Building control systems

CIBSE Guide H

CIBSE

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Note from the publisher

This publication is primarily intended to provide guidance to those responsible for the design, installation, commissioning, operation and maintenance of building services. It is not intended to be exhaustive or definitive and it will be necessary for users of the guidance given to exercise their own professional judgement when deciding whether to abide by or depart from it.

Contents

1 Introduction: the need for controls

Summary

This introductory section provides an overview of the Guide and will be of value when preparing the general case for a control system. It demonstrates the importance of controls in ensuring effective and efficient control of a building in order to:

— provide comfortable and productive working conditions

— provide the proper environment for industrial processes

— operate in an energy efficient manner

— be environment friendly.

1.1 Overview of Guide H

The first edition of CIBSE Guide H was published in 1985 as a CIBSE Applications Manual: *Automatic building controls and their implications for systems design*. The many developments since then, particularly in the fields of microprocessor control and communications networks, have necessitated the production of an entirely new edition. The aim of the Guide has been restated since the first edition to reflect the growing importance of IT, and now reads:

> 'to provide the building services engineer with a sufficient understanding of modern control systems and relevant information technology to ensure that the best form of control system for the building is specified and that proper provision is made for its installation, commissioning, operation and maintenance.'

The structure of the Guide is indicated in Table 1.1. This introductory section sets out the benefits to be gained from a modern building control system and will be of value in making the case that adequate provision be made at an early stage for a proper control system. The following section deals with the different types of control mode and their application in different situations; advice is given on the setting up and tuning of controllers to ensure stable operation.

Chapters 3–6 deal with the practical design of control systems, starting with the hardware components, then their incorporation into control systems by linking them into networks, and then two sections on control strategies for HVAC systems and whole buildings. The Guide thus starts with the constituent components and progresses to complete systems. The user may prefer to consult the control strategies for systems of interest and then refer back in the Guide to obtain a fuller understanding of the component parts.

Section 7 deals with the relation between building management systems and information technology. The

Table 1.1 Organisation of the Guide

Chapter	Subject
1 Introduction	The contribution that a modern building management system can make to the efficient and economical operation of a building
2 Control fundamentals	The basic types of control operation that are found in practice, ranging from the simple thermostat to microprocessor controlled self-learning algorithms. Guidance on the application of different control types and their tuning for optimum operation
3 Components and devices	The whole range of hardware components that constitute a control system, including sensors, valves, dampers, actuators, motors and basic controllers
4 Systems, networks and integration	The means by which components are brought together to form an operating control system. The various BMS architectures the major standard protocols for bus systems. Characteristics of networks and the extension to full systems integration
5 Control strategies for subsystems	Control strategies for the fundamental parts of HVAC systems: safety interlocks, boilers, chillers, water and air systems, lighting
6 Control strategies for buildings	Control strategies for whole buildings. Avoiding conflict between subsystems. Illustrations of successful control installations
7 Use of BMS-derived data	The relation between BMS and IT. Energy monitoring and targeting, maintenance scheduling, facilities management
8 Management issues	The importance of the procurement method on the BMS design process. Commissioning, CDM requirements and cost issues

building management system (BMS) and information technology (IT) system may share a communications network and the information gathered by the BMS can be used by the IT system for further purposes, enhancing the value of both systems. The final chapter shows the importance of the building procurement process in determining whether adequate resources are devoted to the design and installation of a suitable BMS and emphasises the necessity of taking control requirements into consideration at an early stage in the design process.

1.2 Modern control systems

Good controls are essential for the safe and efficient operation of a modern building. The control system does more than keep the inside of a building comfortable for the occupants. It is required to keep the HVAC plant operating efficiently, to ensure that all plant operates safely in the event of any unforeseen circumstances, and it must be capable of two-way communication with the personnel charged with its operation. While it may be self-evident that modern, highly serviced buildings require a sophisticated control system, it should be realised that simpler buildings relying on a heating boiler and natural ventilation can still benefit from a modern BMS. The increasing emphasis on energy conservation and reduction of greenhouse gas emissions serves to increase the importance of efficient controls.

The late 1970s saw the introduction of digital data technology, in which information is transmitted not as an analogue electrical value, but as a sequence of numbers. Digital data transmission is less susceptible to error than analogue transmission and it is standard practice to construct the signal protocol in such a way that it is possible to detect whether an error has occurred during transmission. This was the beginning of direct digital control (DDC). It required the codification of rules by which values are converted to numerical messages for sending; such messages have to contain not only the value of the variable under consideration, but additional information such as the origin and destination of the message and error-checking information. Such conventions on the structure of the messages are the basis of data communication protocols. At the early stage of DDC, data handling was centralised and multiplexing circuits were used so that the central unit could contact each remote unit as required. As computing power rapidly increased, the functionality of the central control unit became more and more sophisticated, with the ability to handle increasing amounts of data and to perform additional functions such as the monitoring of energy consumption and the printing or reports.

The advent of the microprocessor allowed considerable computing power to be incorporated in a small device and this meant that it was now no longer necessary for all control and monitoring functions to be carried out by a large centralised computer. Intelligent outstations placed around the building became capable of carrying out local control functions, while communicating with a central supervisor which could oversee their actions, receive any alarm signals and alter set points or operating times as required. There has been enormous progress in the field of data communication and the application of local area networks (LANs), which allow microprocessors and computers to communicate with each other over standardised networks. Communication may be extended to link together the operation of several buildings, which may be located miles apart, or even in different countries.

All these have contributed to the modern building management system. In this Guide the term 'control system' or 'building control system' is used to cover all control elements, including hardware, controllers, any linking network and central controllers. The term BMS refers to a system where components are able to communicate with each other and generally implies some form of central supervisor, which permits monitoring and control of the building from a single point. The period that saw the development of the BMS has also seen the rise in IT. A modern operation, whether it is office or factory, is likely to distribute and process large amounts of information dealing with the operation of the business. There may be advantages in linking the IT system and the BMS, either for the economy of using shared networks or for the more efficient integration of management control over the many activities taking place in a building.

1.3 Sustainable development and the global environment

Sustainable development is defined by the UN World Commission on Environment and Development(1) as 'development which meets the needs of the present without compromising the ability of future generations to meet their own needs'.

This means meeting four objectives simultaneously:

- social progress which recognises the needs of everyone
- effective protection of the environment
- prudent use of natural resources
- maintenance of high and stable levels of economic growth and employment.

Buildings are a vital aspect of development in general and therefore need to embrace this concept and well-designed control systems have a very significant contribution to make, a contribution which will increase in significance as control systems technology develops.

1.3.1 Social issues

People use buildings and a key strand of sustainable development is recognising this. It is now taken for granted that buildings should be safe (i.e. hazards identified, risk assessments undertaken, mitigating measures implemented), secure (i.e. protected against unauthorised access) and comfortable (thermally and visually).

Recently, 'hard' security and safety have converged and it is to be expected that users will have to undergo some form of inspection on entry to a building and, once inside, will then be under some degree of surveillance. The building control regime therefore includes these systems, which will increasingly adopt software-based technology to provide a degree of intelligence or intuition in identifying threats or hazards.

Traditionally the building control systems, exemplified by a building management system (BMS) were deemed only to be concerned with HVAC control with (at most) interfaces to the fire alarm, voice alarm/public address system, lighting control systems etc. This will not suffice to meet the requirements of society and building control systems should now be defined in terms of all these systems (i.e. all the above should be regarded as 'building control systems').

Building control systems will have to provide holistic control of a building not just in the thermal environment but also for instance in the control of light, particularly the balance between natural and artificial light.

Well-designed building control can return control to the users (the ultimate in recognising the needs of everyone) and can also monitor the way they are doing so and advise them if it could be done better, for example to reduce energy use.

Information provided in a user-friendly fashion can engender a sense of comfort and security in users for example in airports, railway stations and government offices.

The ever-increasing use of computers enables a degree of intelligence to be incorporated into any physical object in a building. It places a duty on the designer to harness this technology and the information it brings in such a way that the societal object of putting people first is preserved.

1.3.2 Environmental protection and the use of natural resources

The most effective way building control systems can contribute to the protection of the environment is by helping to reduce energy consumption in buildings and to reduce the consumption of natural resources including water. These have a lever effect in that reduced energy consumption reduces carbon emissions and the consequent climate change, while also reducing the demand for natural resources with consequential benefits to future generations.

Energy reduction in buildings may be achieved by a wide rage of engineering approaches, e.g. natural ventilation and solar heating versus 'micro-CHP' and phase-change media for heat or cooling storage.

While the first of these approaches may appear to be 'low-tech' and the second 'high-tech', this is in fact not the case: both harness current technology and, in particular, the control system required to implement either is likely to increase in sophistication. This is because the falling cost of system processing power and memory allows the designer to implement complex control strategies that were previously neither feasible nor cost effective.

In the 'low-tech' solution, while the plant may be simple, increasingly sophisticated techniques will be adopted in controlling such devices as dampers, window blinds and lights, with the building control systems being linked directly into meteorological measurements.

In the 'high-tech' solution, the plant will require sophisticated control techniques to achieve efficiency, more akin to automobile engine management than current HVAC control systems.

Ubiquitous computing will allow the internal environment to be micro-monitored to validate the design basis of the heating and ventilation system. It will also allow all mechanical and electrical plant to be operated closer to its performance limits with embedded monitoring of all key performance parameters providing feedback when equipment performance deviates from normal. These techniques, already adopted in the process industries, have been proven to increase efficiency by running plant in its optimal mode, increase availability and increase utilisation.

1.3.3 Economic growth

Economic growth depends on wealth creation and it is now recognised that an increasing amount of wealth is created not in the industrial sector but in the service sector in shops, offices, hotels and restaurants.

The ways in which the building control systems contribute to wealth creation include the following:

— *Reduced operating costs*: not just in terms of energy, but also in the life cycle cost of the building services. Increasingly sophisticated techniques for monitoring their condition and performance, which facilitate failure prediction and performance/condition-based maintenance result in reduced cost of operation and maintenance and increased life.

— *Building performance*: performance in this context is the measure of how well the building is performing its primary function. Building services make a significant contribution in terms of, for example, customer enjoyment (lighting and HVAC) in shops, and safe, high throughput in airports and railway stations by means of intelligent and user-friendly information displays.

— *Informed workforce*: it is widely recognised that a workforce that is well informed about its environment performs more efficiently. Building control systems should not only inform employees about their environment, but also provide a degree of control over it where appropriate.

1.4 The indoor environment

The function of the building services and their associated control system is to provide an environment within the building appropriate to the activities taking place therein. Several factors contribute to feelings of thermal comfort and their incorporation into the predicted mean vote (PMV) index is set out in BS EN 7730(2). Research(3) strongly suggests that people adapt to their environment, allowing temperature settings to fall in winter and rise in summer(4). This has important implications for the design of naturally ventilated buildings. Guidance on the required conditions for a range of occupations and activities is given in CIBSE Guide A(4). Decisions on allowable excursions of the conditions outside the recommended comfort bands, e.g. during a summer heatwave, will have important repercussions on plant sizing. The specified control tolerances will affect the design and cost of the control system. The indoor environment affects not only comfort, but also productivity and health. Relevant legislation is referred to as appropriate in the text. The Fuel and Electricity (Heating) (Control) (amendment) Order 1980[5], specifies a maximum heating level of 19 °C in non-domestic buildings. The law has not been rigorously enforced. While it is difficult to substantiate precise claims of productivity gains, there is little doubt that comfortable conditions will have a beneficial effect. Surveys have consistently shown that the speed with which management attends to complaints is very important. Those companies where management attends promptly to problems are highly rated by the occupants[6]. The client's point of view for the specification of offices is represented in *Best Practice in the Specification for Offices*[7]. While the primary function of a building control system has been the control of temperature and humidity, the increased awareness of sick building syndrome (SBS) and other building related illnesses has emphasised the requirement to ensure good indoor air quality. The demands of energy conservation and healthy ventilation are sometimes in conflict, necessitating better attention to the control of ventilation to ensure a satisfactory compromise. More attention is being given to the quality as well as quantity of ventilation.

There are many buildings that house processes and operations which have their own special requirements for environmental control. Examples are low temperature for food preparation, high and controlled humidity for paper fabrication, clean rooms for electronic assembly. The pharmaceutical industry has its own special regulations for control of the environment, both for drug production and for animal housing. Companies producing goods for export may need to meet the requirements set down by the customer's country. It is outside the scope of this Guide to give the many regulations; it is the responsibility of the client or his representative to ensure that they are taken into account at an early stage in the design.

1.5 Energy efficiency

Building controls have a vital role to play in preventing waste of energy. The amount of energy required to run a building is determined by:

(*a*) thermal efficiency of the building envelope
- thermal insulation
- airtightness
- provision for passive solar gains

(*b*) requirements of the indoor environment
- temperature schedule
- ventilation needs
- humidity control
- indoor air quality
- lighting requirement
- hot water requirements
- lifts and mechanical services

(*c*) processes within the building
- IT equipment
- industrial processes.

The above requirements taken together demand a level of base energy, which is the energy required to meet the business needs of the building operation. This provides a minimum level of energy expenditure. Any reduction in base energy requirement implies a change in building construction or use. The difference between actual energy expenditure and the base requirement represents avoidable waste. Examination of data from a number of UK buildings shows avoidable waste levels in the range 25 to 50%; in a well-managed building, avoidable waste levels of below 15% are achieved[8].

Avoidable waste has many causes, including:

- poor time and temperature control of the building interior
- ineffective utilisation of internal heat gains
- plant oversizing
- excessive ventilation
- low operating efficiency of the HVAC system
- poor system design and installation
- standing losses
- unnecessary use of artificial lighting and air conditioning.

The control system affects most of the above. Detailed applications will be found elsewhere in this Guide. Major contributions of the control system in reducing waste are:

- the limitation of heating and cooling to the minimum period necessary; this usually includes the use of optimum start controllers and some form of occupancy detection to avoid excessive out-of-hours use
- prevention of unnecessary plant operation and boiler idling
- monitoring to give early warning of malfunction or inefficient operation.

