8.15). The plant input is more oscillatory in the case of fuzzy logic control, with the plant limiting capacity resulting in a levelling of the profiles.

The second result set is used to assess the performance of the humidity controller. The simulated profiles (shown in Figure 8.16 for the main office) indicate that the zone relative humidity levels, whilst generally unsatisfactory for other periods, are within the prescribed limits (35%-65%) during the occupied period. The comfort criterion listed is based on the following values: an activity level of 90, a clothing level of 0.80 and an air speed of 0.01 m/s. The psychrometric states for the plant components are as depicted in Figure 8.17 for the occupied period.



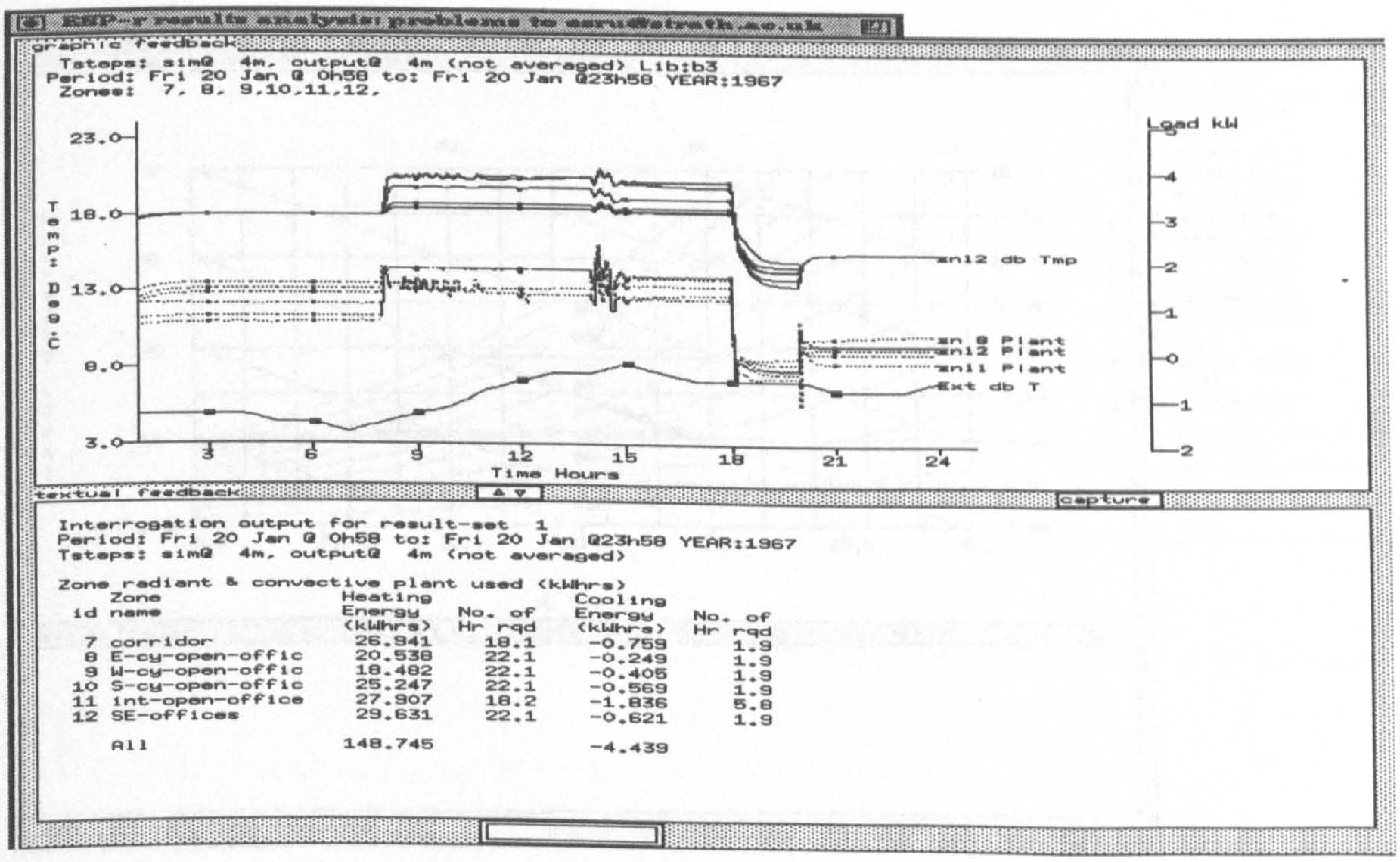
```
Tsteps: sim@  4m, output@  4m (not averaged) Lib:b6
Period: Fri 20 Jan @ 0h58 to: Fri 20 Jan @23h58 YEAR:1967
Zones:  7, 8, 9,10,11,12,
```

```
Interrogation output for result-set  1
Period: Fri 20 Jan @ 0h58 to: Fri 20 Jan @23h58 YEAR:1967
Tsteps: sim@  4m, output@  4m (not averaged)

Zone radiant & convective plant used (kWhrs)
    Zone                    Heating                Cooling
 id name                    Energy    No. of       Energy     No. of
                            (kWhrs)   Hr rqd       (kWhrs)    Hr rqd
  7 corridor                 31.256     18.1       -0.857        2.0
  8 E-cy-open-offic          21.077     22.2       -0.325        1.8
  9 W-cy-open-offic          18.080     22.1       -0.579        1.9
 10 S-cy-open-offic          35.458     22.7       -0.114        1.3
 11 int-open-office          34.466     22.1       -1.038        1.9
 12 SE-offices               26.803     18.1       -1.447        5.9

    All                     167.141                -4.360
```

(a) Ideal control



```
Tsteps: sim@  4m, output@  4m (not averaged) Lib:b3
Period: Fri 20 Jan @ 0h58 to: Fri 20 Jan @23h58 YEAR:1967
Zones:  7, 8, 9,10,11,12,
```

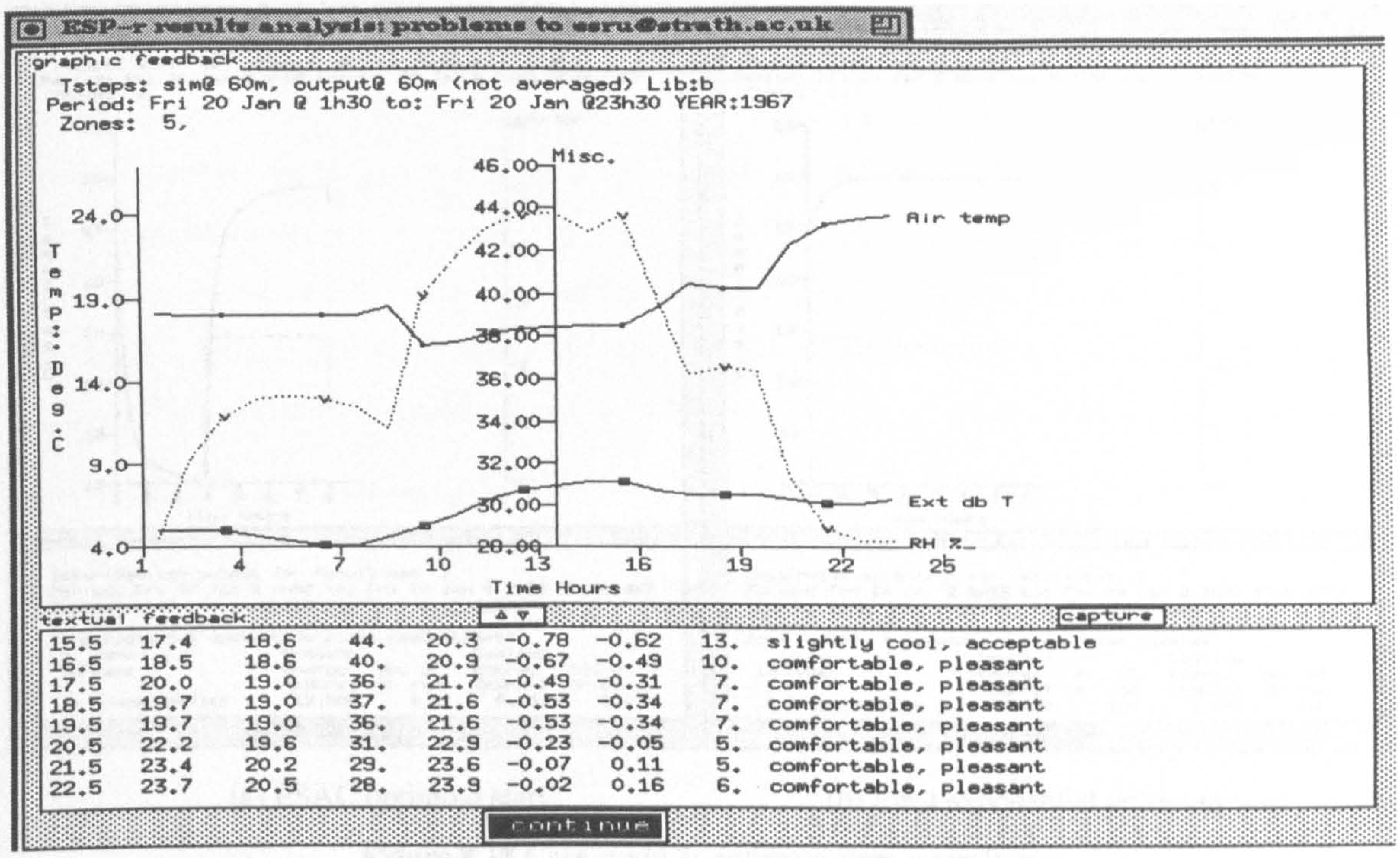
```
Interrogation output for result-set  1
Period: Fri 20 Jan @ 0h58 to: Fri 20 Jan @23h58 YEAR:1967
Tsteps: sim@  4m, output@  4m (not averaged)

Zone radiant & convective plant used (kWhrs)
    Zone                    Heating                Cooling
 id name                    Energy    No. of       Energy     No. of
                            (kWhrs)   Hr rqd       (kWhrs)    Hr rqd
  7 corridor                 26.941     18.1       -0.759        1.9
  8 E-cy-open-offic          20.538     22.1       -0.249        1.9
  9 W-cy-open-offic          18.482     22.1       -0.405        1.9
 10 S-cy-open-offic          25.247     22.1       -0.569        1.9
 11 int-open-office          27.907     18.2       -1.836        5.8
 12 SE-offices               29.631     22.1       -0.621        1.9

    All                     148.745                -4.439
```

(b) Fuzzy logic control

Figure 8.15 Case study 3: control regimes, 08.00-14.00 hours.



```
 Tsteps: sim@ 60m, output@ 60m (not averaged) Lib:b
Period: Fri 20 Jan @ 1h30 to: Fri 20 Jan @23h30 YEAR:1967
 Zones:  5,
```

```
15.5   17.4    18.6    44.   20.3  -0.78  -0.62   13.  slightly cool, acceptable
16.5   18.5    18.6    40.   20.9  -0.67  -0.49   10.  comfortable, pleasant
17.5   20.0    19.0    36.   21.7  -0.49  -0.31    7.  comfortable, pleasant
18.5   19.7    19.0    37.   21.6  -0.53  -0.34    7.  comfortable, pleasant
19.5   19.7    19.0    36.   21.6  -0.53  -0.34    7.  comfortable, pleasant
20.5   22.2    19.6    31.   22.9  -0.23  -0.05    5.  comfortable, pleasant
21.5   23.4    20.2    29.   23.6  -0.07   0.11    5.  comfortable, pleasant
22.5   23.7    20.5    28.   23.9  -0.02   0.16    6.  comfortable, pleasant
```

Figure 8.16 Case study 3: humidity control

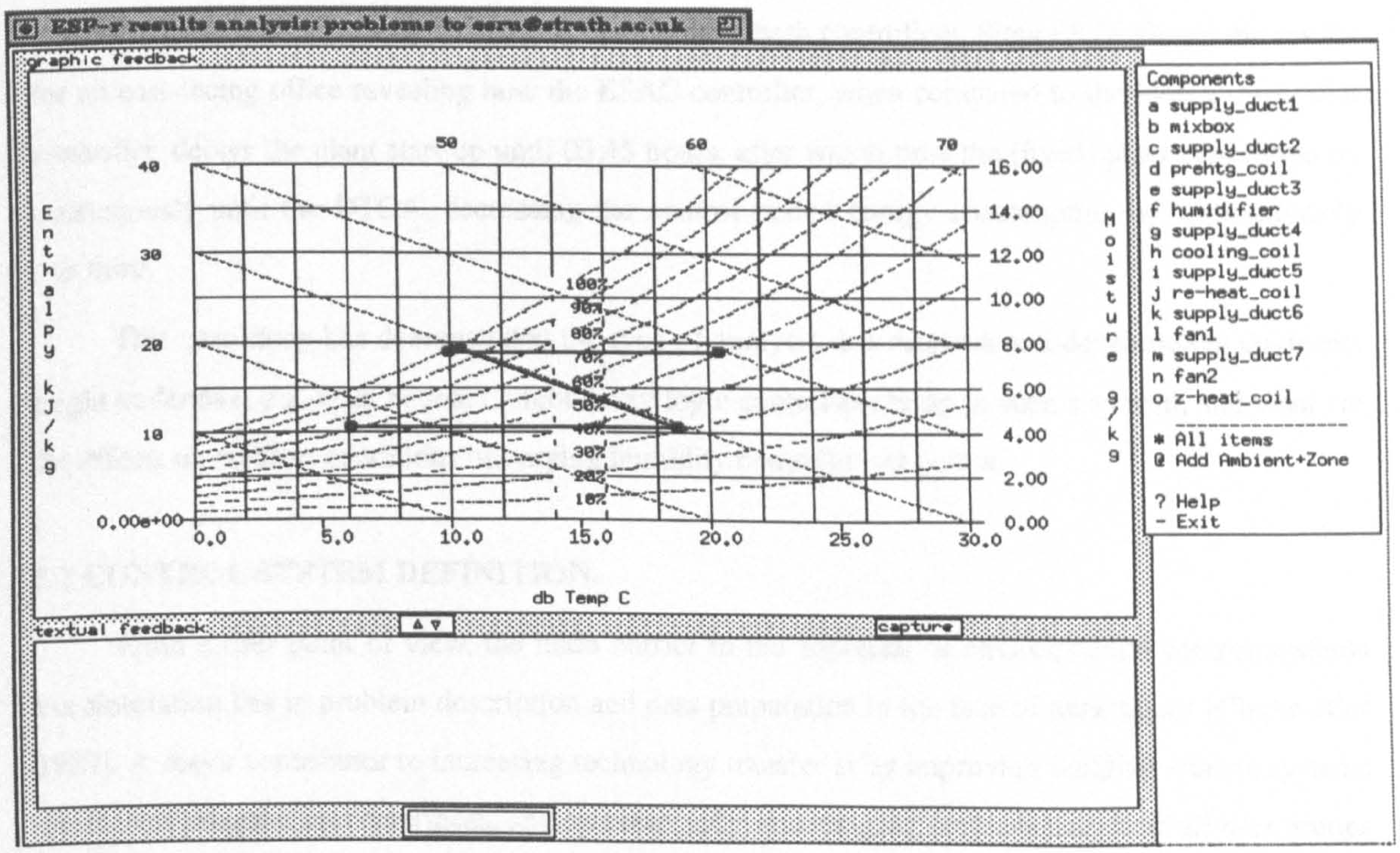
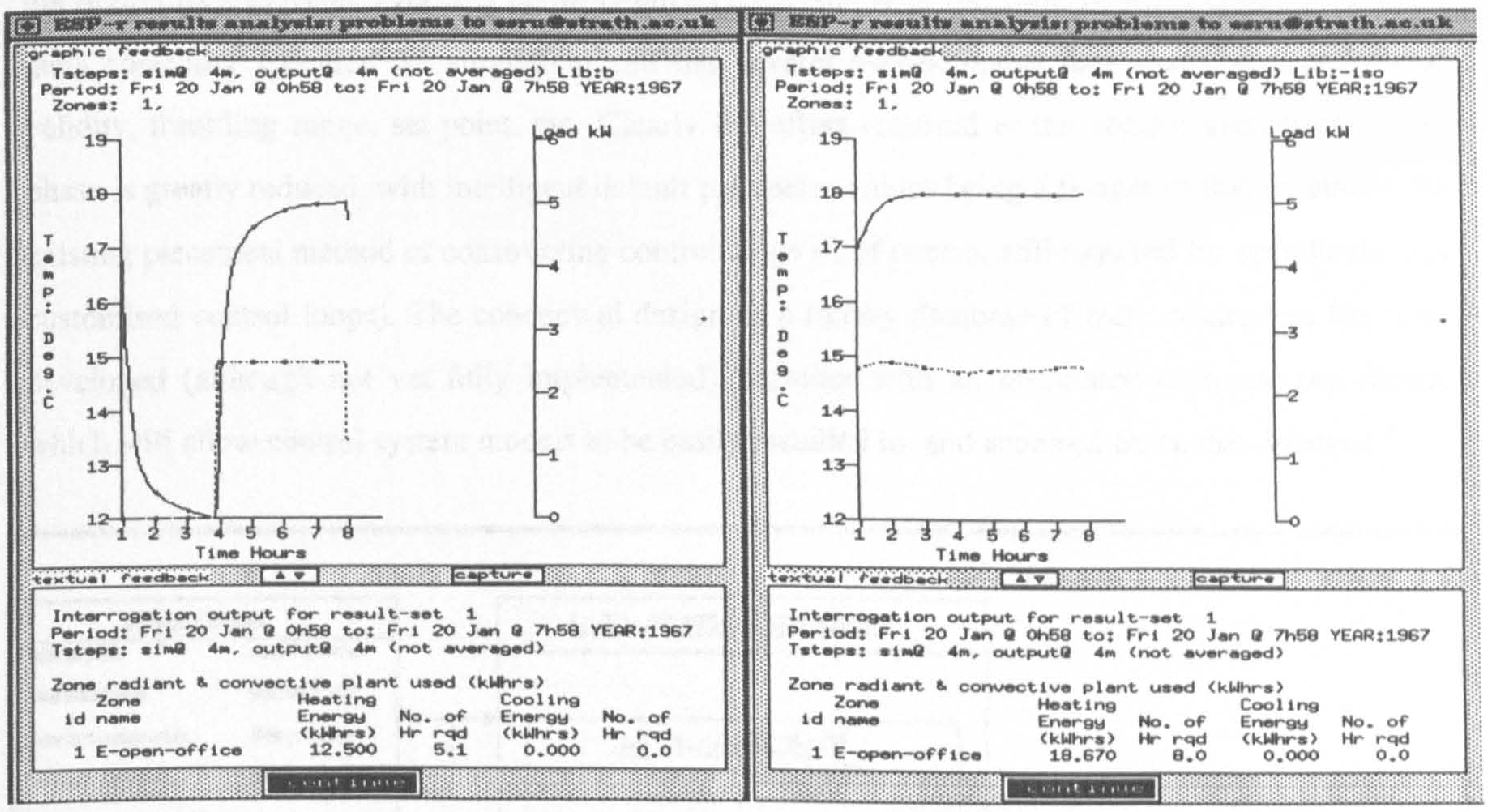


Figure 8.17 Case study 3: psychrometric plot for air-conditioning plant



```
 Tsteps: sim@  4m, output@  4m (not averaged) Lib:b
Period: Fri 20 Jan @ 0h58 to: Fri 20 Jan @ 7h58 YEAR:1967
 Zones:  1,
```

```
Interrogation output for result-set  1
Period: Fri 20 Jan @ 0h58 to: Fri 20 Jan @ 7h58 YEAR:1967
Tsteps: sim@  4m, output@  4m (not averaged)

Zone radiant & convective plant used (kWhrs)
   Zone                   Heating               Cooling
 id name                  Energy    No. of      Energy    No. of
                          (kWhrs)   Hr rqd      (kWhrs)   Hr rqd
  1 E-open-office          12.500      5.1        0.000      0.0
```

```
 Tsteps: sim@  4m, output@  4m (not averaged) Lib:-iso
Period: Fri 20 Jan @ 0h58 to: Fri 20 Jan @ 7h58 YEAR:1967
 Zones:  1,
```

```
Interrogation output for result-set  1
Period: Fri 20 Jan @ 0h58 to: Fri 20 Jan @ 7h58 YEAR:1967
Tsteps: sim@  4m, output@  4m (not averaged)

Zone radiant & convective plant used (kWhrs)
   Zone                   Heating               Cooling
 id name                  Energy    No. of      Energy    No. of
                          (kWhrs)   Hr rqd      (kWhrs)   Hr rqd
  1 E-open-office          18.670      8.0        0.000      0.0
```

(a) ESAC optimum start

(b) Ideal exponential optimum start

Figure 8.18 Case study 3: optimum start controllers.

The final result set compares the effects of employing an ESAC optimum start controller with an ideal optimum start controller. The desired-time-of-arrival (DTOA), the target temperature (18 °C) and the available flux capacity (2.5kW) is the same for both controllers. Figure 8.18 shows the results for an east-facing office revealing how the ESAC controller, when compared to the ideal exponential controller, delays the plant start-up until 03.45 hours, after which time the (fixed) plant capacity is on continuously until the DTOA, decreasing the control period energy consumption by approximately one third.

This case study has demonstrated the type of analysis that research and development engineers might undertake, e.g. what benefits might fuzzy logic controllers bring to such a system, and what are the effects on comfort conditions of varying humidity controller set points.

8.2 CONTROL SYSTEM DEFINITION.

From a user point of view, the main barrier to the appraisal of environmental control systems via simulation lies in problem description and data preparation in the face of uncertainty [Clarke *et al* 1989]. A major contributor to increasing technology transfer is by improving building control systems simulation program user-interfaces, and, consequently, encouraging professionals from all user groups to employ simulation in control system design and operation.

One way in which the control system definition process can be improved is by developing the concept of the *meta controller*, which is a controller having predefined parameters as specified in a database entry (Figure 8.19), and which typically comprises several component control loops. The control structure described in Section 3.5 may then be further extended and enhanced to offer the user the option of specifying (via *prj*) entire control (sub)systems in the form of meta controllers. Each meta controller specified for simulation still has several user-definable data items, e.g. periods of validity, throttling range, set-point, etc. Clearly the effort required at the control system definition phase is greatly reduced, with intelligent default parameter values being a feature of this scheme. (The existing piecemeal method of constructing control loops is, of course, still required for specification of customised control loops). The conceptual design of a library database of meta controllers has been developed (although not yet fully implemented), together with an associated technical pro forma, which will allow control system models to be easily installed in, and accessed from, this database.†

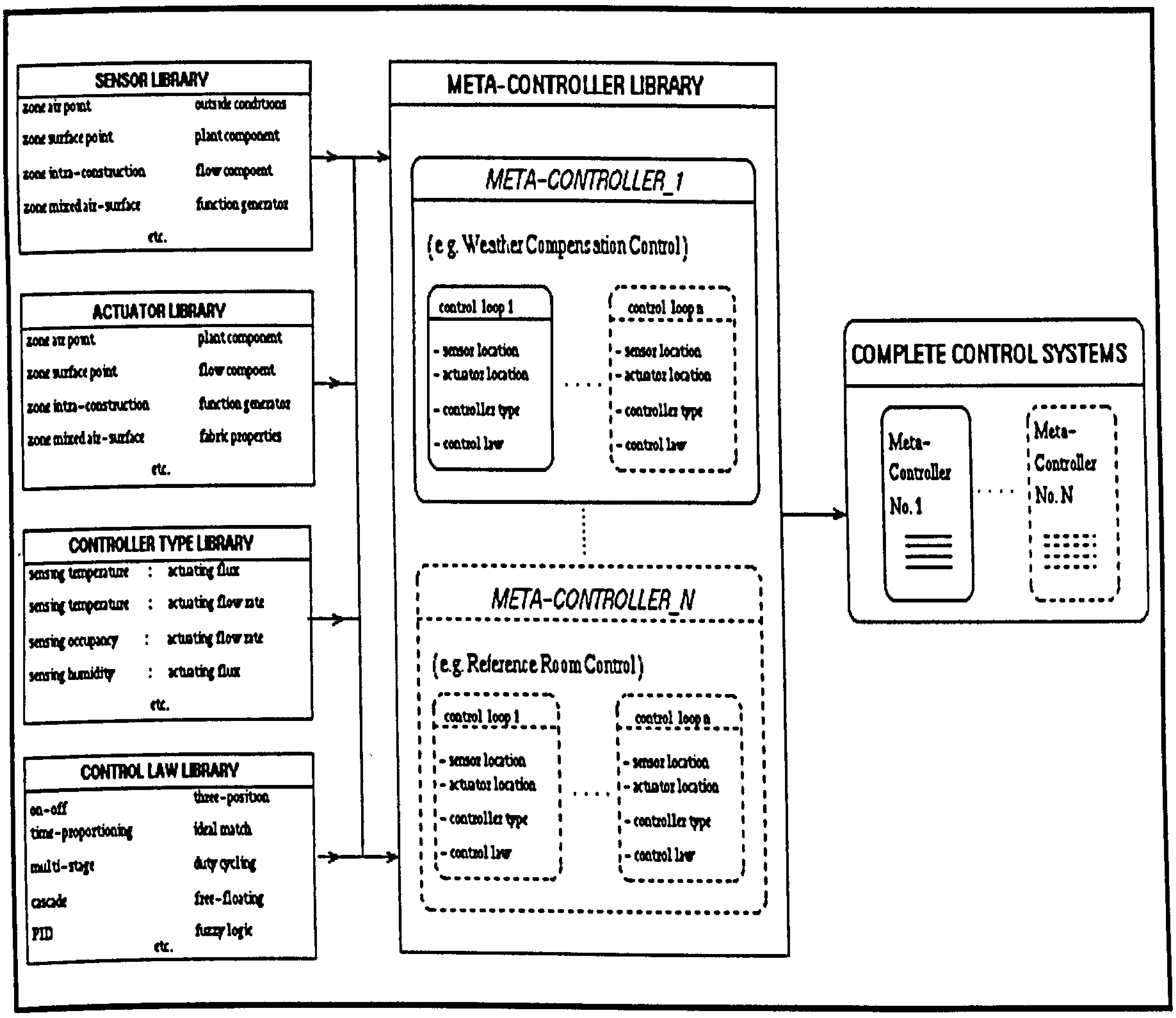


Figure 8.19 ESP-r Meta Controller database.

Two sample meta controllers are now described: firstly, a weather compensator controller; and secondly, a multiple heater coil control system. The weather compensator (Figure 8.20) acts to modulate the boiler output according to external air temperature. The meta controller consists of one control loop with the sensor location (outside), sensed property (external air temperature), actuator location (boiler), actuated property (heating flux), controller type (type 0) and control law

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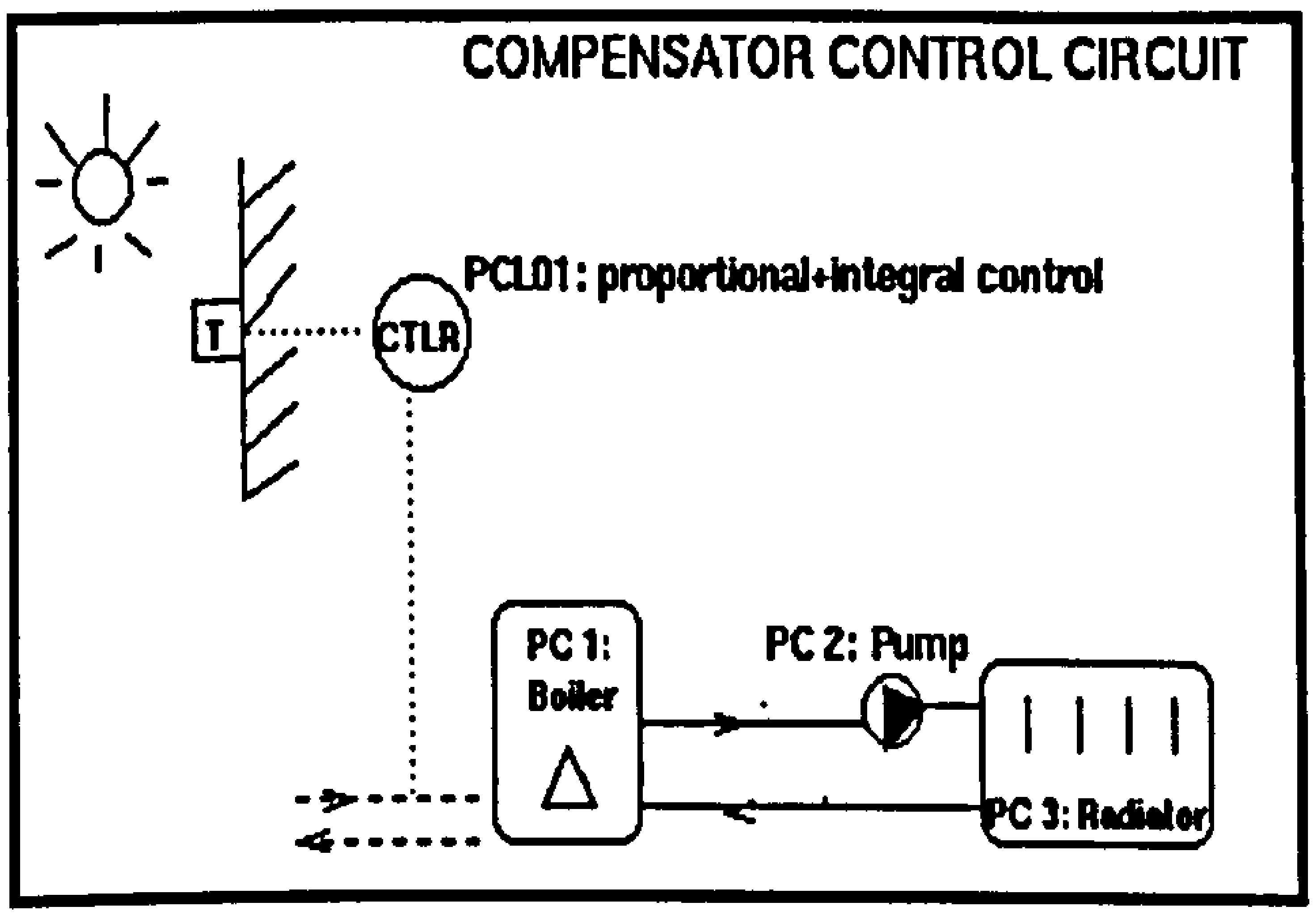
† A library of ESP-r meta controllers is presented in *Appendix C*.

(proportional+integral) predefined in the meta controller library database entry; the user only has to specify control day types and control periods and accept/amend default controller definition data items (set-point, etc.).



LEGEND.	
CTLR:	Controller
T:	Outside temperature sensor
PC:	Plant component
BC:	Boiler component (==PC1)
ud:	User defined.
IAT:	Integral action time
DAT:	Derivative action time
PB:	Proportional band

META CONTROLLER DATABASE ENTRY.

Meta controller type:	Compensation control.
Number of loops:	1
For loop 1:	
Sensor details:	-3 0 0 0
Actuator details:	-1 BC 1 0
Controller type:	0
Control law:	1
No. of misc. data items:	7
Default misc data:	1, 10000, 0, 80, 10, 0, 0

MAPPING ON TO SYSTEM CONTROL CONFIGURATION FILE.

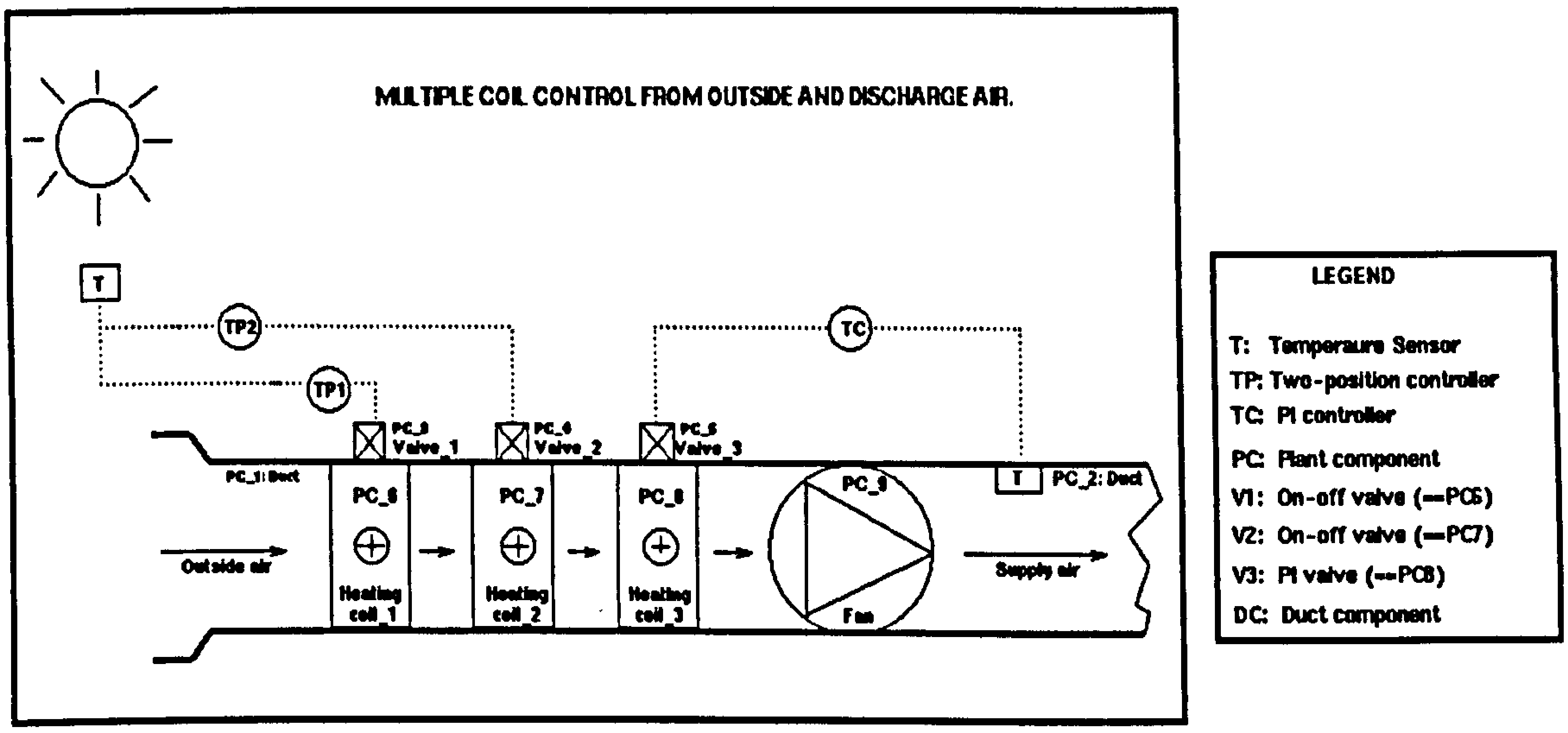
```
Problem title.           # COMPENSATOR
* Plant                  # Plant-side control loop
Compensator control.
 1                       # Number of control loops
* Control loops
 -3 0 0 0                # sensor located outside
 -1 1 1 0                # actuator located at boiler, node 1.
   ud                    # number of day types (user defined)
# For each day type:
   1                     # number of control periods
  ud  ud                 # start day ; finish day (user-defined)
 0 1 0.                  # ctlr type 0; lawl ; period start:00.00
   7                     # no. of misc data items
 1 10000, 0, 80, 10, 0, 0 # mode; Qmax; Qmin; Set-point; PB; IAT; DAT
```

Figure 8.20 *MC01:* Weather Compensator Meta Controller.

The multiple heater coil control system (Figure 8.21) comprises three control loops. The functional description of the circuit is as follows:-

- discharge PI controller TC modulates valve_3 to maintain constant discharge temperature;
- outdoor controller TP1 fully opens valve_1 when outdoor air temperature drops to 5°C;
- outdoor air controller TP2 fully opens the valve_2 when outdoor air temperature falls below 1°C.