Approved Documents L2A and L2B[9,10] provide overall guidance on how to satisfy the energy performance provisions of Part L of the Building Regulations[11]. The Approved Documents refer to a 'second tier' document, *Non Domestic Heating, Cooling and Ventilation Compliance Guide*[12], as a source of detailed guidance on means of complying with the requirements of Part L, including the minimum provisions for controls associated with the various heating, cooling, ventilation and hot water systems for both new and existing buildings. The *Compliance Guide* also indicates further control options that will improve energy efficiency beyond the minimum requirements of the Part L.

1.6 Information technology and systems integration

A modern building contains several technical services in addition to heating and ventilation, such as lighting, lift control, security and access control, closed circuit television (CCTV) systems, as well as the information technology network necessary for the user's business operation. All these services communicate within their own system using some form of network. There are major potential benefits if the various systems can communicate with each other, using the same communications network or a limited number of compatible networks:

— the reduction in cabling and infrastructure cost

— the ability of the systems to share information with each other.

This process is known as systems integration. At its most basic level, it means that devices from different manufacturers may use the same communications network, communicating with their peers and not interfering with other equipment. At the most advanced level, all systems within a building use the same communications network, exchange information with each other and are controlled from a single supervisor. For instance, the presence detectors of a lighting control system may feed information on out-of-hours occupancy to the security and access control systems. Full integration is also known as the intelligent building concept.

HVAC control systems operate in real time, ensuring proper operation of the environmental control system. The information generated may be fed into the information technology system where it can be used for the production of reports, energy monitoring and targeting and the preparation of maintenance schedules. Modern BMS technology enables systems to be interrogated, monitored and controlled from anywhere in the world, via common IT and web browser applications.

1.7 Building operation

A well-planned control system offers improved management of building services and can form the core of an integrated facilities management system, covering other building-related services such as access control, security, energy monitoring and targeting, information technology and maintenance. The amount of direct involvement by staff in the day-to-day running of an HVAC system has steadily reduced over recent years. However, it would be a mistake to assume that the control system can be left to take care of itself from the moment of handover. The client must choose from a range of options, from running the building services in-house with the client organisation's own staff, to outsourcing to a service bureau who may supervise efficient operation, deal with occupant requests and organise maintenance, all from a remote supervisor. Whichever form of organisation is chosen, there should be clear ownership of the control system with unambiguous responsibility for its successful operation. This requires a commitment by the client to ensure adequate resources for the operation and maintenance of the building control system; part of this commitment is the provision of proper training for staff. The organisation should ensure prompt and effective response to requests or complaints from the building occupants; several studies have confirmed the importance of rapid response in ensuring occupant satisfaction with their place of work.

The software which has been developed for BMS supervisors has greatly simplified the day-to-day management of even large BMSs and will show savings in operating staff costs compared with a simpler system which requires frequent attention. With the development of wide area networks, it is possible to have remote supervision. This enables skilled personnel to be located at a single site and able to monitor the performance of several BMSs in scattered buildings, leaving less qualified staff to carry out the daily operation on site. There will also be a saving in maintenance costs as the BMS is able to keep run-time records of all equipment, allowing maintenance to be planned effectively. Early warning of failure is available from monitoring. Plant life is extended by the reduction in hours of use that is obtained by scheduling, by reducing unnecessary device operation or unstable hunting and by reducing fan and pump speeds.

1.8 Benefits of a BMS

When deciding on the appropriate type of control system to specify for a building, it is necessary to remember that the benefits of a modern control system are enjoyed variously by the different groups of users involved with the building. Table 1.4 lists some of the benefits to be achieved with an effective modern BMS. It goes without saying that these benefits will only be obtained if the system is properly specified, installed, commissioned, operated and maintained. It is the function of this guide to assist in achieving that goal.

Table 1.4 Benefits of a BMS

Beneficiary	Benefit
Building owner	Higher rental value Flexibility on change of building use Individual tenant billing for services
Building tenant	Reduced energy consumption Effective monitoring and targeting of energy consumption Good control of internal comfort conditions Increased staff productivity Improved plant reliability and life
Occupants	Better comfort and lighting Possibility of individual room control Effective response to HVAC-related complaints
Facilities manager	Control from central supervisor Remote monitoring possible Rapid alarm indication and fault diagnosis Computerised maintenance scheduling Good plant schematics and documentation
Controls contractor	Bus systems simplify installation Supervisor aids setting up and commissioning Interoperability enlarges supplier choice

1.9 Summary

Effective control of the heating, ventilating and air conditioning systems in a building is essential to provide a productive, healthy and safe working environment for the occupants. Without a properly functioning BMS the activities carried out in the building will be disadvantaged. Along with good building design and efficient HVAC plant, the BMS plays a vital role in the prevention of energy waste and reducing the environmental impact of the building.

Modern BMSs are based on intelligent controllers which may be programmed to carry out a wide range of control functions. Typically, a number of controllers are employed, each controlling an item of plant or an HVAC subsystem. The controllers communicate with each other and with a central supervisor over a local area network (LAN). The system manager is able to monitor and control the entire BMS from one point.

The scale and complexity of the control system should be appropriate to the building and its operation; highly effective and reliable control may be achieved with relatively simple control systems. However, when considering the cost effectiveness of a BMS, all the operational benefits that flow from a well-managed facility should be taken into account: not only energy saving but also the reductions in staffing cost, improved maintenance scheduling and the benefits of system integration with other building facilities. Such facilities as access control, security and lighting may be integrated with the BMS, giving total building management from one point. There is steady progress towards compatibility between products, so that devices from different manufacturers may share the same LAN and event interact directly with each other. The goal of freely interchangeable devices is termed interoperability.

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10 *Conservation of fuel and power in existing buildings other than dwellings* Building Regulations 2000 Approved Document L2B (London: NBS/Department for Communities and Local Government) (2006) (available from http://www.planningportal.gov.uk/england/professionals/en/1115314110382.html) (accessed July 2008)

11 The Building Regulations 2000 Statutory Instruments 2000 No. 2531, as amended by The Building (Amendment) Regulations 2001 Statutory Instruments 2001 No. 3335 and The Building and Approved Inspectors (Amendment) Regulations 2006 Statutory Instruments 2006 No. 652 (London: The Stationery Office) (dates as indicated)

12 *Non Domestic Heating, Cooling and Ventilation Compliance Guide* (London: NBS/Department for Communities and Local Government) (2006)

2 Control fundamentals

Summary

This chapter introduces the concept of feedback and the control loop. It describes the basic control modes used in HVAC controls, including:

— simple on/off control
— proportional, integral and derivative control
— optimisers and compensators
— intelligent controls.

Issues of stability are dealt with and methods of tuning control loops for the best combination of response speed and stability are given. The section goes on to discuss advances in adaptive controls, which learn by experience how to optimise operation of a controller.

2.1 General

A control system consists of three basic elements: a sensor, a controller and a controlled device (see Figure 2.1). The sensor measures some variable such as temperature and transmits its value to the controller. The controller uses this value to compute an output signal, which is transmitted to the controlled device, which then acts to change the output of the load, which acts on the controlled system. The majority of cases relevant to this Guide involve closed loop systems, where the controller is attempting to control the variable whose value is being measured by the sensor. The results of its actions are fed back to the controller input and the system is said to have feedback. In the example shown in Figure 2.1, the controller is attempting to maintain room temperature at a set point. A low room temperature results in increased output from the heater, which then raises the room temperature. This increase is detected by the sensor and transmitted to the controller, which alters its output accordingly to reduce the difference between set point and the measured value of the controlled variable. In the discussion of control modes that follows, it is implicitly assumed that the system is inherently controllable. Poor design may result in a system that is practically impossible to control; this will be discussed further below.

Open loop or feed forward systems operate without feedback. As before, the operation of the controlled device is a function of the value measured by the sensor, but this does not result in a change to the measured variable. A weather compensator is an example of open loop control, where an external air temperature sensor is used to control the flow temperature in a heating circuit used to heat a building. The control system has no way of knowing if the desired internal temperature has been achieved.

In practice, a control loop may have more than one input signal and more than one output signal. Groups of control loops can be chained together to create control sequences. The simple description above implies that the input and

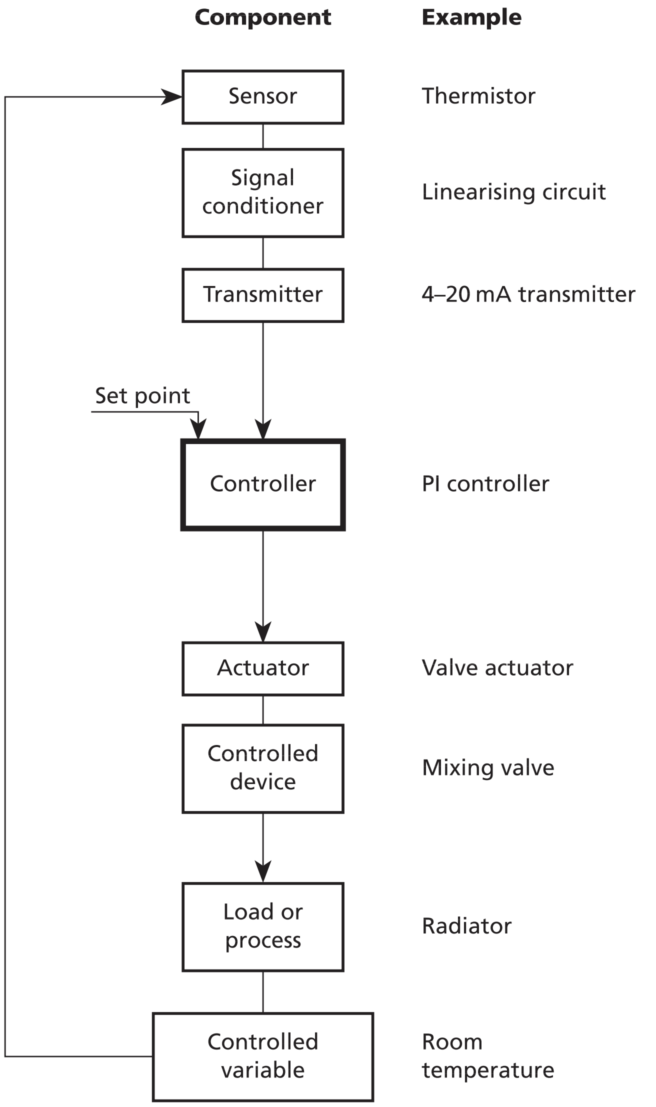

Figure 2.1 The components of a control system; in practice, some components may be combined

output of the controller are continuous variables and this is so for such variables as temperature. An important part of practical control systems is a set of complex interlocks, where the operation of one part of the system is contingent on the operating state of several other variables and systems. Many inputs and outputs are thus binary (on/off) in nature. When preparing a points list, it is conventional to refer to them as digital inputs and digital outputs (DI and DO); this does not imply DDC.

2.2 Control modes

Consider again the simple closed loop system of Figure 2.1. The way in which the control system responds to a change in the controlled variable is described by the control mode. Several control modes are in use and it is important to select the appropriate mode for the job in hand.

2.2.1 Two-position (on/off) control

In this mode, the controlled device gives either maximum or minimum output, typically on and off. Figure 2.2 illustrates two-position control for a simple heating system. It is desired to control temperature at the set point. For reasons that will become clear, it is necessary for there to be a temperature differential between switching on and switching off of the controlled device. With the heating on, the space temperature rises until the sensor output exceeds the set point. The heating then switches off and stays off until the temperature falls through the differential and reaches the lower limit, whereupon it comes back on and the cycle repeats. The temperature interval between the upper and lower limits is termed the differential gap or differential band; in American usage it may be referred to as the deadband. Within the differential gap the output may be either on or off, depending on the last switching operation. In accordance with present convention, the set point is taken to be the upper point of the differential gap; earlier conventions take it to be the centre point. The room temperature continues to increase for a time after the heating system has been switched off; this is caused by, for example, hot water present in the radiators. Two-position control results in a swing of temperature about the set point and a mean temperature that normally lies below the set point; some systems when operating under light loads may give a mean temperature above the set point. The swing may be reduced by reducing the differential, but at the cost of increased frequency of switching, with attendant wear on the system. The peak-to-peak variation in space temperature is termed the swing or operating differential and the differential of the controller itself, i.e. the differential that becomes apparent by turning the dial of the thermostat, is known as the mechanical or manual differential.

The common domestic room thermostat is an example of a two-position controller. The inherent differential of the thermostat is of the order of 3 K, for mechanical reasons necessary to provide a snap action operation of the contacts to avoid arcing. The operating differential may be reduced by incorporating an accelerator heater in the thermostat. A low-powered heater within the body of the thermostat is wired in parallel with the load and comes on with the heating system. This has the result of increasing the temperature seen by the thermostat, resulting in earlier closure. The frequency of switching therefore increases, giving a lower operating differential and reduced temperature swings in the room. The effect of the accelerator is to reduce the mean room temperature achieved in practice below the set temperature and this control offset increases with load. This is equivalent to the load error found with proportional control and the action of the accelerated thermostat may be described as pseudoproportional.