Rather than defining, in full, three independent control loops, the composite meta controller requires the user to merely specify controller time schedules, the interface allocating - from the meta controller database - default control loop data entries in the system control configuration file.



META CONTROLLER DATABASE ENTRY

Meta controller type: Multiple coil control.
Number of loops: 3

For loop 1:
Sensor details: -3 0 0 0
Actuator details: -1 V1 1 0
Controller type: 12
Control law: 8
No. of misc. data items: 7
Default misc data: 1,5,7,1,0,0,0

For loop 2:
Sensor details: -3 0 0 0
Actuator details: -1 V2 1 0
Controller type: 12
Control law: 8
No. of misc. data items: 7
Default misc data: 1,1,5,1,0,0,0

For loop 3:
Sensor details: -1 DC 1 0
Actuator details: -1 V3 1 0
Controller type: 2
Control law: 2
No. of misc. data items: 7
Default misc data: 1,0.001,0,20,3,0,0

MAPPING ON TO SYSTEM CONTROL CONFIGURATION FILE.

```
 Problem title.             MULTIPLE COIL CONTROL
  * Plant
   3                        # Number of control loops
  * Control loops           # Control loop 1
   -3 0 0 0                 # sensor located outside.
   -1 1 1 0                 # actuator located at on-off valve_1
     ud                     # number of day types (user-defined)
# For each day type:
    ud  ud                  # start day ; finish day (user-defined)
      1                     # number of control periods.
    12  8  0.               # ctlr type 12; law 8   period start:0.00
      7                     # no. of misc data items;
 1,10,18 1,0,0,0            # misc data items .....
 * Control loops            # Control loop 2
    -3 0 0 0                # sensor located outside.
    -1 1 1 0                # actuator located at on-off valve_2.
      ud                    # number of day types (user-defined)
# For each day type:
     ud ud                  # start day ; finish day (user-defined)
       1                    # number of control periods.
     12  8  0.              # ctlr type 1; law 8   ;period start:0.00
       7                    # no. of misc data items
 -1,5 10,1,0,0,0            # misc data items .....
 * Control loops            # Control loop 3
    -1 2 1 0                # sensor located at duct component.
    -1 1 1 0                # actuator located at PI control valve_3.
      ud                    # number of day types (user-defined)
# For each day type:
     ud ud                  # start day ; finish day (user-defined)
       1                    # number of control periods.
     2  2  0.               # ctlr type 2; law 2   ; period start:0.00
       7                    # no. of misc data items
  1,0.001,0,20,3,0 0        # misc data items .....
```

Figure 8.21 *MC03:* Multiple Coil Meta Controller.

8.3 EMULATION.

An area currently receiving attention within the modelling community is the use of *emulation* as a means of evaluating *real* BEMS performance by connecting the BEMS to the simulated building HVAC system via a hardware interface. Purpose-built, domain-specific simulators have been designed and produced for the study and evaluation of BEMS. One such emulator is SIMBAD (SIMulator for Buildings And Devices) [Visier and Nejad 1992]. It consists of a data processing environment by which a control system or real BEMS can be connected by way of an interface (Figure 8.22). The data processing environment is composed of a workstation and an energy simulation program, HVACSIM+ [Clark 1985]. The latter includes a set of building, heating and air conditioning equipment models. The interface, which is made up of a data acquisition and control unit enables the real input/output applied to the BEMS to be linked to the sensors and actuators which are simulated on the workstation.

The problems associated with the development and use of BEMS can be divided into hardware and software. To investigate both issues, the International Energy Agency (IEA) launched two research projects. The hardware problems were studied in the IEA Annex 16 project [IEA 1991]; the software problems were considered in the IEA Annex 17 emulation project [Lebrun and Wang 1993]. Two simulation programs were used in the Annex 17 emulation study, HVACSIM+ and TRNSYS [SEL 1988]. Six emulators were developed by the project participants: three using HVACSIM+ and three using TRNSYS.

The energy saving potentials and performance of BEMS control strategies on hydronic heating and air-conditioning systems were evaluated. This evaluation indicated that the emulation of building, HVAC and BEMS is a powerful method of developing BEMS strategies, and that the building emulator provides an appropriate testing approach for real BEMS under simulated 'real' working conditions. Emulation applications may be summarised as:

- BEMS software and hardware commissioning;
- evaluation of performance of BEMS control strategies and algorithms;
- controller pre-tuning;
- training and education of BEMS operators.

The present work has equipped ESP-r with several features necessary for emulation studies, including:-

- simulation time-step variation (1 second to 60 minutes) and simulation time-clock manipulation as a function of control system parameters;
- a multiple point sensing and actuation capability;
- advanced DDC-based controller algorithms;
- a hierarchical systems modelling capability.

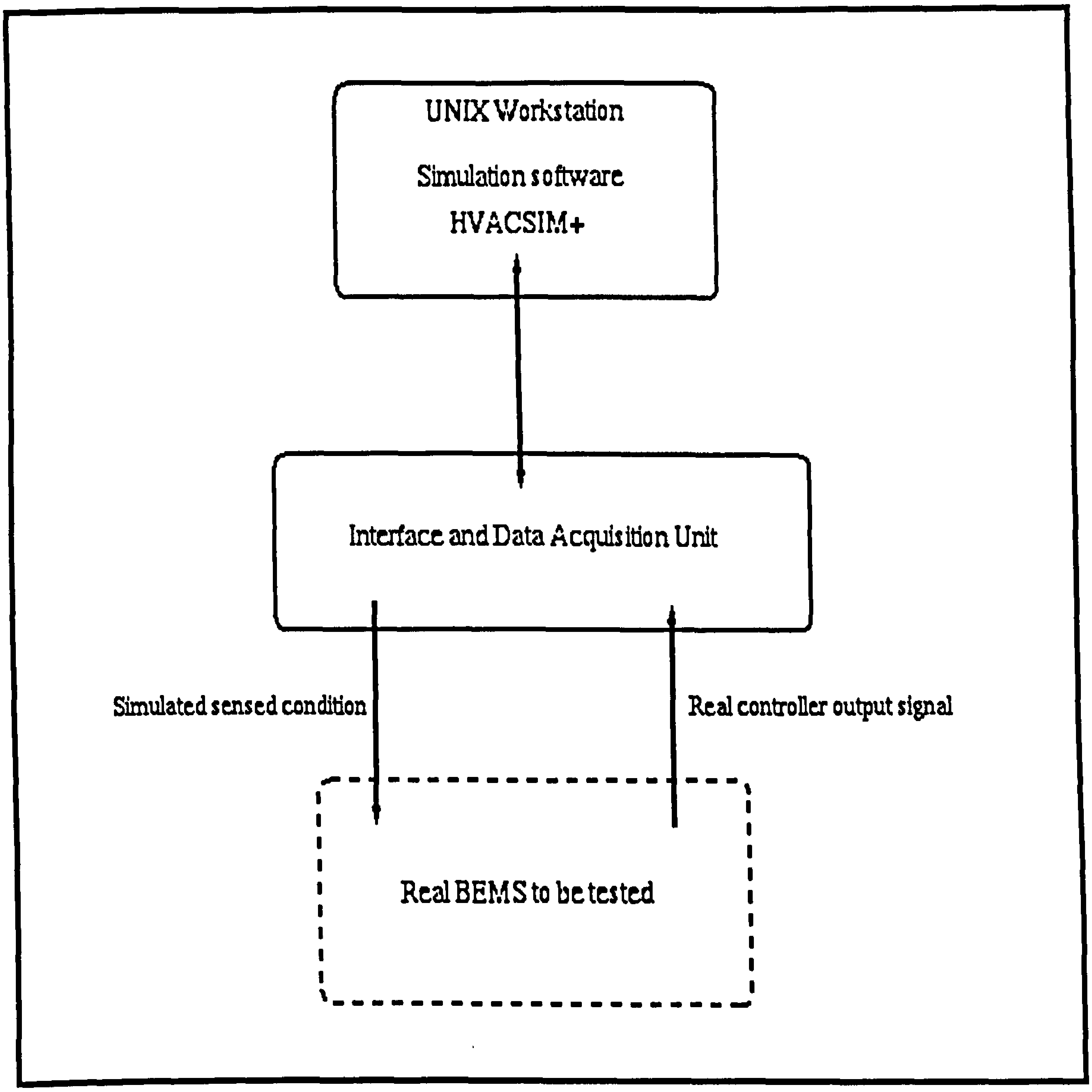


Figure 8.22 The CSTB emulator, *SIMBAD [Visier and Nejad 1992].*

In order for ESP-r to participate in emulation studies, a hardware interface would be required, the principal function of which is to couple the BEMS to the sensors and actuators of the simulated plant. Analogue-to-digital converters (ADCs) are connected to the analogue outputs of the BEMS, which would normally be connected to the plant actuators. The digital-to-analogue converters (DACs) are connected to the BEMS in place of the plant sensors. As with the hardware interface device used in the IEA project [Haves and Dexter 1989], a special component model would be required to read the simulation clock and control the data transfer in both directions. In the case of HVACSIM+, the component model is configured so that it does not participate in the iterative solution of the simulation equations; a similar facility would be required to synchronise the hardware interface and ESP-r numerical solvers.

The emulation studies undertaken to date have focused on assessment and commissioning of plant-side controllers [Haves *et al* 1991 and Kelly *et al* 1991]. However, similar techniques may also be applied to the assessment of *integrated* practical event, flow, plant, power and zone controller subsystems - in the case of ESP-r, facilitated by the multi-system control modelling approach elaborated in Section 3.5. The main stages involved in the interactive system emulation process are as follows.

- *Stage 1.* At each simulation time-step, the subsystem control executive is called as normal to direct processing of the control function.
- *Stage 2.* The subsystem control function either processes the sensed condition (illuminance level, thermophysical property, pump volumetric flow rate, etc.) as normal or, if the loop is under test, writes this value to the hardware interface data channel: in the former case, *Stage 3a* is followed; in the latter, *Stage 3b* is carried out.
- *Stage 3a.* The ESP-r subsystem control function algorithm processes the sensed value to produce an actuator signal.
- *Stage 3b.* The practical controller under test processes the sensor output, subsequently writing the generated actuator signal to the hardware interface data channel.
- *Stage 4.* The subsystem control executive processes the actuator signal as normal, e.g. for building-side control, this signal is used in conjunction with the building control system equation set to establish the future time-row control point condition as elaborated in Section 3.5.

The control loops processing *real* actuator signals and those processing ESP-r controller algorithms may be switched at any time during the simulation as depicted in Figure 8.23.

The above scheme offers the possibility of employing emulation techniques for the validation of all ESP-r subsystem control function algorithms. This may be achieved by carrying out both *Stage 3a* and Stage 3b for the control loop(s) under test, i.e. the sensed condition is used to generate a time-series of actuator signals by both ESP-r *and* the practical BEMS, thereby enabling empirical validation of the controller algorithm. Moreover, inter-model validation may be facilitated by replacing ESP-r with a substitute simulation program in the emulator and comparing the generated time-series of controller output signals.

The main categories of control system programs users have been identified. The control system modelling features developed in the present work were assessed in terms of their applicability. Finally, future developments in the areas of applicability have been discussed.

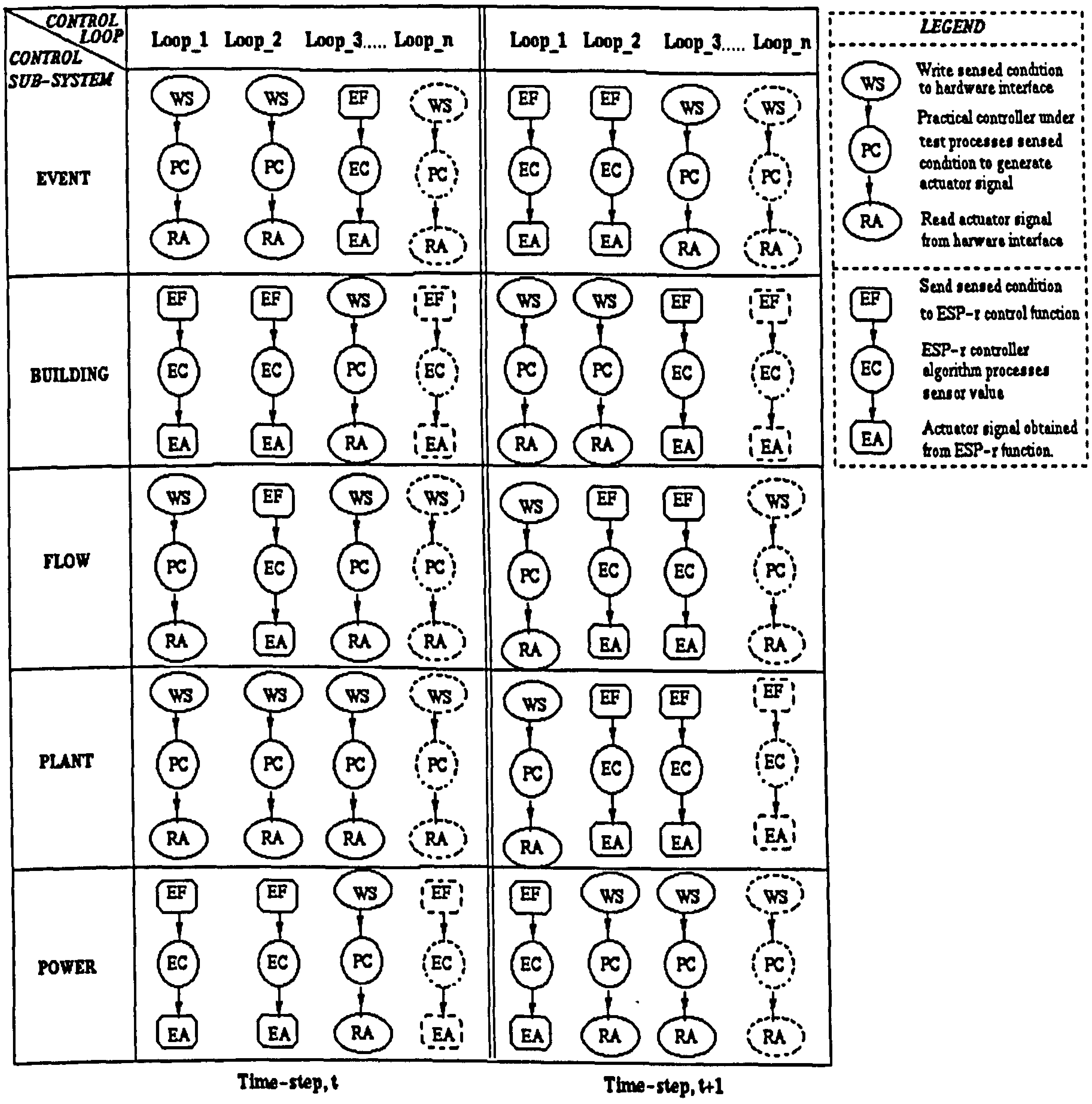


Figure 8.23 Emulation: integrated control subsystems.

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Chapter 9

CONCLUSIONS AND FUTURE WORK

The need for a capability to model advanced building control systems has been demonstrated in terms of the comparative assessment of system performance, and the quest for truly intelligent buildings. Having defined the practical objectives (thermal comfort, optimum fuel consumption and optimised environmental control system performance), the main goal of the work was to develop/enhance building performance evaluation tools to enable this capability. The schemes introduced facilitate the modelling and simulation of many advanced building control strategies at an appropriate level of abstraction.

In this chapter, the general conclusions of the present work are summarised. These are followed by recommendations for future work in this area.

9.1 CONCLUSIONS.

Optimisation of building control system design and operational strategies has assumed greater importance not only for reasons of economy and environmental impact, but also because of occupant comfort and safety. Buildings and their associated control systems are highly complex, making any optimisation attempt non-trivial. In order to accommodate this complexity, and provide effective design-decision support, building performance simulation programs can be employed.

While such programs typically provide assessments of simple building control strategies, there are no facilities for the modelling and simulation of advanced hierarchical, multiple input, multiple output (MIMO) control schema as they exist in practical state-of-the-art BEMS. The main goal of this work was therefore to enable the modelling of advanced control within a fully integrated, whole building, dynamic energy simulation program in order to facilitate high integrity control system modelling. It was argued that the only way to analyse a real system rigorously is to provide a mechanism that allows the inclusion of all the energy and mass flow paths which interact within the real system.

In the field of control system simulation, the need for a generalised control system entities database has been identified. Based on an extensive review, the following objectives were set: firstly, to identify the set of required system entities as present in real building control systems; secondly, to develop corresponding control system modelling schemes and refine existing facilities to increase the integrity of the modelling process; thirdly, to verify the concepts and models by installation and subsequent testing within the ESP-r system.

The control system simulation capabilities and robustness of the ESP-r system have been improved. Composite and multiple point sensing and actuation capabilities have been developed and installed in ESP-r. A numerical technique which facilitates the modelling of control to comfort criteria (PMV) was demonstrated. Models for non-ideal sensing and actuating elements were added to account for installed and operational characteristics. Numerical techniques were designed to facilitate the modelling of time-dependent operational characteristics.

Simulation time-step and clock adjustment features were developed and tested on building/plant problems. Time-step controllers were modified to allow for time-step reductions based on user-defined control system criteria. Controllers which implement iteration in addition to time-step reduction were added to eliminate the burden on the user when selecting appropriate time-step reduction trigger values. These controllers were found to be suitable for applications where control system dynamics are of particular importance, e.g. highly non-linear systems. A simulation clock adjustment controller was developed to allow the simulation of system-level controllers. It also facilitates the introduction of predictive-iterative controller techniques. A simulation clock pause controller was designed to allow on-line control system parameter modification.

Matrix solvers have been developed to allow the efficient practical simulation of complex control systems. This entailed the development of a supervisory matrix processing technique compatible with the techniques already active in ESP-r. A library of global control algorithms have been added to ESP-r. Control systems of a hierarchical nature can now be handled, allowing a range of BEMS strategies to be investigated. A number of new zone control functions have been added to ESP-r's control function database. An environment suitable for the installation of Artificial Intelligence (AI) based controller models has been created.

The rationale of energy simulation assisted control (ESAC) was explained and subsequently demonstrated by means of practical examples. The conceptual framework of ESAC is not system specific; it can be generalised to apply to any thermal system and extended for use in industrial and non-industrial processes. A library of ESAC algorithms was installed in ESP-r. New algorithms can be added as required.

Modifications have been carried out to enable the establishment of a user-friendly problem definition process, thus reducing the burden on the user. A control system 'meta controller' database has been developed to allow standard and customised control systems and subsystems to be specified. This constitutes a methodology for the interactive definition of the control system being proposed for simulation. The results handling structure of ESP-r has been extended to allow control system parameter recording, display and analysis.

A verification and validation methodology was outlined. Techniques employed included critical evaluation of the theory and checking of source code together with analytical, inter-model and empirical validation tests. Accordingly, the validity and verification of the developed schemes and their installation in ESP-r were concluded.

Generally, as a system modelling tool, the application of these techniques could be extensive. The new schemes can be used to achieve a wide range of application at a suitable level of abstraction, and provide a unified mathematical structure for control systems modelling in general. Theoretically, the methods will allow the investigation of new design features and the identification of optimum control systems. ESP-r's capability to handle real BEMS strategies and multi-domain problems has been demonstrated by examples which varied in complexity from simple, single loop circuits to complex multi-level networks comprising fabric, plant, flow and control interaction.

9.2 FUTURE WORK.

The present work is merely a step towards an envisaged intelligent, integrated, building design system, and work remains to be done in the area of advanced building control systems modelling. In the context of the present work, several areas of future research can be identified as follows.

3-dimensional control algorithms. The current ESP-r multi-dimensional gridding scheme supports only free-floating and ideal building-side control algorithms. This is because these algorithms employ only the uni-directional nodal state variables. If these state variables were replaced by local variables within the control related subroutines, then all the available control algorithms could be supported by the multi-dimensional gridding scheme.

Artificial Intelligence (AI) controller modelling. Due to time constraints, modelling of artificial intelligence (AI) based controllers in this project was restricted to the creation of an environment suitable for the installation of fuzzy logic controllers. Future work in this area should involve installation of models for neural network and genetic algorithm based controllers.

Validation of control system modelling schemes. It is well recognised that standard benchmarks and validation tests should be incorporated into the simulation program [Macdonald 1997]. It should also be made easier to carry out sensitivity analyses in order to establish the effect of controller parameter changes (e.g. throttling range, gain, hysteresis) and determine the most important factors.

Further validation exercises are necessary with empirical work moving away from test cells to more realistic buildings. Ideally, this would involve a comparison of simulation and empirical results for an existing BEMS. Most existing data for building control systems is for small-scale, zone-level systems.

Simulation based BEMS. As discussed in Chapter 6 and Chapter 8, future BEMS will have on-line simulation software to orchestrate the control strategy. The main requirements for a simulation program forming part of a coupled simulation-BEMS scheme are:

- The process model should be sufficiently accurate.
- The simulation program should have an exhaustive range of controller models and be capable of handling multiple-level, multiple input-output systems in rapid predictive-iterative mode.

- The program should be capable of responding to stimuli from the real system in a timely fashion in order to accommodate the needs of the process (i.e. at least several orders of magnitude faster than the process).
- There should exist suitable signal interface devices and equipment.

ESP-r meets the first three requirements. However, future work requires to be carried out in order to design and develop interface equipment capable of linking ESP-r to a practical BEMS.

Condition monitoring. An essential aspect of designing the functional elements of control systems is a regular assessment of reliability and failure rates. At the design stage, reliability comparisons are made between alternative designs. At other times, they are done to determine if the proposed system meets a specification. Clearly, reliability needs to be considered during the modelling process if future simulation programs are to play an important role in the design and operation of BEMS. At present this element is not modelled although recent years has seen an increase of activity in this area: e.g. Dexter and Trewhella [1990] describe a fuzzy rules-based model in which the number of starts, stops and reversals are taken to indicate fatigue-induced wear on the actuator.

Control system designers often expect some demonstration of claimed reliability figures, e.g. specification often calls for a minimum *demonstrated* mean-time-to-failure (MTTF) [Cluley 1993]. This would normally require samples of the component to be tested for lengthy periods of operation under the most arduous of working conditions. Generally, the testing of equipment to be used in benign surroundings such as computer rooms and laboratories requires a minimum of environmental control, but as the environment to be simulated becomes more severe, with greater excursions of temperature, humidity, etc, then laboratory testing can become problematic. For example, boiler plant control equipment will be subjected to high temperature and humidity levels, and subjected to changes in power supply voltage and frequency. However, such conditions can be adequately simulated in a software environment, saving years of laboratory testing time and associated expense.

Data input and uncertainty. One of the principal barriers to the use of energy simulation tools is the problem of data input in the face of uncertainty. Control systems often require a substantial amount of input data at a level of sophistication which is not available at the early design stages. Such a barrier must not be used as a justification for over-simplification of the physical laws and operation of systems. User input errors are also a frequent source of modelling error. This is understandable considering the large amount of input data required for the definition of problems. One way to minimise such errors is to incorporate intelligent defaulting and interactive range checking. With control system simulation, difficulties are often encountered when extracting input parameters from published data. Manufacturer's data are usually related to steady-state test conditions resulting in a lack of data for the dynamic case. In order to obtain full benefit from dynamic simulation, more specific controller data should be obtained and made available to modellers.

From all of the above, it is clear that the objectives of this study have been fulfilled and that the work is a step in the direction of imitating the reality of control systems. With the continuous advances in information technology and increasing computer processing power, the prospect for energy simulation is promising. The technology is now beginning to overcome the major barriers to practical application, such as data availability for control system definition and advanced human computer interface to cater for the practical needs of the profession. It is hoped that the present work will trigger new thoughts and encourage further developments in the area of building control systems modelling and simulation.

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APPENDIX A: GLOSSARY OF TERMS

* Cross-references are indicated by entries in *italics*.

GLOSSARY OF TERMS.

Access time. The time interval between the request for information and the instant that this information is available. This is often the time taken for one complete access of a *peripheral* by the *central processing unit.*

Actuator. A means provided to execute the output from the *controller* (i.e. the *control action),* through operating a *final control element.* This control action is determined such as to reduce the error between the *measured value* and *desired value* of the *controlled variable.*

Accuracy of an input. The maximum expected deviation of the indicated value from the true value.

Accuracy of an output. The maximum expected deviation of the actual value from the desired value.

Adaptive control. The primary objective of adaptive, 'self-learning' or *'heuristic'* control is to reduce uncertainties concerning knowledge of the environment and system dynamics in an on-line or real time fashion and to alter controller parameters so as to cause system operation to continuously seek better performance Thus more accurate control is achieved over a wider range of external conditions since control parameters are automatically adjusted as conditions vary. The need for manual re-tuning to adjust for seasonal variations is eliminated.

Algorithm. A calculation method that produces a control output by operating on an *error signal* or a time-series of error signals.

Analog signal. A continuously changing variable.

Analog-to-Digital Converter (ADC or A/D). A hardware device used to convert an *analog signal* into discrete voltage or current values proportional to the analog input.

Aperiodic damping. A system of *damping* so large that after having being subject to a single constant or instantaneous disturbance, the system tends to a state of equilibrium, without oscillating around it.

Applications software. In a *BEMS,* programs that provide functions such as *DDC algorithms,* energy management and lighting control, cf. *Operating Software.*

Arithmetic summation of uncertainties. The sum of the moduli of uncertainties. The most pessimistic method of combining uncertainties. If three uncertainties are estimated at +/-3% each then the arithmetic sum is +/-9%.

Artificial Intelligence. The process of enabling computers to mimic human learning and decision-making.

Availability. The proportion of the switched-on time during which the equipment is available for work, cf. *maintainability* and *reliability.*

Automatic control system (also automatic regulating system). A system that reacts to a change in the variable it controls by adjusting other variables to restore the system to the desired balance.

Average control. If the value of the *control variable* depends on the location of the *sensor,* it may be necessary to apply *corrector action* in proportion to the average *deviation* measured in several locations.

'Bang-Bang control'. see *On-Off control.*

BEMS (Also 'BAS', 'BMS' and 'CEMCS'). A computerised system which operates to monitor and control the energy usage in a building. Energy management, *HVAC,* safety, security, operations schedules, commissioning and maintenance functions can all be provided under the overall supervision of a *central station* computer and operator.

Binary switching. A facility which can be provided by a microprocessor based *step controller.* Each physical step controls a load which is twice the size of the one preceding it, i.e. the loads are split in the ratios 1:2:3:4 etc. The order in which the physical steps are switched is such that a four step controller can control in 10 stages, a six step in 63 stages, and so on. The most common application is in the control of electric heater batteries.

Boiler compensation. An operation which changes the operating temperature of a boiler usually according to the outside air temperature.

Boiler optimisation. An energy management function which acts to balance boiler operation to loads and control combustion air. See also *Oxygen trim.*

Boost period. The period immediately prior to the occupancy period during which plant is operated at its full rate capacity. See also *Optimum Start Controller* and *Soft Start Controller.*

Cascade control. A control system in which one controller provides the set-point for one or more other controllers.

CEMCS. Comprehensive Energy Management and Control System. See *BEMS.*

Central station. This is the heart of a *BEMS,* and also the main communication channel for the operator. Here is contained the software and the main storage of *data* relating to the plant and buildings controlled.

Centralised intelligence. Description of a system where algorithm processing is only possible at the *central station.* The outstations are dormant when not in contact with the central station.

Centralised system. A *BEMS* in which all executive control takes place at the *central station.*

Closed-loop control.A system possess monitoring *feedback,* the *deviation signal* formed as a result of this feedback being used to control the action of a *final control element* in such a way as to tend to reduce the *deviation* to zero, cf. *open-loop.*

Communications module. Controls the transmission between other controllers and between controllers and a central computer based on an established bus protocol.

Comparing element (also 'Error detector'). A *control element* which compares the *measured value* and the *desired value* then sends an *error signal* (measured value minus desired value) to the part of the *controller* which determines *control action.* The control action implemented acts to reduce the magnitude of the error signal.

Compensation control. A process of automatically adjusting the *control point* of a given *controller* to compensate for changes in a second *measured variable* (e.g., outdoor air temperature). For example, the hot *deck* control point is normally reset upward as the outdoor air temperature decreases. Compensation control is one form of *open-loop control.* See also *Boiler compensation* and *Weather compensation.*

Continuous action. The action of an *element, regulator* or *automatic control system* whose output is a continuous function of its input signal.

Controllability. Degree of difficulty in controlling the *controlled variable.* This depends on the delays which occur between a change in conditions at one point and its manifestation at another point. This delay can be of two kinds: *distance-velocity* and *transport lag,* which have different effects on the system. Together they determine the dynamic characteristics of the plant.

Controlled medium. The medium in which the *controlled variable* exists. In a temperature control system, the controlled variable is the space temperature and the controlled medium is the air within the space, cf. *Controlled agent.*

Controlled variable. The quantity or condition that is measured and controlled.

Controlled sequence. Equipment operating order established upon a correlated set of environment data conditions.

Controller. A piece of equipment which combines the functions of at least the *set-point* input element, *comparing element,* and the amplifying and signal processing element for an *automatic control system.* Its purpose is to receive input from a *sensor* and then derive the proper correction output to be sent to the *actuator.*

Controller type. In ESP-r, the controller type controls the actuated property sensed by the *sensor* and actuated by the *actuator.*

Control action. The action generated by the *controller* and fed to the *correcting unit,* i.e. the relationship between the input signal and the output signal of a control element, cf. *Control mode.*

Control agent. The medium in which the *manipulated variable* exists. In a steam heating system, the control agent is the steam, and the manipulated variable is the flow of steam, cf. *Controlled medium.*

Control element. A general term for a constituent part of a control system.

Control function. Generally, this term is used for the operations carried out by an *automatic control system.* Within ESP-r, the BUILDING control strategy is comprised of one or more control functions. These are associated with the building zones to define the time-dependent control objectives. A PLANT system, on the other hand, is governed by one or more *control loops.* In essence, control functions and control loops are the same, differing only in the types of *control laws* used to link the *sensor* and *actuator.*

Control law. In ESP-r, this defines a control *algorithm* which represents the logic or "control action" of a *controller.* For example, the control law implemented may be *PID control.*

Appendix A: Glossary of Terms.

Control loop. Generally, this term means any control network consisting of the *control elements* required for *automatic control.* However, in ESP-r, this term is reserved for those control loops which govern the PLANT network control system - the BUILDING control strategy comprising one or more *control functions.* The control loop comprises three *control elements:- a sensor,* a *controller* and an *actuator.* For example, a plant network may consist of an air-handling unit supplying hot air to one zone, and cold air to a second zone. An ESP-r control loop for this system could be:- a SENSOR located in the centre of the zone to measure the air temperature, a CONTROLLER (with *PID control action)* to determine a correction signal such as to reduce the magnitude of the *error signal (measured value - desired value),* and an ACTUATOR to receive this signal, and operate the *final control element* (in this case a throttling valve in the heating/cooling coil's hot/cold water supply line). Thus, if the measured zone temperature is not equal to the desired value, the air supplied to the zone will receive an increase in energy from the coil in accordance with the PID algorithm.

Control mode. The OVERALL type of control exercised over the process, cf. *Control action.*

Control parameter. A variable used in the *control algorithm* e.g. *set-point, proportional band.*

Control point. The actual value of the *controlled variable.*

Control point adjustment. The procedure for changing the operating point of a local loop *controller* from a remote location.

Control range. The change between the initial and the potential value of the controlled condition.

Conventional controllers. All controllers with the exception of *microprocessor-based controllers.* Thus the term 'conventional controllers' describes the following *analogue controllers:- pneumatic controllers, hydraulic controllers,* fluidic controllers, electrical controllers and electronic (solid-state) controllers.

Corrective action. *Control action* that results in a change of the *manipulated variable.* Initiated when the *controlled variable* deviates from the *set-point.*

Cumulative uncertainty. Cumulative uncertainty will arise in successive stages of the calibration chain of a measuring instrument. This is usually compounded into a single value supplied by the calibration laboratory.

Cycle. One complete execution of a repeatable process. In basic heating operation, a cycle comprises one on period and one off period in a *two-position control system.*

Cycling. A periodic change in the *controlled variable* from one value to another. Uncontrolled cycling is called *hunting.*

Critical damping. The limiting degree of *damping* such that any decrease in the amount of damping would result in a change from *aperiodic damping* to *under-damping.*

Damper. A *final control element* which acts to regulate the flow of air through a duct.

Data Gathering Panel (DGP). See *Outstation.*

Day economization. A control scheme which permits heating or cooling plant to be turned off completely if the anticipated fall or rise in internal temperature does not exceed pre-selected limits within a period, usually 1 hour.

Deadband. A range of the *controlled variable* in which no *corrective action* is taken by the controlled system and no energy is used. See also *Zero energy band.*

DDC. See *Direct Digital Control.*

Dead time. The time interval between a change in a signal and the initiation of a perceptible response to that change.

Decentralised intelligence. A system where *data* processing is carried out at *outstations* as well as at the *central* station.

Deck. In HVAC terminology, the air discharge of the hot or cold coil in a duct serving a conditioned space.

Demand. The term used to describe the maximum rate of use of electrical energy over a specific period of time.

Demand control (also 'Demand Limiting', 'Load Limiting', 'Load Control' and 'Load Shedding'). An energy management technique used to monitor a facility's energy use in order to limit the peak demand by automatically shutting down selected equipment, on a priority basis, for short periods of time. Demand limits are pre-programmed into the demand control software for this purpose. Demand control is most often applied to electrical usage, and sometimes steam plant. Unlike most other BEMS techniques, monetary benefits are not a direct result of energy savings since electricity usage is often merely postponed, not eliminated. The benefits are reduced demand charges to the customer and alleviated peak demand for utilities.

Demand limiting. See *Demand control.*

De-multiplexer. In a *BEMS,* a device used to separate two or more signals previously combined by a compatible multiplexer for transmission over a single circuit.

Derivative action. The action of a *controller* in which the output signal is proportional to the direction and the rate of change of *deviation* of the input signal. This means that the derivative action term 'looks' to the future, by examining the rate of change of the error. It is the controller's 'accelerator' and 'brake' and is used in addition to *proportional action,* and possibly *integral action,* to improve a controller's response to sudden or large load changes. It cannot be used by itself since it does not respond to a constant error.

Derivative action time (DAT). In a controller having *proportional + integral action,* the time interval in which the part of the signal due to proportional action increases by an amount equal to the part of the output signal due to *derivative action,* when the derivative action is changing at a constant rate.

Derivative Kick. Electronic 'noise' can cause sudden changes in the sensor signal input to the *controller* resulting in sudden error changes in the controller output. This is especially true in the derivative part of a *P+I+D* controller where this sudden rate of change causes the *derivative action* term to change dramatically. A change in *set-point* can also produce derivative kick and, to a lesser extent, *proportional kick.*

Deviation signal. The difference between the *set-point* and the *measured value.*

Digital-to-Analog Converter (DAC or D/A). A hardware device used to convert a digital signal into a voltage or current proportional to the digital input.

Digital signal. A discrete-time signal with quantized amplitude. If the discrete-time signal can assume a continuous range of values, then it is called a 'sampled-data signal'.

Direct Digital Control (DDC). A *control loop* in which a *microprocessor-based controller* directly controls equipment based on *sensor* inputs and *set-point* parameters, i.e. the plant is under the direct control of software (either in an *outstation* or *central station)* and not through the intermediary of some non-programmable controller. The programmed control sequence determines the output to the equipment.

Discontinuous control. The controller produces a maximum or minimum output signal at an upper and lower pre-set limit of the *measured variable,* in order to maintain the measured variable between the limits (differential). Although there may be an optimum value, this is never maintained. The measured value is always increasing or decreasing. There are basically two types of discontinuous control:- *Step control* and *Float control.* Discontinuous control is an inexpensive and relatively simple form of control. However, when the desired value has to be constantly maintained, some form of *continuous control* must be used.