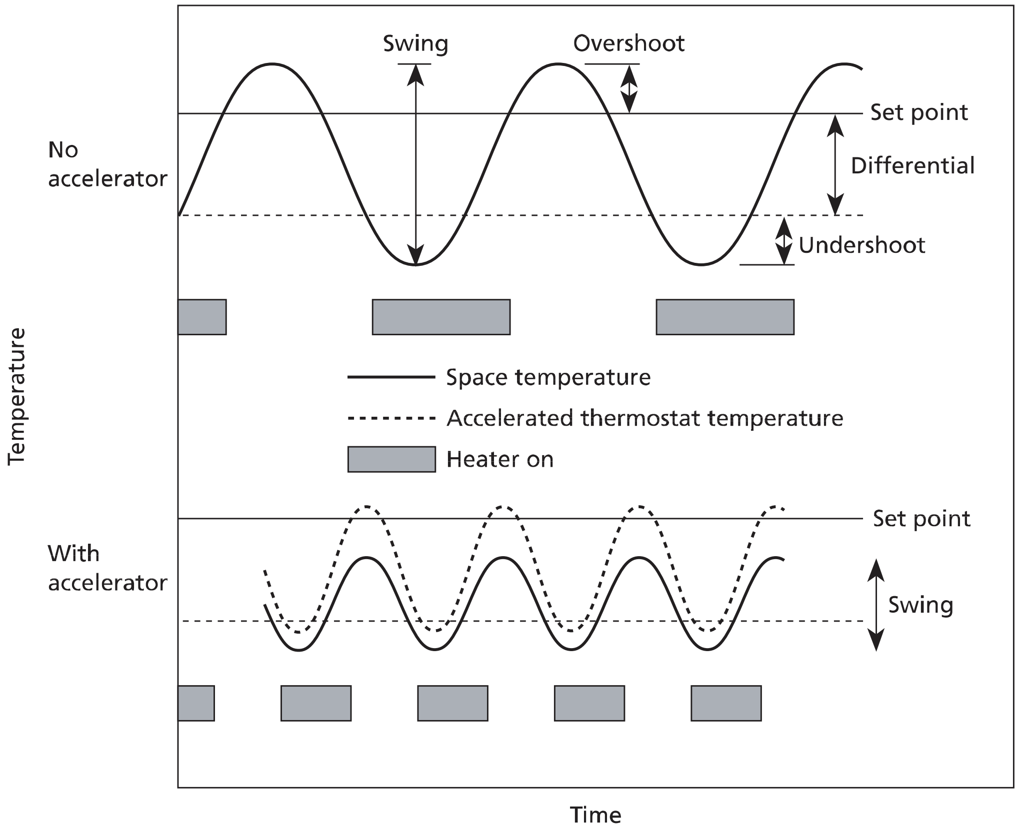

Figure 2.2 Two-position (on/off) control

Floating control is a form of two-position control which requires that the controlled device can have its output increased or decreased by a slow-moving actuator. It is also known as three-position or tristate control. A typical example would be a motorised valve controlling flow of hot water. The valve moves slowly towards open or closed position during the application of a signal from the controller; with no signal, the valve stays where it is and holds its position. The output of the controller is now three rather than two position: increasing, decreasing and off (i.e. no change). Figure 2.3 illustrates this mode of control. When the room temperature exceeds the upper temperature limit, the controller signals the valve to start closing. The valve slowly moves towards the closed position, reducing the heat supply to the room. When the room temperature falls to the upper limit, the controller switches off and the valve stays where it is. The room temperature now floats within the neutral zone, until it crosses either the upper or lower temperature limit, whereupon the valve is driven in the appropriate direction. Such a system is designed to have a long operating time between fully open and closed positions of the controlled device; with a short operating time the action behaves like simple on/off control. Floating control is used for systems where the sensor is immediately downstream from the coil, damper or other device that it controls. It is not suitable for systems with a long dead time. A variant is proportional speed floating control, where the further the value of the controlled variable moves outside the neutral zone, the faster the actuator moves to correct the disturbance. This is in fact very similar to integral action.

2.2.2 Proportional control

Proportional control requires a continuously variable output of the controlled device. The control system produces an output which is proportional to the error signal, i.e. the difference between the value of the controlled variable and the set point. For the controller to produce an output to match the load on the system, it is necessary that there be an offset between the controlled variable and the set point. In

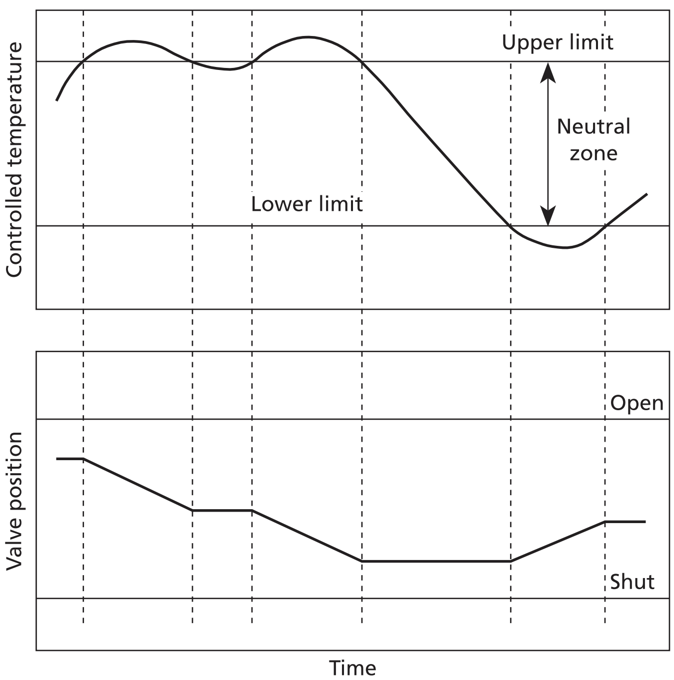

Figure 2.3 Floating control

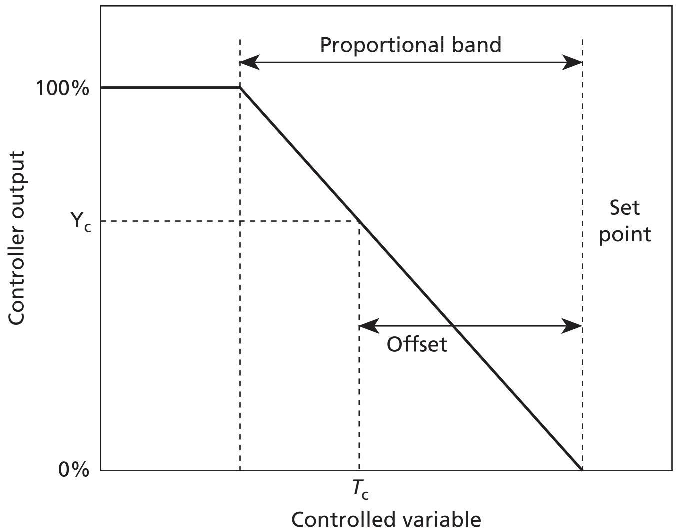

Figure 2.4 Proportional control showing steady-state conditions with the controlled variable at T_c with a controller output Y_c; T_c is at an offset or load error below set point (sometimes the set point is in the middle of the proportional band)

steady-state conditions, a proportional controller produces an offset or load error, which increases with the load on the system. Figure 2.4 shows the operation of a proportional controller for a heating system. The control output increases from 0 to 100% as the input falls from the set point through the proportional band, also known as the throttling range. It can be seen that in steady-state conditions the equilibrium value of the control point will be below the set point and that this offset will increase with load, e.g. in colder weather when the heating load is greater. For cooling systems, the equilibrium value will be above the set point.

The proportional band may be expressed in units of the physical quantity being controlled, e.g. °C, %RH, pascal, or as a percentage of the controller scale range. If, for instance, the controller has a scale range of 0–80 °C and a proportional band of width 20 K, the proportional band is 25%. The gain of a proportional controller is the reciprocal of the proportional band, expressed either in physical units, e.g. K^{-1} or non-dimensionally, e.g. a proportional band of 50% is equivalent to a gain of 2.

Figure 2.5 shows the response of a proportional control system to a change in demand. The value of the controlled variable follows a damped oscillation before settling down to the steady offset temperature. The amount of offset may

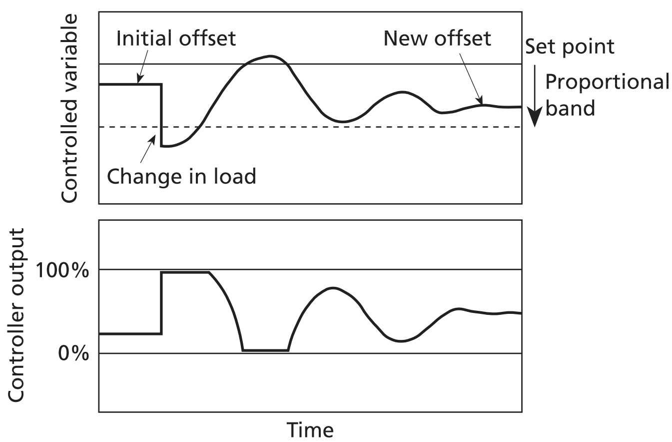

Figure 2.5 Response of a proportional controller to a sudden change in load

be reduced by narrowing the proportional band, but at the risk of introducing instability; as the proportional band is reduced, the control action approaches on/off.

A form of proportional control known as time proportioning may be achieved even if the output device is only capable of a two-position output, e.g. high/low or on/off. The output from the controller varies the ratio of on/off times within a constant cycle period, e.g. if the cycle time is 10 minutes and the controller calls for 40% output, the output device will be switched on for 4 minutes and off for 6 minutes. The cycle time may be set independently; it should be sufficiently long to avoid any problems of wear caused by too frequent switching of the controlled device, but shorter than the response time of the overall system. The method is suitable for systems with long response times, where it will give much lower temperature swings than simple on/off control. The control behaviour is similar to a proportional system and will show a load error. Time proportioning control may be used for the control of electric resistive heaters where the switching frequency is limited by the requirement to avoid electrical disturbances on the supply(1).

2.2.3 Integral control

Integral control is not often found on its own, but is normally combined with proportional control in a PI controller. In its pure form it produces a rate of change of the output of the controller proportional to the deviation from the set point or, in other words, the output is a function of the integral over time of the deviation from the set point. When the controlled variable is at the set point, the rate of change of output is zero. The system should therefore settle to a steady-state condition, with steady output and zero offset. The control mode is similar to floating control, but with a zero width neutral zone and variable rate of change of output: compare with proportional-speed floating control. It is illustrated in Figure 2.6.

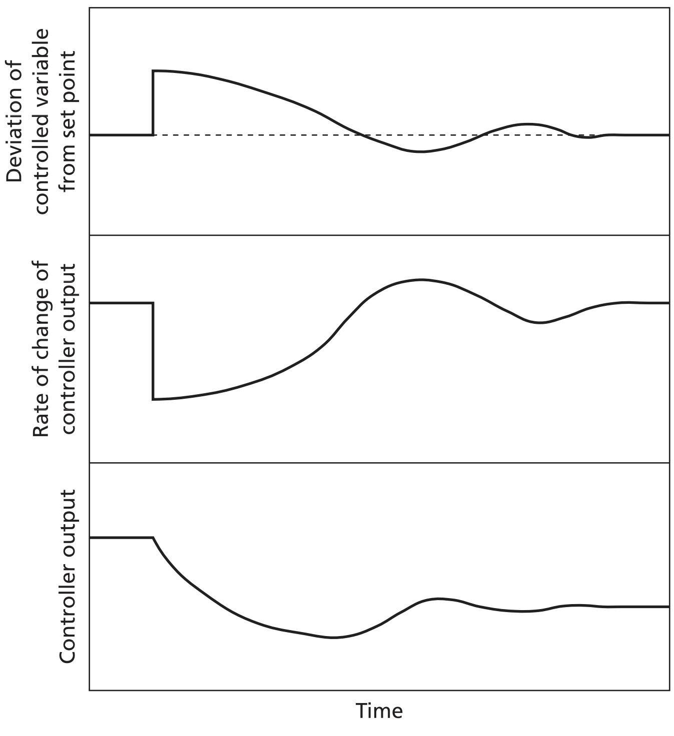

Figure 2.6 Pure integral control action; the system is initially in steady state and the figure shows the response to a step decrease in set point

When integral control is used by itself, it must be used in systems with short time constants and fast reaction rates. It is not suitable for a system with slow responses or long time lags, where it will over-correct. A typical controlled device is a valve driven by a variable-speed actuator, which gives the required variable rate of change of control response. A constant-speed actuator may be used where the controller provides a variable duration pulsed current to give effective variable speed. The speed of closure of the valve must be slow compared to the speed of response of the controlled system. The more common combination of proportional and integral control is discussed below.

2.2.4 Proportional plus integral (PI) control

Adding integral control to a proportional controller compensates for the load error. This is probably the most widely used mode in HVAC control and when correctly set up is capable of providing stable control with zero offset. The controller integrates the deviation from set point over time and uses this value to adjust the control output to bring the controlled value back towards the set point. The proportional band may therefore be increased to give stable control; the load offset that would otherwise be introduced is eliminated over time by the integral action. The integral setting is characterised by the integral action time, which is the time it takes for the integral term of the control output equation to match the output change due to the proportional term on a step change in error. Alternatively, the integral setting may be characterised as the reset rate, which is the inverse of the integral time, and measured in resets per minute. Most PI controllers are interactive, where the integral gain is multiplied internally by the gain setting of the proportional action (see Appendix A2). The practical implication is that the proportional band may be adjusted without affecting the integral time. A non-interactive controller has independently adjustable gains for the proportional and integral actions, and so adjusting the proportional gain will alter the integral action time as defined above. A long integral time will increase the steady state load error; in the limit of infinite integral action time the PI controller becomes a simple proportional controller. However, if the integral time is reduced to a value comparable to or less than the time constant of the controlled system, instability will result.

The output of the integral term depends on the past history of the controlled variable, and problems may result on start-up where the controller treats the preceding off period as a long-term error. This is known as wind-up. Wind-up will also occur if the controller output is 100% and the error remains positive; in this situation the integral action will continue to increase to a huge positive value. When the system becomes controllable again, a long period of negative error will be required to unwind the integral term and return to normal operation. Controllers incorporate anti-wind-up features to prevent this, either by locking the integrator at the pre-existing value whenever the controller output is at either extreme, or by limiting the integrator to some maximum value, typically 50% of full output. Similar problems can occur on starting up a system and some systems disable the integral action on start-up until the system is controlling within the proportional band.

2.2.5 Proportional plus integral plus derivative (PID) control

Derivative action provides a control signal proportional to the rate of change of the controlled variable. This has the effect of reducing control action if the controlled variable is rapidly approaching the set point, anticipating that the variable is about to reach the desired value and so reducing overshoot. It is therefore of value in systems with high inertia. Derivative action can cause problems in practice. If the measured variable is subject to rapidly varying random changes, the derivative action of the controller will produce an erratic output, even if the amplitude of the changes is small. See the note on derivative kick in Appendix A1 Derivative action is never used on its own, but is combined with proportional and integral action to produce PID control, also known as three-term control. A three-term controller is capable of maintaining a zero offset under steady conditions, while being able to respond to sudden load changes.

The gain setting of the derivative action is defined as the derivative action time, which is the time, usually measured in minutes, taken for the proportional term to match the derivative term when the error changes linearly with time. Derivative action is not normally required in HVAC applications and setting the derivative time of a PID controller to zero results in PI action. Three-term PID action is used mainly in process control applications.

Figure 2.7 shows the ideal characteristics of PID control on the behaviour of the controlled variable on start-up. With proportional control only, the output is a function of the deviation of the controlled variable from the set point. As the controlled variable stabilises, a residual load error results. With the addition of integral control, the controlled variable eventually returns to the set point, but there is still some overshoot before stable operation is achieved. Adding derivative control reduces the overshoot and the final set point is achieved in a shorter time.

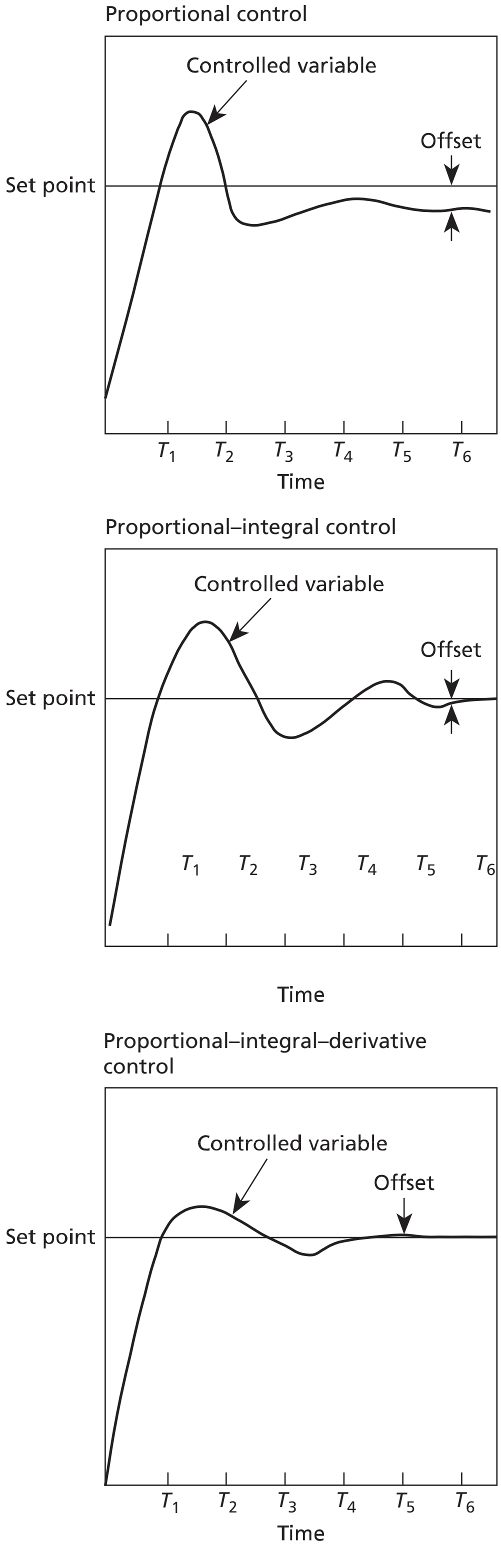

Figure 2.7 Illustration of PID control modes

2.2.6 Digital control

Microprocessor controllers operate by sampling values of the controlled variable at discrete intervals of time. The microprocessor then calculates the required controller output. For the most part, the processor mimics the analogue control modes described above. The controller is able to store past values of the controlled variable, which are needed to calculate derivative and integral terms. Programmable controllers are described in more detail in 3.8. One important difference between analogue and digital controllers is the effect of sampling rate. The frequency of sampling is limited by the speed of the processor and any multiplexing of the controller input, plus the ability of the network to transmit frequent messages. If the sampling rate is too low, instability may result if the controller is delayed in taking appropriate control action. Where there is a sufficiently fast sampling time, some controllers update the control output at intervals which are longer than the sampling interval; the interval between changes in output is known as the loop reschedule interval. Some controllers allow the loop reschedule interval to be adjusted independently from the sampling interval of the controller.

The control equations described in Appendix A2 are transformed in a digital controller into discrete time algorithms. The standard PID equation is called the position algorithm, since the position of the control element is related to the output signal. An alternative is the velocity or incremental algorithm. At each time step, the controller makes an adjustment to the position of the controlled device which is proportional to the change in the deviation of the controlled variable from the set point since the last sample, plus a term proportional to the deviation. Incremental control usually employs a slow moving actuator. At each time step, the controller calculates the required change in actuator position and sends a timed pulse to the actuator to move it the required amount. This control mode is similar to the floating control mode described in 2.2.1. It is found to work well and has the advantage of avoiding integral wind-up. The disadvantage is that the controller has no information on the actual position of the controlled device. If knowledge of the position is required, the controller can integrate the controller output and calculate the position of the controlled device. This integration calculation requires to be re-zeroed at intervals. This may be done by driving the actuator to a limit stop to provide a fix of its position. This may be done automatically each day during out-of-hours operation. The mathematical treatment of incremental control is given in Appendix A1

2.2.7 Cascade control

For some applications it is an advantage to divide the controller into two subsystems: a submaster controller which controls an intermediate part of the controlled system, and a master controller which adjusts the set point of the submaster loop. A typical application is for temperature control of a large space, where the master controller controls the supply air temperature set point as a function of space temperature, and a submaster controller controls the supply air temperature by modulating the heating coil valve (Figure 2.8).

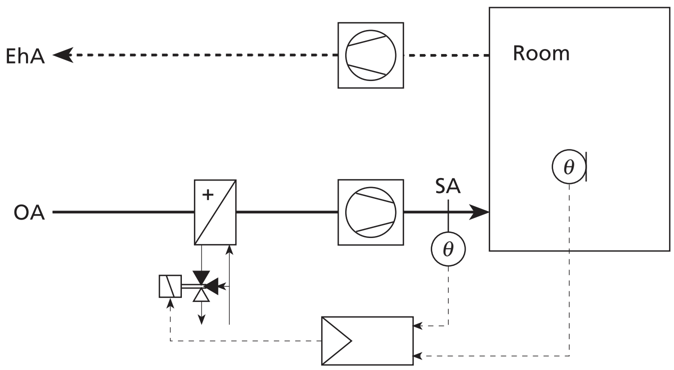

Figure 2.8 Cascade control; the room temperature is used to reset the set point of the controller controlling the supply air temperature

In its standard form, the submaster controller provides control of the supply air temperature against variations in incoming air temperature or fluctuating heating coil water temperature. The master controller resets the supply air temperature set point as a function of the space temperature using PI control. Care may be necessary to avoid instability if both loops use integral action. Some confusion in terminology may be found. An unambiguous term for this system of control is cascade control, and is used in this Guide. Cascade control is also commonly known in the UK as reset control. In the USA simple integral control may be referred to as reset, and a cascade controller is commonly referred to as master–submaster. The terms master–slave and primary–secondary are also used to refer to the two control loops. Cascade control is used when PI control alone is not suitable or will not provide stability, for instance where the space temperature responds slowly to variations in supply air temperature.

2.2.8 Time lags

In any feedback control loop, the response of the controlled system, as seen by a change in the sensor output, does not happen instantaneously upon a change in the controlled output. Two types of delay may be identified. A transport delay, also known as a distance– velocity lag, represents the time it takes for the heating or other medium to travel from its source to the point where its heat begins to be transferred to the controlled space. In large installations, distances can be very long and it can take some minutes for a change in water temperature at the boiler house to reach distant points in the building. The second type of delay, termed a transfer lag, depends on the time taken to increase the temperature of a component due to its thermal capacity. Consider the simple heating circuit of Figure 2.9. When the controller gives the signal to open the valve, hot water flows towards the heating coil, taking a time equal to the distance velocity lag to reach it. A series of first-order transfers then take place: primary water to heating coil, heating coil to calorifier water, water to cylinder material and finally cylinder metal to the sensor. The resultant response of the temperature sensor is shown. This is typical of a higher-order response, and may be approximated by a combination of dead time and first order response as shown.

All lags contribute to poor control. Integral or floating control is unsuitable for systems with a significant dead time, since the controller will continue to change the output

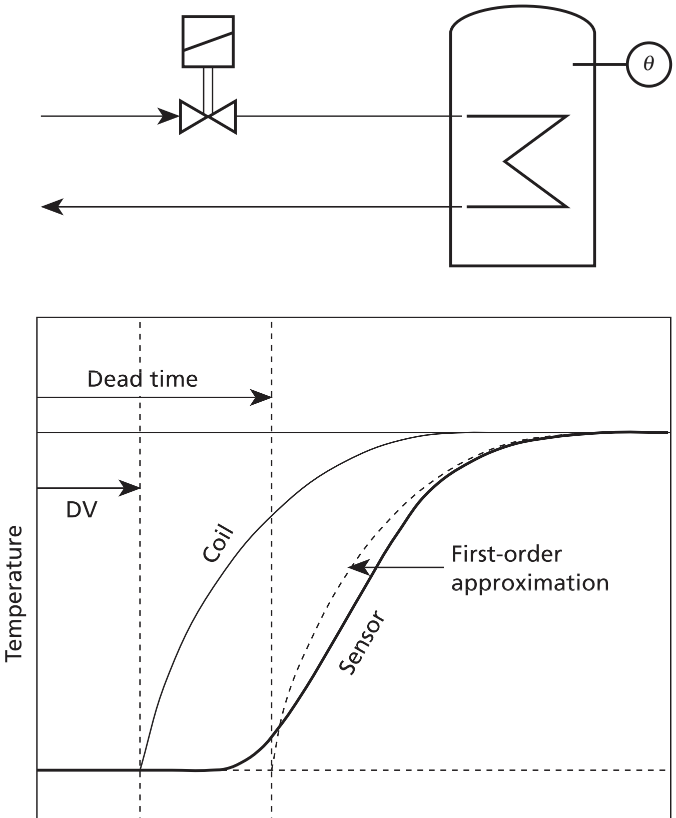

Figure 2.9 Response of system with dead time. On opening the valve at $t = 0$ there is a distance–velocity lag DV before the primary hot water reaches the heating coil. The coil then heats up with a first-order response. The sensor has a higher-order response, which may be approximated by a first-order response with dead time

during the dead time, resulting in overshoot. PI control is then more suitable. The proportional control, with adequately wide proportional band, provides a stable control, and the integral action, with suitably long integral time, removes the load error.

2.2.9 Logic control

The use of microprocessor-based DDC controllers offers enormous freedom to the controls designer, since virtually any control strategy may be programmed into the controller software. In practice, digital controllers are based on the well-understood control modes described in this section. The widely used universal controller, which incorporates pre-programmed control modules in its software is described in 3.8. The controller may be configured to meet the requirements of the actual control strategy to be implemented. Some examples of logic control are given in 5.8.2 and 5.14.3.2.

The controllers incorporate a number of logic control functions which may be used to improve control operation. Some examples are:

— *Hysteresis*: the hysteresis module only passes a change in input which is greater than a preset amount. It can be used to stop the control system responding to small fluctuations in the controlled variable, so reducing control action and wear.

— *Averaging*: the averaging module is used to produce a mean value of a number of inputs. For example, the system may be set up to control mean zone temperature, averaged over several temperature sensors. Sophisticated versions may be programmed to ignore extreme values.

— *Logic operators*: logic modules provide the full range of Boolean AND, NOT, OR and XOR gates. They are used to provide software interlocks, e.g. preventing operation of a heating system when windows are open. Safety-critical interlocks should be hard-wired.

— *Look-up tables*: functional relationships can be provided in the form of look-up tables. Examples are the conversion of a thermistor resistance to a temperature or the software linearisation of a controlled element characteristic.

The full range of available modules is too great to list here. The range of modules is sufficient to cover most control requirements and the controller manufacturers provide examples of control strategies to assist in configuration. If required for special situations, it is possible to write control strategies using a high level programming language, such as BASIC or C.

2.2.10 Choice of control mode

When selecting the appropriate control mode, the following considerations should be taken into account:

— the degree of accuracy required and the amount of offset that is acceptable

— the type of load changes expected, including amplitude, frequency and duration

— the system characteristics, such as the number and duration of time lags and speed of response of subsystems

— the expected start-up situation.

In general, use the simplest mode that will meet the requirements. Using a complicated mode may result in difficulties in setting up and lead to poorer rather than better control. Derivative control is not normally required in HVAC systems. Its function is to avoid overshoot in a high inertia system by measuring the rate of approach to set point and reducing control action in advance. It is used in some boiler sequencers, where it will inhibit bringing an additional boiler on line if the rate of rise of water temperature shows that the operating boilers will achieve the required temperature on their own. Table 2.1 lists typical applications.

Table 2.1 Recommended control modes

Application	Recommended control mode	Notes
Space temperature	P	
Mixed air temperature	PI	
Coil discharge temperature	PI	
Chiller discharge temperature	PI	
Air flow	PI	Use wide proportional band and short integral time. PID may be required
Fan static pressure	PI	Some applications may require PID
Humidity	P	Possibly PI for tight control
Dewpoint	P	Possibly PI for tight control

2.3 Optimum start

One of the most important functions of a building control system is time control, ensuring that plant is switched off when not needed. Substantial energy savings may be made by intermittent heating or cooling of a building compared with continuous operation. The savings achievable from intermittent heating compared with continuous heating depend on several factors. The savings will be greater in a lightweight building which cools and heats up quickly; any estimation of overall running costs must take into account all relevant factors. Heavyweight buildings are able to absorb peak gains and benefit from night cooling, which may outweigh any savings from intermittent heating. In general, intermittent heating and cooling will be more beneficial in the following situations:

— lightweight building (low thermal mass)

— short occupancy period

— generously sized plant.