Discrimination control. A *control mode* in which *sensor* signals from a number of sensors are fed to the *controller,* which then decides on which sensor value to use when comparing a sensed value with the *desired value.* For example, in some multi-zone air-heating systems, the sensed temperature 'selected' is the one indicating the zone with the maximum heating requirements. In this way, the heat energy input to the system supply air is kept to a minimum.

Distance/Velocity lag. The *dead time* between an alteration in the value of a signal and its manifestation unchanged at a later part of the system, arising solely from the finite speed of propagation of the signal. For example, if a flow detector is located at a distance of 10 m from a mixing valve and the position of the valve is suddenly changed, then if the water velocity is 0.5 m/s, it will take 20 seconds for the new temperature front to arrive at the detector; thus the distance/velocity lag equals 20 seconds. As long as the distance/velocity lag has not elapsed, the controller is neither in a position to counteract the effect of a disturbance nor to correct that of any action it may have initiated.

Distributed intelligence. See *Decentralised systems.*

Distributed Processing Unit. See *Outstation.*

Downtime. The time to locate a fault and then repair it.

Droop. A sustained deviation between the *control point* and the *set-point* in a *two-position control system* caused by a change in the heating or cooling load.

Duplex transmission. Simultaneous independent transfer of *data* in two directions, cf. *Half-duplex.*

Appendix A: Glossary of Terms.

Duration Adjust Type signal (DAT signal). This scheme is used to modulate an intermediate device by sending it a train of on/off signals where the on to off ratio varies, according to the proportional duty cycle. A common example is DAT control of a thyristor which in turn varies the amount of energy supplied to an electric heating element, cf. *Position Adjust Type Signal.*

Duty cycling. A control method which alternates or cycles the sequence of plant.

Economiser control. An energy management function which aims to minimise energy consumption by the use of 'free-cooling'. Internal heat generation in a building may require the *HVAC* to provide cooling, even though the air temperatures are lower than the *thermostat* set-point. Under this condition, it is possible to introduce outdoor air into the building to provide all or part of the cooling normally accomplished by refrigeration equipment. To use this 'free-cooling', the economiser measures the dry-bulb temperature of the return air and the outdoor air, and selects an appropriate amount of the cooler air for the building conditioning by adjusting outdoors, return and exhaust *dampers.*

Effective dead time. In order to emphasize the essential difference between transfer lag and exponential lag, the term 'effective dead time' is used to denote the time interval between the change of a signal and the build-up of the response to a specific proportion, say until 5% of the final change has taken place.

Electrical control. A control system that operates on line or low voltage and uses a mechanical means, such as a temperature-sensitive bimetal, to perform control functions such as actuating a switch or positioning a potentiometer. The *controller* signal usually operates or positions an electric *actuator,* or may switch an electrical load either directly or through a relay.

Electronic control. A control circuit that operates on low voltage and uses solid-state components to amplify input signals and perform control functions, such as operating a relay or providing an output signal to position an actuator. The *controller* usually furnishes fixed control routines based on the logic of the solid-state components.

Emulation. *Real time* simulation. An emulator consists of a real time simulation of the building and plant together with a hardware interface that is used to connect the simulator to a *BEMS.* The outputs from the control system are read by the hardware interface and used as the boundary values for the simulation of the building and plant. The simulated outputs of the *sensors* are transmitted through the hardware interface to the control system, which then responds by producing a new set of outputs.

Enthalpy control. An energy management function which is similar to *economiser control,* only more sophisticated. In enthalpy control, the TOTAL heat content (sensible + latent) of the building return air and outside air is measured, and the enthalpy controller adjusts the *dampers* to select the air with the least total heat content for cooling.

Equal-percentage valve. This type of valve is designed to produce equal percentage change in flow for equal increase change in valve lift.

Equalised Run Time (ERT). A facility which can be provided by a microprocessor based step controller. Rather than load in one direction and unload in the other (last on - first off), ERT loads and unloads to equalise the time in which each step is made, or is in the on position by adopting a first on - first off schedule. In this way, the run times for each plant item in multiple compressor and boiler installations are equalised , cf. *Step control* and *Intelligent step control*

Error detector. See *comparing element.*

Error signal. The difference between the *measured value* and the *set-point* or *desired value.*

Event initiated programs. Computer *programs* initiated on the occurrence of an input/output operation or an alarm condition.

Expert system. The embodiment in a computer of a knowledge-based component from an expert that offers intelligent advice or takes an intelligent decision and, in addition, is able to justify its own reasoning. An expert system is a computer program that learns, deduces, diagnoses and advises. The style adopted to attain these characteristics is rule-based programming. The rules are based on logic and standard computer statements. Expert systems can be useful for setting up control strategies in a *BEMS.*

Fabric Protection Control. A control function, the aim of which is to prevent condensation occurring.

Field Interface Device (FID). In a *BEMS,* this serves as a point of consolidation for *sensors* and *controllers.*

Feedback control. The simplest way to automate the control of a process is through feedback control. *Sensors* are installed to measure the values of the *controlled variables.* These values are then transmitted to feedback control hardware which makes a comparison between the *set-point* or the *desired value* of the *controlled variable* and the *measured value* of these same variables. Based upon this *'error'* the feedback controller calculates signals that reflect the required value of the *manipulated variable.* These signals are then transmitted automatically to the *final control elements,* which act to alter the manipulated variable in such a manner as to reduce the error signal. Feedback control acts to eliminate errors. This is in contrast to *feed-forward control,* which operates to stop the error occurring in the first instance.

Feed-forward control. The transmission of a supplementary signal along a secondary path, parallel to the main forward path, from an earlier to a later stage. This means that it works to eliminate errors occurring in the first place by forecasting the likely disturbance. However, if not ALL disturbances are forecast correctly then poor control will result. Feed-forward control, while conceptually more appealing, significantly escalates the technical and engineering requirements of the overall design. The very sophisticated calculations must reflect an awareness and understanding of the EXACT effects that the disturbances will have on the *controlled variable.* With such understanding, the feed-forward controllers are able then to compensate for the disturbances. Feed-forward control is reserved for only a very few of the control loops within a plant. Thus, pure feedforward control is rarely encountered and the more common situation is for *feedback control* with some feedforward control loops included. See *Open-loop control* and *Compensation Control.*

Field Processing Unit. See *Outstation.*

Final control element. A device such as a valve or *damper* that acts to change the value of the *manipulated variable.* It is positioned by an *actuator.*

Firmware. Programmed *microprocessor-based controllers* that cannot be re-programmed or altered.

Floating action (Also Three-position control). This term refers to a controlled device which can stop at any point in its stroke and can be reversed without completing its stroke. The *controller* must have a 'dead-spot' or neutral zone in which it sends no signal but allows the device to 'float' in a partly open position. For good operation, this system requires a rapid response in the *controlled variable,* otherwise it will stop at an intermediate position.

Fluidic controller. A controller that exploits the DYNAMIC properties of a fluid (e.g. the 'Coanda Effect'), as distinct from *hydraulic controllers* and *pneumatic controllers,* which utilise the STATIC properties of a fluid.

Forcing function. Externally applied time-dependent function, e.g. a step change in the *set-point* or disturbance.

Forward path. The path that connects the *reference value* to the *controlled variable.*

Free-Float control. A building/plant system in which there is no active control strategy.

Function sequence systems. Many digital control systems require control events to occur in a sequence for which an output state produces a change in the input state. That is, where each event is not so much time dependent as dependent on the completion of the previous event. This process of change producing change continues until some overall objective has been met is termed 'function sequence system control', cf. *Time-sequence control.*

Fuzzy logic controller. An artificial intelligence based controller which attempts to mimic the human decision-making process.

Gain. This is defined as 100%/PB. See *Proportional band.*

Gain margin. The factor by which the gain must be increased in order to produce instability.

Global points. Allows designated points to share their *data* with other bus connected devices.

HVAC. Heating, Ventilating and Air-Conditioning.

Half-duplex transmission. Transfer of *data* in two directions but by alternate, one way at a time, independent transmission, cf. *Duplex transmission.*

Heuristic controller. See *Adaptive control.*

Homeostatic control. In a *BEMS,* toward a predetermined state of equilibrium between adjacent but interdependent elements of a system. This is obtained by use of digital metering devices combined with a *microprocessor-based controller.*

Humidistat. A device used in control systems for switching plant to maintain a relative humidity at some *set-point.* The output signal is usually sent via a relay device to the *final control element.*

Hunting. Prolonged self-sustained oscillation of undesirable amplitude.

Hysteresis. For sensors, a measure of the differences in indicated steady state value for identical conditions when approached from higher and lower states. For actuators, a measure of the differences in output for a system responding to the identical steady state input when approached from different directions. Hysteresis may have a physical cause, e.g. wear in the actuator gearbox, or a control effect, e.g. *deadband* or failure. It can be confused with failure to approach steady state in a reasonable time.

'Ideal' control. Control that involves no time lags and with all *control elements* behaving linearly.

Incremental control. A form of *modulating control* where the control device is sent an increase - hold - decrease signal from two binary outputs working as a pair. With this type of control it is possible to provide a form of *proportional+integral (PI)* control action without position feedback from the actuator of the controlled device.

Indirect control. This means automatic operation of a control device located in the energy flow stream via an intermediary system.

Inherent regulation (also 'Self-regulation'). Many simple *processes* are characterised by the fact that a new steady-state is reached automatically, i.e. without interference by manual or automatic control.

Intelligent step control This is a microprocessor based *step controller* or sequencer, which can be programmed or selected for different operational modes such as *binary switching* and *equalised run time*. A second advantage which this type of step controller has over the motorised version is its ability to provide easily adjustable time delays.

Integral action. The action of a *control element* whose output signal changes at a rate which is proportional to its input signal size. The integral term may be considered as the 'memory' of the *controller,* looking at past errors. It acts to remove *offset.* It can be used in conjunction with *derivative control action* (I+D) or, more commonly, with *proportional action (P+I)* or proportional and *derivative action (P+I+D).*

Integral action time (IAT). In a control system having *P+I control action,* the time interval in which the part of the output signal due to *integral action* increases by an amount equal to the part of the output signal due to the *proportional action,* when the *deviation* is unchanging.

Integral Gain. Defined as the ratio of *proportional gain* to *integral action time.*

Integral wind-up. It is possible for a *final control element* to be in a 'fully open' position but the *controlled variable* to be some way from the set-point. For example, this often occurs during the morning heat-up period. The error will persist for some time and the *integral action* term will become large. This error is called the 'integral wind-up error'.

Interchangeability. The maximum difference in indicated value between two sensors chosen at random, connected to the same interface and exposed to identical conditions.

Lag. A delay in the effect of a changed condition at one point in the system, or some other condition to which it is related. Also, the delay in response to the *sensing element* of a control loop due to the time required for the sensing element to sense a change in the sensed variable.

Limit control. A control system in which, for reasons of comfort or efficiency, the *controlled variable* is prevented from exceeding or dropping below a certain value.

Linear control system. A control system in which the *transfer function* between the controlled condition and the command signal is independent of the amplitude of the command signal. The characteristics of a linear system may be described by a linear differential equation of the first degree, which remains true over the range being considered.

Load control. See *Demand control.*

Load limiting. See *Demand control.*

Load shedding. See *Demand control.*

Local feedback. See *Cascade control.*

Long term stability. The maintenance of repeatability over a long period of time, e.g. one year.

Maintainability. A measure of the speed with which loss of performance is detected, the fault located, repairs carried out and completed, and a check made that the equipment is functioning normally again, cf. *availability* and *reliability.*

Majority voting. A form of *discriminatory* control. Sensed values are input to the controller, which establishes, for each input signal, a corresponding 'dummy' output signal. The 'resultant' controller output signal is determined from the majority of the dummy outputs. For example, if there are 3 input sensors to an *on-off* controller, and 2 result in an ON status and 1 results in an OFF status, the resultant controller output signal will indicate an ON status.

Master-submaster (also master-slave control). see *Cascade control.*

Microprocessor-based control. A control circuit that operates on low voltage and uses a microprocessor to perform logic and control functions, such as operating a relay or providing an output signal to position an actuator. Electronic devices are primarily used as sensors. The controller often furnishes flexible *DDC* and *BEMS* control functions.

Minimum phase systems. see *Non-minimum phase systems.*

Mean active repair time (MART). This applies to *repairable items,* and indicates the average time an item may be expected to be out of service for maintenance and repair, given that the required tools/parts are to hand.

Mean time between failures (MTBF). This applies to *repairable items:* if an item fails, say five times over a period of use totalling 1000 hours, the mean time between failures would be 1000/5, or 200 hours. The MTBF is a measure of the likelihood that equipment will break down in a given period. $MTBF = MTTF + MTTR$

Mean time to failure (MTTF). This applies to *non-repairable items,* and indicates the average time an item may be expected to function before failure.

Mean time to repair (MTTR). This applies to *repairable items,* and gives the average time an item may be expected to be out of service for maintenance and repair, including any order/delivery times.

Measured Value. The physical quantity that is measured by the *transducer,* i.e. the input to the transducer.

Modulating. A *control action* that adjusts by minute increments and decrements.

MODEM. An acronym for MOdulator/DEModulator. This is a hardware device used in a *BEMS* to change digital information to and from an analog form to allow transmission over communication links.

Multiplexer. A type of field panel used in *BEMS* to minimize data transmission costs by using time-sharing transmission techniques.

Night purge. An energy management function (rarely used in the U.K.) in which 100% outdoor air is introduced to the building prior to starting up the air-conditioning equipment, thereby reducing the cooling load.

Night set-back control. An energy management function which acts to reduce the occupancy temperature by a few degrees, with the heating ticking over to maintain it. It is not usually as effective compared to the modern practice of intermittent heating, where the system is switched off overnight.

Non-minimum phase systems. In terms of feedback control theory, minimum phase systems are stable systems having zeroes in the left-half side of the complex s-plane, i.e. all denominator terms contribute phase lag whilst numerator terms contribute phase lead. Systems with zeroes in the right half of the s-plane (non-minimum phase systems) are inherently unstable (due to additional phase lag).

Offset. A sustained deviation between the *control point* and the *set-point* of a *proportional control* system under stable operating conditions.

On-off control. A special case of *two-step control* in which one of the output signal values is zero.

Open-loop control. A control system in which no monitoring *feedback* is used. An open-loop system assumes a fixed relationship between a controlled condition and an external condition. It does not take into account changing space conditions from internal heat gains, infiltration/exfiltration, solar gain, or other changing variables in the building. Open-loop control alone does not provide close control and may result in underheating or overheating. For this reason, open-loop systems are not common in residential and commercial buildings. See also *Feed-forward fontrol* and *Compensation control.*

Optimum start/stop controller. This controller alters the time that the *HVAC* equipment starts/stops depending on the weather conditions. It works by using an external *sensor* and, occasionally, an internal sensor, to bring in the heating/cooling plant at the latest possible time to get the building/zone(s) to the required temperature by the start of occupancy.

Outstation (Also 'Field Processing Unit', 'Data Gathering Panel', 'Distributed Processing Unit', 'Field Interfacing Device', and 'Substation'). In a *BEMS* system, this is the unit (with inputs from the *sensors* and outputs to the *actuators)* which controls the plant. It is often situated in the plant room.

Over-damping. *Aperiodic damping* in which the degree of *damping* is greater than that required for *critical damping.*

Overlay system (Also 'BEMS reset system'). A *BEMS* which is overlaid onto conventional analogue control systems providing reset signals to change temperature, humidity settings, etc. This contrasts with *Integrated DDC.* where the BEMS provides direct digital control of temperature, humidity and pressure, eliminating the need for discrete analogue controller.

Oxygen trim. An energy management function in which an attempt is made to reduce heat losses from a boiler's exhaust gases, i.e., the aim is to try and approach the stochiometric ('ideal') air/fuel ratio.

Phase-cut signal. This is where a sine wave is cut off part way through the cycle to produce a continuously varying output signal from a controller. The signal is then used to directly control a magnetic actuator.

Over-ranged. A term used for *proportional controllers* when the load changes sufficiently to cause the *control point* to move above or below the limits of the *proportional band.*

PID controller (also P+I+D controller). A three-term controller having *proportional action, integral action* and *derivative action.* This enhances the *P+I* control algorithm by adding a component that is proportional to the rate of deviation (derivative action) of the deviation of the *controlled variable.* This compensates for system dynamics and allows for faster control response.

Pneumatic controller. A *controller* which uses compressed air as the *control medium.* All the required control terms are readily available, e.g. *step control, PID,* etc.

Point. A physical source or destination for *data* in the form of *analogue* or *digital* signals.

Position adjust type signal. A controller output using two binary signals, working as a pair. Normally, they drive a reversing actuator by sending either an increase, hold, or decrease command. When used with *DDC* the controller may calculate the percentage opening of the controlled device based on the actuator running time to go from fully closed to fully open.

Potential value. The limiting value of the controlled condition that tends to be attained following a particular adjustment of the corrector unit, all other factors which may effect the value of the controlled condition being maintained constant.

Predictive control. A control system which attempts to predict the affects of a disturbance on the future output. Predictive control forms the basis of many self-tuning control methods, cf. *Adaptive control.*

Preheat period See *Boost period.*

Process control characteristic. This gives information on how the *controlled variable* is affected by small changes in the intermediate position of the *final control element.*

Programmable point. A control or *monotoring* point for which the user may program an associated control scheme.

Programmed start/stop. An energy management function which operates to selectively shut down electrically-operated equipment. This is accomplished on a predetermined time-schedule, usually paralleling occupancy schedules.

Proportional action. In this type of *control action,* the output of the controller is proportional to the *error.* If the error is large, the signal output to the actuator is large, and if the error gets smaller, the output signal gets smaller proportionally. The relationship between the two is determined by a constant called the *proportional gain.* The error band within which the output is between 0% and 100% is called the *proportional band.* The higher the *gain,* the higher the proportional band. The main problem with proportional control is *offset.* This can be reduced by the addition of *integral action,* although proportional action alone is used successfully in many situations where the degree of offset is tolerable. A sluggish response to sudden, or very large, load changes may be improved by incorporating *derivative action.*

Proportional band (PB). That range of values of *deviation* corresponding to the full operating range of output signal of the controlling unit resulting from *proportional action* only. The PB can be expressed as a percentage of the range of the controlled condition which the measuring unit of the controller is 'designed' to measure. With *HVAC* control systems, the proportional band is expressed in absolute units, with industrial control, the proportional band is expressed in percentages (of the input value).

Proportional controller. A controller with *proportional action* only.

Proportional control factor. The broken loop amplification at an infinite period with any *integral action* removed from the *controller.*

Proportional gain. The inverse of the *proportional band.*

Proportional-speed controller. A variation of *floating control* is proportional-speed control. In this type of controller, the farther the control point moves beyond the deadband, the faster the actuator moves to correct the deviation.

Process. A general term that describes a change in a *measurable variable* (e.g. the mixing of return and outdoor air streams in a mixed-air control loop and heat transfer between cold water and hot air in a cooling coil). Usually considered separately from the *sensing element, control element* and *controller.*

Process reaction rate (PRR). The rate at which the plant responds to a disturbance. Usually plotted with the *control variable* on the y-axis and time on the x-axis.

Proportional kick. See *Derivative kick.*

Pseudo point. See *Soft point.*

Pull down period. The time taken for a measured temperature to reduce from some given higher value to a required *set-point.*

Pulsed input. The representation of a value by a series of abrupt and relatively short cyclic changes in a signal.

Random uncertainty or random error. The likely difference between a single 'measurement and the mean of the distribution of such measurements.

Rangeability. Ratio of maximum controllable flow to minimum controllable flow. It follows that there is a minimum quantity which a valve, for example, can reliably control. Rangeabilities of the order of 30:1 are considered reasonable, cf. *Valve turn-down ratio.*

Rate action. See *Derivative action.*

Ratio control. A controller which operates to maintain a pre-determined ratio between two quantities (e.g. air-flow).

Real Time. A situation in which a computer monitors, evaluates, reaches decisions and effects control with the *response time* of the fastest phenomenon.

Reference value. See *Set-point.*

Regulating system. See *Automatic control system.*

Reliability. The characteristic of an item expressed by the probability that it will perform a required function under stated conditions for a stated period of time, cf. *availability* and *maintainability.*

Repeatability. For sensors, a measure of the differences in the indicated steady state value when exposed to identical conditions on different occasions. For systems, a measure of the differences in output for a system responding to the identical steady state input on different occasions. In repeatability testing the component approaches the steady state condition from the "same direction" e.g. from cold to hot for a temperature sensor, thus repeatability excludes hysteresis.

Reproducibility. Similar to repeatability but inclusive of hysteresis.

Reset action. See *Integral action.*

Reset rate. Defined as the inverse of the *Integral action time.*

Resolution. The minimum change in a variable that can be observed. In *digital* systems, this is related to the number of bits used by the *analogue to digital converter (ADC)* in the controller. For an 8 bit system the resolution is 1 in 2^8, i.e. 0.4% of range. 8 bit resolution is now considered inadequate for BEMS inputs and most systems use 12 bit (or better) ADC although for technical reasons the resolution may be quoted as 11 bit, i.e. 0.05% of range.

Response time. The time interval, with regard to a step input signal, between the input and the first coincidence of the output signal with the final steady-state value of the output signal.

Root mean square of uncertainty. The square root of the sum of the squares of the uncertainties. If there uncertainties are estimated at +/-3% each then the root sum of squares is +/-5.2% (compare with the arithmetic sum of 9%).

Run time. Accumulates equipment on or off time and transmits totals periodically to the central station. On-off cycle counting can also be accumulated as a maintenance indicator. Alarm annunciation occurs if run time or cycle time count limits are exceeded.

Sampled-data signal. A *digital signal,* the amplitude of which can assume a continuous range of values.

Sensing element. A device or component that measures the value of a variable.

Self-acting controller. A controller where no external connections are necessary. Many work by means of a capillary tube. Most self-acting controllers are of the *proportional control* type.

Self-adapting optimiser. *Optimisers* are based on the linear approximation of the relationship between the preheat time and the *set-point* temperature. However, as the cooling of the building changes with the weather, so does the preheat curve. Thus, a new 'straight-line relationship' is required, otherwise the optimiser will be inaccurate. Flexible movement of the line is achieved on microprocessor-based controllers by employing 'self-adaptive' techniques to tune the line to the response of the building and heating system.

Self-tuning controllers. A type of *controller* which has the capability to determine, dynamically, its control parameters such as:- *gain, integral action time* and *derivative action time.*

Self-regulation. See *Inherent regulation.*

Sensitivity. The minimum change in input value that can be reliably detected. For a sensor, the minimum change in the sensed variable that can be reliably detected. This may depend both on *resolution,* external influences and "noise".

Settling time. The time required following the initiation of a specified stimulus (step change, ramp or sinusoid) to a system for the output to enter and remain within a narrow band centered on its steady state value, e.g. within +/-2% of the steady state value.

Sequential control (Sequencer). Refer to *Step controller.*

Set-point. The value on the controller scale at which the *controller* is set (e.g. the desired room temperature as set on a *thermostat).* The desired *control point.*

Smart sensor. A *sensor* in a *BEMS* which has an in-built *ADC,* a communication section, some memory to store look-up tables, and also the ability to directly control the *final control element.*

Soft point. A point that can be referenced as if it were a *monitoring* or control point in a BEMS although it has no associated physical location. It may have a set value or be the result of a given *algorithm.*

Soft start. An *optimum start* routine in which, for reasons of thermal stability, the rate of increase of control point temperature is limited.

Span. The quoted range of operation from minimum to maximum input or output e.g. 10 °C to 60 °C. Accuracy, *hysteresis,* etc. may be quoted as "% of span". Equivalent to full scale deflection (FSD).

Speed of response. A measure of how quickly a system responds to a change in input.

Split-range control. A control system in which a definite sequence of events takes place in order that a certain *manipulated variable* may have first preference as a means for the process control.

Stability. Two types of instability occur in control systems:- 'Monotonic' instability and 'Oscillating instability'. In monotonic instability, the *controlled variable* begins to increase as a function of time. In oscillating instability, the value of the controlled variable begins to oscillate with growing amplitude as a function of time. The first type of instability is usually due to a failure of the control system to function, whereas the second is usually caused by a mismatch of the control system to the process. The control system begins to amplify an error at some critical frequency instead of driving it to zero. Note that instability is as much a part of microprocessor-based control systems as in *conventional control systems.* This is in part because the strategy of control is the same in either case and is the strategy which can create instability.

State-space analysis. The state-space approach is used by control engineers to study the internal 'states' as well as input/output relationships. The state-space is a vector space of dimension equal to the order of the system. The *transfer function* is usually transformed into a state-space form by the 'direct-programming' method.

Steady-state error. The difference between the *measured value* and the *desired value* as the time tends towards infinity. There are three types of steady-state errors:- Constant steady-state or 'Proportional Error', Constantly varying or 'Velocity Error' and Constantly accelerating or 'Accelerating Error'.

Step control. A control method in which a multiple-switch assembly sequentially switches equipment (e.g. electric heaters, multiple chillers) as the *controller* input varies through the *proportional band.* Step controllers may be *actuator* driven, electronic or directly activated by the sensed medium (e.g. pressure, temperature).

Step input. An instantaneous change between two steady state input values. This is commonly used to determine the response characteristic of a system.

Substation. See *Outstation.*

Supervisory control. The predecessor of *DDC.* In supervisory control, it is the central computer (and not the *outstation's* microprocessor) which determines the *analogue* controller's *set-point.* (Note that the controller in 'Supervisory control" is still of the analogue type, as opposed to *DDC* in which the controller is microprocessor based). The main computer coordinates and balances the operation of all the outstations in order to achieve optimum efficiency and comfort levels, and also to supervise energy management functions. Typical supervisory control functions include *programmed start/stop, economiser cycle* and *load control.*

System-level controller. In a *BEMS,* a *microprocessor-based controller* that controls centrally-located *HVAC* equipment such as VAV supply units. The *controllers* typically have a library of control programs, and many control more than one mechanical system from a single controller, cf. *Zone-level controller.*

Systematic uncertainty or systematic error. A constant uncertainty or error in one direction due to an experimental factor, e.g. calibration uncertainties in reference instrumentation

Thermostat. A device used in control systems for switching plant to maintain a temperature at some *set-point.* The *sensor* and *controller* elements are combined. The output signal is usually sent via a relay device to the *final control element.*

Three-position control. See *Floating action.*

Three-term controller. A *controller* with *proportional + integral + derivative action (PID).*

Throttling range. In a *proportional controller,* the *control point* range through which the *controlled variable* must pass to move the *final control element* through the full operating range. Expressed in values of the controlled variable (e.g. K, %RH). Also called the *proportional band.* In a proportional room *thermostat,* the temperature change required to drive the *manipulated variable* from full off to full on.

Time and event programs. Initiates a predetermined series of control actions based on time of day, elapsed time, alarm condition or a point status change.

Time constant. The time required for a dynamic component such as a *sensor* or a control system, to reach 63.3% of the total response to step change in its input. The 95% response time is then approximately equal to 3 times the time constant. Typically used to assess the responsiveness of a component.

Time proportional action. A *control action* in which on/off devices are switched on for a time proportional to the *error signal*. The time proportional controller keeps the plant on for a defined fraction of a time period which is set by the operator when the system is configured.

Time schedule. Record of the desired changes of a variable or operational status with respect to time.

Time-sequence control. In *digital* control, systems, the state of the next output is determined by the lapse of time from the start of the previous state. Such a process is usually encountered as part of an overall sequence involving functional dependence. (See *Function sequence systems.)* It is a characteristic of this type of control sequence that it depends only on the passage of a fixed amount of time and not on the state of any variable in the system.

Transducer. A device which converts the quantity being measured into an optical, pneumatic, mechanical, hydraulic or electronic signal. Transduction is the energy conversion process that takes place, i.e. from one form of energy to another, e.g. pneumatic to electronic.

Transfer function. Is a 'prescription' which will give the output response for any specific history of input.

Transient response. The time variation of an output signal when an input signal or disturbance of specified nature is applied.

Transient peak value. The maximum value of the output signal in a *controller's* response to a step function input signal.

Transport lag. Occurs when energy is transferred through a resistor to or from a capacity.

Triac. In electronic control systems, a relay switch used to bring in other equipment, e.g. a pump.

TRV. Thermostatic radiator valve. This is a control valve which has the *sensor, controller* and *actuator* functions combined in one device. Wax expands with an increase in space temperature to throttle the water flow rate through the radiator.

Two-position controller. A *controller* whose output signal changes from one predetermined value to another predetermined value when the *deviation* changes sign.

Two-position controller with overlap. A controller where the output signal has one predetermined value when its input signal exceeds a certain threshold, and another when its input signal is less than a second threshold. The difference between the two thresholds is the 'differential' or 'overlap'.

Two-term controller. A controller with either *proportional* + *integral (PI) action* or *proportional* + *derivative (PD) action.*

Underdamping. A degree of damping sufficiently small that after the system has been subjected to a single disturbance, one or more cycles or oscillations are executed by the system.

Unitary controls. Some components, such as chillers, boilers and air-handling units, come packaged with their own controls or control systems, but which are capable of interfacing with a BEMS.

Unity feedback. This is where the feedback through the sensor is accurate, the sensor has little thermal mass and lags are short.

Valve authority. Ratio of pressure across a fully opened valve to the pressure drop across the remainder of the circuit.

Valve regulation. Ratio of maximum to minimum controlled flow.

Valve turndown ratio. Ratio of maximum normal (usable) flow to minimum controllable flow, cf. *Rangeability.*

Valve positioner. A control valve accessory which transmits a loading pressure to an *actuator* to position the valve exactly as required by the *controller.* It helps overcome *hysteresis* and lags due to friction.

Virtual point. See *Soft point.*

Weather compensation. A control *algorithm* which varies the temperature of the heating and cooling medium with respect to the outside temperature. Can incorporate internal temperature reset which senses the space condition and applies a correction to the heating medium temperature if the desired space temperature is not achieved. See also *Boiler compensation.*

Wild coil. A coil where no control is exercised over either the temperature or the flow-rate of cooling or heating.

Zero energy band. An energy conservation technique that allows the temperatures to float between selected settings, thereby preventing the consumption of heating or cooling energy while the temperature is in this range.

Zone-level controller. A *microprocessor-based controller* that controls distributed or unitary *HVAC* equipment such as VAV terminal units, fan coil units and heat-pumps. These *controllers* typically have standard control sequences, relatively few connected input/output devices, and are dedicated to specific applications.

Zoning. The practice of dividing a building into sections for heating and cooling control so that one *controller* is sufficient to determine the heating and cooling requirements for the section

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APPENDIX B: ESP-r CONTROL FUNCTIONS

B.1. ESP-r CONTROL ALGORITHMS: LOGIC FLOW CHARTS.

A selection of ESP-r control functions is presented here in flow-chart form. Note that in the case of the building-side control functions, the mixed sensing and mixed actuation options - available with all functions - are omitted for clarity. *B1, B2 and B3* are the building control system equation set coefficients (Section 3.5).

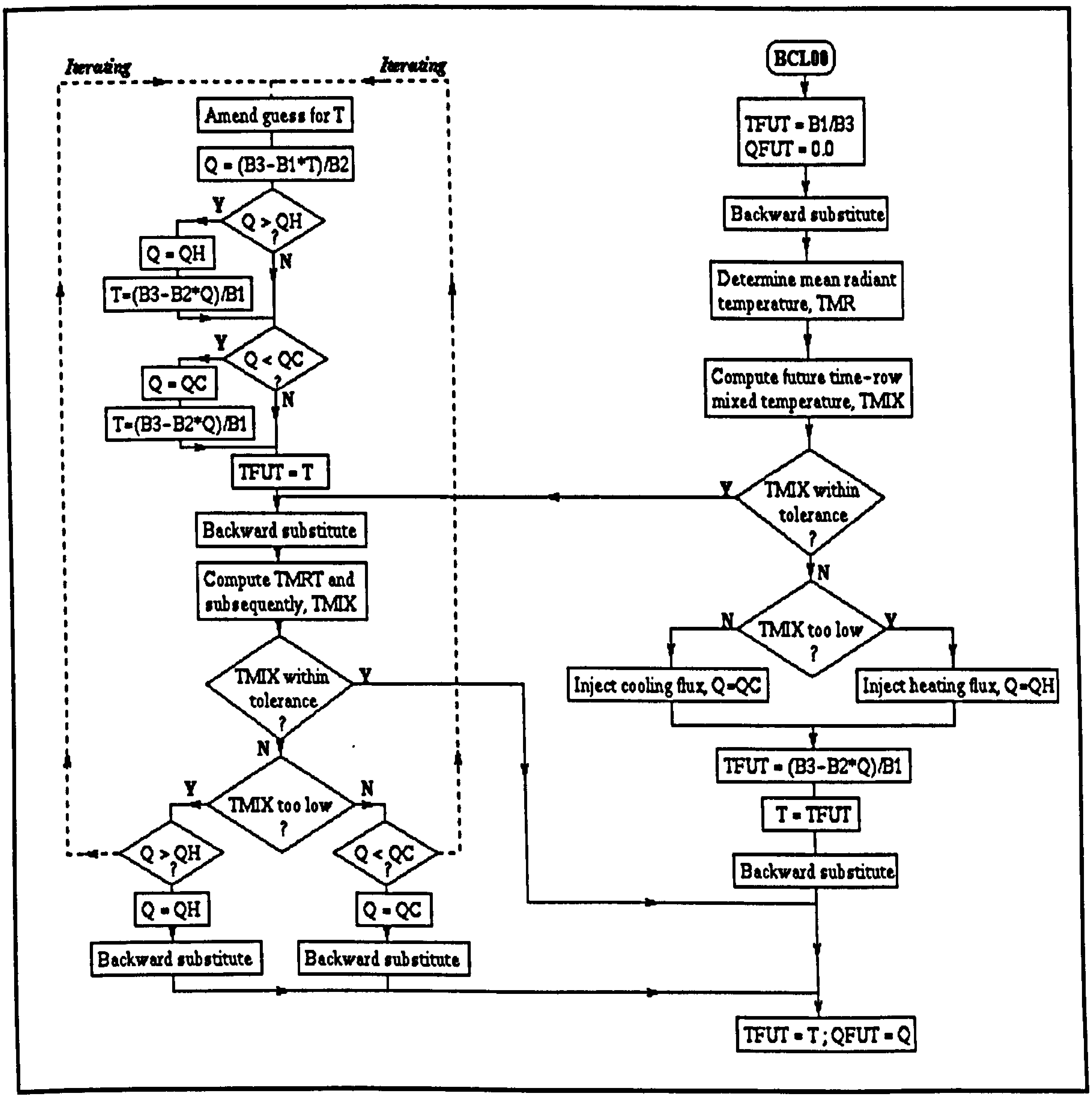


Figure B.1 *BCL00:* Mixed air-surface sensor.