Simple timeswitch control can be effective and is suitable for heating systems with a heat output of up to about 30 kW; above this figure, an optimum start controller is recommended. The time of switching on prior to occupancy is selected to ensure that the heating system has time to achieve a comfortable temperature at the start of the occupancy period. If this is correct in cold weather, the system will come on unnecessarily early in mild weather, giving higher energy consumption than necessary. Nor will a simple timeswitch be able to cope with the longer preheat period necessary after a weekend or holiday. An optimum start controller, or optimiser, is designed to calculate the latest switch on time under a range of operating conditions. Figure 2.10 illustrates the required control characteristic. During the unoccupied period, the plant normally operates to provide a minimum temperature to provide protection for the building fabric and contents. This is typically 10 °C but may be lower. Separate frost protection must be provided for the heating system.

The primary function of the optimiser is to calculate the latest switch on time. Several algorithms have been proposed. The most widely used is BRESTART[2]. This calculates the switch-on time as a function of both internal space temperature and external air temperature. Most controllers incorporate a self-learning or adaptive feature. By following the building performance over a few weeks, the controller sets its internal parameters to match the characteristics of the actual combination of building and heating system. The optimiser also selects maximum heat output from the heating system during the warm-up period by disabling any weather compensator that may be fitted. The boost is terminated and compensation restored when the building reaches the desired temperature.

An optimum stop function may be fitted, whereby heating or cooling is switched off before the end of the occupancy period, at a switch-off time calculated to ensure that the space temperature does not drift outside predetermined comfort limits by the end of the occupancy period. With air-handling systems, the zone air temperature will approach the building fabric temperature within about 15 minutes after switch-off. This may not provide comfortable conditions and so limits the usefulness of optimum stop strategies. Optimum stop is used less often than optimum start and the potential savings are less.

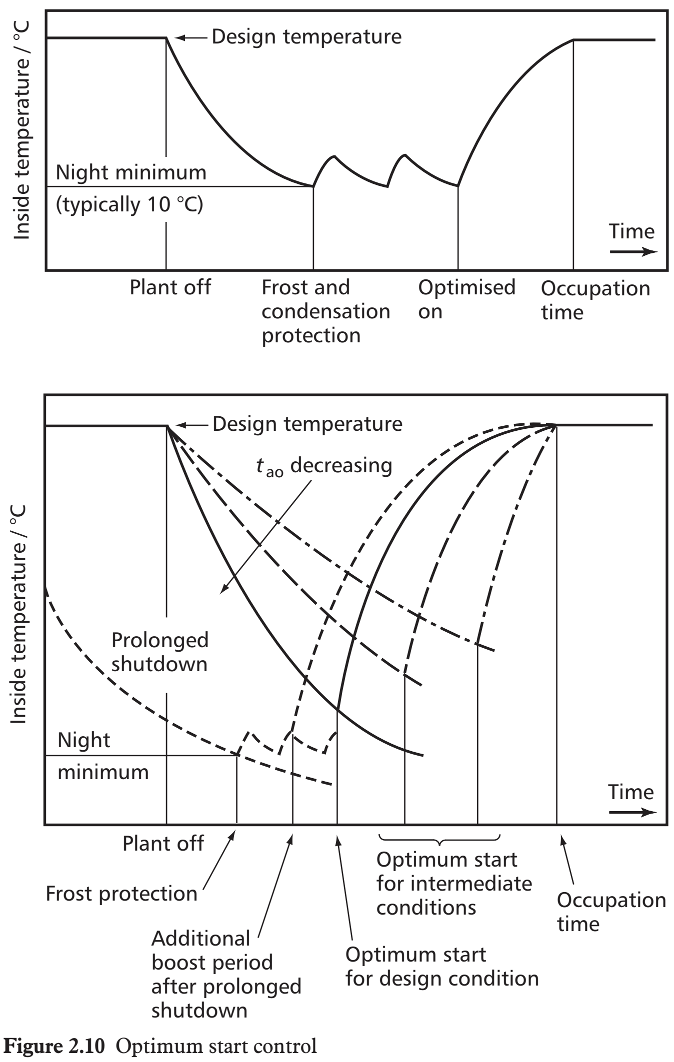

Figure 2.10 Optimum start control

2.4 Weather compensation

A building heating system is designed to provide full heating on a design day; in practice an additional margin is allowed to provide extra power during the boost period of intermittent heating. The capacity of the heating system is therefore greater than required for operation in all but the coldest condition. For buildings heated by a conventional radiator system, operation during mild weather with the flow temperature at the full design value, typically 80 °C, results in control problems, high temperature swings and consequent discomfort; it also results in wasteful heat loss from the hot water circuit.

Compensation control allows the whole building to be controlled as one unit, or as a limited number of zones, thus eliminating the need to provide a large number of separate space temperature controls. It has the added advantage of limiting heat loss in the event of increased load, e.g. if windows are opened. If used as the only form of temperature control, it requires the radiator size to be carefully matched to the heat requirement of the building; since this is virtually impossible to do in advance, provision must be made for balancing the system and adjustment of the compensator control characteristic. A practical solution is to use weather compensation and trim local temperatures by the use of thermostatic radiator valves.

The form of the weather compensator control characteristic is shown in Figure 2.11. The controller allows adjustment of the minimum and maximum flow temperatures and the slope of the characteristic curve. The heat output from a radiator is proportional to the 1.3 power of the difference between mean radiator temperature and room temperature and so the linear characteristic shown in the figure will tend to overheat in cold weather. Some controllers provide a two-slope or curved line to allow for this. This is discussed in detail by Levermore[3].

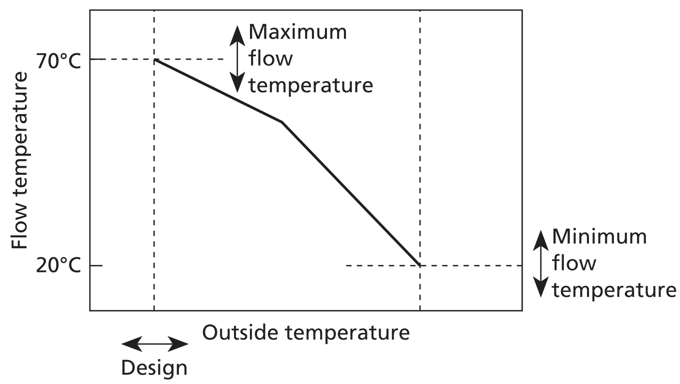

Figure 2.11 Weather compensation control characteristic with two adjustable slopes

Figure 2.12 shows a common method used in smaller buildings of providing a compensated flow temperature. Water from the boiler is blended with cooler water from the secondary circuit return in a three-port mixing valve. The temperature sensor is downstream of the valve and responds quickly to temperature changes in the flow. For larger buildings or special circumstances, more complex control arrangements may be needed. Where different parts of the building respond differently to external climatic conditions, it will be necessary to subdivide operation into zones, and perhaps add additional external sensors, e.g. a solar detector to aid control of the southern side of the building.

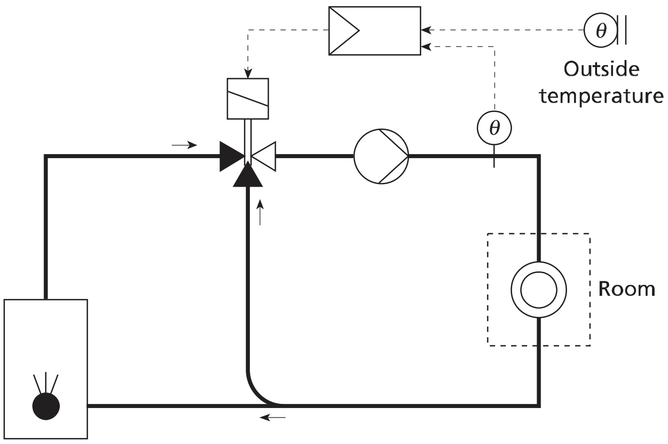

Figure 2.12 Weather compensator controlling flow temperature

The simple weather compensator described above is an example of open loop control; there is no feedback from zone temperature and the achievement of satisfactory temperature depends on the accuracy of setting up the characteristic relationship between outside temperature and flow temperature. The setting of the characteristic curve should be reviewed whenever there is a change in building use, which may affect the level of internal gains, or modification such as fitting insulation. Variations in solar gain with season or changes in shading due to foliage may also affect the settings. There are two modifications to the simple weather-compensated circuit which give improved control and are becoming more commonly used:

— *Zone trim*: the standard weather-compensated circuit is used, with a zone trim applied to the compensated water flow temperature. The trim modifies the set point by a margin proportional to the difference between the measured zone temperature and the desired set point.

— *Cascade control of zone temperature*: the outside temperature sensor is not used, but replaced by an internal zone sensor. This provides the input to a PI controller which resets the water flow temperature. This gives stable effective control of indoor temperature with no offset.

2.5 Stability and tuning

The stability of a control system is concerned with its response to a disturbance. The disturbance may be a change in the external load, e.g. an increase in solar gain though the windows of a building. The HVAC system is required to react to bring the controlled variable (room temperature) back towards the desired value. For practical reasons, the stability of a system is usually considered in terms of its reaction to a sudden change in set point:

— *Stable*: after the change in set point, the controlled variable sooner or later settles down to a new steady value. On the way, there may be oscillations about the eventual steady-state value. All the systems shown in Figure 2.7 are characterised as stable; the presence of an offset from the set point (load error) is no disqualification.

— *Unstable*: the system does not achieve a steady state following a disturbance. There are two types of unstable response:

  (*a*) *Oscillatory*: the controlled variable continues to oscillate or hunt about the set point.

  (*b*) *Non-oscillatory*: the controlled variable continues to increase or decrease until it reaches a limiting value.

Non-oscillatory instability is unlikely to be produced in an HVAC system except by a design or installation error. For example, confusing the connection of room temperature sensors in different rooms will produce unstable control: an increase in heat load in Room A will reduce the heat input to Room B; the sensor in Room B will then demand more heat for Room A. Instability may be produced by the intervention of the occupants. If an occupant opens a window because the room is too warm and this results in cool outdoor air blowing over a poorly placed thermostat, heat input to the room may be increased.

On/off control inevitably produces an oscillating value of the controlled variable. If the proportional band of a proportional controller is reduced below a critical value, the control system goes into oscillation. When considering the effects of oscillation, it is necessary to distinguish variations in the controlled variable from changes in the position of the controlled device and the associated system output. The system output in an on/off system necessarily swings from 0 to 100%. However, the swing in the controlled variable may only be a fraction of a degree where an accelerated thermostat is used. A large variation in system output does not therefore necessarily imply unsatisfactory controlled conditions.

Most buildings and their HVAC systems have a high thermal mass and in consequence change temperature fairly slowly. As a result, building control systems may be relatively insensitive to poor setting up of the control system, and a control system that is hunting may produce conditions that are acceptable to the occupants. Hunting behaviour may only be evident on directly observing movement of the actuators or by detailed logging of system behaviour by the BMS. A control system which hunts is unsatisfactory for several reasons:

— it produces excessive wear on valves and actuators

— temperature cycling may produce undesirable effects on plant and equipment

— it may produce instabilities in other parts of the system.

Some variation of control output and movement of the controlled device is inevitable as the system responds to small changes occurring within the building. The opportunity should be taken to observe the action of the controlled devices at a time when the HVAC system is controlling in a steady state. Any movement should be slow and of small amplitude. It is difficult to give figures which are of general application. However, as a rule of thumb, action should be taken to investigate the stability of the system if any controlled device is cycling with an amplitude greater than 20% of its full range, or is changing position by more than 20% in a period of 10 minutes.

The following factors must be taken into account to ensure a stable operating control system:

— correct tuning of controllers

— interactions between control loops

— stable operation must be ensured over all operating conditions, e.g. variation of system gain with load

— the influence of sampling period.

Interaction between control loops

An HVAC system may contain many control loops, the actions of which interact with each other. Consider, for instance a network of heat emitters controlled by two-port valves, being fed from a common secondary circuit. Each two-port valve is controlled by a local control loop which maintains a zone temperature. The movement of one valve in response to a change in load will alter the pressure seen by the other circuits, causing a change in flow, with a resultant alteration in the controlled variable and consequent movement of the valves. This in turn will change the pressure seen by the original two-port valve. It is possible for the circuits to interact in such a way that the valves do not achieve a steady equilibrium position, but continue to hunt.

A general principle that applies to any feedback control loop is that the sensor must measure the response of the controlled variable relevant to that loop and not any other. The effects of interchanging the connection of sensors in adjacent rooms is an obvious example. If one room is below its set point, additional heat will be supplied to the other room. This will result in a reduction in heat supply to the first room, giving maximum heating to one room and none in the other.

A more subtle variation of this problem occurs when the two controlled zones overlap. Consider the example of adjacent VAV boxes supplying a common space. Each box has its own temperature sensor, but the nature of the space and the air flow patterns is such that the two temperature sensors show the same value. If the set points of the two VAV boxes are not identical, one will show a small positive error and the other a small negative error. Since it is impossible for both to have zero error simultaneously, the effect of PI control will be to produce integral wind-up, which over time will result in one box being driven to maximum output and the other to minimum. This effect may be mitigated by using proportional-only control where there is a danger of adjacent boxes interacting. The use of intelligent VAV boxes or fan coil units allows groups to be programmed with a common set point, with one unit acting as a master, controlling the others as slaves.