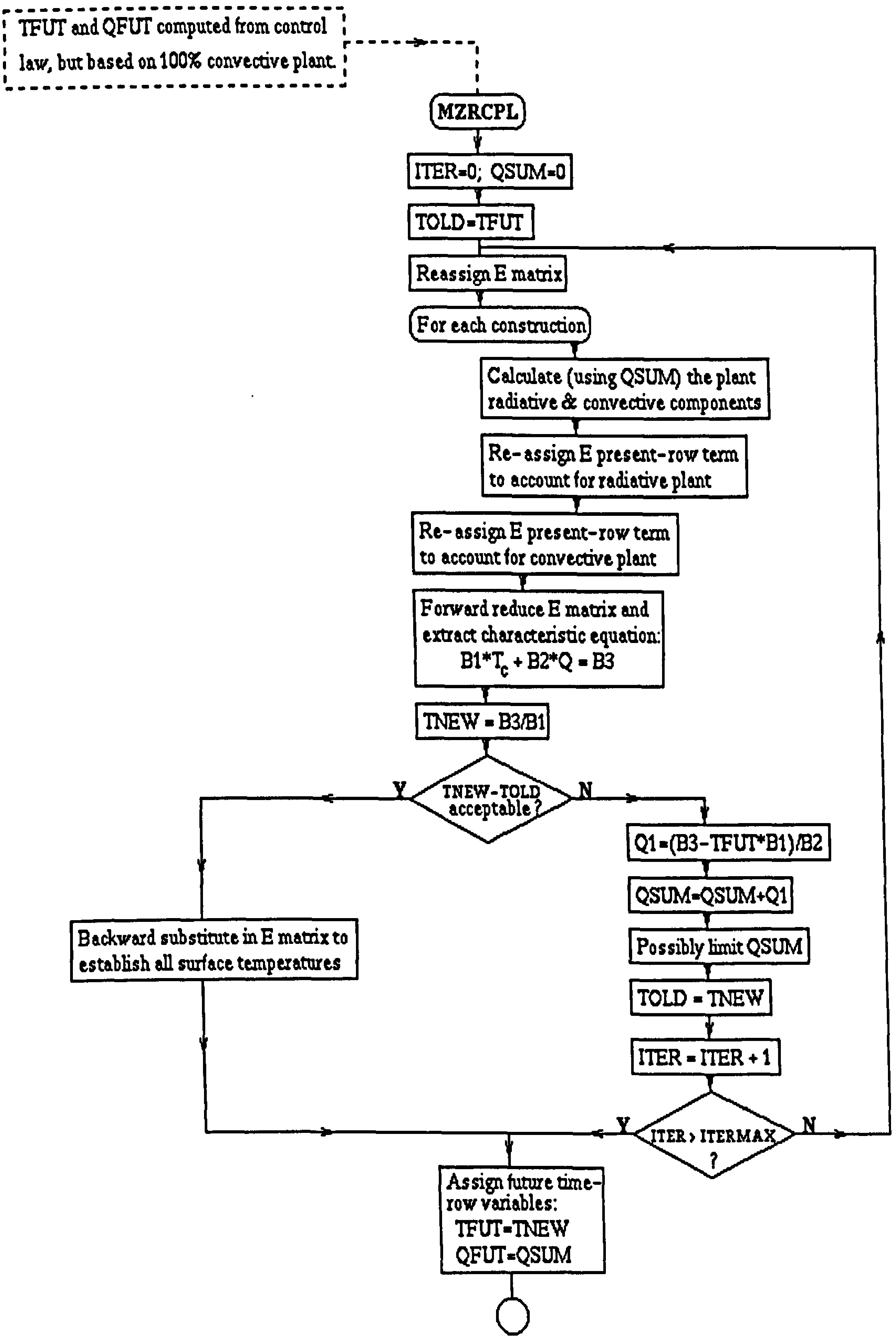


Figure B.2 *MZRCPL:* Numerical algorithm for modelling mixed air-surface actuation.

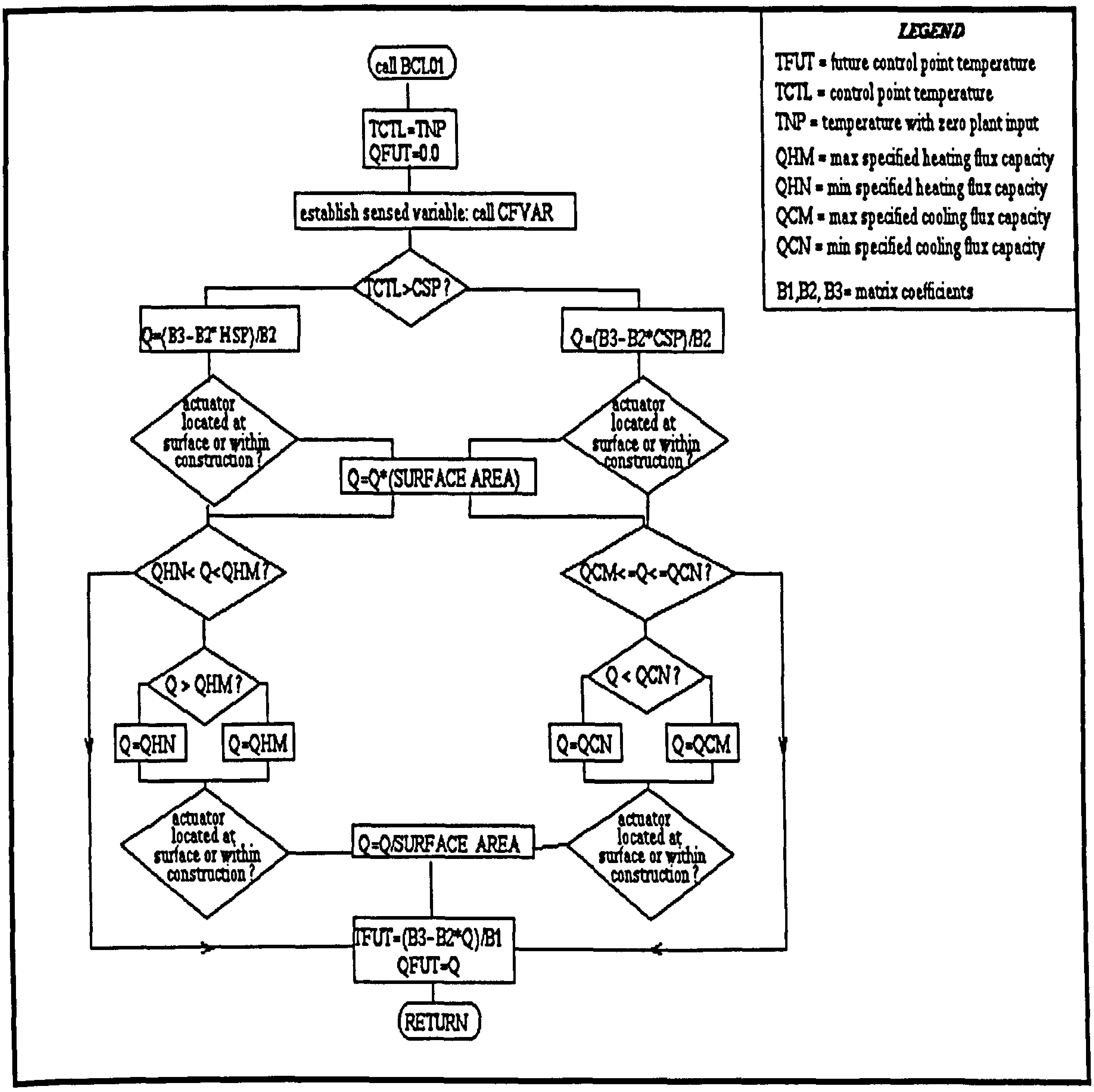


Figure B.3 *BCL01:* Ideal controller.

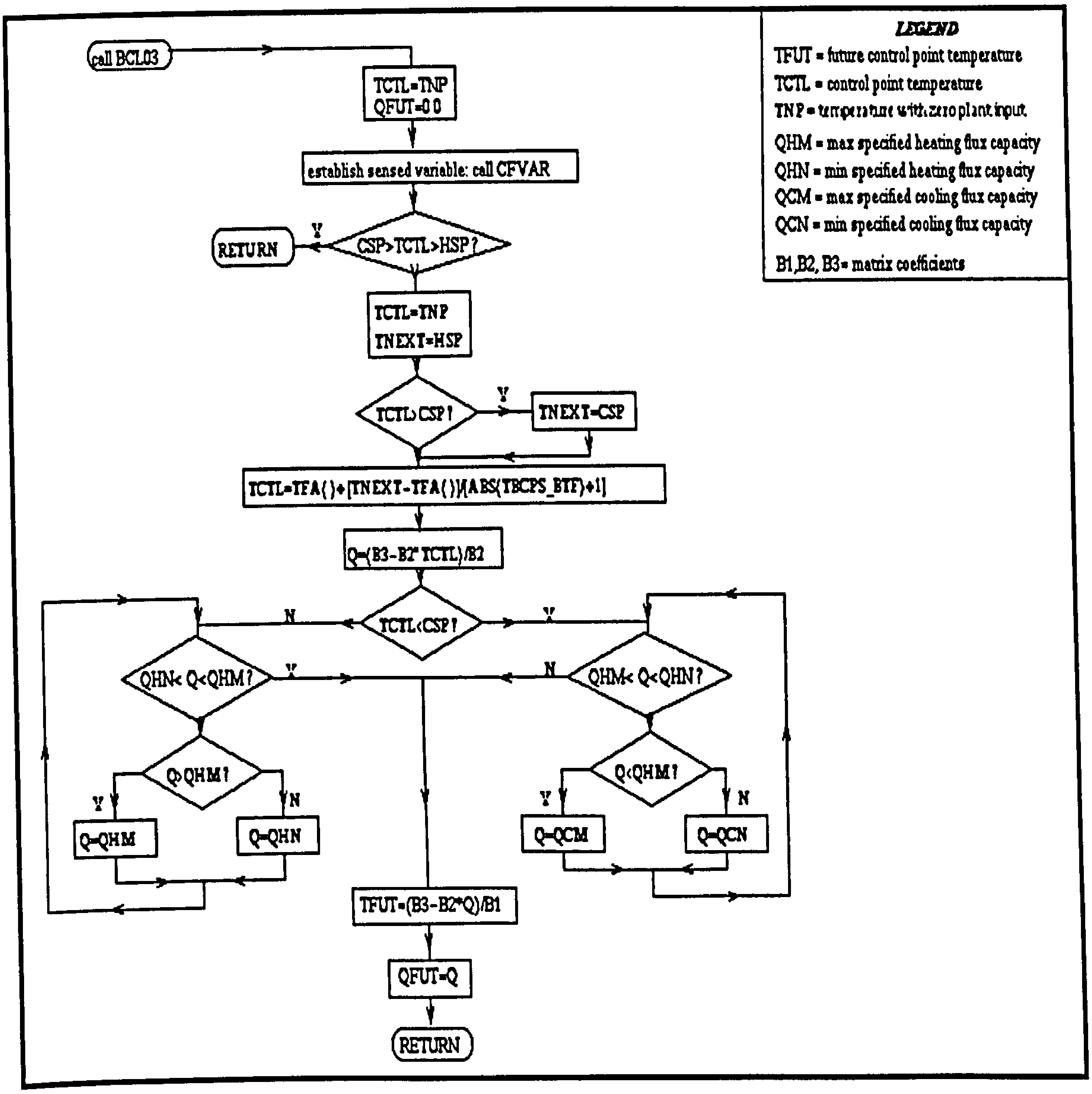


Figure B.4 *BCL03:* Ideal optimum start controller.

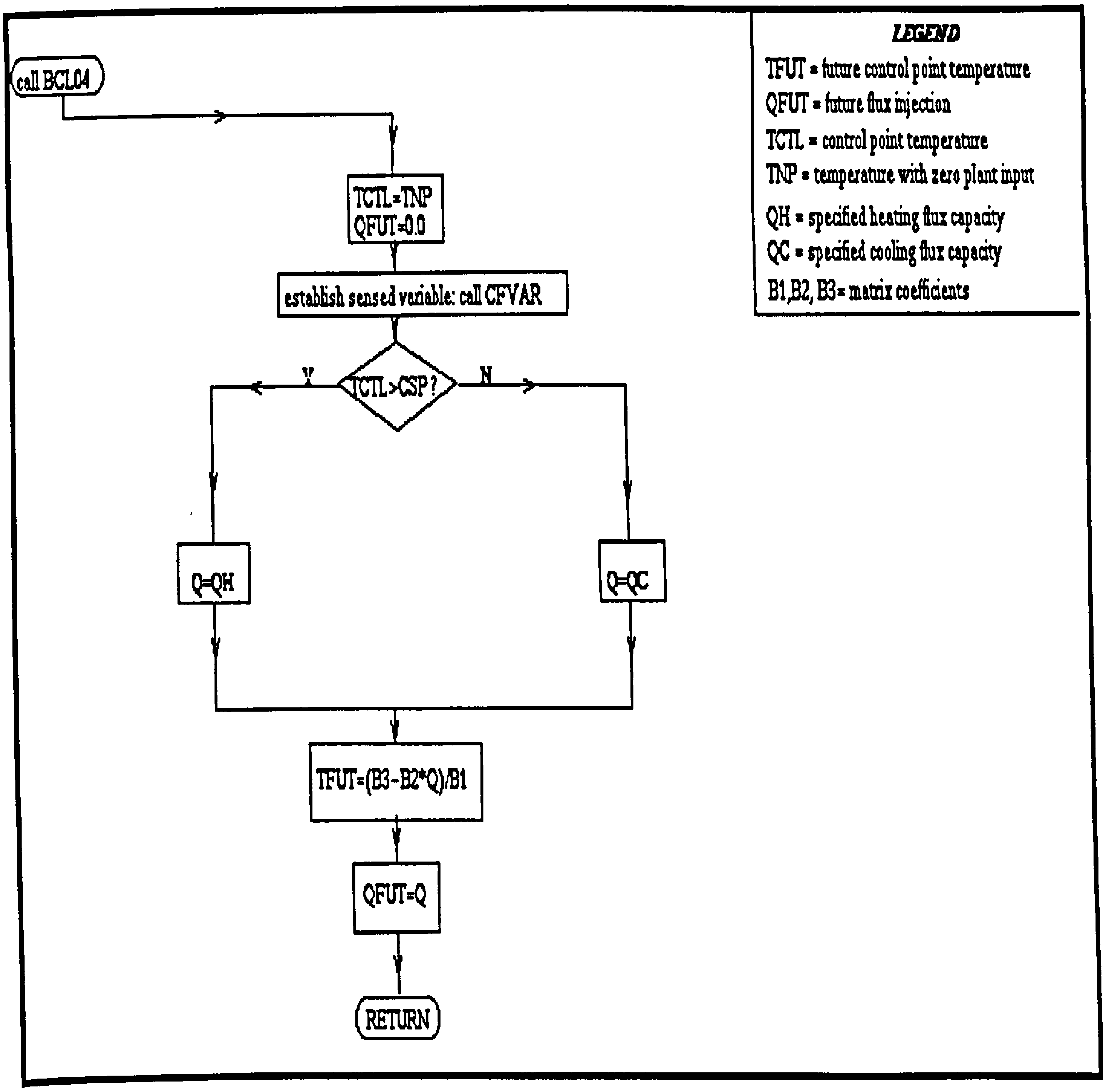


Figure B.5 *BCL04:* Fixed flux input/extract.

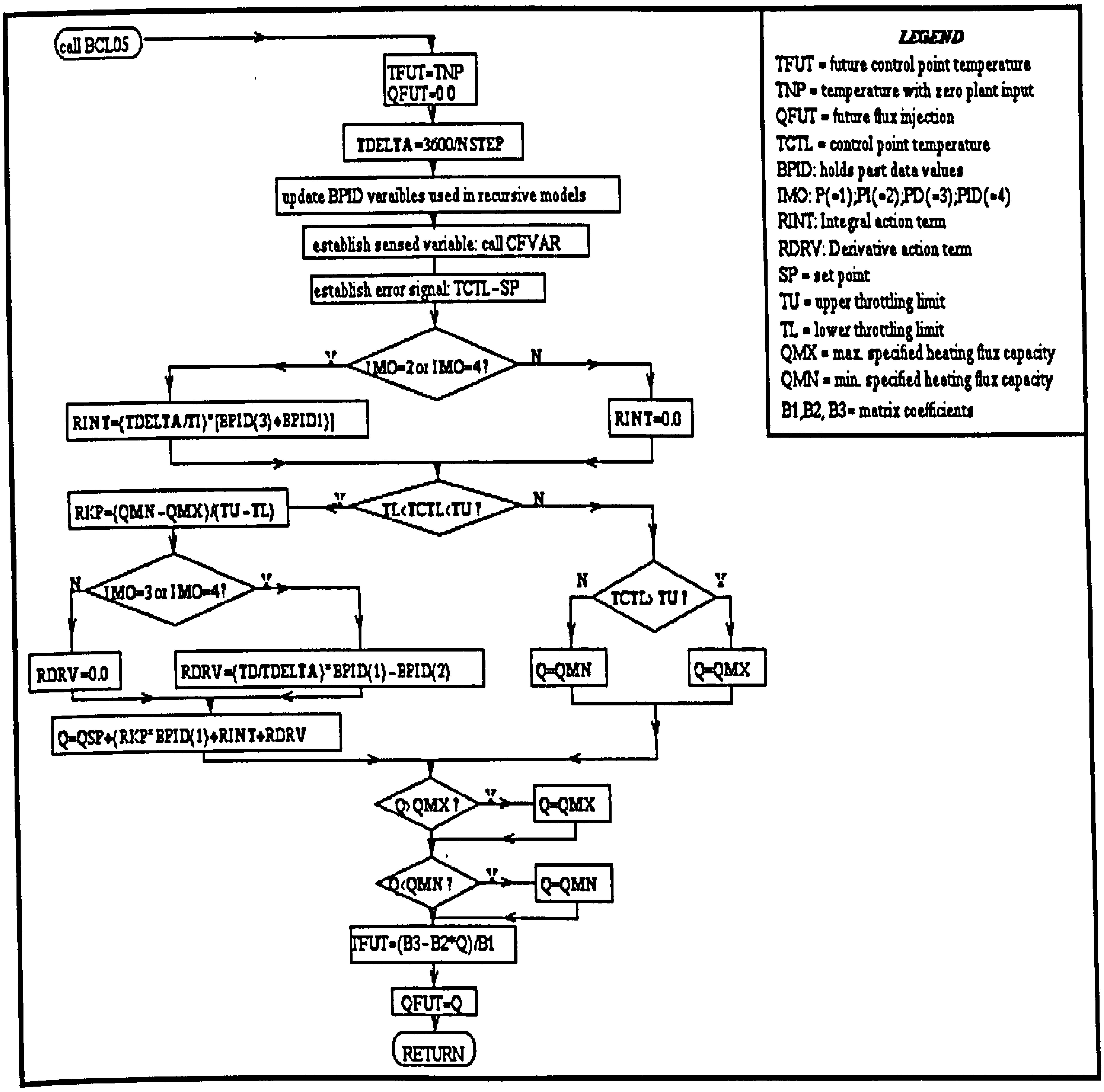


Figure B.6 *BCL05:* PID controller.

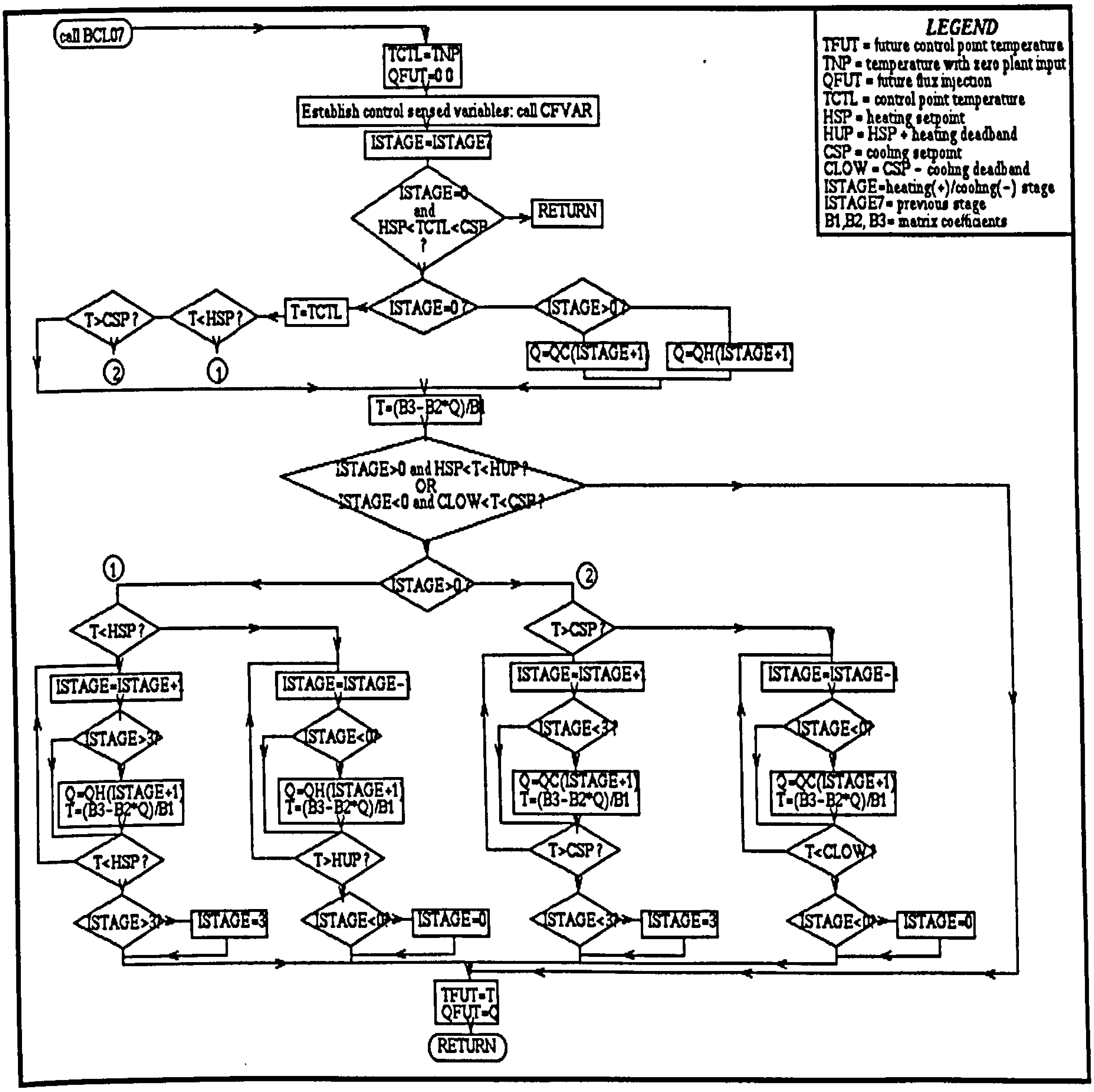


Figure B.7 *BCL07:* Multi-stage controller.

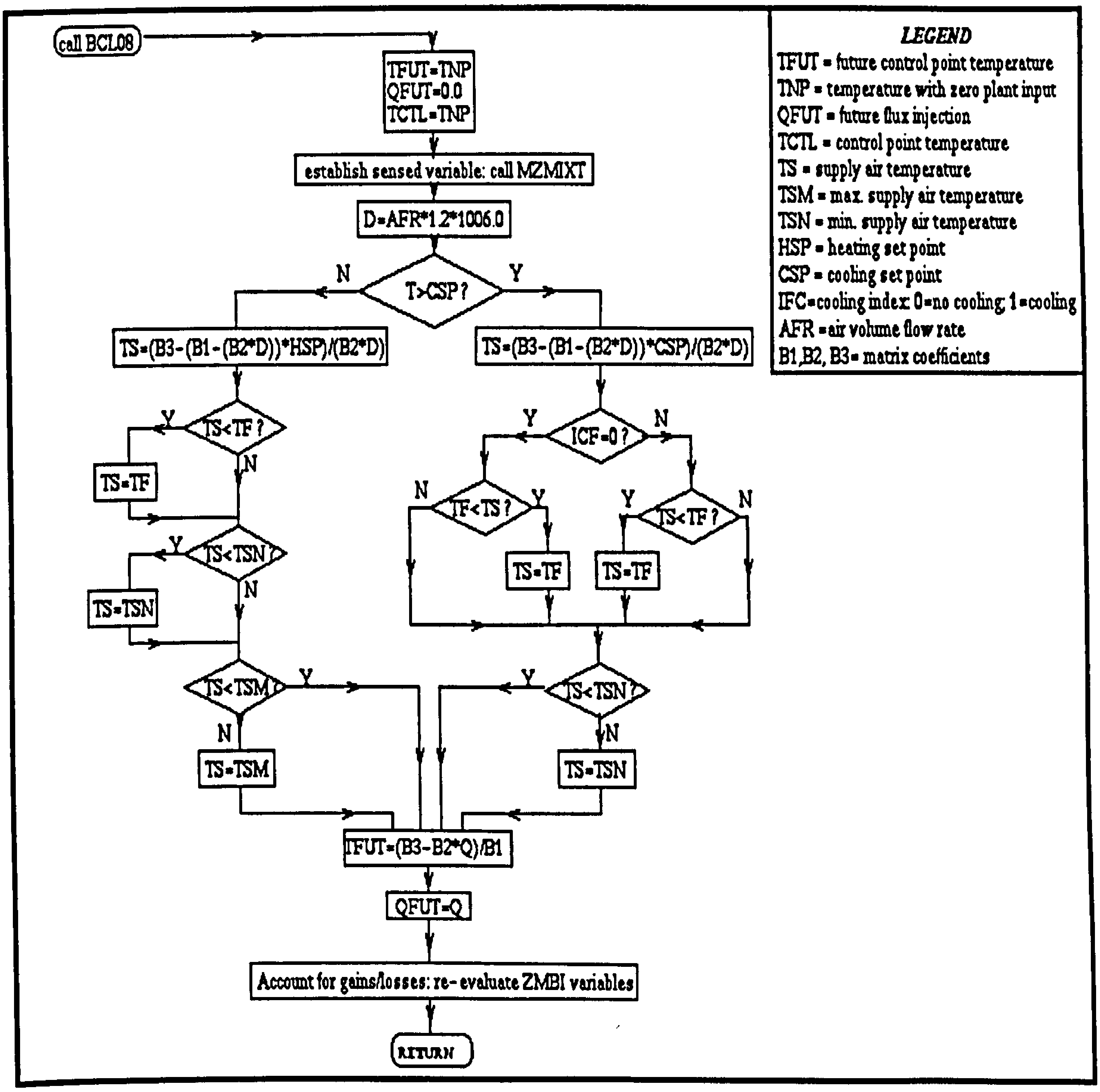


Figure B.8 *BCL08:* CAV controller.

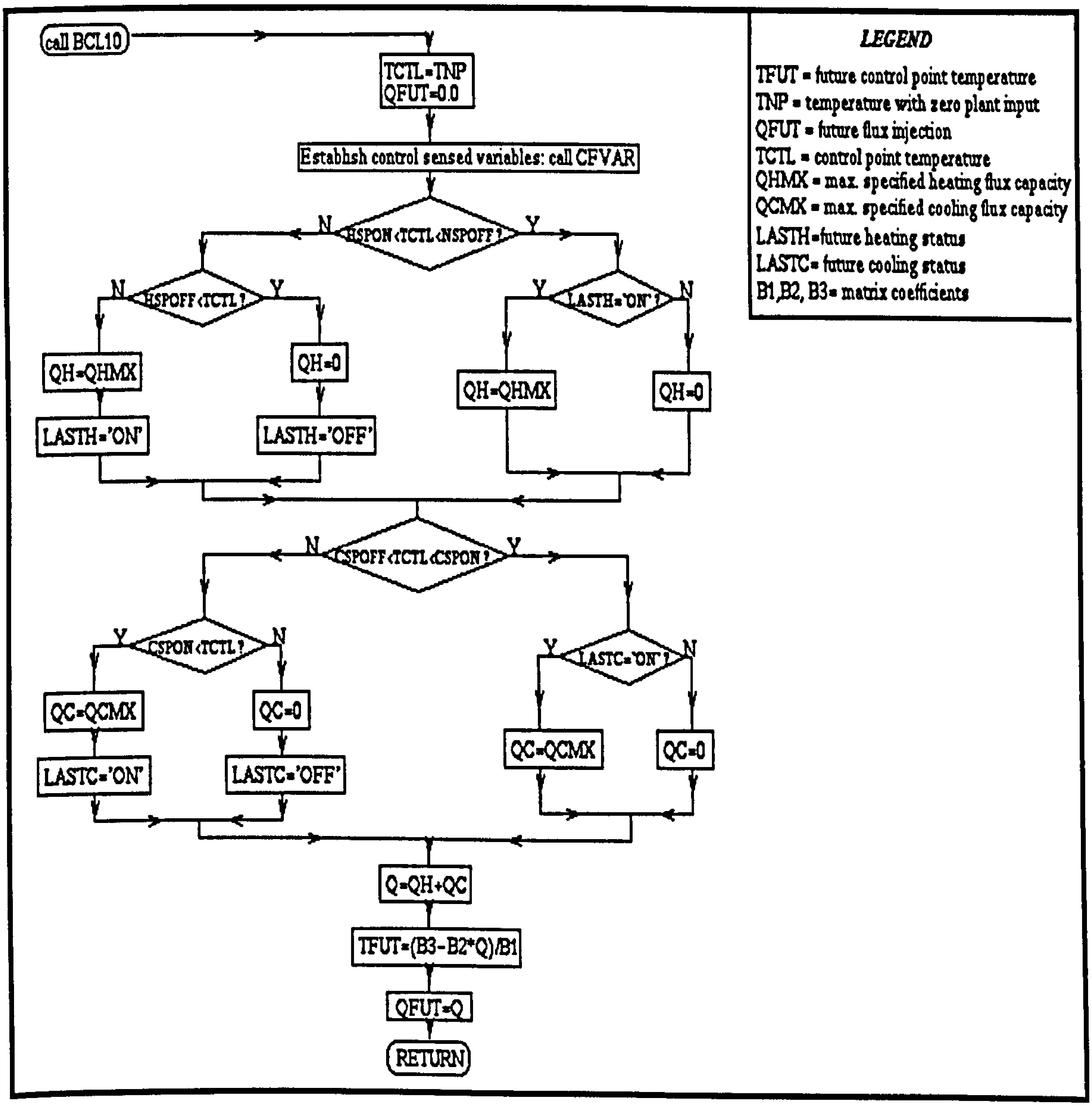


Figure B.9 *BCL10:* On-Off controller.

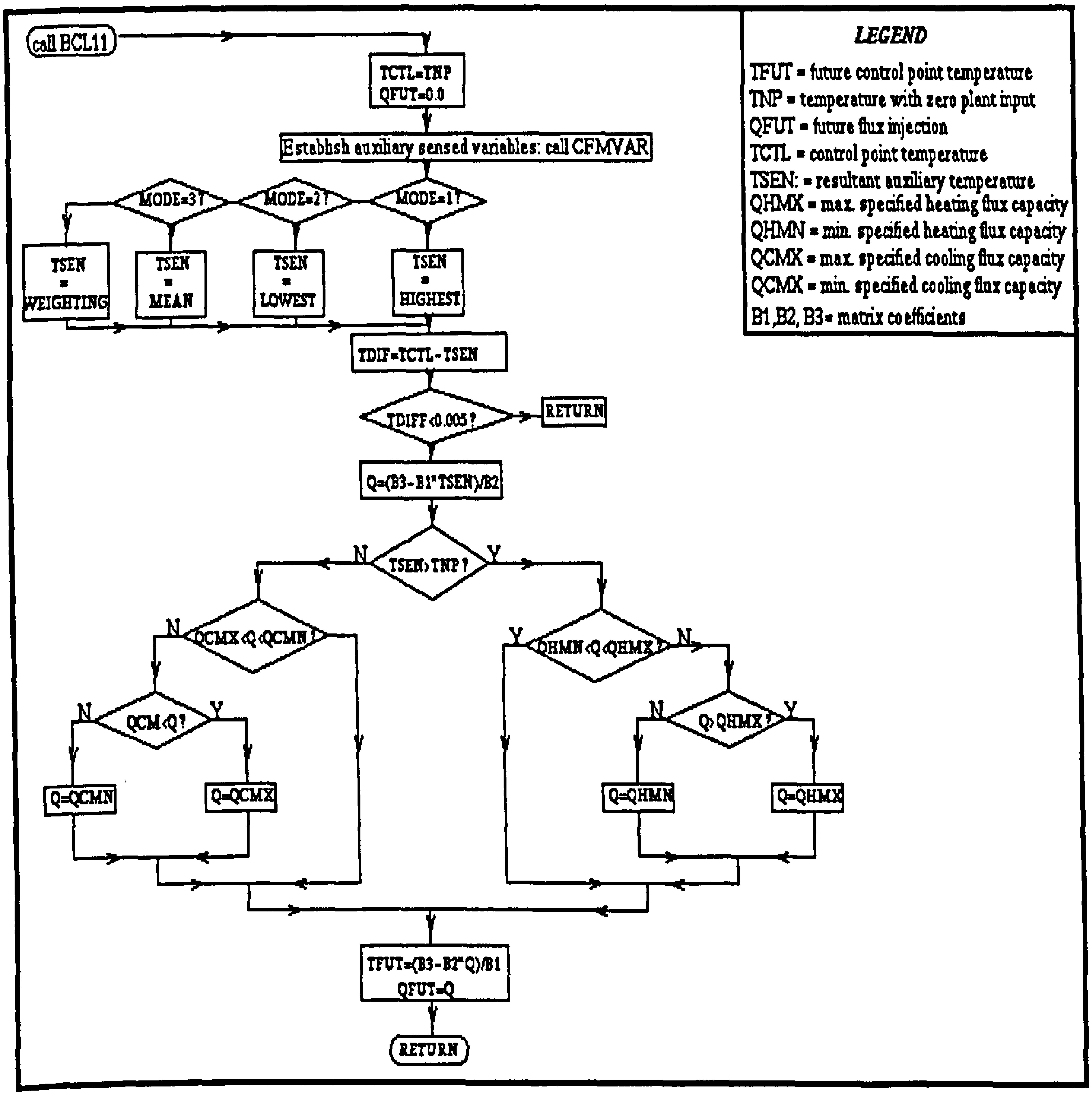


Figure B.10 *BCL11:* Ideal pro-rata controller.

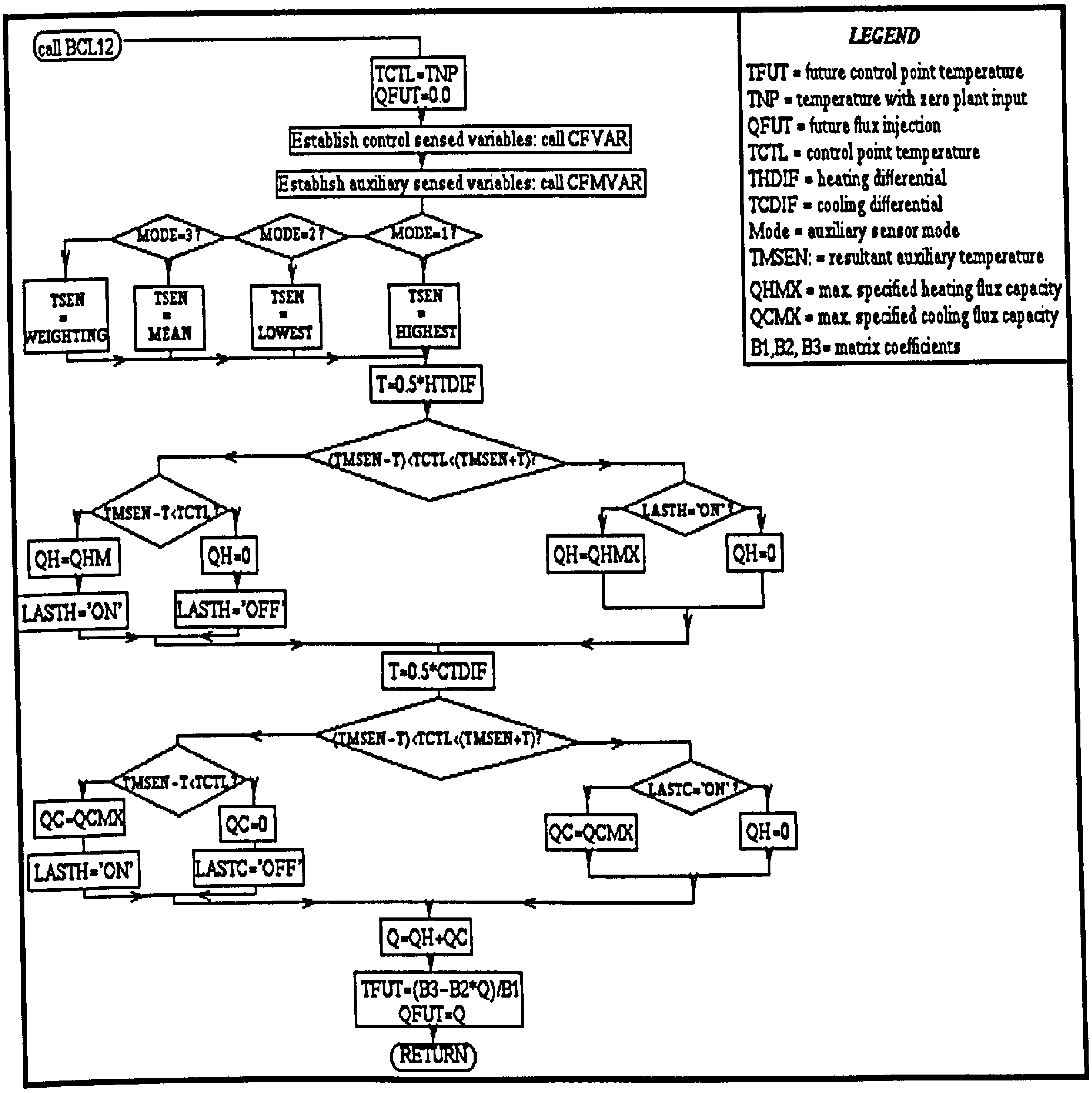


Figure B.11 *BCL12:* Two-position pro-rata controller (ideal).

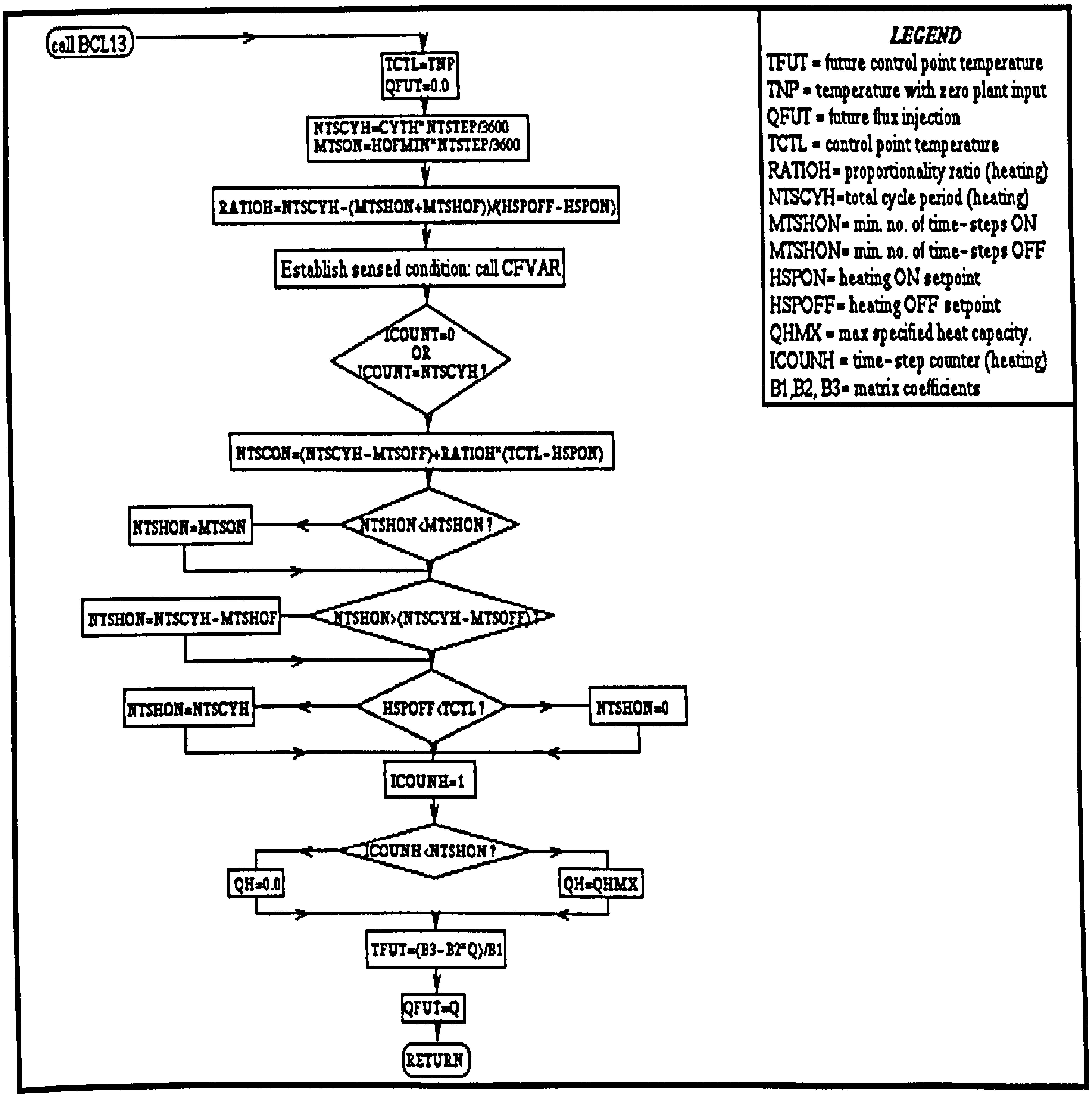


Figure B.12 *BCL13:* Time-proportioning controller.

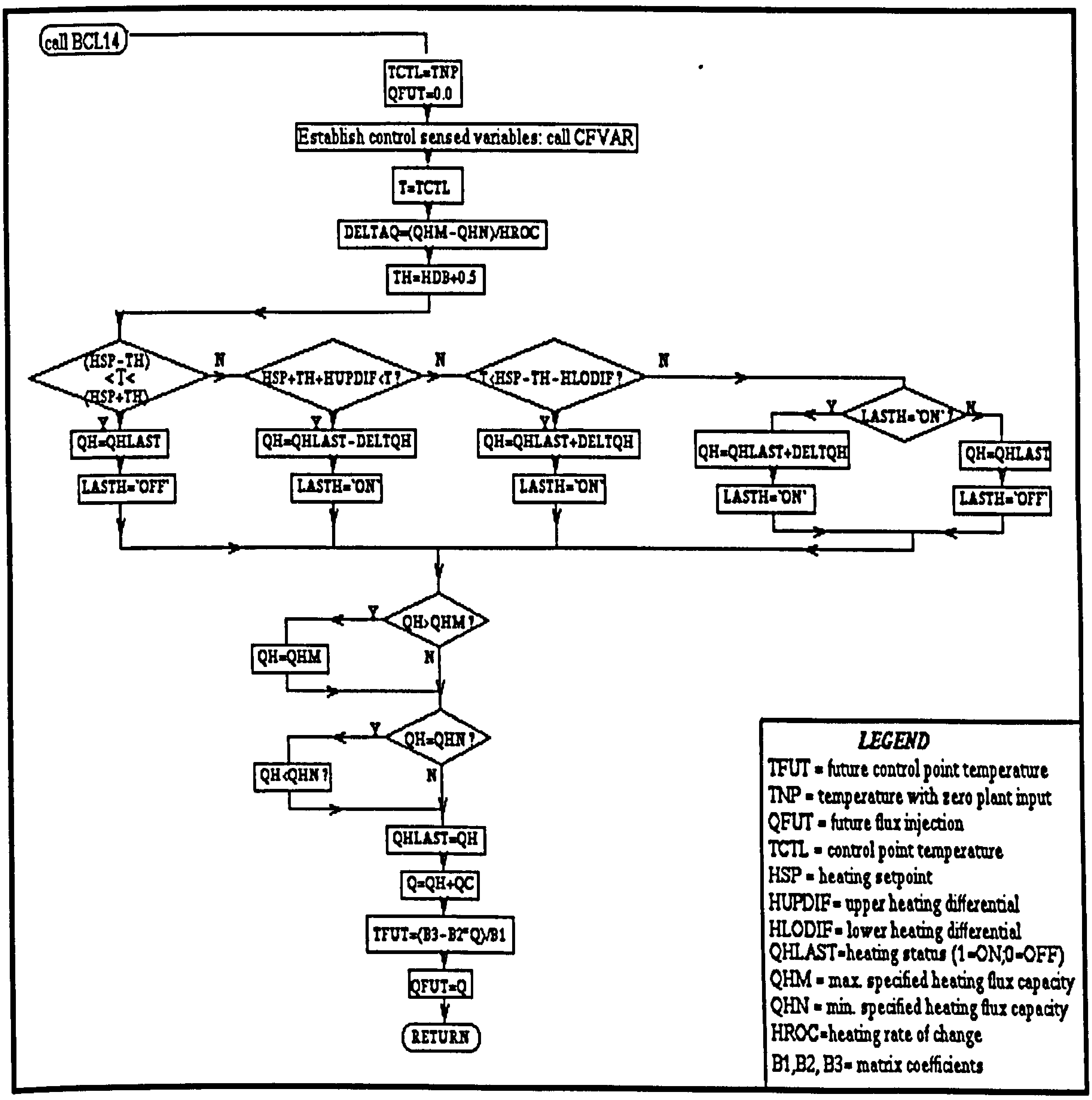


Figure B.13 *BCL14:* Three-position controller.

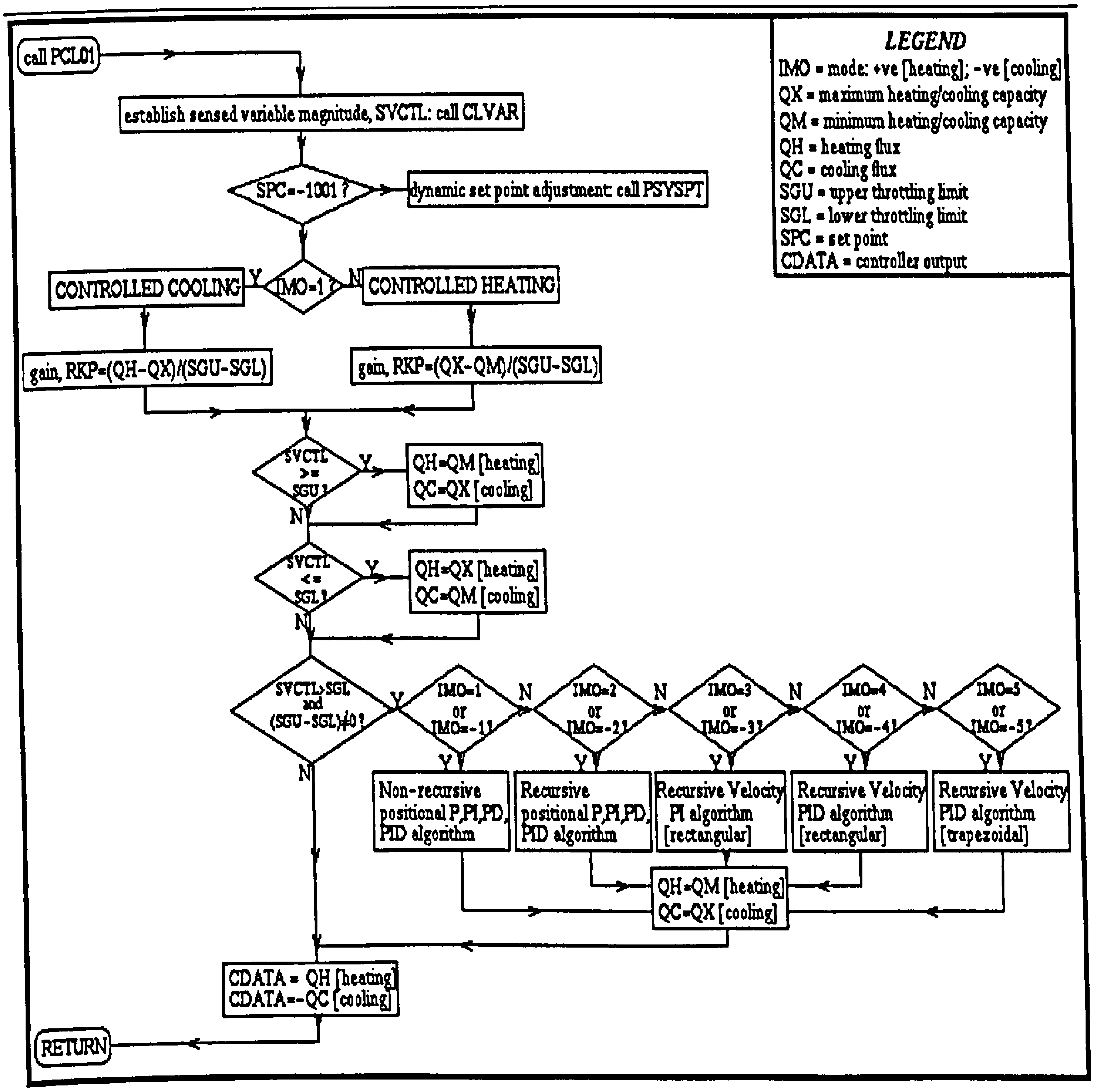


Figure B.14 *PCL01:* PID flux controller.

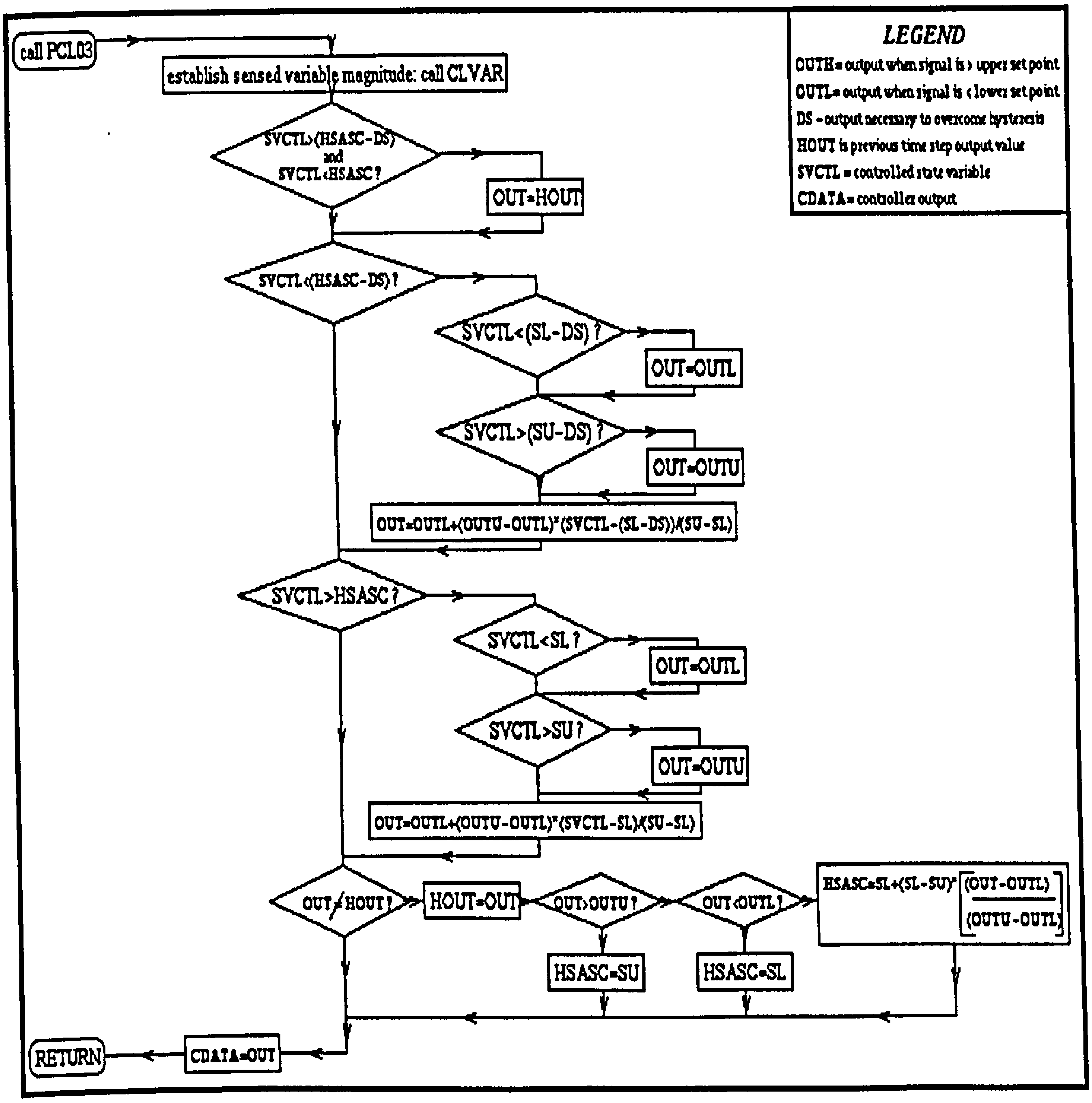


Figure B.15 *PCL03:* Proportional numerical controller.

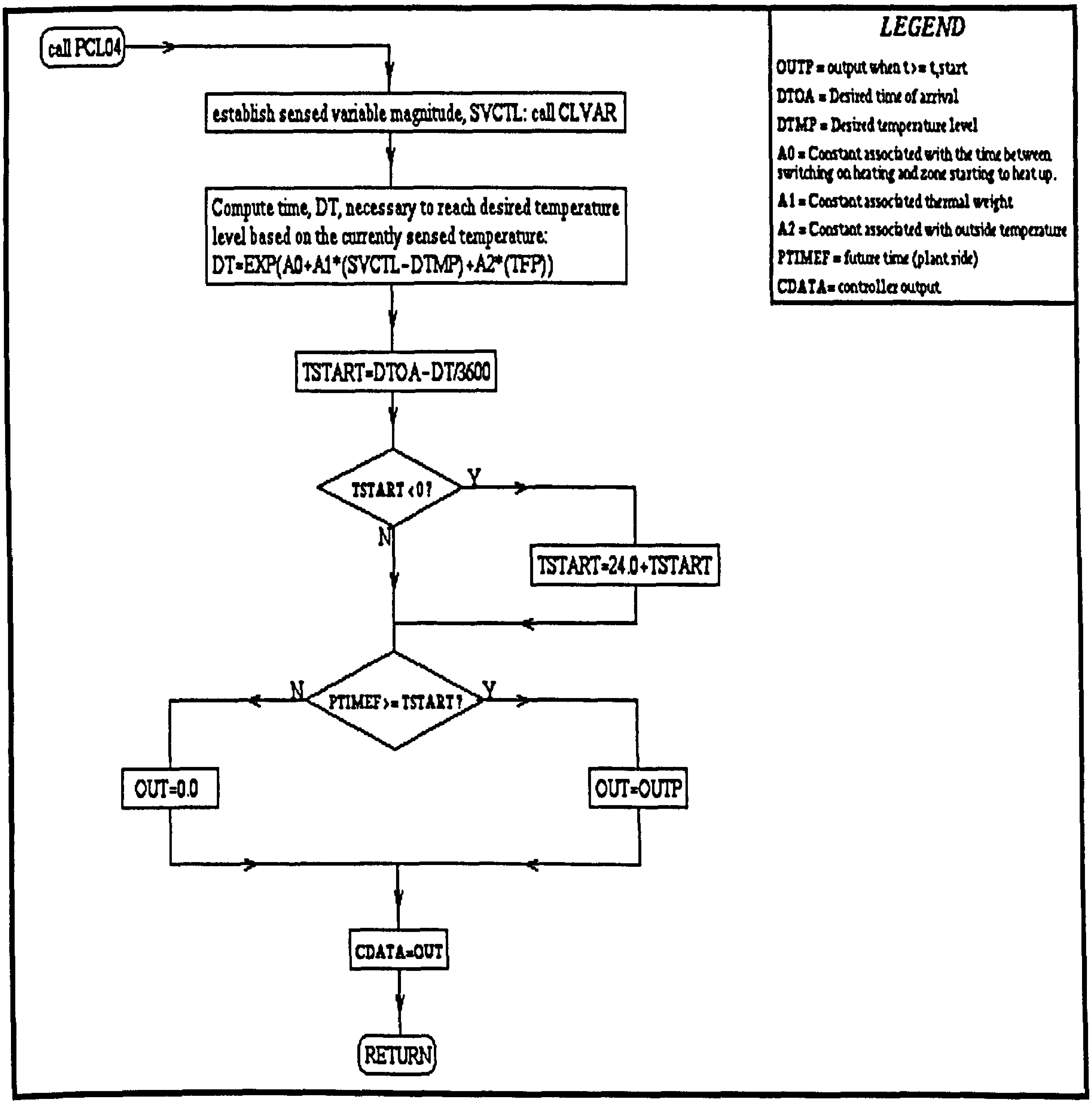


Figure B.16 *PCL04:* Optimum start controller.

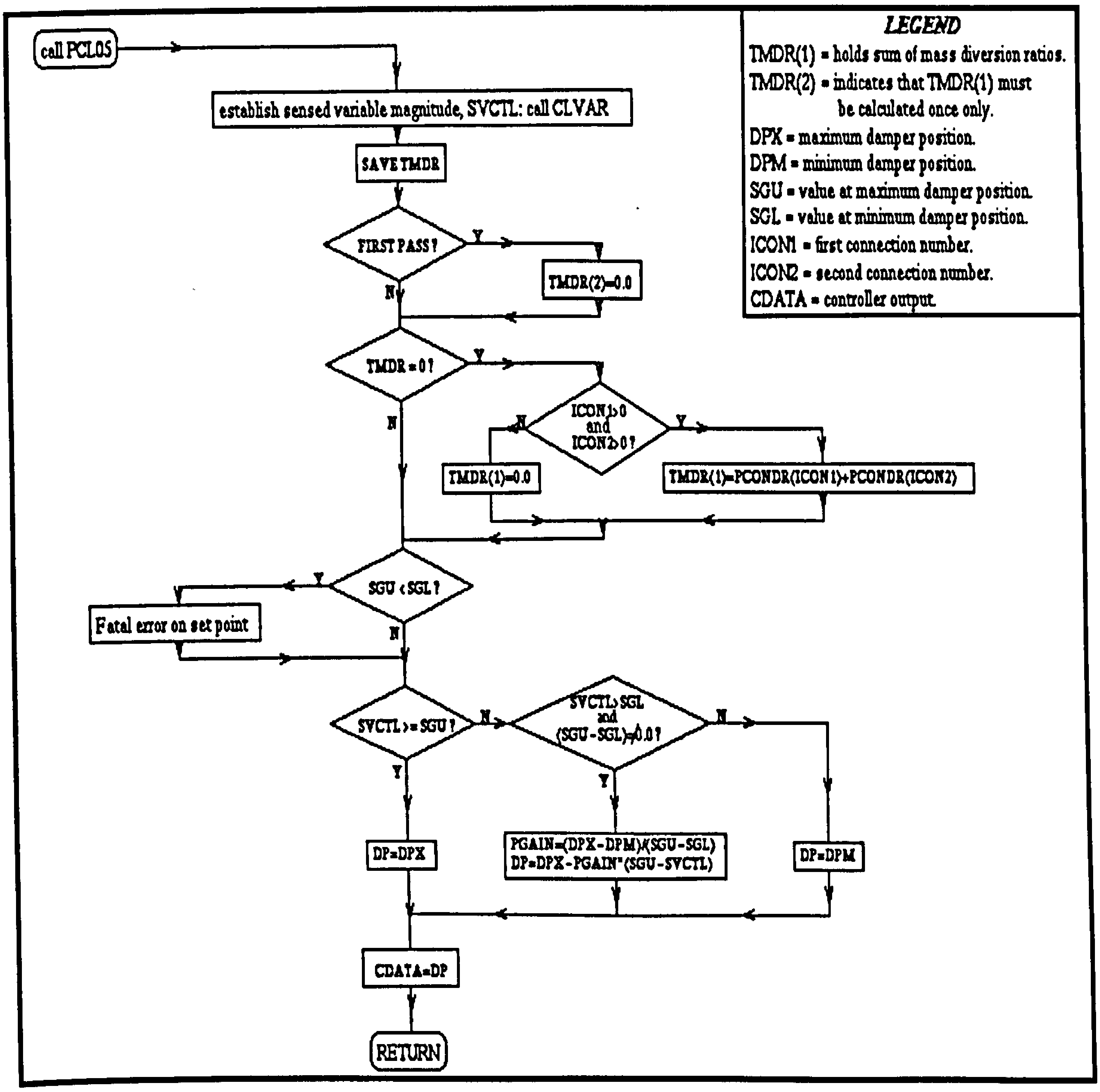


Figure B.17 *PCL05:* Proportional damper controller.

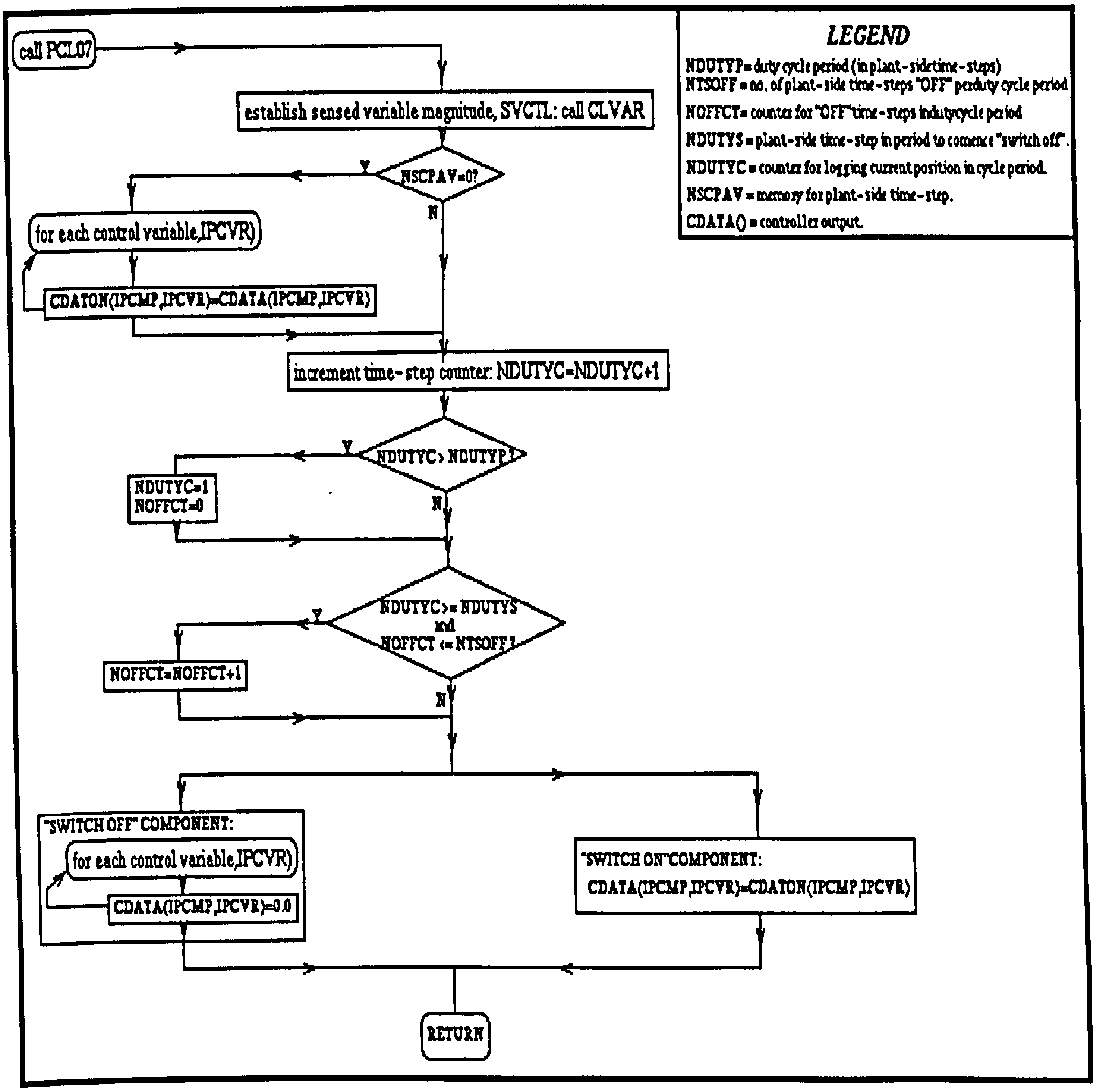


Figure B.18 *PCL07:* Duty cycle controller.

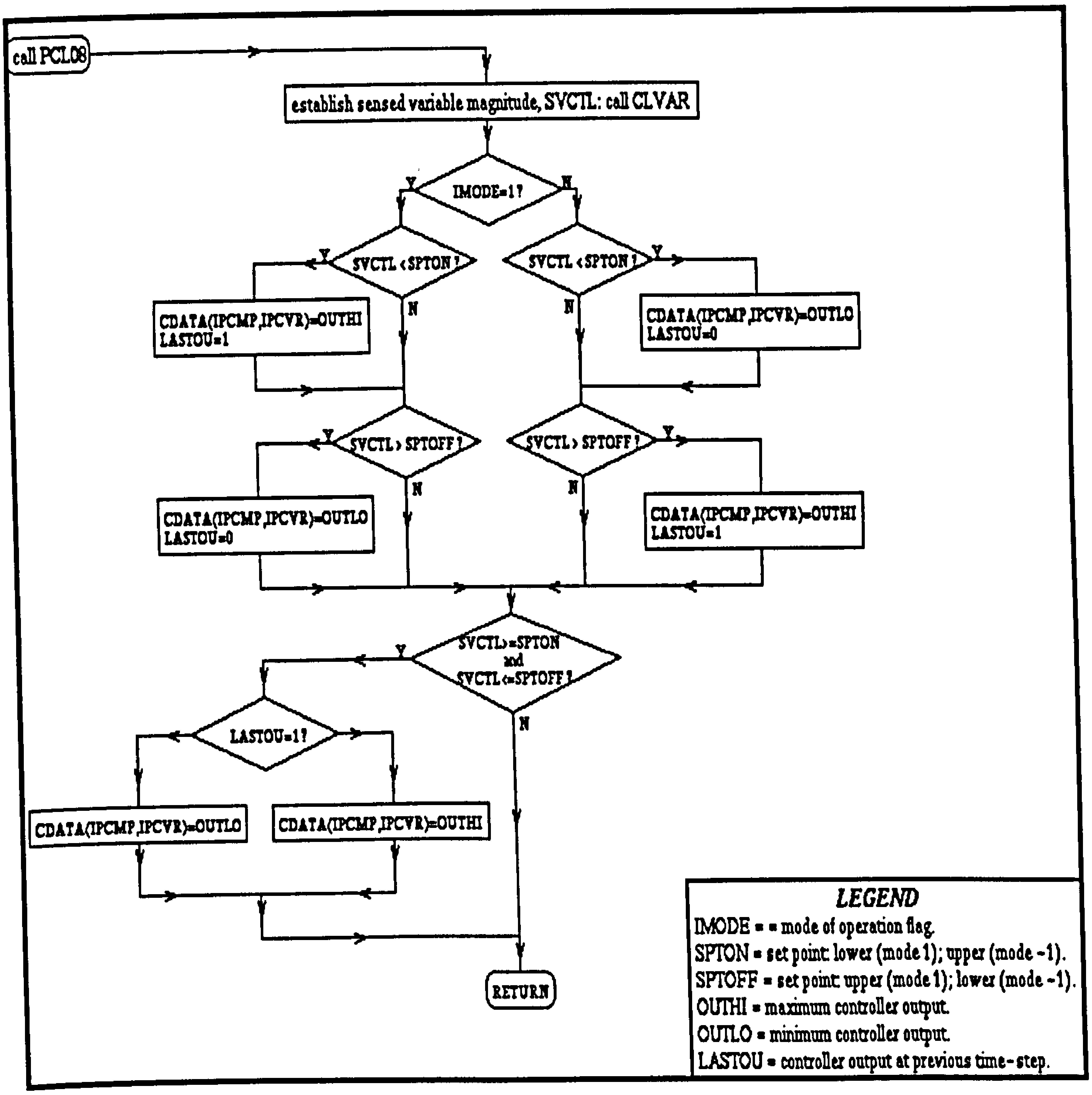


Figure B.19 *PCL08:* Single sensor two position controller.

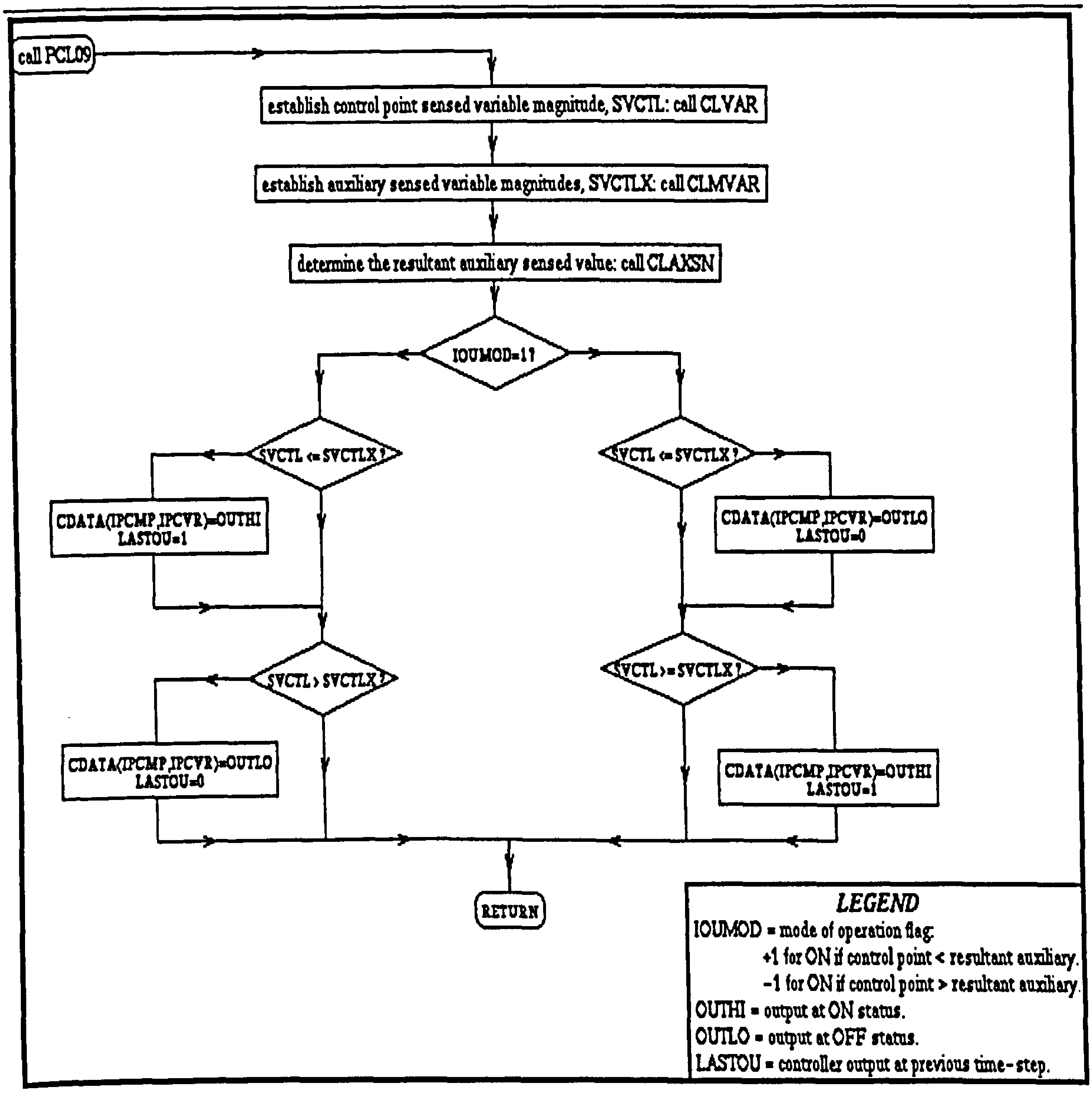


Figure B.20 *PCL09:* Multiple sensor two position controller.