Operating conditions

An HVAC system is designed to operate over a wide range of conditions. Most design work is done at design conditions, where the system is required to produce maximum output. For most of the year, the system operates at part load where control behaviour may be different from design conditions. Consider for instance a VAV system. The supply air is cooled by a cooling coil, which is modulated to control the air temperature. If the air flow is half the design maximum, then the change in valve position to produce a given change in air temperature will be about half that required at full flow, i.e. the gain of the system has doubled. There is therefore a risk of instability if the control loop is tuned at design conditions. To ensure stability, tuning should be done in conditions which produce a high system gain.

Sampling time

Digital control systems measure the controlled variables at intervals known as the sampling time. The sampling time is determined by:

— the time period required by the A/D converter

— any multiplexing between sensor inputs

— density of traffic on a bus system.

Too fast a sampling time will require an unnecessary amount of data handling by the BMS. However, too slow a sampling time may be inadequate to detect changes in the system in time to take appropriate control action. Where the sampled values are stored for evaluation, too slow a sampling rate can produce unsatisfactory or misleading information; a high frequency variation sampled at too low a frequency may be interpreted incorrectly as a low frequency variation; this is known as aliasing. The correct sampling frequency may be selected by reference to Shannon's sampling theorem, which states that provided a signal contains no component with a frequency higher than f_{max}, the signal may be reconstituted from a set of samples taken with frequency at least twice f_{max}. In practice, sampling frequencies of 10 times the theoretical value are used[(3)].

2.5.1 Tuning

The behaviour of a control loop under changing conditions is affected by the controller settings. Incorrect settings of the controller parameters may lead to unstable behaviour, resulting in large output swings, or else sluggish response and a deviation from the desired set point. Optimum performance from a controller depends on the correct settings for the control parameters. Two forms of response may be considered to represent the acceptable boundaries of sensitive and sluggish behaviour:

— *Quarter wave response*: following a disturbance, the system response overshoots the new equilibrium value and approaches equilibrium in a series of damped oscillations. The amplitude of the first overshooting wave is four times that of the second.

— *Critically damped*: this response is the fastest approach to the new equilibrium value that can be achieved without any overshoot.

Values of the parameters may be found by carrying out in situ tests on the control loop. There are two common techniques used in estimation:

- closed loop ultimate cycling method (oscillation test)
- open loop reaction curve method (transient response).

Both require the behaviour of the control loop to be recorded; parameter settings may then be calculated from the measured response. Several calculation methods are available and may be selected to give the desired behaviour; they are summarised in Appendix A1. It must be emphasised that the parameters calculated in this way should be regarded as guide values. Since system gain often varies with operating conditions, control loop behaviour will also vary. To ensure stable operation under all conditions, tuning should ideally be done under conditions of high system gain. Where there is doubt, the parameters should be adjusted as follows to reduce risk of instability:

- proportional band increased
- integral action time increased
- derivative action time decreased.

2.5.2 Practical tuning

Before starting formal tuning procedures, it is advisable to check the system manually. If manual operation is unsatisfactory, the problems should be rectified before tuning the loop. Adjust the set point manually between several positions and observe:

- Is the process noisy: are there rapid fluctuations in the controlled variable?
- Is there appreciable hysteresis or backlash in the actuator?
- Is it easy to maintain and change a set point?
- In which operating region is the process most sensitive?

Some general principles should be borne in mind before starting to tune a control loop.

- In order for tuning procedures to work properly, the final output to the controlled device should have a proportional action. An on/off controller cannot be tuned satisfactorily.
- The controlled device should be within its operating range, i.e. not driven to fully open or closed, nor operating in a region where movement of the final actuator has little effect on the process output.
- Where cascade control is being tuned, tune the inner (submaster) loop first. Where a control loop depends on the stability of some other part of the system, tune the primary service first, e.g. tune a primary water circuit to ensure flow temperature stability before tuning any of the secondary loops.
- Some controllers operate more than one controlled device, e.g. a temperature controller may operate both heating and cooling coils. It may be necessary to disable operation of one of the outputs to prevent it being brought into operation during tuning if the controlled variable overshoots.

Determining the controller settings by the formal methods detailed in Appendix A2 may not always be practicable. Experience has shown the following adjustments will often give suitable settings.

- *Proportional band*: a conservative starting point for the proportional band is a value equal to the change in the controlled variable produced by a 50% change in plant output.
- *Integral time*: a conservative initial value for the integral time is to set it equal to the open loop time constant, estimated as the sum of the component time constants, e.g. actuator, sensor and HVAC process.
- *Derivative time*: derivative control is applied when there are significant delays in the control loop. Try an initial value of derivative time equal to 50% of the loop dead time.
- *Sampling time*: set to no more than 25% of the open loop time constant; greater sampling times may result in unstable control.

Guidance on typical initial controller settings will generally be provided by the manufacturer. Table 2.2 shows suitable settings for some common applications, which may be used if better information is not available.

Table 2.2 Typical settings for a PI controller

Controlled device	Controlled quantity	Proportional band	Integral time (min)
Heating coil	Zone temperature	2 K	0
Preheat coil	Duct temperature	3 K	4
Chilled water coil	Duct temperature	8 K	4
Humidifier	Zone RH	15% RH	15
Dehumidifier coil	Duct RH	15% RH	4
Thermal wheel	Duct air temperature	4 K	4
Run around coil	Supply air temperature	6 K	4
Recirculation damper	Mixed air temperature	4 K	4
Ventilation supply	Zone CO_2 concentration	100 ppm	10
Room terminal unit	Zone temperature	3 K	4
Supply fan	Static pressure	1000 Pa	1

2.5.3 Self-tuning controllers

The methods described above for tuning PID controllers are based on standard control theory, which makes assumptions about the linearity of the controlled system. In practice, the formal tuning methods may have disadvantages:

- *Effort*: tuning control loops during commissioning is time consuming and it may be difficult to allocate the skilled effort required when under pressure of time. There is a temptation to leave the controllers at factory preset values, which are unlikely to be optimum.

— *Non-linearity*: the tuning methods assume that the control system is linear and that the system gain remains constant. System gains vary with load and are likely to vary both over the day and over the year. Correct choice of valve or damper authority and characterisation helps to improve system linearity, but it is not always possible to achieve good linearity over the range of operations encountered.

Several means of automatic tuning of controllers have therefore been developed. There are different approaches:

— *Autotuning*: autotuning software automates the tuning procedure by exciting a controlled response and calculating the optimum control settings. It is initiated by a controls engineer during commissioning or when required. Autotuning is applicable when the system characteristics are constant.

— *Adaptive techniques*: where the operating characteristics of the control system vary substantially, it is desirable to use a form of self-tuning that acts continually to optimise the control settings. The different approaches are:

  (*a*) *Gain scheduling*: if the variation of optimum settings of controller parameters with plant operating condition can be established, then the parameters are automatically adjusted as a function of plant operation. Gain scheduling is effective when the operating dynamics of the system are well understood.

  (*b*) *Adaptive control*: where the changes in plant dynamics are large and unpredictable, a controller which continuously tunes itself is desirable. Adaptive controllers use some form of plant model or pattern recognition. A commonly found form of adaptive control is to be found in optimum start controllers, which are described below.

2.5.3.1 Autotuning

Several manufacturers market controllers with an in-built autotuning facility. Software within the controller automates the tuning procedure by exciting a response from the plant and calculating the control parameters from the observed response. The controller is then set to the new parameters; the engineer may be required to accept them before they are applied. Before tuning, the process must be in a steady-state condition. The tuning action is initiated by the controls engineer, normally by simply pressing a button. The controller parameters remain fixed between tuning sessions. An autotuner is therefore unable to compensate for variations in system gain and the tuning process should therefore take place under representative operating conditions. In many HVAC systems there is interaction between different control loops. When using an autotuner it is important to select the order in which the loops are tuned to minimise any interactions. Start with fast-responding local control loops; when these have been tuned move to larger slower loops. The use of autotuning can give significant improvements in performance coupled with a substantial reduction in commissioning time compared with conventional PID controllers. Further details are to be found in Wallenborg[4] and Astrom *et al*[5].

2.5.3.2 Adaptive techniques

The control characteristics of an HVAC system may vary with operating conditions. The characteristics and authority of valves and dampers affect linearity of response of a system and the achievement of a linear characteristic of a complex system over its whole operating range is difficult. The gain of a system will also change with operating conditions, e.g. the change in flow temperature produced by an optimiser or the change in inlet air temperature with season will produce changes in system gain. Since a high system gain tends to produce control instability, controllers must be tuned when the plant gain is high. This will ensure stability, but control performance may be sluggish in low gain conditions. There is therefore an advantage to using a controller which will retune itself automatically in response to changing conditions.

If the performance of the control system is well understood, it is possible to monitor the operating conditions of the plant and adjust the control parameters in accordance with a data table which relates control parameters to operating conditions. This process is known as gain scheduling, though it is not limited to adjusting the controller gain; derivative and integral times may be adjusted as required. Gain scheduling is not strictly a form of adaptive control, since no learning is involved. The relation between plant operating conditions and optimum controller settings must be known in advance. It is possible to build up a schedule of control parameters by initiating autotuning under a range of operating conditions.

If the changes in plant dynamics are large and unpredictable then a controller which continuously tunes itself has great advantages. Adaptive controllers learn the operating conditions of the plant and control system by observing the response to changes in set point or external disturbances. In order to protect the system against unreliable parameter estimates, additional software is used to supervise the system to prevent poor control performance in unpredictable situations; this is known as jacketing software. There are two basic approaches to adaptive control:

— Pattern recognition methods analyse the controlled response and recalculate new values of control parameters. Oscillations and offsets are measured and new control gains calculated when significant adjustments are required. A pattern recognition adaptive controller (PRAC) is described in Seem[6]. The method was developed for systems that can be modelled as a first-order plus dead-time response, which includes most HVAC systems. The controller is claimed to be easy to use and provide near optimal control. It has been used successfully in a number of HVAC situations.

— Indirect methods employ a model of the process which is continually updated by comparison with behaviour of the real plant. The model is then used to calculate updated values of the control parameters. This method may be combined with neural networks.

Adaptive controllers and self-tuning controllers have yet to find wide application in the HVAC industry, though they offer potential benefits in reduction in commissioning time, increased actuator life and improved environmental control. Their operation may be adversely affected if tuning is attempted in the presence of plant failure or periodic disturbances. An adaptive controller which continuously seeks to optimise its operation may act to compensate for plant degradation and so delay needed maintenance action.

2.6 Artificial intelligence

Conventional controllers, whether analogue or digital, rely on a precise mathematical relation between input and output. For a well-behaved system operating in a consistent environment, a well-tuned PID controller will give satisfactory control. However, many real systems involve uncertainties, non-linearities and variations in their operating environment. There may be multiple inputs which affect the desired control output. Such complications may be difficult to incorporate in a conventional controller. Advances in artificial intelligence and the availability of improved processing power are leading to the development of new types of controller. 'Fuzzy logic' and neural networks show great promise in dealing with some aspects of HVAC control and their application is certain to grow.

Fuzzy logic is a means of decision making based on a set of rules of the type 'IF (A is true) THEN (take action B)'. The rules are written based on knowledge and experience of the system to be controlled and are expressed in near natural language[7]. Fuzzy logic differs from conventional logic in that a statement may have degrees of truth or, more formally, a point can have simultaneous degrees of membership of several fuzzy sets. This represents the way we deal with situations in real life; there is, for instance, no abrupt transition between 'comfortable' and 'cool'. Figure 2.13 illustrates the chain of operations in a fuzzy logic controller, for the simple example of a single input, single output controller; one of the advantages of fuzzy logic is its ability to deal with multiple inputs and outputs. The controller accepts a crisp input; crisp means an exact numerical value, such as the deviation of a measured temperature from the set point. The controller then 'fuzzifies' the input, by establishing the degree of membership of the several fuzzy sets which have been defined in the controller. For instance, a measured room temperature may have 80% membership of the set 'comfortable' and 20% membership of the set 'cool'. The controller then applies the inference rules, which are of the form 'IF (the room is cool) THEN (set heating to half power)'. This results in an output which has membership of several fuzzy output sets; this output is then 'defuzzified' to produce a crisp output value which is used to control the plant. The defuzzification process is analogous to the fuzzification process, where the degree of membership of several output sets is combined to produce a crisp output.

The main advantages of fuzzy control are that it does not require a model of the process to be controlled and that it is possible to incorporate the results of operational experience into the set of rules. These would be otherwise difficult to incorporate into a conventional control algorithm. Fuzzy controllers have been developed for HVAC systems and it has been found that they offer advantages of robustness, energy saving and fast response, compared with conventional PID control[8]. Simple fuzzy controllers are often found to exhibit undesirable oscillation when the system is controlling near the set point. It is possible to use the rate of change of the controlled variable as additional input to the controller. Extra fuzzy rules are added to modify the controller output according to the rate of change; this helps provide smooth control at conditions near the set point and is a common feature in fuzzy controller designs.

Neural networks attempt to reproduce the way the human brain learns by experience. In brief, a neural network device accepts data from a number of inputs, processes the data using a series of non-linear processing elements and produces a set of output data. What distinguishes a neural network from other types of processor is that it does not depend on a model or even an understanding of the process, but is capable of learning by experience. Learning algorithms are employed which adjust the internal parameters to optimise the performance of the network. Accordingly, a period of training is necessary before a neural network can achieve satisfactory performance. Neural networks are applicable where a high degree of non-linearity exists and there is a large amount of data available for training the network. Both these criteria apply to a BMS. A number of promising applications to HVAC systems have been identified[9]:

- *Condition monitoring*: incipient plant failure may be detected by changes in performance. This requires knowledge of how the plant operates under a wide range of conditions and the ability to detect variations; a neural network can be trained to do this.
- *Optimisation*: the operation of a complete HVAC system is highly non-linear, making it difficult to optimise performance under a range of load conditions. A neural network can be applied to learn the system behaviour and then used off-line to investigate optimum control strategy.
- *Energy monitoring*: neural networks have the potential to learn the consumption patterns against key variables such as occupancy, time of day, weather and process activity. Deviations from the expected pattern can then be detected, giving early warning of increased energy consumption.