B.2. ESP-r CONTROL ALGORITHMS: SUPPLEMENTARY DATA ITEMS.

B.2.1 Building control functions.

Table B.2.1.1 Mixed temperature controller

Reference	User-specifiable miscellaneous data items					
BCL00	1	2	3	4	5	6
	Set-point (upper)	Set-point (lower)	Heating flux (max)	Heating flux (min)	Cooling flux (max)	Cooling flux

Table B.2.1.2 Ideal controller

Reference	User-specifiable miscellaneous data items					
BCL01	1	2	3	4	5	6
	Heating flux (max)	Heating flux (min)	Cooling flux (max)	Cooling flux (min)	Heating set-point	Cooling sp

Table B.2.1.3 Ideal (exponential) pre-heat (or cool) controller

Reference	User-specifiable miscellaneous data items					
BCL03	1	2	3	4	5	6
	Heating flux (max)	Heating flux (min)	Cooling flux (max)	Cooling flux (min)	Heating set-point	Cooling sp

Table B.2.1.4 Ideal fixed heat injection/extraction

Reference	User-specifiable miscellaneous data items			
BCL04	1	2	3	4
	Heating capacity	Cooling capacity	Heating set-point	Cooling set-point

Table B.2.1.5 Proportional+integral+derivative controller

Reference	User-specifiable miscellaneous data items					
BCL05	1	2	3	4	5	6
	Mode	Heating flux (max)	Heating flux (min)	Heating Set-point	Heating throttling	Cooling flux (max)
	7	8	9	10	11	-
	Cooling flux (min)	Cooling Set-point	Cooling throttling	Integral action time (mode=2,4)	Derivative action time (mode=3)	Derivative action time (mode=4)

Table B.2.1.6 Building and plant linker

Reference	User-specifiable miscellaneous data items			
BCL06	*If coupling type < 4 :*			
	1 Supply component	2 Component node	3 Coupling type	4 Max heating flux
	5	6	7	
	Max cooling flux	Extract component	Component node	
	If coupling type = 4 :			
	1	2	3	4
	No. of coupled supply components	No. of coupled extract components	Coupling type	Max heating flux
	5	6—>		
	Max cooling flux	List of coupled components ...		

Table B.2.1.7 Multi-stage controller with hysteresis.

Reference	User-specifiable miscellaneous data items			
BCL07	1	2	3	4
	Heating (stage_0)	Heating (stage_1)	Heating (stage_2)	Heating (stage_3)
	5	6	7	8
	Cooling (stage_0)	Cooling (stage_1)	Cooling (stage_2)	Cooling (stage_3)
	9	10	11	12
	Heating set-point	heating dead band	Cooling set-point	Cooling dead band

Table B.2.1.8 Variable Supply Temperature Controller.

Reference	User-specifiable miscellaneous data items		
BCL08	1	2	3
	Max supply temperature	Min supply temperature	air volume flow rate (m3/s)
	4	5	6
	Heating set-point	Cooling set-point	Cooling availability (0=No;1=Yes)

Table B.2.1.9 Heat pipe control model

Reference	User-specifiable miscellaneous data items		
BCL09	1	2	3
	Iteration flag (0=No;1=Yes)	Construction containing heat pipe	Outermost heat pipe node
	4	5	6
	Innermost heat pipe node	Critical temperature	Maximum number of iterations
	7	8	9
	temperature difference tolerance	Flux difference tolerance	Trace flag (0=No;1=Yes)

Table B.2.1.10 On-off controller

Reference	User-specifiable miscellaneous data items		
BCL10	1	2	3
	Max heating capacity	Max cooling capacity	Heating ON set-point
	4	5	6
	Heating OFF set-point	Cooling ON set-point	Cooling OFF set-point

Table B.2.1.11 Multi-sensor ideal pro-rata controller

Reference	User-specifiable miscellaneous data items			
BCL11	1	2	3	4
	Max heating capacity	Min heating capacity	Max cooling capacity	Min cooling capacity
	5	6	-	-
	No. of auxiliary sensors	Mode of operation	-	-
	7	8	9	10
	Auxiliary sensor item_1	Auxiliary sensor item_2	Auxiliary sensor item_3	Auxiliary sensor item_4
	(11)	(12)	(13)	(14)
	Auxiliary sensor item_1	Auxiliary sensor item_2	Auxiliary sensor item_3	Auxiliary sensor item_4
	11 (15)	-	-	-
	(Mode=4 only) Sensor weighting			

Table B.2.1.12 Multi-sensor on-off pro-rata controller				
Reference	User-specifiable miscellaneous data items			
BCL12	1	2	3	4
	Max heating capacity	Max cooling capacity	Heating differential	Cooling differential
	5	6	-	-
	No. of auxiliary sensors	Mode of operation	-	-
	7	8	9	10
	Auxiliary sensor item_1	Auxiliary sensor item_2	Auxiliary sensor item_3	Auxiliary sensor item_4
	(11)	(12)	(13)	(14)
	Auxiliary sensor item_1	Auxiliary sensor item_2	Auxiliary sensor item_3	Auxiliary sensor item_4
	11 (15)	-	-	-
	(Mode=4 only) Sensor weighting			

Table B.2.1.13 Time-proportional on/off controller				
Reference	User-specifiable miscellaneous data items			
BCL13	1	2	3	4
	Max heating capacity	Max cooling capacity	Heating ON set-point	Heating OFF set-point
	5	6	7	8
	Cooling ON set-point	Cooling OFF set-point	Total htg cycle period	Min heating ON cycle period
	9	10	11	12
	Min heating OFF cycle period	Total clg cycle period	Min clg ON cycle period	Min clg OFF cycle period

Table B.2.1.14 Floating ('three-position') controller

Reference	User-specifiable miscellaneous data items			
BCL14	1	2	3	4
	Heating set-point	Heating dead band	Heating shut differential	Heating open differential
	5	6	7	8
	Cooling set-point	Cooling dead band	Cooling shut differential	Cooling open differential
	9	10	11	12
	Max heating flux	Min heating flux	Heating actuator rate-of-change	Max cooling flux
	13	14	-	-
	Min cooling flux	Cooling actuator rate-of-change		

Table B.2.1.15a Fuzzy logic controller

Reference	User-specifiable miscellaneous data items		
BCL15	1	2	3
	Fuzzy membership data set	Mode (1=PI;2=PD)	Set-point
	4	5	6
	Defuzzification	Scale factor (error)	Scale factor (change of error)
	7		
	Scale factor (output)		

Table B.2.1.15b Fuzzy logic controller: supplementary data items.

Item No.	Item description
1	* Fuzzy Control
2	Number of fuzzy sets
	For each set:
3	Set number
4	Number of membership functions for 'change of error' variable
5	Labels for for 'change of error' variable
6	Membership coordinates for 'change of error' variable
7	Number of membership functions for 'error' variable
8	Labels for for 'change of error' variable
7	Number of membership functions for 'output' variable
8	Labels for for 'output' variable
9-->	nXn look-up table: x x x x x x x x x x x x x x x x x x x x x x x x x
10+n	*Next set:*

Table B.2.1.16 Null controller

Reference	User-specifiable miscellaneous data items	
BCL16	1	2
	Scale	Offset

Table B.2.1.17 Materials thermo-physical properties change controller.

Reference	User-specifiable miscellaneous data items	
BCL99	1	2
	Mode (0=no substitution; 1=substitution)	Multi-layer constructional database reference for 1st construction
	3	4
	Multi-layer constructional database reference for 2nd construction	Multi-layer constructional database reference for 3rd construction

B.2.2 Plant control functions.

Table B.2.2.1/2 PID (Proportional+integral+derivative) control functions.

Reference	User-specifiable miscellaneous data items		
PCL01/2	Mode (algorithm type)	Heating/cooling capacity (max)	Heating/cooling capacity (min)
	Set-point	Throttling range	Integral action flag
	Integral action time	Derivative action flag	Derivative action time
	Dynamic set-point only:		
	Bypass flag	Mode (reheat or supply)	Mixing box reference
	Supply duct reference	Return duct reference	Supply set-point
	Reheat set-point		

Table B.2.2.3 Numerical controller

Reference	User-specifiable miscellaneous data items				
PCL03	1	2	3	4	5
	Output (max)	Output (min)	Signal upper (SU)	Signal lower (SL)	Hysteresis (DS)

Table B.2.2.4 Optimum start controller

Reference	User-specifiable miscellaneous data items		
PCL04	1	2	3
	Output at start-up	Desired-time-of-arrival	Desired temperature
	4	5	6
	Heating plant constant	Building constant	Temperature constant

Table B.2.2.5 Proportional damper controller

Reference	User-specifiable miscellaneous data items		
PCL05	1	2	3
	Max damper position	Min damper position	Value at max damper position
	4	5	6
	Value at min damper position	First connection number	Second connection number

Table B.2.2.6 Null controller		
Reference	User-specifiable miscellaneous data items	
PCL06	1	2
	Scale	Offset

Table B.2.2.7 Duty Cycle controller			
Reference	User-specifiable miscellaneous data items		
PCL07	1	2	3
	Duty cycle period	Time-steps 'OFF' per period	1st time-step 'OFF' per period

Table B.2.2.8 Two-Position controller			
Reference	User-specifiable miscellaneous data items		
PCL08	1	2	3
	Mode (1=direct;-1=reverse)	Set-point 'ON'	Set-point 'OFF'
	4	5	6
	Output (high)	Output (low)	Sensor lag (time-steps)
	7		
	Actuator lag (time-steps)		

Table B.2.2.9 Multiple input two-position controller				
Reference	User-specifiable miscellaneous data items			
PCL09	1	2	3	4
	Output (high)	Output (low)	Mode (1=direct;-1=reverse)	No. of auxiliary sensors
	5	6	7	
	Function mode	Sensor lag (time-steps)	Actuator lag (time-steps)	
	8	9	10	11
	Auxiliary sensor_1 data_1	Auxiliary sensor_1 data_2	Auxiliary sensor_1 data_3	Auxiliary sensor_1 data_4
	11 -->	--	--	--
	Other auxiliary sensor data	-	-	-
	Then, if function = 4:			
	Sensor weightings			

Table B.2.2.10 Zero energy band controller			
Reference	User-specifiable miscellaneous data items		
PCL10	1	2	3
	Max output (high)	Min output (high)	Max output (low)
	4	5	6
	Min output (low)	Set-point	Dead band

Table B.2.3 Fluid control functions.

Table B.2.3.1 Fluid ON-OFF controller		
Reference	User-specifiable miscellaneous data items	
FCL00	1	2
	Set-point	Mode (1 = direct; -1 = reverse)

Table B.2.3.2 Fluid proportional controller with hysteresis.			
Reference	User-specifiable miscellaneous data items		
FCL01	1	2	3
	Signal (low)	Relative valve position signal [low] (%)	Signal (high)
	4	5	6
	Relative valve position signal [high] (%)	Signal required to overcome hysteresis	

B.2.4 Global (systems-level) control functions.

Table B.2.4.1 Global on-off controller		
Reference	User-specifiable miscellaneous data items	
GCL01	1	2
	mode	Minimum loops ON (mode=1); Set_point (mode=2)

Table B.2.4.2 Global capacity management controller				
Reference	User-specifiable miscellaneous data items			
GCL02	1	2	3	4 -> nshed+3
	Heating capacity	Cooling capacity	No. of loops shed	Loop list ...

Table B.2.4.3 Global sequence controller

Reference	User-specifiable miscellaneous data items	
GCL03	1	2 -> No. of loops shed + 1
	No. of loops shed	Loop list ...

Table B.2.4.4 Global parameter reset controller

Reference	User-specifiable miscellaneous data items								
GCL04	1	2	3	4	5	6	7	8	9
	Building function	Data item	Reset value	Flow function	Data item	Reset value	Plant function	Data item	Reset value

Table B.2.4.5 Global scale and offset controller

Reference	User-specifiable miscellaneous data items								
GCL05	1	2	3	4	5	6	7	8	9
	Mode	Set-point	Scale	Offset	No. of controllers	Controller_1	-	->	Controller_n

B.2.5 ESAC Functions.

Table B.2.5.1 Simulation-assisted optimum start controller

Reference	User-specifiable miscellaneous data items		
ESACL01	1	2	3
	Heating/cooling capacity	Set-point	Tolerance band
	4	5	6
	Desired time-of-arrival	Trial time difference	Initial trial time flag
	7	8	9
	Heating plant constant (mode=3)	Building constant (mode=3)	Temperature constant (mode=3)

Table B.2.5.2 Simulation-assisted optimum stop controller

Reference	User-specifiable miscellaneous data items		
ESACL02	1	2	3
	Heating capacity	Cooling capacity	Heating set-point
	4	5	6
	Cooling set-point	Desired temperature level	Tolerance band
	7	8	9
	Occupancy departure time	Trial time difference	Initial trial time

B.3. SUPPLEMENTARY ESP-r CONTROLLER MODELS.

The following controller models were installed in ESP-r prior to project commencement.

B3.1 BUILDING CONTROL FUNCTIONS.

These functions are used to establish control function characteristics and constraints in order to allow solution of the building control system equation set (Equation 3.8) as described in Section 3.4. In all cases, the forward-reduced coefficients (B1, B2 and B3) are fed to the active control algorithm, which subsequently processes them according to the control logic, returning the future time-row temperature and plant terms.

The supplementary data items required for the following functions are listed in Appendix B.

BCL00: Mixed temperature controller.

This routine (described in Section 4.4.1.3) solves the building control system equation set in terms of the prevailing control function information and so obtains the desired mixed node temperature in the current zone. To do this, the mixed temperature is computed on the basis of the present time row surface and air point temperatures. (Note that all functions may also have mixed *actuation*).

BCL01: Ideal controller.

This control law will bring the controlled variable to within a specified tolerance range, providing that the heating/cooling capacity is available. There is potential for different heating and cooling set-points. Limiting capacities permit either heating or cooling to be disallowed. A single set-point can be maintained throughout the control period if the same set-point is given for heating and cooling and providing the capacity is available.

For the *BCL01* model, the building control system equation set is of the form:

$$B1\theta_c + B2q_p = B3. \qquad \text{(B.1)}$$

The present time-row control point temperature is obtained and compared with the user-specified desired value. If the control point is within the desired range, the future time-row plant flux injection/extraction is obtained from:

$$q_p = \frac{B3 - B1\theta_c}{B2}. \qquad \text{(B.2)}$$

If, on the other hand, the control point temperature is above/below the desired range, then θ_c is set to the cooling/heating set-point in order to establish the future time-row flux from Equation B.2.

Limiting conditions on the plant capacity may be specified and imposed on the solution.

BCL02: Free-floating controller.

This function is used to model periods during which no control is imposed. The zone and associated plant are allowed to 'free-float' under the influence of the boundary conditions. (Note that this controller should not be confused with *floating* control action, - often termed *three-position control* - which is implemented in ESP-r as control law *BCL14*).

No miscellaneous data items are required for this control function.

BCL03: Ideal pre-heating/pre-cooling controller.

The determination of the optimal strategy of system operation, in terms of plant efficiency, capital costs and running costs, involves addressing the fundamental problem of whether the plant should be operated in continuous or intermittent mode. Two commonly used methods for assessing the benefits accruing from intermittent operation include: Newtonian heating and cooling and Dufton's method [Incropera and De Witt 1990]. Newtonian heating and cooling is one of the simplest examples of a 'steady-state' analytical method and is sometimes classified as 'zero-dimensional'. Dufton's method, although derived on the basis of non-steady state considerations is, in terms of application, a steady state procedure and involves an analytical solution of the one-dimensional Fourier equation.

In Newtonian heating and cooling, the fundamental assumption made is that the internal conductance of an enclosure is high compared with the external surface, i.e. the internal thermal resistance is negligible compared with the external surface resistance. This allows the further assumption that the internal temperature gradient is negligible and therefore all parts of the enclosure can be represented by a single temperature. Consider Figure B.21 which shows a body cooling from temperature T_1 to T_2 over a period of time t_1 to t_2 and being heated from temperature $(T_2 + \Delta T_2)$ to T_3 over a period of time from t_2 to t_3. T_m is the mean temperature during the period from 1 to 3 (i.e. the unoccupied period). The equations derived by the Newtonian method allow computation of the required preheat/cool period (t_2 to t_3) for any given plant margin over and above that necessary for continuous operation or, conversely, the plant margin for any given preheat/cool period can be found. In the algorithm installed in ESP-r, limiting heating and cooling capacities are supplied and within these constraints temperatures will evolve exponentially towards, and if the capacity is available, eventually reaching, the specified set-point temperature of the control period which follows.

At each building-side time-step, the target temperature for the current time-step (assuming heating required), T_{target} is established from:

$$T_{target} = T_{zone} + \frac{(SP - T_{zone})}{abs((TBCPS - BTIMEF) + 1)} \tag{B.3}$$

where T_{zone} is the future time-row zone air point temperature (°C) calculated at the previous building-side time-step, SP is the heating set-point (°C) at the *desired time of arrival*, TBCPS is the active control period start time and BTIMEF is the future time-row simulation time (all times refer to 24 hour time-clock, e.g. 09.00). If T_{target} is less than SP, then the future time-row heat flux, q_f(W) is added according to:

$$q_f = (B3 - B1.T_{target})/B2 \tag{B.4}$$

where B1, B2 and B3 are the building control system equation set coefficients carried through by the forward reduction process.

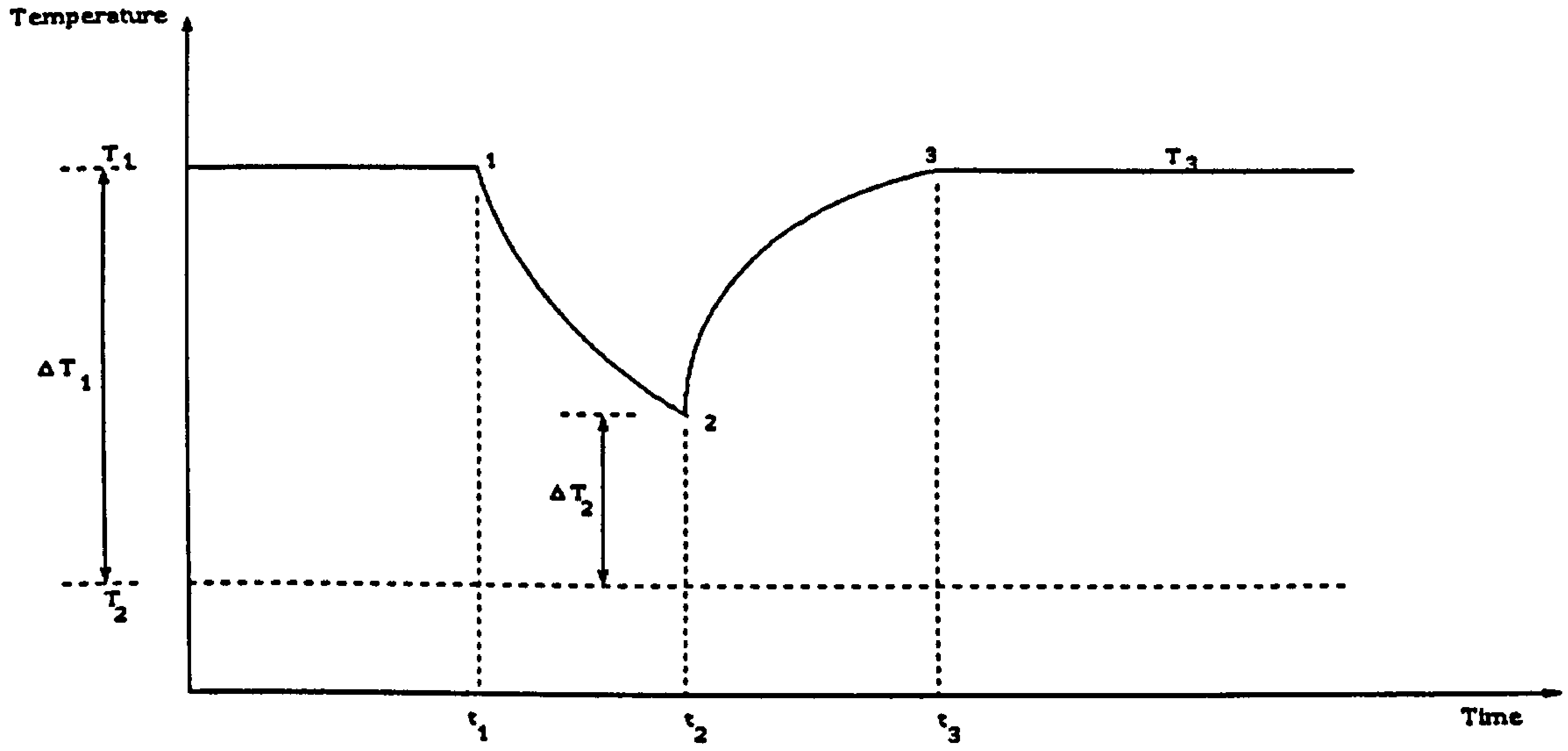


Figure B.21 Newtonian heating.

BCL04:Fixed heat injection/extraction controller

Many buildings using conventional control systems are heated/cooled by injecting/extracting fixed amounts of energy during a given period. For the *BCL04* model, the reduced building control system equation set is used in the form of Equation B.1. If the present time-row control point temperature is greater/less than the cooling set-point, then the future time-row flux input is set to the specified cooling/heating flux. The future time-row control point temperature is obtained from the building control system equation set:

$$\theta_c = \frac{B3 - B2q_p}{B1}. \tag{B.5}$$

If, on the other hand, the present time-row control point temperature is within the specified dead band, then the future time-row flux input is set to zero, and the future time-row control point temperature is obtained from:

$$\theta_c = B3/B1. \tag{B.6}$$

BCL06: Building-plant coupling function.

This control law allows zone input or extract flux to be set as a function of the plant network status, i.e. it is effectively the coupling mechanism between the building-side and the plant-side. The function of this controller is to evaluate the heat injected to the zone air using one of three available calculation methods.

In the first calculation method, the rate at which heat is injected by the plant is ϕ_p (W) and is expressed by the following equation:

$$\phi_p = \dot{m}C_p(\theta_s - \theta_a) \qquad \text{(B.7)}$$

where $\dot{m}$ is the dry air fluid flow rate entering the zone (kg/s), C_p is the specific heat capacity of air at constant pressure (J/kg K), θ_s is the supply air temperature (°C) and θ_a is the zone air temperature (°C). This equation can be solved simultaneously with the building control system equation set:

$$B1\theta_a + B2\phi_p = B3 \qquad \text{(B.8)}$$

where B1, B2 and B3 are the building control system equation set coefficients. This gives the following expression:

$$\phi_p = \frac{\theta_s - (B3/B1)}{1/(\dot{m}C_p) - (B2/B1)}. \qquad \text{(B.9)}$$

In the second method, if 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 the component theoretical model (i.e. the coefficient generator for the radiator component). Note that in both heat transfer calculation methods, θ_a can be calculated directly, or in the case of a building only configuration with mixed radiative/convective plant flux, the B1, B2, and B3 coefficients are modified by successive iteration until θ_a is within a set tolerance. The resulting ϕ_p will then be the total convective/radiative flux. Note also that in the case where a component containment is a building zone and that *BCL06* is not specified, then this will only effect the plant component performance since the building is effectively de-coupled from the plant system.

The final coupling type is for coupling *multiple* plant component supply and extract components. A weighted enthalpy average [Kelly 1997]

$$\theta_{av} = \frac{\dot{m}C\theta_{(1)} + \dot{m}C\theta_{(2)} + \ldots + \dot{m}C\theta_{(n-1)} + \dot{m}C\theta_{(n)}}{\dot{m}C_{(1)} + \dot{m}C_{(2)} + \ldots + \dot{m}C_{(n-1)} + \dot{m}C_{(n)}} \qquad \text{(B.10)}$$

is substituted for θ_s in Equation B.7 to allow determination of the net energy supply.

BCL08: Variable Supply Temperature Controller.

This is an ideal constant air volume (CAV) controller model.

The building control system equation set,

$$B1\theta_c + B2q_p = B3 \qquad \text{(B.11)}$$

is re-expressed in the following form:

$$B1\theta_c + B2\rho\dot{V}C_p(\theta_s - \theta_c) = B3 \qquad \text{(B.12)}$$

where θ_c is the specified zone control set-point temperature (°C), ρ *and* $\dot{V}_c$ are the density and the dry air volumetric flow rate entering the zone (kg/m^3 and m^3/s respectively), C_p is the specific heat of air at constant pressure (J/kg.K), θ_s is the supply air temperature (°C) and B1, B2 and B3 are the building control system equation set coefficients.

Rearranging, gives:

$$\theta_s = \frac{[B3 - (B1 - B2\rho\dot{V}C_p)\theta_c]}{B2\rho\dot{V}C_p}. \qquad \text{(B.13)}$$

The future time-row zone control point temperature, θ_c, may then be evaluated from

$$\theta_c = \frac{B3 - (B2\rho\dot{V}C_p\theta_s)}{(B1 - B2\rho\dot{V}C_p)}. \qquad \text{(B.14)}$$

The future time-row flux injection is then evaluated from

$$q_p = \rho\dot{V}C_p(\theta_s - \theta_c). \qquad \text{(B.15)}$$

B3.2 PLANT CONTROL FUNCTIONS.

PCL00 Switch off controller.

During an active control period, this controller acts to switch the specified actuator by setting all the plant control variables to zero.

No miscellaneous data items are required for this control function.

PCL01/2 Dynamic set point algorithm.

The following humidity control set point algorithm [Kelly 1997] utilises sensed return and supply enthalpies to calculate the supply conditions required to attain the set point conditions in a year-round air handling unit.

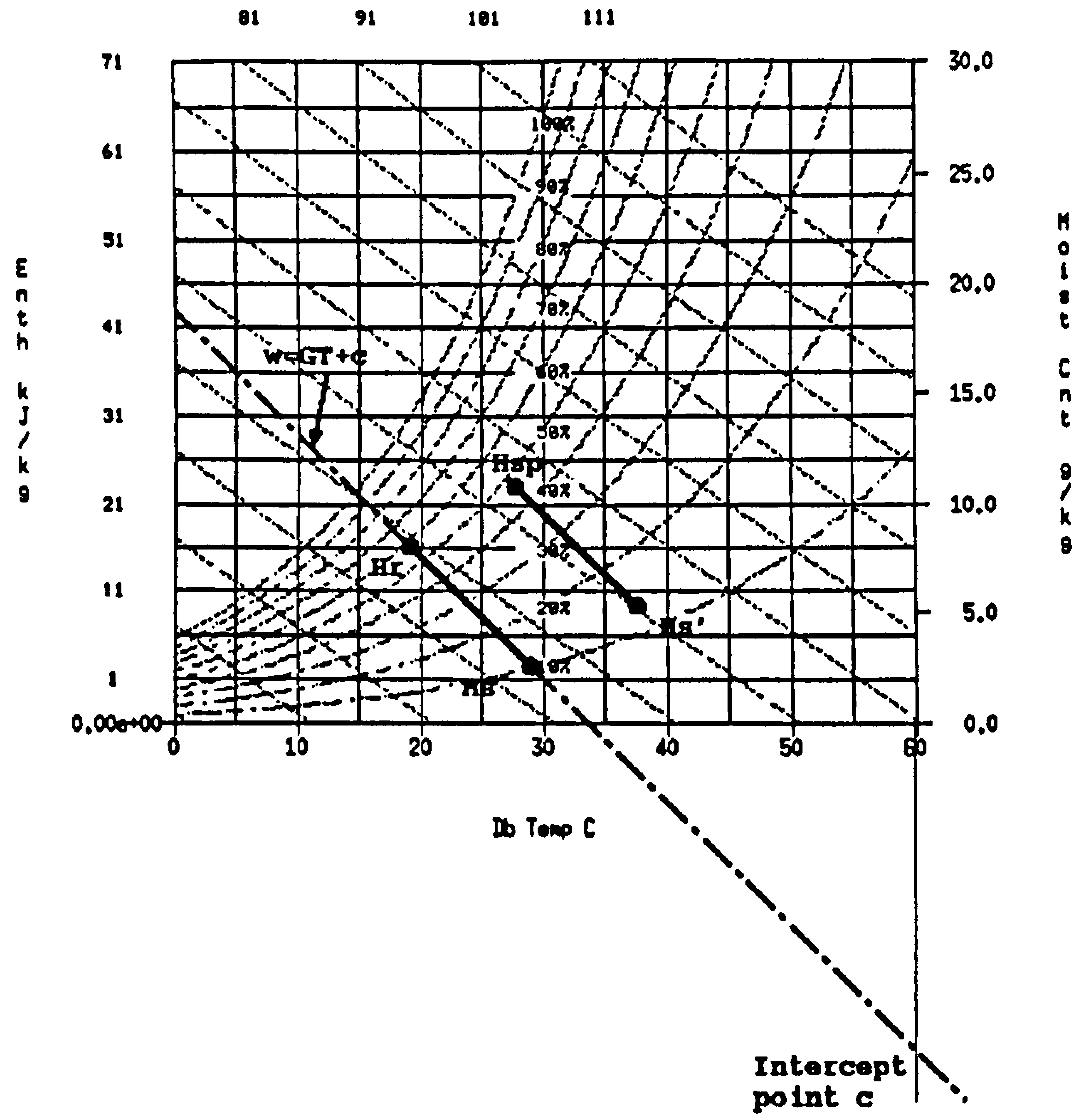


Figure B.22 Diagram of Psychrometric Processes.

The four enthalpies used in the calculation are shown on the psychrometric chart of Figure B.22, H_S - current supply conditions enthalpy, H_R - current return conditions enthalpy, H_{SP} - set point conditions enthalpy and $H_{S'}$ - future supply enthalpy. The known conditions are current supply and return as well as control set point, these properties can be used to calculate the future supply conditions. However to do this two assumptions must be made: firstly the enthalpy drop across supply and return will be the same at set point as at current conditions; secondly, the gradient of the supply-return line G will be the same at set point conditions. Using these assumptions and enthalpy values a value for $H_{S'}$ can now be calculated.

$$\Delta H_{RS} = H_R - H_S \tag{B.16}$$

$$\Delta H_{SPS'} = H_{SP} - H_{S'} \tag{B.17}$$

Assume that;

$$\Delta H_{SPS'} = \Delta H_{RS} \tag{B.18}$$

hence;

$$H_R - H_S = H_{SP} - H_{S'} \tag{B.19}$$

Re-arranging Equation (B.19) the equation for $H_{S'}$ is obtained:

$$H_{S'} = H_S + (H_{SP} - H_R) \tag{B.20}$$

Here the term $H_{SP} - H_R$ represents the error between desired and actual conditions.

Once the value of $H_{S'}$ is known, the set point conditions can be evaluated in terms of temperature and enthalpy. These properties can be used as the set point for an after heater and humidifier in an air-conditioning system.

The line passing through H_S and H_R has a gradient G which is calculated from;

$$G = \frac{w_R - w_S}{T_R - T_S} \tag{B.21}$$

T -temperature, w - moisture content.

As stated earlier the assumption is made that the line passing through $H_{S'}$ and H_{SP} will have the same gradient. The equation of the line is;

$$w = GT + C \tag{B.22}$$

Knowing that the set point SP lies on this line thus allows the calculation of the value of c.

$$c = w_{SP} - GT_{sp} \tag{B.23}$$

$H_{S'}$ which lies upon the line described by Equation (B.22) can be expressed in terms of temperature and moisture content by the equation;

$$H_{S'} = c_p T_{S'} + w_{S'} H_g \tag{B.24}$$

H_g can be approximated to;

$$H_g = 2501 + 1.82T \tag{B.25}$$

Substitution then gives an expression for $H_{S'}$ is obtained purely in terms of temperature;

$$H_{S'} = c_p T_{S'} + w_{S'}(2501 + 1.82T_{S'}) \tag{B.26}$$

This is a quadratic expression of the form

$$1.82G(T_{S'})^2 + (c_p + 1.82c + 2501G)T_{S'} - H_{S'} = 0 \tag{B.27}$$

$$T_{S'} = \frac{-B + \sqrt{Bsup2 - 4AC}}{2A}$$

Where;

$$B = c_p + 1.82c + 2501G \tag{B.28}$$

$$A = 1.82G \tag{B.29}$$

$$C = 2501c - H_{S'} \tag{B.30}$$

The temperature is then found from the positive root of Equation (B.27). The moisture content at the set point is found from back substitution of $T_{S'}$ into Equation (B.22).

Determination of Pre-heat Set Point.FR

Using information from the determination of the supply set points it is possible to determine the temperature set point for the pre-heater. The algorithm assumes, firstly, that the supply air is initially pre-heated and then humidified to 100% relative humidity, and, secondly, that humidification takes place at constant enthalpy - an approximation for constant wet bulb temperature - as shown in Figure B.23 below.

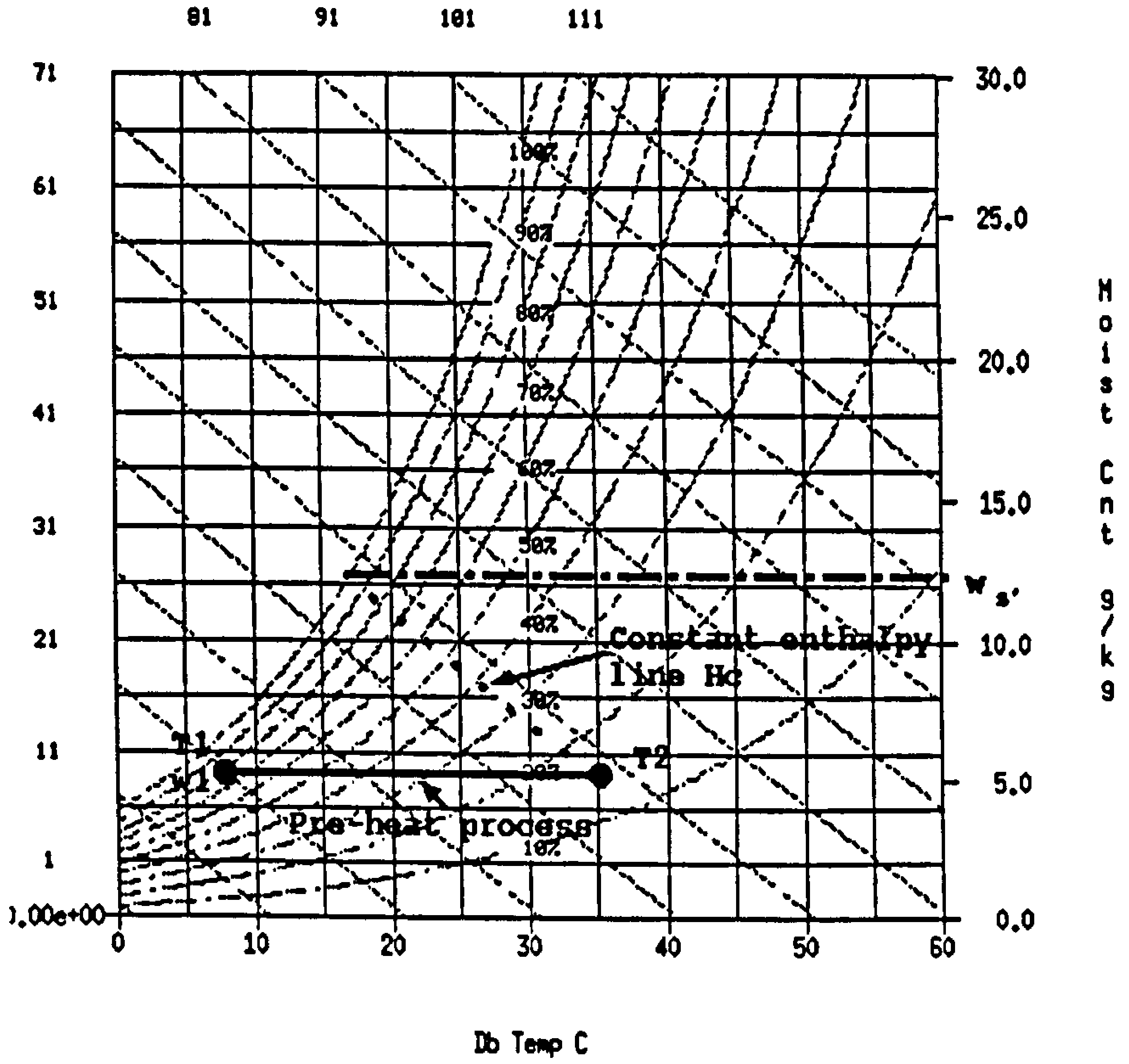


Figure B.23 Diagram of psychrometric processes in pre-heat

From the supply set point algorithm, the value of the supply moisture content $w_{S'}$ is calculated. The value of the constant enthalpy H_c is found where the horizontal line $w = w_{S'}$ cuts the 100% relative humidity curve. The value of H_c is determined using ESP-r psychrometric library routines. The value of the preheat set point T_2 is determined by the point where the line $w = w_1$ (moisture content prior to pre-heat) cuts the line of constant enthalpy H_c. Again the point T_2 is determined using ESP-r psychrometric library routines.

PCL03: Numerical controller.

This function models a basic proportional controller which acts to control some numerical value on the basis of the sensed condition. Controller hysteresis is an option with this function.

PCL05: Proportional damper controller.

This controller acts to modulate dampers according to a linear (proportional) relationship, within limiting constraints, to allow minimum and maximum damper positions.

B3.3 FLUID FLOW CONTROL FUNCTIONS.

Fluid flow network components and/or connections may have variables which are subjected to some control strategy. Control functions establish some sensed condition (based on latest computed values), process it according to the active control logic and return the result for processing by the flow-side solvers.

FCL00: ON-OFF controller.

This controller acts to switch fluid flow components or fluid flow connections ON/OFF according to the sensed conditions.

References.

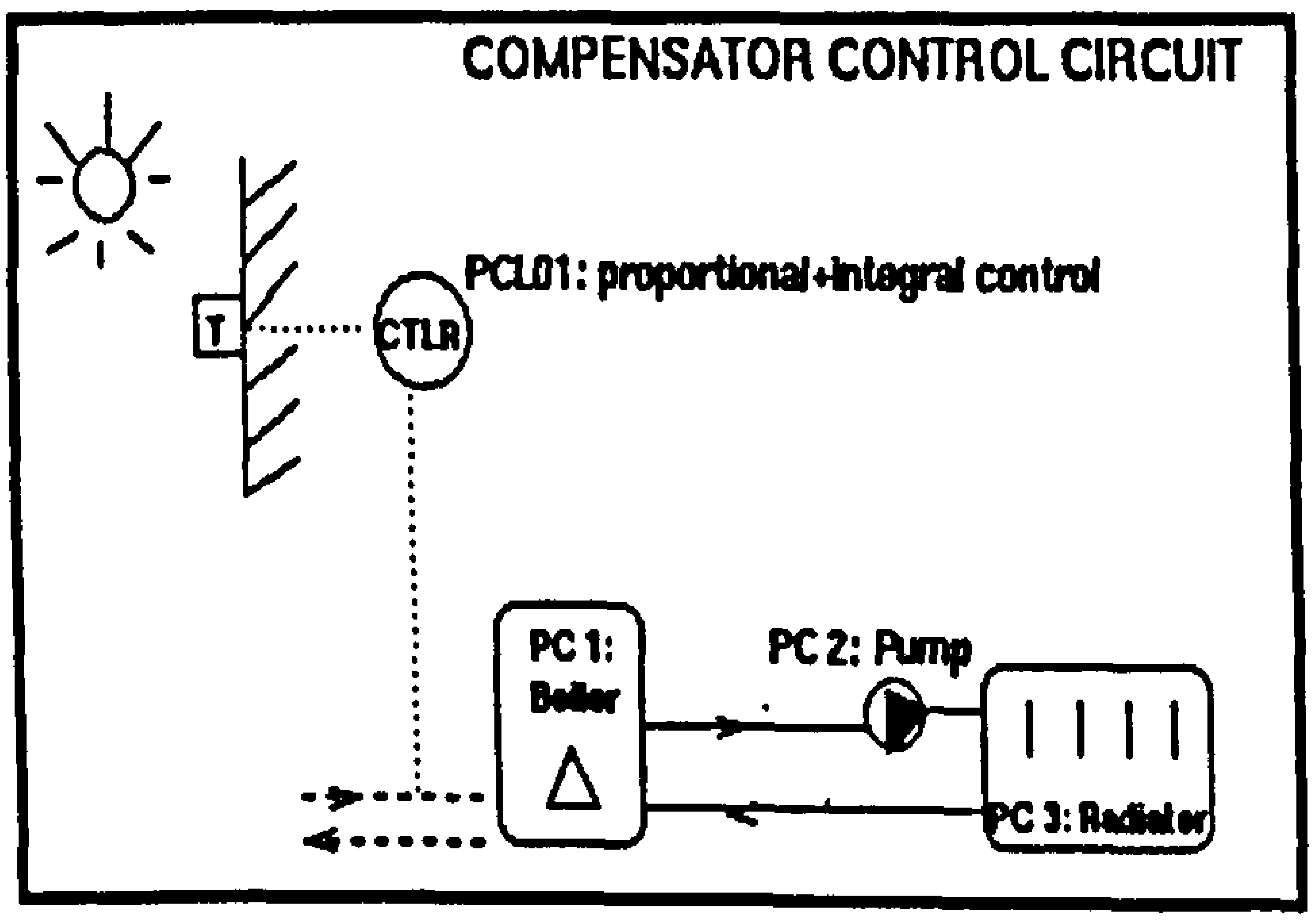
Kelly, N.J., 1997. *'Ph.D Thesis to be submitted'*, ESRU, University of Strathclyde, Glasgow.

Incropera, F.P., and De Witt, D., 1990, *Introduction to heat transfer*, Wiley, New York.

APPENDIX C: ESP-r META CONTROLLER LIBRARY

C.1 ESP-r META CONTROLLER LIBRARY.

A selection from the ESP-r meta controller library is presented here.



LEGEND.

CTLR:	Controller
T:	Outside temperature sensor
PC:	Plant component
BC:	Boiler component (==PC1)
ud:	User defined.
IAT:	Integral action time
DAT:	Derivative action time
PB:	Proportional band

META CONTROLLER DATABASE ENTRY.

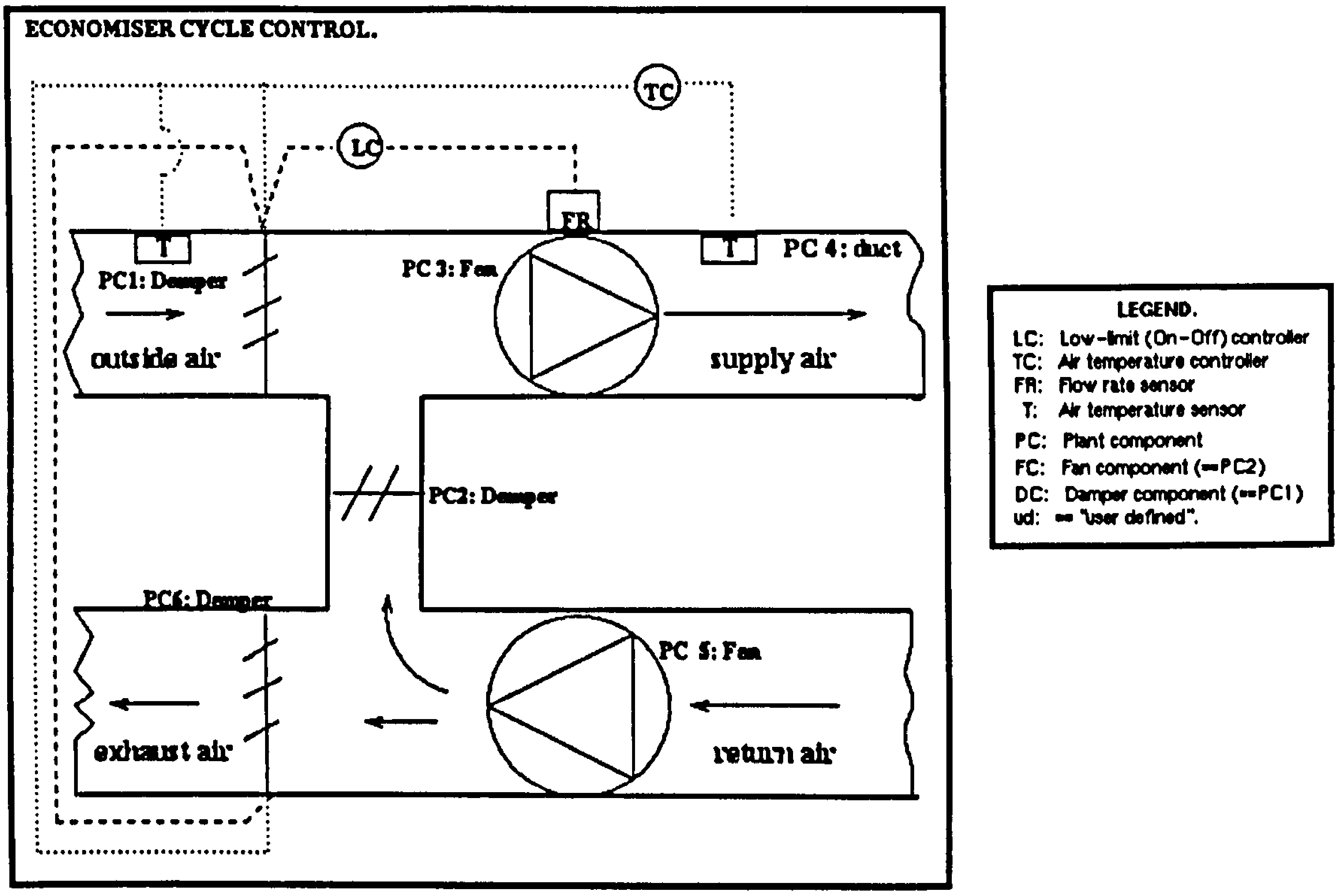
Meta controller type:	Compensation control.
Number of loops:	1
For loop 1:	
Sensor details:	-3 0 0 0
Actuator details:	-1 BC1 0
Controller type:	0
Control law:	1
No. of misc. data items:	7
Default misc data:	1, 10000, 0, 80, 10, 0, 0

MAPPING ON TO SYSTEM CONTROL CONFIGURATION FILE.

```
Problem title.           # COMPENSATOR
* Plant                  # Plant-side control loop
Compensator control.
  1                      # Number of control loops
* Control loops
 -3 0 0 0                # sensor located outside
 -1 1 1 0                # actuator located at boiler, node 1.
    ud                   # number of day types (user defined)
# For each day type:
    1                    # number of control periods
  ud ud                  # start day ; finish day (user-defined)
 0 1 0.                  # ctlr type 0; lavl ; period start:00.00
    7                    # no. of misc data items
 1 10000,0,80,10,0,0 # mode; Qmax; Qmin; Set-point; PB; IAT; DAT
```

Figure C.1 *MC01:* Compensator Meta Controller.

C2



META CONTROLLER DATABASE ENTRY

```
Meta controller type:     Economiser control.
Number of loops:          3

For loop 1:
Sensor details:           -1 FC 1 0
Actuator details:         -1 DC 1 0
Controller type:          14
Control law:              8
No. of misc. data items:  7
Default misc data:  -1,0.001,0.,1.,0.,0,0
For loop 2:
Sensor details:           -1 SD 1 0
Actuator details:         -1 DC 1 0
Controller type:          12
Control law:              8
No. of misc. data items:  7
Default misc data:  -1,30.0.,20.,1.,0.,0,0

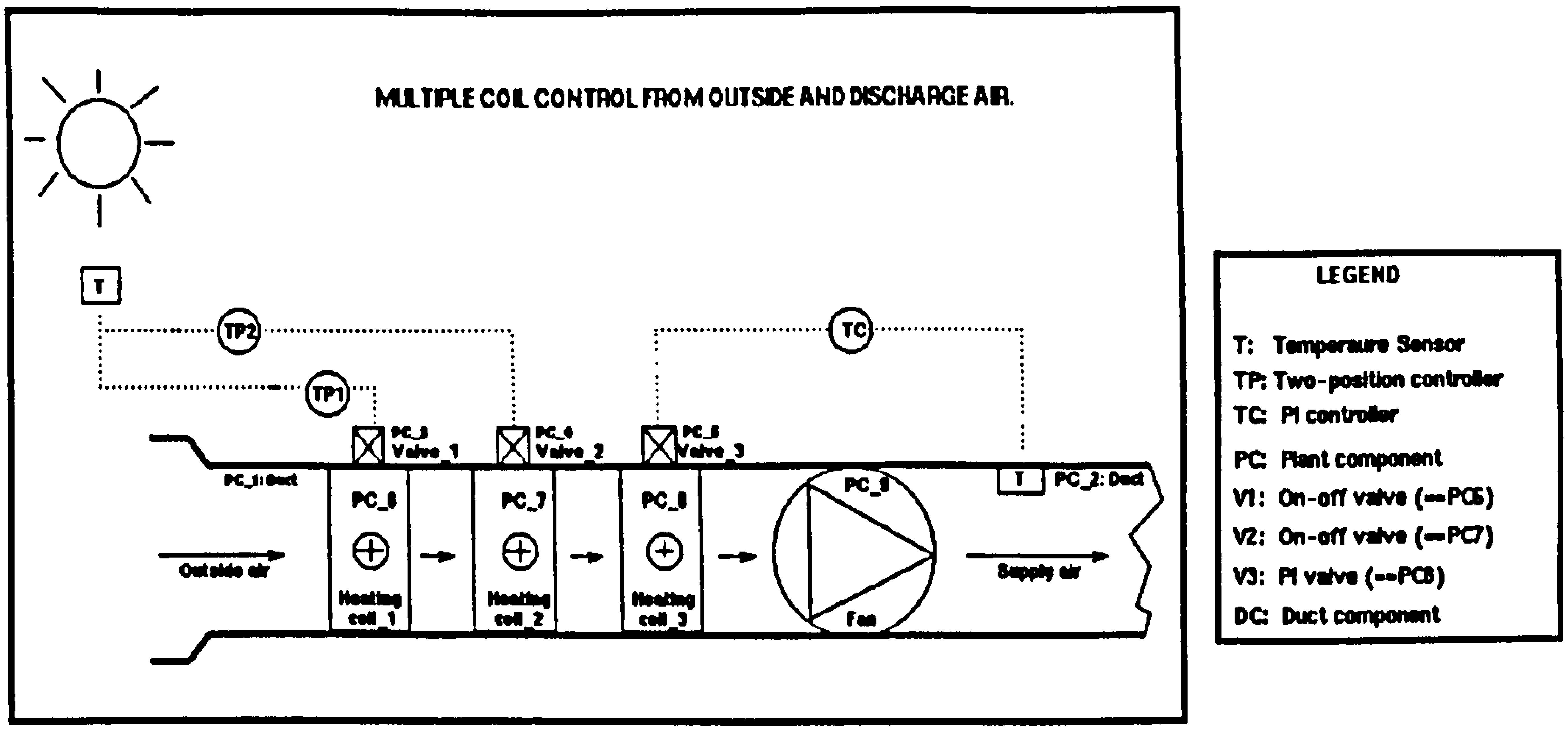
For loop 3:
Sensor details:           -1 SD 1 0
Actuator details:         -1 DC 1 0
Controller type:          12
Control law:              8
No. of misc. data items:  7
Default misc data:  1,30.0.,20.,1.,0.,0,0
```

MAPPING ON TO SYSTEM CONTROL CONFIGURATION FILE.

```
Problem title.              ECONOMISER
 * Plant
  3                         # Number of control loops
 * Control loops            # Control loop 1
  -1 3 1 0                  # sensor located at fan component.
  -1 1 1 0                  # actuator located at damper.
     ud                     # number of day types
# For each day type:        # start day ; finish day
   ud  ud
     1                      # number of control periods.
  14  8  0.                 # ctlr type 14; law 8    period start:00.00
     7                      # no. of misc data items;
-1,0.0001,0.,1.,0.,0,0      # misc data items .....
 * Control loops            # Control loop 2
  -1 4 1 0                  # sensor located at duct.
  -1 1 1 0                  # actuator located at damper.
     ud                     # number of day types
# For each day type:        # start day ; finish day
   ud  ud                   # number of control periods.
     1
  12  8  0.                 # ctlr type 12; law 8   ; period start:00.00
     7                      # no. of misc data items
-1,30.0,20.,1.,0.,0,0       # misc data items .....

 * Control loops            # Control loop 3
  -1 7 1 0                  # sensor located at duct.
  -1 6 1 0                  # actuator located at damper.
     ud                     # number of day types
# For each day type:        # start day ; finish day
   ud  ud
     1                      # number of control periods.
  12  8  0.                 # ctlr type 12; law 8   ; period start:00.00
     7                      # no. of misc data items
1,30.0, 20.,1.,0.,0,0       # misc data items .....
```

Figure C.2 *MC02:* Economiser Meta Controller.



Meta controller type: Multiple coil control.
Number of loops: 3

For loop 1:
Sensor details: -3 0 0 0
Actuator details: -1 V1 1 0
Controller type: 12
Control law: 8
No. of misc. data items: 7
Default misc data: 1,5,7,1,0,0,0

For loop 2:
Sensor details: -3 0 0 0
Actuator details: -1 V2 1 0
Controller type: 12
Control law: 8
No. of misc. data items: 7
Default misc data: 1,1,5,1,0,0,0

For loop 3:
Sensor details: -1 DC 1 0
Actuator details: -1 V3 1 0
Controller type: 2
Control law: 2
No. of misc. data items: 7
Default misc data: 1,0.001,0,20,3,0,0

```
Problem title.                 MULTIPLE COIL CONTROL
 * Plant
  3                            # Number of control loops
 * Control loops               # Control loop 1
  -3 0 0 0                     # sensor located outside.
  -1 1 1 0                     # actuator located at on-off valve_1
     ud                        # number of day types (user-defined)
# For each day type:
    ud  ud                     # start day ; finish day (user-defined)
      1                        # number of control periods.
  12  8  0.                    # ctlr type 12; law 8   period start:0.00
     7                         # no. of misc data items;
 1,10,18 1,0,0,0               # misc data items .....

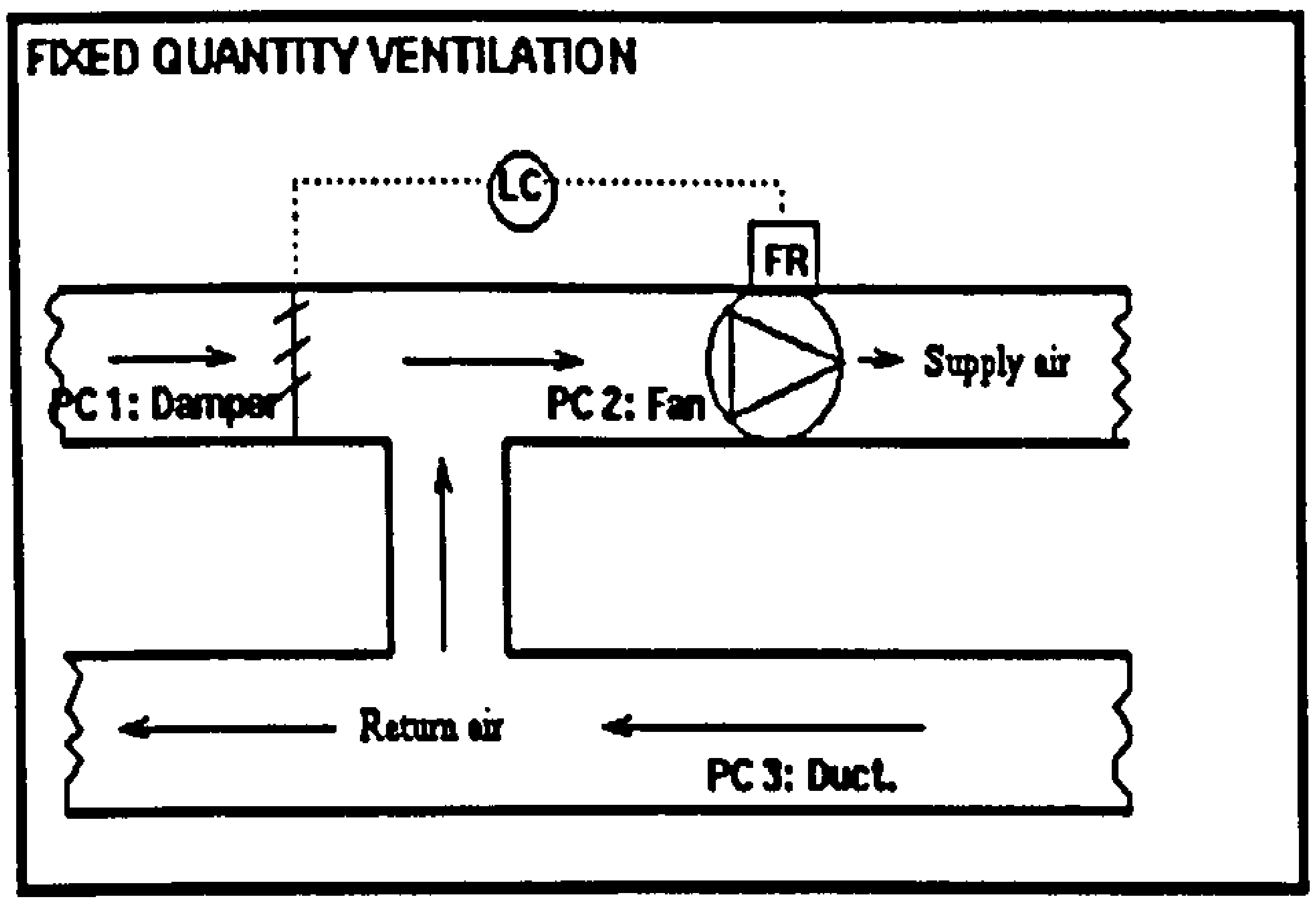
 * Control loops               # Control loop 2
  -3 0 0 0                     # sensor located outside.
  -1 1 1 0                     # actuator located at on-off valve_2.
     ud                        # number of day types (user-defined)
# For each day type:
    ud  ud                     # start day ; finish day (user-defined)
      1                        # number of control periods.
  12  8  0.                    # ctlr type 1; law 8  ;period start:0.00
     7                         # no. of misc data items
 -1,5 10,1,0,0,0               # misc data items .....

 * Control loops               # Control loop 3
  -1 2 1 0                     # sensor located at duct component.
  -1 1 1 0                     # actuator located at PI control valve_3.
     ud                        # number of day types (user-defined)
# For each day type:
    ud  ud                     # start day ; finish day (user-defined)
      1                        # number of control periods.
  2  2  0.                     # ctlr type 2; law 2   ; period start:0.00
     7                         # no. of misc data items
 1,0.001,0,20,3,0 0            # misc data items .....
```

META CONTROLLER DATABASE ENTRY | MAPPING ON TO SYSTEM CONTROL CONFIGURATION FILE.

Figure C.3 *MC03:* Multiple Coil Meta Controller.

c4



LEGEND.

LC: Low-limit (On-Off) controller
FR: Flow rate sensor
PC: Plant component
FC: Fan component (==PC2)
DC: Damper component (==PC1)
ud: == "user defined".

Meta controller type: Fixed quantity ventilation control.

Number of loops: 1

For loop 1:

Sensor details: -1 FC 1 0
Actuator details: -1 DC 1 0

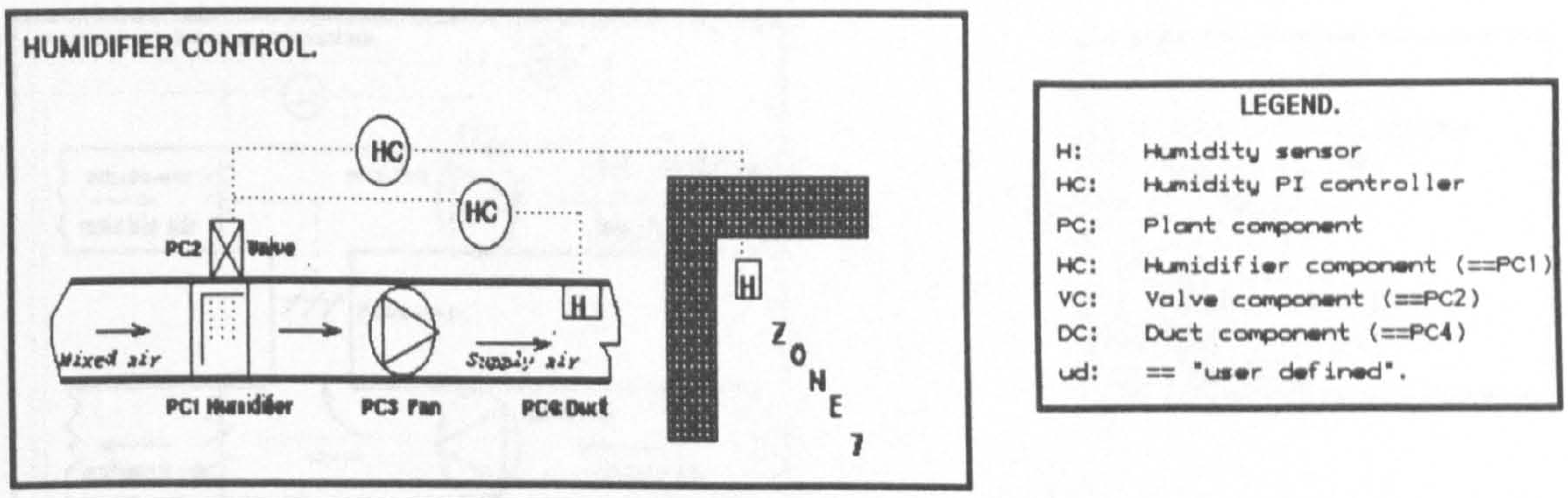
Controller type: 14
Control law: 8
No. of misc. data items: 7
Default misc data: -1, 1, 0.0001, 0, 0, 0

META CONTROLLER DATABASE ENTRY.

```
Problem title.          FIXED QUANTITY VENTILATION CONTROL
* Plant                 # Plant-side control loop
 Fixed quantity ctl.
  1                     # Number of control loops
* Control loops
 -1  2  1  0            # sensor located at fan component.
 -1  1  1  0            # actuator located at damper.
    ud                  # number of day types
# For each day type:    # start day ; finish day
   ud  ud
    1                   # number of control periods.
 14  8   0.             # ctlr type 14; law 8 period start:00.00
     7                  # no. of misc data items
 -1, 1, 0.0001, 0, 0, 0 # mode; o/p hi, o/p lo, act dealy, sen delay
```

MAPPING ON TO SYSTEM CONTROL CONFIGURATION FILE.

Figure C.4 *MC04:* Fixed Outdoor Air Quantity Meta Controller.



LEGEND.

H:	Humidity sensor
HC:	Humidity PI controller
PC:	Plant component
HC:	Humidifier component (==PC1)
VC:	Valve component (==PC2)
DC:	Duct component (==PC4)
ud:	== "user defined".

META CONTROLLER DATABASE ENTRY.

```
Meta controller type:        Humidity controller.
Number of loops:             2
For loop 2:
Sensor details:              -1  DC 1  0
Actuator details:            -1  VC 1  0

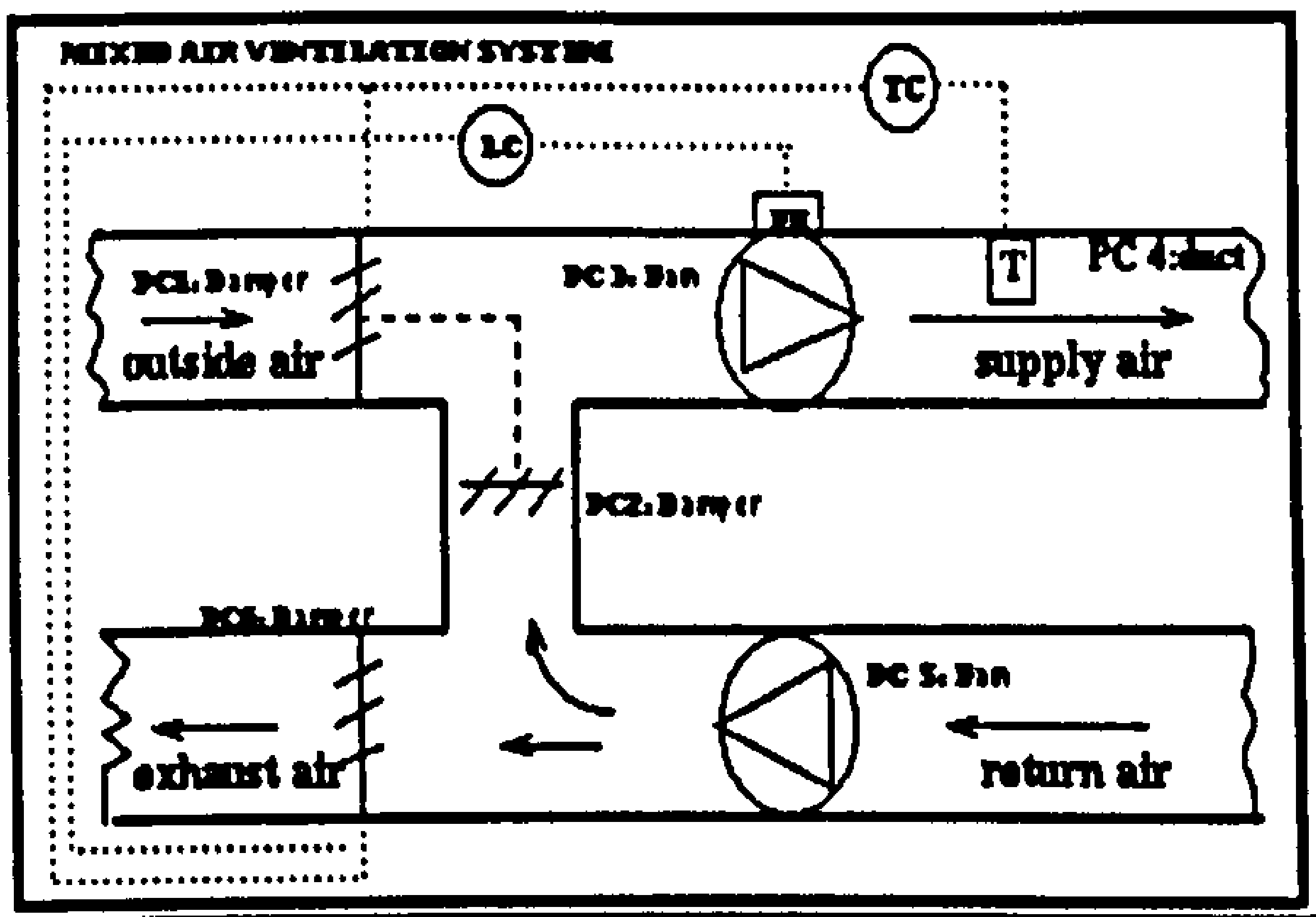
Controller type:             23
Control law:                  2
No. of misc. data items:      7
Default misc data:       -1, 0.001., 0., 1., 0., 0, 0
For loop 2:
Sensor details:               7  0  0  0
Actuator details:            -1  VC 1  0

Controller type:             23
Control law:                  8
No. of misc. data items:      7
Default misc data:       -1, 0.001, 0, 1, 0, 0, 0
```

MAPPING ON TO SYSTEM CONTROL CONFIGURATION FILE.

```
Problem title.                    HUMIDITY CONTROLLER.
 * Plant
Preheat discharge ctl.
  2                               # Number of control loops
* Control loops                   # 1st control loop:
-1  4  1  0                       # sensor located in duct.
-1  2  1  0                       # actuator located at valve.
     ud                           # number of day types
# For each day type:
   ud  ud                         # start day; finish day
        1                         # number of control periods.
23   2   0.                       # ctlr type 23; law 2   ;period start:0.00
     7                            # no. of misc data items
-1, 0.0001, 0., 1., 0., 0, 0      # misc data items
 * Control loops                  # 2nd control loop:
  7  0  0  0                      # sensor located at air point, Zone_7.
 -1  2  1  0                      # actuator located at valve.
      ud                          # number of day types
 # For each day type:
   ud  ud                         # start day; finish day
        1                         # number of control periods.
 23   8   0.                      # ctlr type 1; law 8   ;period start:0.00
      7                           # no. of misc data items
 -1, 0.0001, 0, 1, 0, 0, 0        # misc data items
```

Figure C.5 *MC05:* Humidifier Meta Controller.



LEGEND.

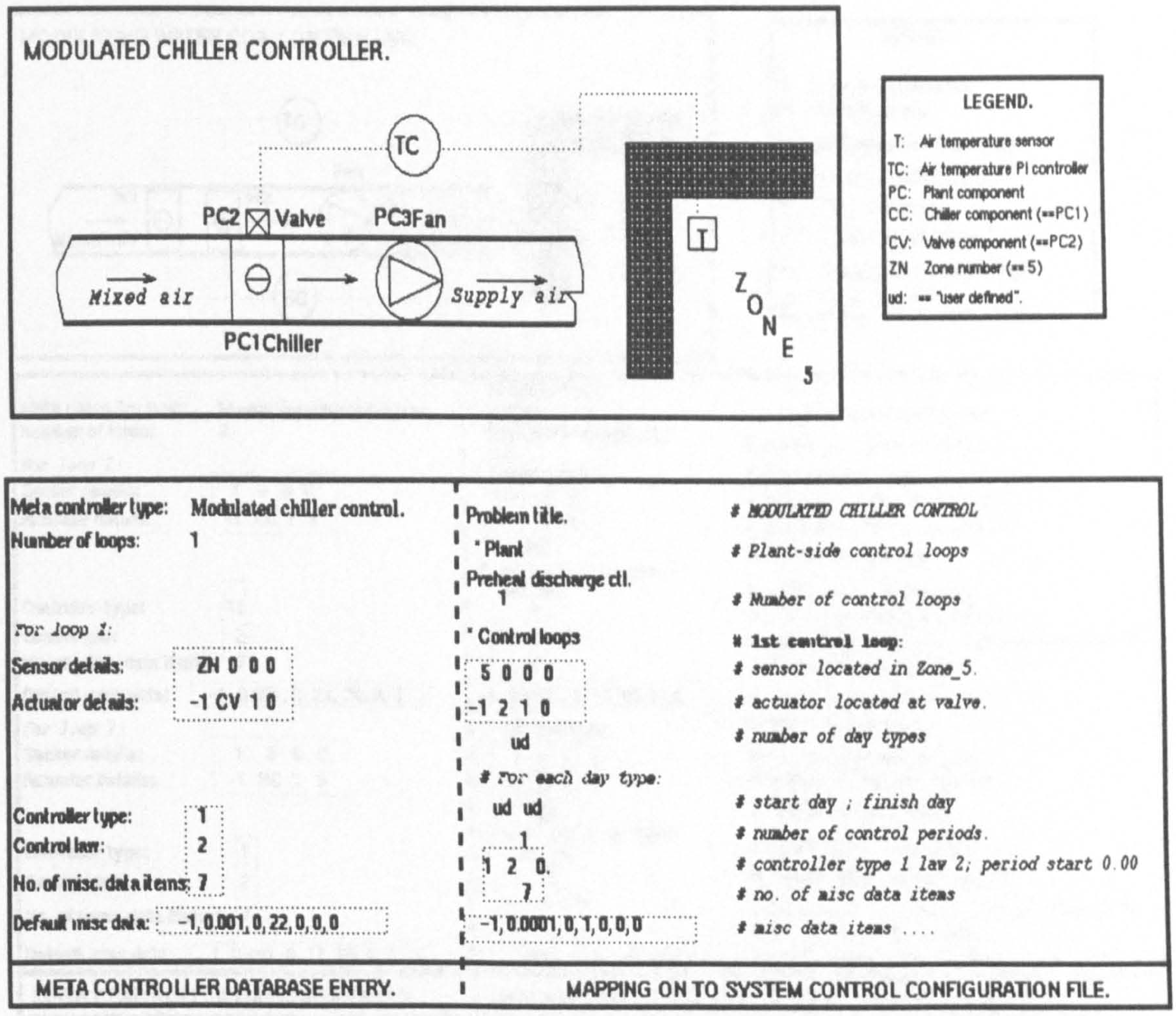
LC: Low-limit (On-Off) controller
TC: Temperature controller
FR: Flow rate sensor
T: Temperature sensor
PC: Plant component
FC: Fan component (=PC2)
DC: Damper component (=PC1)
ud: = "user defined".