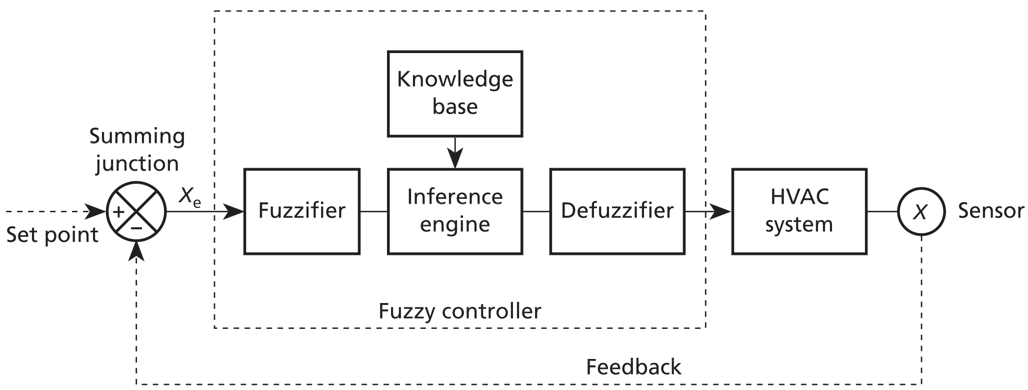

Figure 2.13 Components of a fuzzy controller

2.7 Summary

The section sets out the basic concepts of open loop and feedback control loops. The fundamental control modes used in feedback control are:

— *proportional control*: produces a control output proportional to the deviation of the controlled variable from the desired set point

— *integral control*: produces a control signal proportional to the time integral of the deviation from the set point

— *derivative control*: produces a control signal proportional to the rate of change of the controlled variable.

Proportional control can be used by itself to produce stable, effective control, but produces a load error, i.e. an offset from the set point. Integral action may be added to proportional control to give PI control, which eliminates the load error over time. Derivative control is used to anticipate overshoot in systems of high inertia. PID control can produce rapid response to changes in load with little offset, but is rarely used in building control systems.

Controllers need to be tuned to avoid the problems of instability on the one hand, or sluggish response on the other. Formal methods of estimating the optimum parameter settings are summarised. In addition, practical recommendations are given of values which are likely to be found satisfactory in practice.

Optimum start control is an algorithm that has been developed to turn on heating or cooling at the latest possible time to ensure that comfort conditions are achieved at the start of the occupancy period. The controllers are capable of learning the behaviour of the building and heating system and adjusting the settings accordingly; this is an example of adaptive control. The control of compensated heating circuits is described; flow temperature may be related to either outside weather in internal zone temperature. Developments in intelligent controls are described which are leading to the introduction of adaptive controllers which are capable of continuously retuning themselves to give optimum operation.

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3 Components and devices

Summary

This chapter deals with the hardware components that make up a control system. Guidance is given on the choice of suitable sensors and the importance of correct installation is stressed. Valve sizing and characterisation is covered together with choice of dampers. The use of variable speed drives for pumps and fans is covered.

3.1 Sensors

Sensors form a vital component of any control system. Sophistication in the computing and software functions cannot compensate for inaccurate information provided by poor-quality or inappropriately mounted sensors. The types of sensor available for use in building control systems are reviewed and guidance on selection and installation is given.

3.1.1 General categories

The word sensor is generally used rather loosely to cover all processes between the measured variable and the input to the control module. The functions may be broken down into the following:

— *Sensing element*: a component that undergoes a measurable change in response to a change in the variable to be measured.

— *Transducer*: an active device that produces an electrical signal which is a function of the change in the sensing element.

— *Transmitter*: a device that produces an electrical signal that is a standardised function of the change in the physical variable and which can be used as an input to the control module.

In practice the function of the transducer and transmitter are often combined. Their function may be referred to as signal conditioning, which may include filtering to remove noise, averaging over time, or linearisation. In some systems the sensing element may be connected directly into the controller, e.g. thermocouple input, where the signal conditioning now takes place inside the controller module. The various combinations are categorised as follows.

Status sensors produce a binary (on/off) output depending on whether the measured variable is above or below a set point. The sensors are normally mechanical devices, where a physical movement of the sensing element causes switch contacts to open or close. Typical devices are thermostats, humidistats and pressure switches. The output may be connected to a digital input of a controller for status reporting or software interlock purposes. Safety-critical interlocks are usually hardwired directly to the item of plant which is to be switched off.

Where the condition being monitored is critical, it is important that it be measured directly. For instance, where it is important to shut down part of a system in the event of no air flow, the air flow in the duct should be monitored by a pressure sensitive switch; if the flow is non-critical it may be satisfactory to simply monitor the presence of an electrical input to the fan motor. The general form of output from a status sensor is the provision of voltage-free contacts.

Analogue sensors convert the value of the measured variable into an electrical signal which is input to other devices for measurement and control purposes. Analogue sensors may be subdivided into the following:

— *Passive devices*: which consist of the sensing element only and do not contain a transducer. All signal conditioning is carried out in the controller to which it is connected. Examples include resistance type temperature sensors. No power supplies are required and the sensor is connected via field wiring directly to an analogue input on a controller.

— *Active devices*: which incorporate signal conditioning within the sensor device and include a transmitter which converts the measured value to an industry standard electrical signal for connection via field wiring to an analogue input on the controller. The output of the transmitter commonly takes one of several standard forms shown in Table 3.1. Signal transmission employing a 4 to 20 mA signal requires only a two-wire connection and is suitable for use in hostile

Table 3.1 Standard signals for transmission of sensor readings

Signal	Application
0–10 V DC	Standard for HVAC applications
4–20 mA	Common in process control
Voltage-free contact	For status indication
Pulse	Energy and flow measurement

environments. It is commonly used in process control applications. A 0–10 V transducer requires both a power supply and a signal output, needing a three or four-wire connection. The lower cost of 0–10 V systems leads to its widespread application in HVAC systems.

Intelligent sensors contain a microprocessor that converts the measured value or status of the measured variable into a digitally encoded signal for direct communication over a network for onward transmission to other intelligent devices for control and measurement purposes. In addition, an intelligent sensor may carry out additional data processing before transmitting the value, such as:

— checking upper and lower bounds

— calibration and compensation functions

— calculating derived values, e.g. enthalpy.

3.1.2 Selection requirements

The correct selection and location of sensors is vital to achieving the required performance from any control system. Sensor problems are the most frequent cause of control system malfunctions. A poor-quality sensor may suffer from drift or early failure, resulting in poor control and high maintenance costs.

3.1.2.1 General requirements

The requirements that must be borne in mind when selecting any type of sensor are set out in Table 3.2. Sensor inaccuracy or failure is a major cause of problems in building management systems. Experience shows that the problems are usually caused by incorrect installation, rather than an intrinsic problem with the sensor itself.

3.1.2.2 Accuracy

The claimed accuracy for a sensor does not guarantee that the same accuracy will be achieved at the controller or BMS supervisor, nor that it will be maintained over the operating life of the sensor. The accuracy of the overall measurement system depends on several factors:

— *Accuracy of the sensing element*: the claimed accuracy of the element may not be available over the whole operating range or may be quoted under ideal conditions.

— *Sensitivity*: this is the smallest change in the measured variable that can be detected by the system.

— *Interacting variables*: the condition of the sensor may be affected by other environmental variables, e.g. an air temperature sensor will be affected by thermal radiation or an RH sensor by local variations in air temperature.

— *Stability*: sensors may drift with time and require checking. Stability is likely to be affected by operating conditions.

— *Hysteresis*: the sensor reading may be affected by its past history and speed and direction of change of the measured variable.

— *Mounting*: the mounting and location of the sensor will affect the reading.

— *Signal conditioning*: associated transducers will introduce their own limitations to the accuracy achievable. Some systems ‘filter’ readings first and only transmit when the measured variable has changed by a specified ‘filter factor’. This is used to minimise network traffic.

— *A/D conversion*: the discrimination of any analogue to digital conversion will set a limit to the achievable accuracy. Eight-bit conversion divides the range into 256 steps, 12-bit into 4096 steps. In the latter case, a measurement range of –50 to 150 °C would have a step size of 0.05 K.

Table 3.2 Sensor requirements

Sensor requirement	Checklist
Type	Status, analogue, intelligent
Sensed medium	Air, water, gas, oil
Sensed quantity	Temperature, pressure, velocity, humidity
Location	Space, duct, pipe
Housing	Accessibility, effect on accuracy and speed
Accuracy	Accuracy, resolution, hysteresis, repeatability
Operating range	The range over which the sensor performs accurately
Overload range	The range to which the sensor may be subjected without damage
Response time	Affected by sensor, housing and medium
Protection	Is protection required from a damaging environment?
Maintenance	Calibration requirements, ease of servicing and replacement
Interchangeability	Can sensor be replaced by another from the same or different manufacturer?
Cost	Initial cost and total ownership cost over life cycle

3.1.2.3 Speed of response

Sensors need to respond sufficiently fast to changes in the measured variable so that stable and accurate control can be maintained. The speed of response is characterised by the time constant τ, which is the time taken for the signal output to change by 63% of the final change. The time constant of a sensor in practice includes the effects of its housing, the manner of mounting and the nature of the medium being measured. There may be additional delays introduced by the measurement system; the scan rate of the controller limits the speed of response of the system to a change in the measured variable. Increasing the relative speed of the fluid flowing past the sensor reduces the time constant, up to a speed of about 0.3 m/s for water and 2 m/s for air. Above these speeds there is little reduction in time constant. For accurate and rapid measurement it is possible to measure air temperature with an aspirated thermometer, where air is drawn past the sensing element by a small fan.

The time constant of the sensor should be considered in relation to the rest of the controlled system. Too low a time constant may give problems if short term fluctuations in the measured variable give rise to unwanted control action. This may be dealt with in the controller software, typically by incorporating an averaging function to extend the time constant. Too high a time constant may mean that the control system will respond too slowly to changes in the controlled variable; this cannot satisfactorily be compensated by the control software. The time constant of the sensor is only one part of the time lags involved in a heating and control system; the general problem will be discussed below.

3.1.3 Types of sensor

The following deals with the selection of sensors which are used in control systems. It does not cover more specialised sensors which are used in safety systems, such as gas or refrigerant leak detection. Nor does it include safety sensors which are normally included in plant, such as the fusible links used to detect over-temperature above boilers. Energy metering is covered in 7.1.3 and the use of occupancy detectors in lighting control systems is dealt with in 5.15.1.3.

3.1.3.1 Temperature sensors

Temperature is the most widely measured variable in HVAC applications and several types of sensor are available. Mechanical devices are in general cheap and reliable. The output is a physical displacement which is used to directly operate a switch; the most common example is the domestic room thermostat. The set point may be varied by physical adjustment. They are not used in automatic control systems, except for limit switches. The most widely used sensing elements are listed in Table 3.3; elements used primarily for specialist or technical purposes have not been included.

The specification of a temperature sensor reflects its application. An accuracy of 0.6 K achieved over a 15 to 25 °C range is suitable for zone air temperature measurement, while an accuracy of 0.25 K is needed for control of chilled water temperature. There is little point in specifying greater accuracy than is realistically required; reliability is often more important in practice.

3.1.3.2 Humidity sensors

The measurement of humidity is important in air conditioning control, but presents practical problems of drift and contamination. Simple mechanical sensors are available based on the expansion of hair or a nylon film with increasing atmospheric relative humidity. These elements can be incorporated in humidistats, comparable in operation and application to mechanical thermostats. They are generally reliable and resistant to contamination, but have low accuracy, which worsens outside the range of 20 to 80% RH. While many types of humidity sensor exist, two types have come to dominate in HVAC applications (Table 3.4); the traditional wet and dry bulb psychrometer is not included as it is no longer used in automatic control applications. The capacitative polymer film sensor provides a direct measure of relative humidity and is in widespread use. The sensing element is normally protected by a membrane or netting filter; a sintered metal filter permits the use of an RH probe in air speeds of up to 40 m/s. Where an accurate measurement of dewpoint is required, particularly at low humidities or low temperature, the chilled mirror dewpoint sensor provides the most accurate measurement(1,2). This detects the formation of condensation droplets on a small mirror surface which is cooled by the Peltier effect; the temperature at which condensation is detected provides a direct measure of dewpoint. A recent development detects the onset of condensation using electromagnetic means.

Table 3.3 Temperature sensors

Sensor	Element	Description	Types	Advantages	Disadvantages	Applications
Platinum resistance thermometer (PRT)	Thin metal film on substrate	Electrical resistance increases as a linear function of temperature. Three- or four-wire connection required	Pt100 and Pt1000, available as passive sensors or with inbuilt transmitter	Industry standard. Interchangeable elements, high accuracy, reliable, stable	Cost. Lead wire resistance and self-heating can introduce errors	Widespread
Thermistor	Semiconducting metallic oxides in bead, rod or disc format	Electrical resistance changes with temperature; highly non-linear	Various standards exist; some are supplier specific. Usually negative temperature coefficient (NTC)	Cheap, high sensitivity, small size, wide range available	Accuracy and drift. Short life unless protected against moisture. Signal conditioning required; may not be interchangeable	Widespread. Differential temperature
Nickel resistance thermometer	Wound coil of nickel or nickel alloy wire	Near linear change in resistance with temperature. Higher coefficient than platinum	Standards exist for Ni100 and Ni1000 elements. Alloy elements may be supplier specific.	Moderate to good accuracy. Field wiring has little effect on accuracy Available in special formats, e.g. duct averaging	May need signal conditioning. May not be interchangeable	Widespread

Table 3.4 Humidity sensors

Type	Element	Description	Types	Advantages	Disadvantages	Applications
Capacitive sensor	Thin polymer film acts as dielectric	Film expands with increasing RH, changing capacitance of sensor. Dedicated signal conditioning gives linear output with RH	Supplier specific, range of mountings available	Accurate, reliable and stable	High cost. Drift, particularly if exposed to high RH. Annual recalibration advised	Widespread
Dewpoint	Chilled mirror	Detects dew formation on mirror chilled by Peltier effect. Measurement head incorporates light source, detector and chilled mirror. Sophisticated control gear required	Supplier specific	Direct measurement of dewpoint, high accuracy	Size, expense. Maintenance requirements	High accuracy control

Where RH is measured and a measure of absolute humidity or enthalpy is required, it is necessary to take a simultaneous measurement of air temperature. The air temperature sensor should experience the same environment as the humidity sensor and ideally should be enclosed in the same housing. Sensors are available which incorporate both temperature and RH measurement within the same head and may have enthalpy and dewpoint output options, in addition to the direct measurement of temperature and RH. Measurement of humidity is subject to many uncertainties and it is unreasonable to expect an accuracy in practice of better than 2.5%. Further information on a wide range of sensor types, their errors and calibration methods are given in a guide published by the Institute of Measurement and Control(3).