Meta controller type:	**Mixed air ventilation control.**
Number of loops:	2
For loop 1:	
Sensor details:	-1 FC 1 0
Actuator details:	-1 DC 1 0
Controller type:	14
Control law:	11
No. of misc. data items:	7
Default misc data:	-1, 0.001., 0., 1., 0., 0, 0
For loop 2:	
Sensor details:	-1 SD 1 0
Actuator details:	-1 DC 1 0
Controller type:	12
Control law:	11
No. of misc. data items:	7
Default misc data:	-1, 0.001., 0., 1., 0., 0, 0

```
Problem title.
* Plant                          # Plant-side control loop
Mixed air vent ctl.
 .1                              # Number of control loops
 * Control loops                 # Control loop 1
  -1  3  1  0                    # sensor located at fan component.
  -1  1  1  0                    # actuator located at damper.
      ud                         # number of day types
# For each day type:             # start day ; finish day
    ud  ud
      1                          # number of control periods.
   14   8    0.                  # ctlr type 14; lav 8   period start:0.00
    7                            # no. of misc data items;
-1, 0.0001, 0., 1., 0., 0, 0     # misc data items .....
* Control loops                  # Control loop 2
   -1  4  1  0                   # sensor located at fan component.
   -1  1  1  0                   # actuator located at damper.
      ud                         # number of day types
# For each day type:             # start day ; finish day
    ud  ud
      1                          # number of control periods.
   12   11   0.                  # ctlr type 14; lav 8 ; period start:0.00
    7                            # no. of misc data items
 -1, 0.0001, 0., 1., 0., 0, 0    # misc data items .....
```

META CONTROLLER DATABASE ENTRY. | MAPPING ON TO SYSTEM CONTROL CONFIGURATION FILE.

Figure C.6 *MC06:* Mixed Air Meta Controller.



META CONTROLLER DATABASE ENTRY.

Meta controller type: Modulated chiller control.
Number of loops: 1

For loop 1:

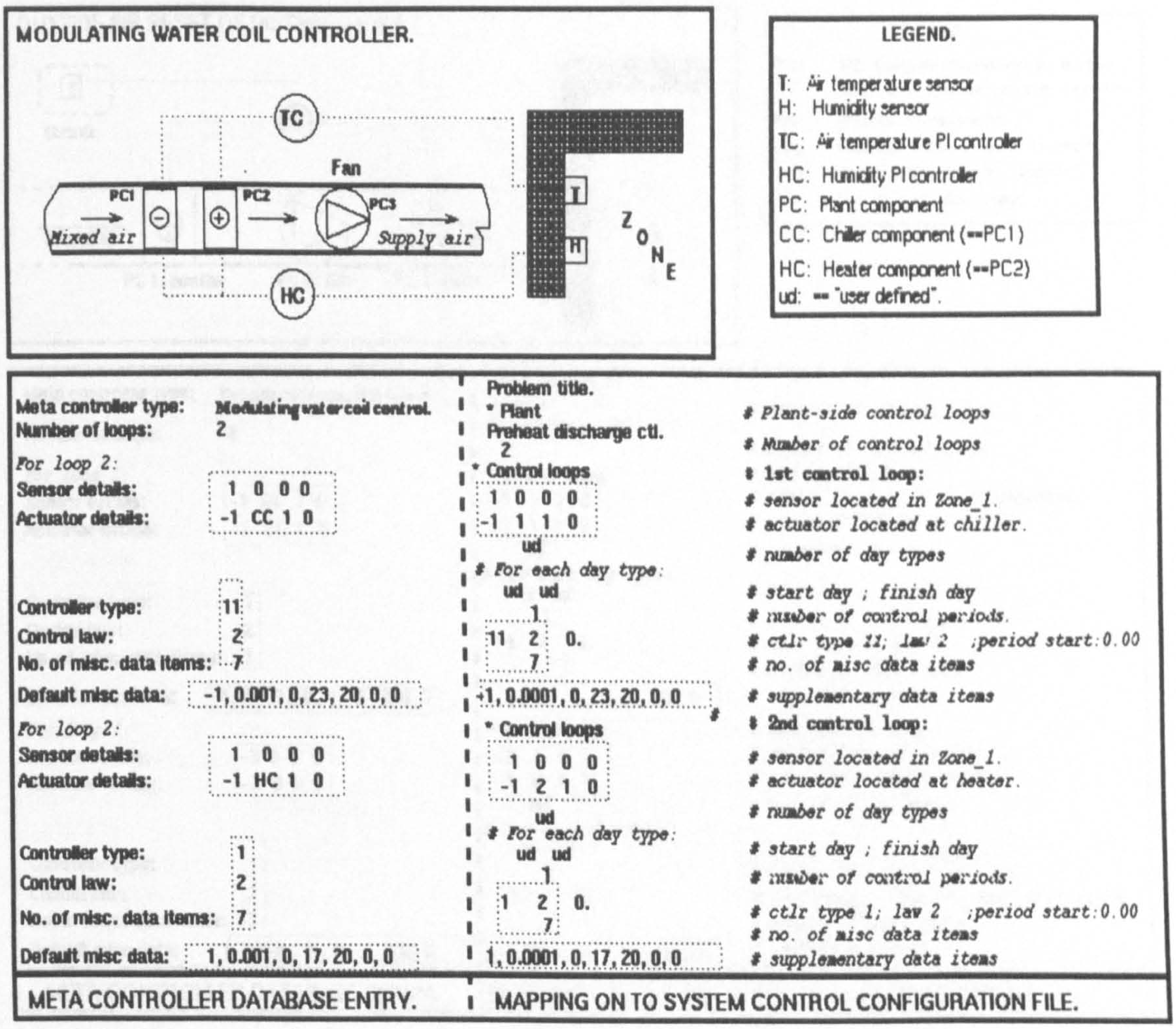
Sensor details: ZN 0 0 0
Actuator details: -1 CV 1 0

Controller type: 1
Control law: 2
No. of misc. data items: 7
Default misc data: -1, 0.001, 0, 22, 0, 0, 0

MAPPING ON TO SYSTEM CONTROL CONFIGURATION FILE.

```
Problem title.                # MODULATED CHILLER CONTROL
 * Plant                      # Plant-side control loops
Preheat discharge ctl.
   1                          # Number of control loops
 * Control loops              # 1st control loop:
 5 0 0 0                      # sensor located in Zone_5.
-1 2 1 0                      # actuator located at valve.
    ud                        # number of day types
  # For each day type:
  ud  ud                      # start day ; finish day
     1                        # number of control periods.
 1  2  0.                     # controller type 1 law 2; period start 0.00
     7                        # no. of misc data items
 -1, 0.0001, 0, 1, 0, 0, 0    # misc data items ....
```

Figure C.7 *MC07:* Modulated Chiller Meta Controller.



LEGEND.

T: Air temperature sensor
H: Humidity sensor
TC: Air temperature PI controller
HC: Humidity PI controller
PC: Plant component
CC: Chiller component (==PC1)
HC: Heater component (==PC2)
ud: == "user defined".

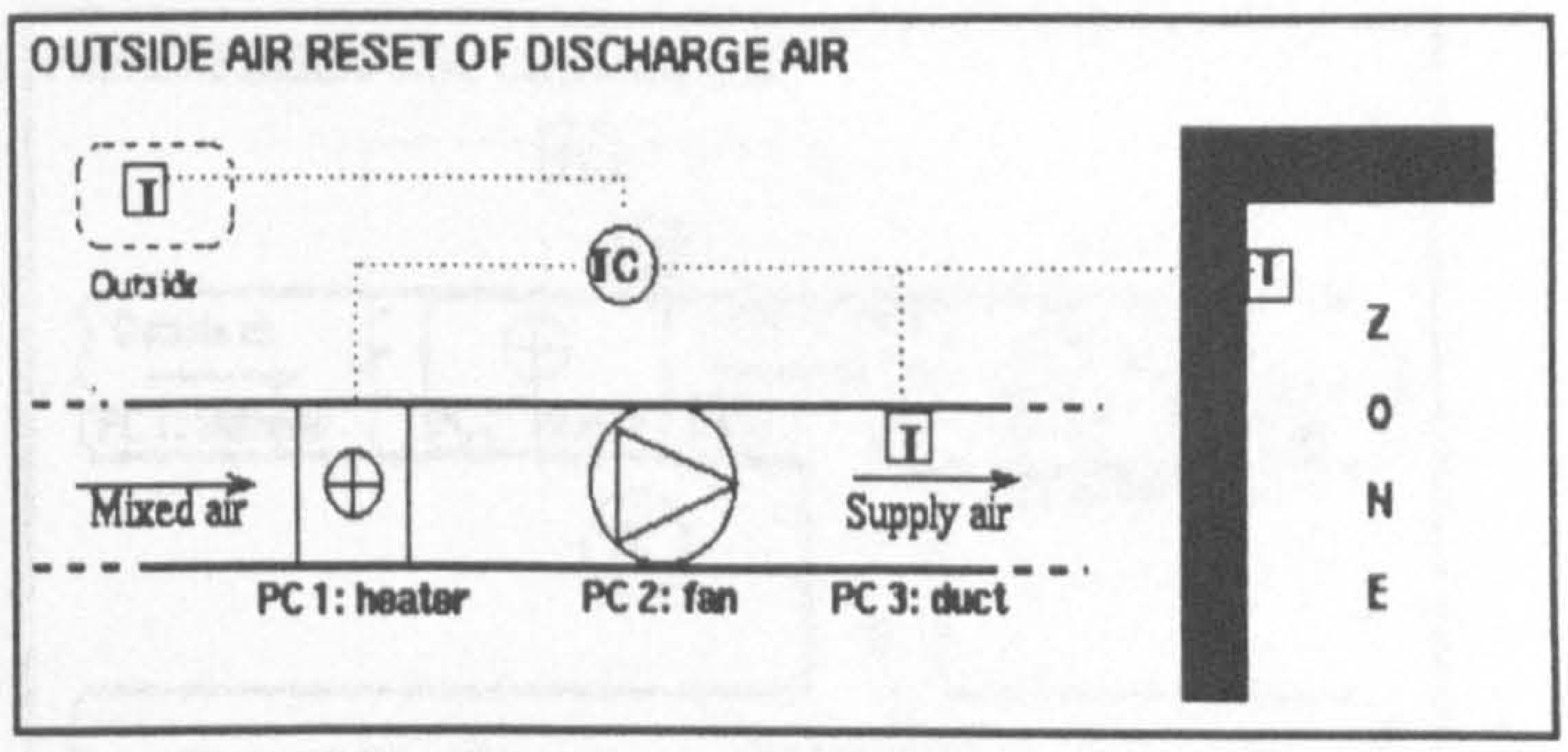
META CONTROLLER DATABASE ENTRY.

Meta controller type:	**Modulating water coil control.**
Number of loops:	2
For loop 2:	
Sensor details:	1 0 0 0
Actuator details:	-1 CC 1 0
Controller type:	11
Control law:	2
No. of misc. data items:	7
Default misc data:	-1, 0.001, 0, 23, 20, 0, 0
For loop 2:	
Sensor details:	1 0 0 0
Actuator details:	-1 HC 1 0
Controller type:	1
Control law:	2
No. of misc. data items:	7
Default misc data:	1, 0.001, 0, 17, 20, 0, 0

MAPPING ON TO SYSTEM CONTROL CONFIGURATION FILE.

```
Problem title.
 * Plant                                  # Plant-side control loops
Preheat discharge ctl.
  2                                       # Number of control loops
* Control loops                           # 1st control loop:
 1  0  0  0                               # sensor located in Zone_1.
-1  1  1  0                               # actuator located at chiller.
    ud                                    # number of day types
# For each day type:
  ud  ud                                  # start day ; finish day
       1                                  # number of control periods.
11   2    0.                              # ctlr type 11; law 2   ;period start:0.00
     7                                    # no. of misc data items
-1, 0.0001, 0, 23, 20, 0, 0               # supplementary data items
                                 #
 * Control loops                          # 2nd control loop:
   1  0  0  0                             # sensor located in Zone_1.
  -1  2  1  0                             # actuator located at heater.
      ud                                  # number of day types
 # For each day type:
    ud  ud                                # start day ; finish day
         1                                # number of control periods.
 1    2    0.                             # ctlr type 1; lav 2   ;period start:0.00
      7                                   # no. of misc data items
1, 0.0001, 0, 17, 20, 0, 0                # supplementary data items
```

Figure C.8 *MC08:* Modulated Water Coil Meta Controller.



LEGEND.

TC: PI temperature controller
T: d.b air temperature sensor
PC: Plant component
HC: Heater component (==PC1)
DC: Duct component (==PC3)
ud: == "user defined".

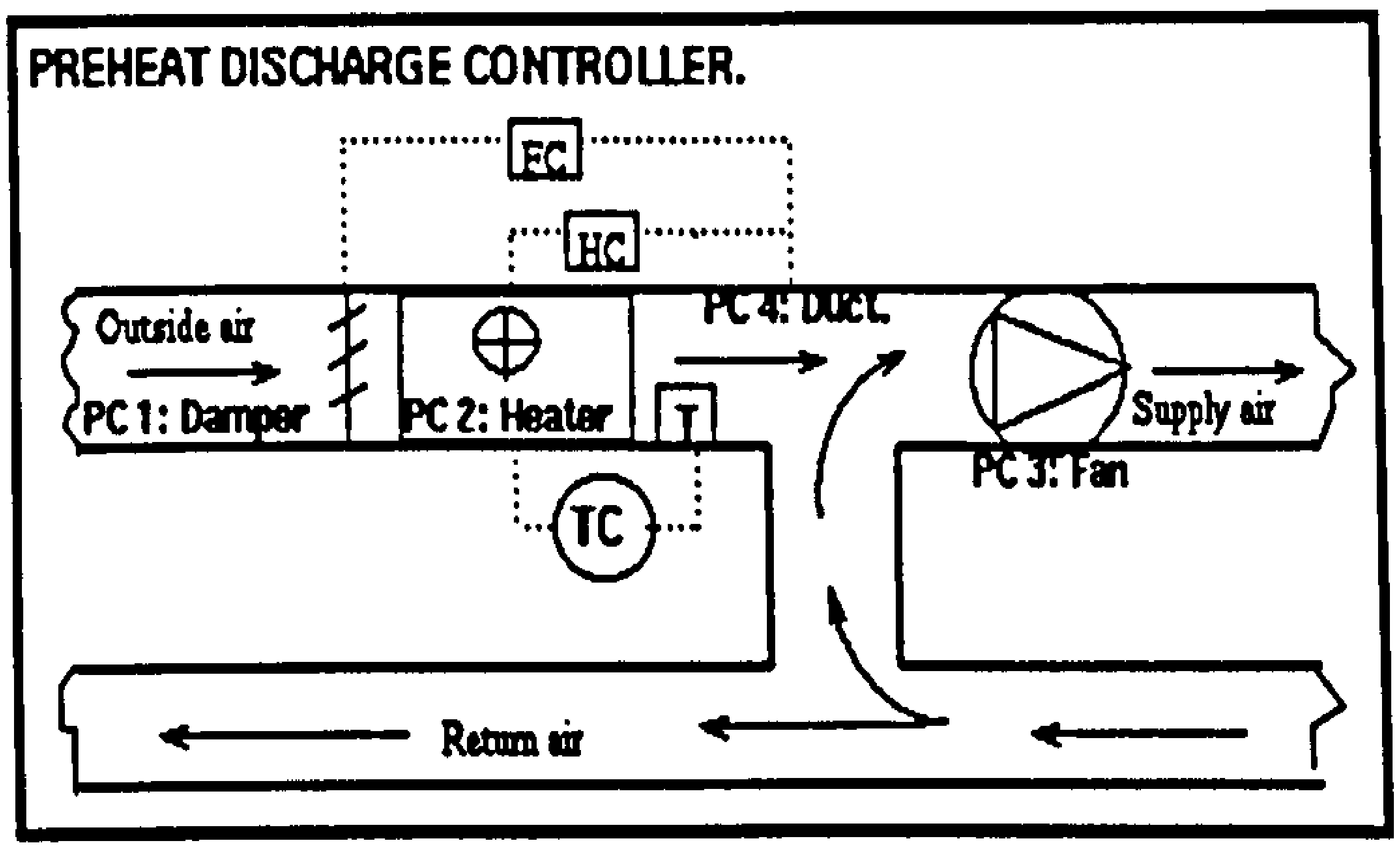
Meta controller type: Outside air temperature reset
Number of loops: 2
For loop 1:
Sensor details: -1 DC 1 0
Actuator details: -1 HC 1 0
Controller type: 1
Control law: 2
No. of misc. data items: 7
Default misc data: 1, 0.001., 0., 1., 0., 900, 0
For loop 2:
Sensor details: -3 0 0 0
Actuator details: -2 0 0 0
Controller type: 1
Control law: 2
No. of misc. data items: 7
Default misc data: 1, 0.001., 0., 1., 0., 900, 0

META CONTROLLER DATABASE ENTRY.

```
Problem title.
 * Plant                              # Plant-side control loop
Outside air reset
  2                                   # Number of control loops
 * Control loops                      # 1st control loop
-1  3  1  0                           # sensor located at duct component.
-1  1  1  0                           # actuator located at heater.
    ud                                # number of day types
# For each day type:
   ud  ud                             # start day ; finish day
      1                               # number of control periods.
 1  2   0.                            # ctlr type 1; law 2 ; prd start:00.00
      7                               # number of data items.
1, 0.0001, 0., 1., 0., 900, 0         # misc data items.
 * Control loops                      # 2nd control loop
-3  0  0  0                           # sensor located outside.
-2  0  0  0                           # cascaded actuator output.
    ud                                # number of day types
# For each day type:
   ud  ud                             # start day ; finish day
      1                               # number of control periods.
 1  2   0.                            # ctlr type 1; law 2 ; prd start:00.00
      7                               # number of data items.
1, 0.0001, 0., 1., 0., 900, 0         # misc data items.
```

MAPPING ON TO SYSTEM CONTROL CONFIGURATION FILE.

Figure C.9 *MC09:* Outside Air Reset Meta Controller.



LEGEND.
T: Air temperature sensor
HC: Air temperature PI controller
FC: Flow rate on-off controller
PC: Plant component
DC: Damper component (==PC1)
HC: Heater component (==PC2)
FC: Fan component (==PC3)
DTC: Duct component (==PC4)
ud: == "user defined".

```
Meta controller type:       Preheat discharge control.
Number of loops:            2
For loop 2:
Sensor details:             -1 DTC 1 0
Actuator details:           -1 PC1 1 0

Controller type:            14
Control law:                8
No. of misc. data items:    7
Default misc data:          1,1,30 34,0,0
For loop 2:
Sensor details:             -1 DTC 1 0
Actuator details:           -1 PC2 1 0

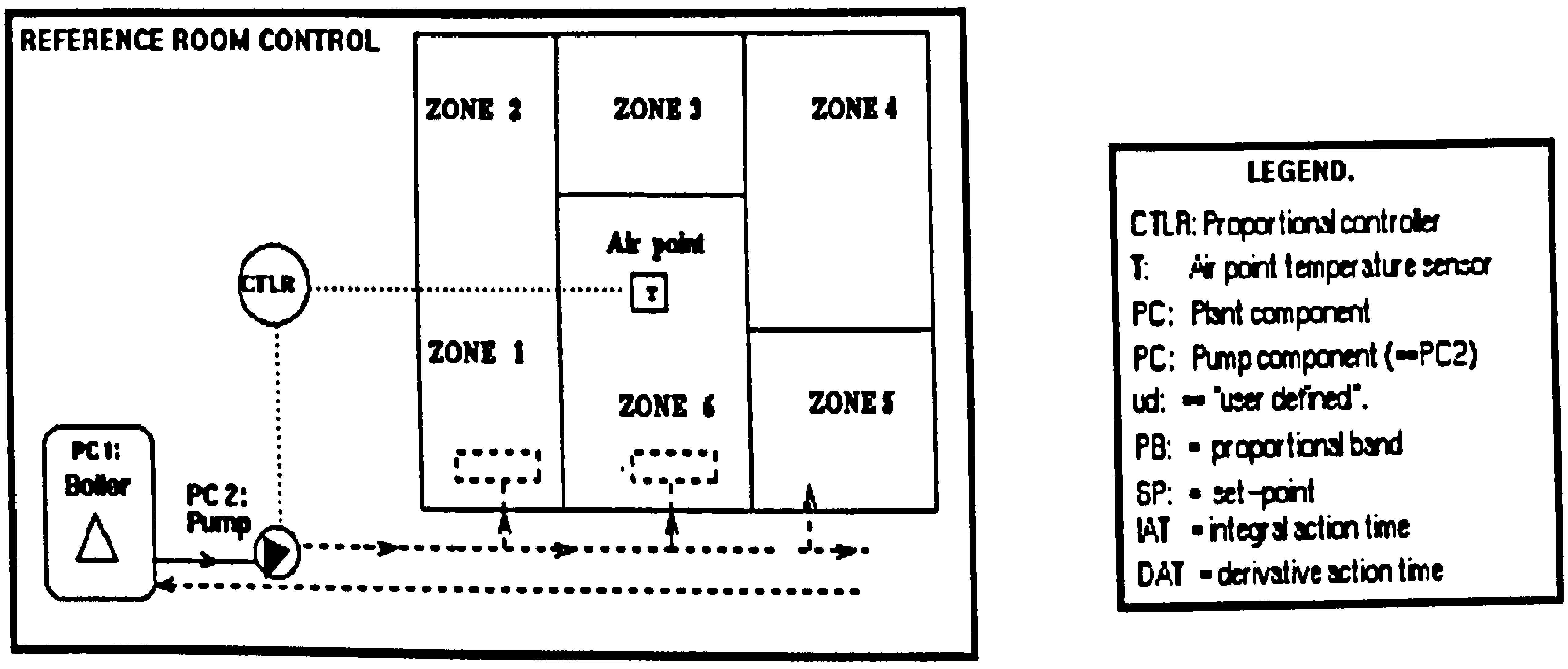
Controller type:            2
Control law:                2
No. of misc. data items:    7
Default misc data:          1,0.001,0,32,4,0,0
```

META CONTROLLER DATABASE ENTRY.

```
Problem title.
 * Plant                        # PREHEAT DISHARGE CONTROL
Preheat discharge ctl.
  2                             # Number of control loops
* Control loops                 # 1st control loop:
-1  3  1  0                     # sensor located at duct component.
-1  1  1  0                     # actuator located at damper.
     ud                         # number of day types
# For each day type:
  ud  ud                        # start day ; finish day
       1                        # number of control periods
14  8   0.                      # ctlr type 14; law 8; period star 0.00
      7                         # no. of misc data items
1,1,0,0.0001,1,0,0              # supplementary data items
 * Control loops                # 2nd control loop:
 -1  4  1  0                    # sensor located at duct component.
 -1  1  1  0                    # actuator located at heater.
     ud                         # number of day types
 # For each day type:
   ud  ud                       # start day ; finish day
       1                        # number of control periods
 2   2   0.                     # ctlr type 2; law 2; period star 0.00
       7                        # no. of misc data items
 1,0.001,0,32,4,0,0             # supplementary data items
```

MAPPING ON TO SYSTEM CONTROL CONFIGURATION FILE.

Figure C.10 *MC10:* Preheat Discharge Meta Controller.



Meta controller type: Reference room control

Number of loops: 1

For loop 1:

Sensor details: 4 0 0 0
Actuator details: -1 PC1 0

Controller type: 1
Control law: 2
No. of misc. data items: 7
Default misc data: 1, 0.001, 0, 21, 3, 0, 0

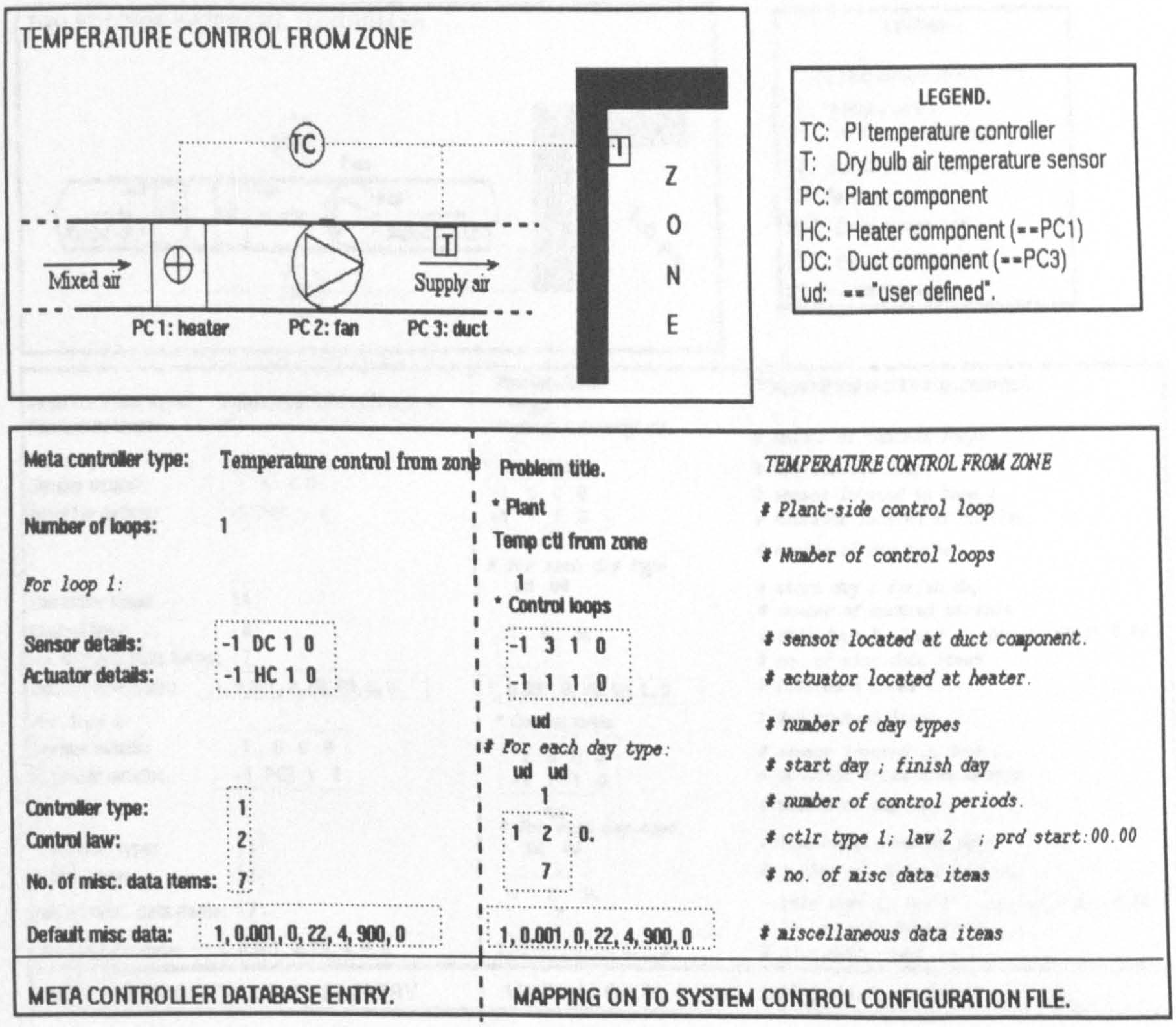
META CONTROLLER DATABASE ENTRY.

```
Problem title.          REFERENCE ROOM CONTROL
* Plant                 # Plant-side control loop
 Ref room temp ctl.
  1                     # Number of control loops
* Control loops
  4 0 0 0               # sensor located at Zone 4 air point.
 -1 2 1 0               # actuator located at pump, node 1.
    ud                  # number of day types
# For each day type:
  ud  ud                # start day ; finish day
    1                   # number of control periods.
  1  2  0.              # ctlr type 1; law 2 ; period start:00.00
     7                  # no. of misc data items
 1 0.001 0 21 3 0 0     # mode; flow max & min; SP; PB; IAT; DAT
```

MAPPING ON TO SYSTEM CONTROL CONFIGURATION FILE.

Figure C.11 *MC11:* Reference Room Meta Controller.

C12



Meta controller type: Temperature control from zone

Number of loops: 1

For loop 1:

Sensor details: -1 DC 1 0

Actuator details: -1 HC 1 0

Controller type: 1

Control law: 2

No. of misc. data items: 7

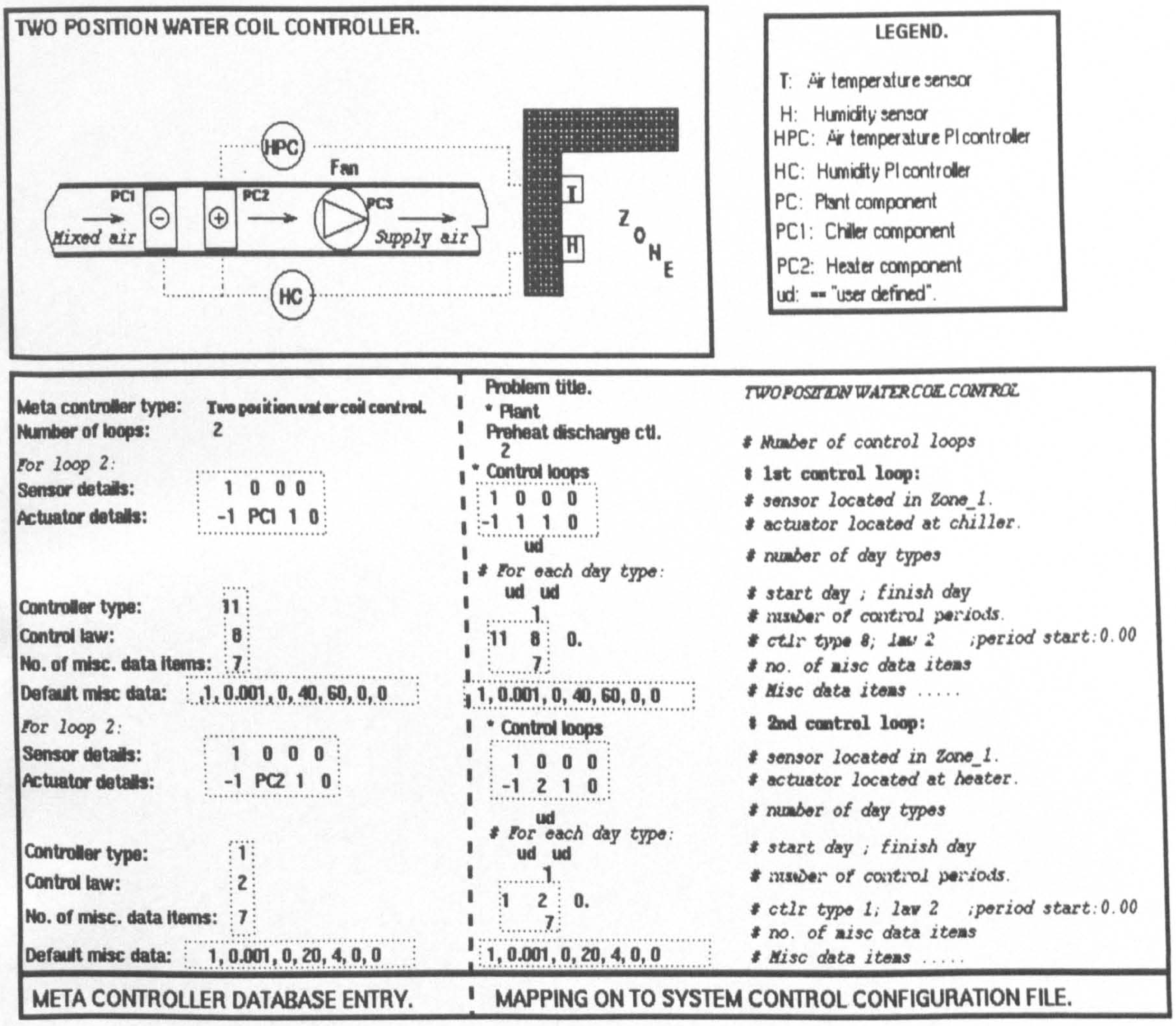
Default misc data: 1, 0.001, 0, 22, 4, 900, 0

META CONTROLLER DATABASE ENTRY.

```
Problem title.                     TEMPERATURE CONTROL FROM ZONE
* Plant                            # Plant-side control loop
Temp ctl from zone
1                                  # Number of control loops
* Control loops
-1 3 1 0                           # sensor located at duct component.
-1 1 1 0                           # actuator located at heater.
ud                                 # number of day types
# For each day type:
ud ud                              # start day ; finish day
1                                  # number of control periods.
1 2 0.                             # ctlr type 1; law 2   ; prd start:00.00
7                                  # no. of misc data items
1, 0.001, 0, 22, 4, 900, 0         # miscellaneous data items
```

MAPPING ON TO SYSTEM CONTROL CONFIGURATION FILE.

Figure C.12 *MC12:* Zone Temperature Reset Meta Controller.



META CONTROLLER DATABASE ENTRY.

Meta controller type: Two position water coil control.
Number of loops: 2

For loop 2:
Sensor details: 1 0 0 0
Actuator details: -1 PC1 1 0
Controller type: 11
Control law: 8
No. of misc. data items: 7
Default misc data: ,1, 0.001, 0, 40, 60, 0, 0

For loop 2:
Sensor details: 1 0 0 0
Actuator details: -1 PC2 1 0
Controller type: 1
Control law: 2
No. of misc. data items: 7
Default misc data: 1, 0.001, 0, 20, 4, 0, 0

MAPPING ON TO SYSTEM CONTROL CONFIGURATION FILE.

```
Problem title.                  TWO POSITION WATER COIL CONTROL
 * Plant
Preheat discharge ctl.
  2                             # Number of control loops
* Control loops                 # 1st control loop:
 1  0  0  0                     # sensor located in Zone_1.
-1  1  1  0                     # actuator located at chiller.
     ud                         # number of day types
# For each day type:
   ud  ud                       # start day ; finish day
       1                        # number of control periods.
11   8    0.                    # ctlr type 8; law 2    ;period start:0.00
       7                        # no. of misc data items
1, 0.001, 0, 40, 60, 0, 0       # Misc data items .....
 * Control loops                # 2nd control loop:
   1  0  0  0                   # sensor located in Zone_1.
  -1  2  1  0                   # actuator located at heater.
     ud                         # number of day types
 # For each day type:
    ud  ud                      # start day ; finish day
        1                       # number of control periods.
 1   2    0.                    # ctlr type 1; law 2    ;period start:0.00
        7                       # no. of misc data items
1, 0.001, 0, 20, 4, 0, 0        # Misc data items .....
```

Figure C.13 *MC13:* Two-position Water Coil Meta Controller.