In some applications, such as the control of chilled ceilings, it is necessary to anticipate the formation of condensation on a chilled surface. Two major types of sensor are used. One is a dedicated form of humidity meter. The sensing element is contained in a small metal housing which is held in good thermal contact with the cold surface. The attached control unit provides a digital signal output when the RH at the sensor reaches a preset level of 97% and so anticipates the formation of condensation. The other type detects the initial formation of condensation by monitoring the electrical resistance across an array of conducting tracks on a substrate held in good thermal contact with the cold surface.

3.1.3.3 Pressure sensors

Pressure is the most commonly measured quantity after temperature. Most pressure sensors consist of a diaphragm or bellows, which moves under the influence of the pressure applied across it. The movement is a function of the applied pressure and the measurement problem is fundamentally a measure of displacement.

Pressure may measured relative to atmospheric pressure, when it is termed gauge pressure, or else as a differential pressure across two points in a system. Building static pressure may vary appreciably over a building and the reference atmospheric pressure against which gauge pressure is measured must be carefully considered. Pressure within a building is affected by mechanical ventilation, door and window opening and the stack effect. An outside static pressure sensor should be mounted in free air at least 2 m above a surface and fitted with a wind shield. The bellows or diaphragm construction depends more on the working pressure than on the medium and most pressure sensors may be used with air, water or other media. The types of pressure sensor listed in Table 3.5 are classified by transducer, rather than the pressure sensing element. Where fluctuating pressures or vibration are to be measured, use may be made of piezoelectric transducers, which can respond to sonic frequencies. A wide range of mechanical pressure switches is also available, which operate as status sensors and are used where safety interlocks are required, e.g. to detect fan operation.

Table 3.5 Pressure sensors, classified by transducer

Sensor	Element	Description	Advantages	Disadvantages	Applications
Capacitive	Diaphragm or bellows with capacitive transducer	Movement of bellows alters capacity	Low cost	Low output, signal conditioning required	Low pressure air. Duct static or filter differential pressure
Inductive	Diaphragm or bellows with inductive transducer	Movement of bellows operates a linear variable differential transformer	Rugged construction	Expensive; temperature compensation may be difficult	As for capacitative
Strain gauge	Diaphragm or bellows with strain gauge transducer	Strain gauge bonded to pressure sensing element	Rugged, linear output	Low output signal	High pressure, chilled water, steam
Potentiometer	Diaphragm or bellows connected directly to variable resistor	Movement of pressure sensing element operates a variable resistor	Inexpensive, high output	Low accuracy, large size, wear may shorten life	

3.1.3.4 Velocity and flow

Strictly, velocity implies both speed and direction. In practice, the direction of flow is determined by the duct or pipe and a speed measurement is all that is required. The flow in a duct may be measured directly or derived from a velocity measurement and knowledge of the cross-sectional area of the duct; corrections for temperature and pressure may be required. For well-developed flow in a straight pipe, it is possible to assume the velocity distribution over the cross-section of the duct. This requirement is generally satisfied by positioning the sensor so that there is a distance between the sensor and any disturbance of 10 pipe diameters before the sensor and five after. If this is not possible, multiple measurements will be required to provide some form of averaging. Several methods of velocity and flow measurement are available (Table 3.6). For control purposes it may be possible to monitor differential pressure across a fixed restriction, such as a heating coil or louvre; devices which have a variable resistance, such as filters or cooling coils, must not be used for this purpose.

3.1.3.5 Air quality

The use of demand-controlled ventilation (DCV) requires a measure of the condition of the indoor air. Carbon dioxide concentration is becoming the most generally accepted measure (Table 3.7). While it does not give a complete indication of the various contaminants, it gives an overall measure of the relation between occupancy and ventilation. Multi-gas sensors, based on a tin oxide layer, respond to a number of possible contaminants, but the integrated response does not necessarily reflect the air quality as perceived by occupants. They are therefore not generally recommended for DCV[4,5]. Multi-gas sensors have applications in areas where there is a low concentration of people, but smells are a potential problem, for example restaurants and bars. Sensors sensitive to particular gases are required for specialised ventilation control applications, such as car parks. Indirect methods, such as counting the total building occupancy or predicting it from a work schedule, may be used instead of air quality measurement for ventilation control.

3.1.4 Sensor mounting

A sensor can only measure the state of its own sensing element. Care must be taken to ensure that this is representative of the physical quantity being measured. The following general guidelines should be borne in mind:

— Ensure that the sensor is in a position representative of the variable to be measured.

— Take care that temperature and humidity sensors are screened from direct radiation, particularly sunlight.

— Take account of the active and inactive sections of the sensor probe.

— Ensure adequate immersion of the sensor in the medium. Heat conduction along a sheath can affect readings.

Table 3.6 Velocity and flow sensors

Sensor	Element	Description	Types	Advantages	Disadvantages	Applications
Pitot tube	Tube with opening at upstream end	The stagnation pressure of the air brought to rest in the tube is proportional to the square of the air speed. The difference between stagnation and static pressures is measured by a suitable pressure gauge	Can be obtained in the form of arrays which perform an averaging function over the area of the duct, e.g. Wilson grid	Inexpensive, but duct averaging sensor may be expensive	Requires unidirectional air flow above 3 m/s. Can become blocked with dirt	Air speed when direction is determined. Air flow rate for VAV units
Hot wire anemometer	Heated fine wire or thermistor bead	The sensor element is heated by an electric current to a constant temperature. The current is a function of the fluid speed	Available as grid for measuring flow rate in duct	Measures mass flow, resistant to contamination, short time constant. Can measure low flow rates	Fragile, expensive	Air flow. Available in arrays. Use thermistor type for non-directional flow
Orifice plate	A plate with a precisely defined hole is inserted into the duct	The pressure drop across the plate is proportional to the square of the velocity. Transducer may sense mass or volume flow rate	Calibrated plates with integral pressure tapping are available. Venturi devices operate on a similar principle; they have a lower pressure loss but are bulkier	Robust, no moving parts	Erosion of orifice will affect accuracy. Has to be fitted in straight section. Not suitable for low flows. High pressure loss	Can be used for air, water or steam
Turbine flow meter	Bladed turbine immersed in the fluid	The speed of rotation is proportional to flow. A magnetic detector produces a pulse train with frequency proportional to rotor speed	May be full bore, mounted between flanges, or a small insertion device mounted in the centre of the pipe	Moderate cost. Good accuracy. Wide range of velocities and low pressure loss	Susceptible to damage when used with water	Metering of water and natural gas. Heat metering

Table 3.7 Gas sensors

Sensor	Element	Description	Types	Advantages	Disadvantages	Applications
CO_2 sensor	NDIR optical cell (non-dispersive infrared)	Measures the absorption of infrared radiation by CO_2 in air	Wall-mounted housing with CO_2-permeable membrane for DCV applications	Small size, insensitive to humidity or other vapours	Cost	Demand-controlled ventilation for occupied spaces
Multi-gas sensor	Tin oxide film	Detects oxidation on a heated tin dioxide surface. Sensitive to heavy odours, smoke and solvent gases	Various wall and duct housings available	Sensitive to wide range of contaminants	Relative rather than absolute measure of contamination	Multi-contaminant situations. Carbon dioxide control preferred for occupied spaces
Specified pollutant	Non-dispersive infrared	Uses infrared absorption. Sensor is specific to pollutant	Available for several gases	High accuracy and stability	High cost	Car park ventilation control (carbon monoxide and nitrogen dioxide); swimming pools (chlorine); air pollution monitoring (sulphur dioxide)
Obscuration	Optical cell	Detects absorption of light beam by suspended particles		High accuracy and stability	High cost	Roadway and tunnel ventilation control

— Provide a tight sealing hole adjacent to every duct mounted sensor for the insertion of a test sensor.

— For pipe sensors use a separable pocket. Ensure that the sensor is a close fit in the pocket and use a thermal conductive paste.

— Use flexible cable. A rigid cable could disturb the position of the sensor.

— Sensor cables should be provided with a 'drip loop' to prevent water running into the sensor housing.

— Allow sufficient spare cable to allow for removal.

— Record the location of all concealed sensors.

— Fix a labelling plate next to every sensor, not on the device itself.

— Allow for stratification and use more than one sensor or an averaging sensor if necessary.

— Position duct temperature sensors downstream of supply fans.

3.1.5 Calibration sensors

Sensors should be routinely checked and recalibrated. The frequency of checking depends on the nature of the sensor; it will be greatest for sensors in challenging environments and those subject to drift. Exposure to extreme conditions may affect calibration; this is a problem with RH sensors exposed to high humidities.

Sensor calibration may be performed by using the sensor to measure a standard condition, or to compare the sensor reading with that of a standard instrument. The former is more common in the laboratory that in the field. Standard relative humidities may be produced using saturated solutions of salts and it is possible to obtain a set of calibration vessels into which humidity probes can be inserted for checking. It is more common to check sensors by comparison against a reference standard. This should be a good quality instrument reserved for this purpose which has itself a certificate to prove that its calibration is traceable to a national standard. The accreditation of calibration and testing laboratories in the UK is carried out by the United Kingdom Accreditation Service, which incorporates NAMAS (National Accreditation of Measurement and Sampling). Care must be taken to ensure that the sensor under test and the reference standard are in fact experiencing the same environment. Provision of test mounting points adjacent to pipe- and duct-mounted sensors is good practice and enables a rapid check to be carried out.

3.2 Actuators

An actuator responds to the output signal from a controller and provides the mechanical action to operate the final control device, which is typically a valve or damper. A wide range of actuators is available and the chosen actuator must:

— match the mechanical requirements of the controlled device

— match the characteristics of the control system, especially the output signal of the controller

— be suitable for its operating environment.

The major mechanical division is between linear and rotary actuators. Linear actuators are required for use with lift and lay valves. Rotary actuators tend to be used on shoe valves and butterfly valves. Actuator and valve are selected to be dimensionally compatible, so that the actuator spindle connects directly to the valve stem; many manufacturers provide matched combinations. Linear actuators may be used to operate dampers using a linkage to provide the required rotary movement. Movement is provided by an electric motor operating through a reduction gear train, producing relatively high torque at low speed. Where specified, a spring return mechanism is incorporated, which is wound as the motor operates. In the event of power failure, the actuator is returned to the specified position. It is now possible to obtain microprocessor-controlled devices for particular applications, e.g. a unit which combines differential pressure sensor, controller and damper actuator for the control of VAV boxes.

The actuator must be suitable for its operating environment. The manufacturer's data gives safe operating ranges of temperature and humidity and often the IP protection number (see Table 3.13, page 3-24). Where the operating environment is likely to be corrosive, as in a swimming pool or industrial setting, advice should be obtained from the manufacturer.

A range of modulating magnetic valves is obtainable, where a movable magnetic core moves in a solenoid and transfers the linear stroke directly to the integral valve. The valves are reliable and fast, capable of precise regulation, resulting in a high rangeability, coupled with a fast response time of only 1 s. The solenoid itself is operated by a 0–20 V phase cut signal, but in-built electronics allow operation from a standard 0–10 V DC signal input. The high rangeability and precise control makes these valves suitable for demanding situations and installations where the valve may be required to operate at low authority, requiring stable control at low valve openings.

Thermic actuators contain a solid expansion medium which is heated by an electrical resistance heater. When power is applied to the actuator, the heating effect causes the medium to expand, producing a linear motion of the spindle. On cooling, the spindle retracts by pressure of a built-in spring.

Thermic actuators are robust and silent. Full stroke is about 3 mm and stroke time is a few minutes. Modulating control can be achieved with pulse width modulation; some models use a standard 0–10 V signal. Models are available designed to operate radiator valves.

Some gas valve applications use electro-hydraulic actuators, where a motor pumps hydraulic oil against a rolling diaphragm and piston. The piston then drives open the valve against the force of a spring. Once the valve is fully open, an internal relief valve is closed, the pump is switched off and the valve remains open without further application of power. To close the valve, the relief valve is opened and the spring forces the oil back into the reservoir.

3.2.1 Mechanical characteristics

A linear actuator requires the following quantities to be specified:

— *Thrust*: the thrust is measured in newtons and must be sufficient to close the valve against the differential pressure acting across the valve plug. In some hydraulic systems employing two-port valves, closing forces may be considerable, up to the full pump head. Manufacturers supply tables of maximum differential pressures for valve/actuator combinations.

— *Stroke*: the stroke of the actuator spindle must be sufficient to provide full operation of the valve. The stroke is normally adjustable to suit the valve; in many actuators this is self-set automatically.

— *Running time or stroke time*: this is the time taken for the actuator to travel over the full operating range. The low gearing of the electric motor used to drive the actuator spindle produces low operating speeds and the actuator operates at several seconds per mm travel, giving a stroke time of the order of minutes. This speed of movement may be an integral part of the control loop and is required to be input to the controller during configuration. Depending on the type of actuator motor and its control, the running time may be invariant or else dependent on the load.

Rotary actuators are used to operate dampers and butterfly or ball valves. The actuator produces a rotary movement which is coupled directly to the control element. The actuator has the following specification:

— *Torque*: he operating force is given as the torque in N·m. Damper manufacturers supply tables of the required torque for their dampers as a function of damper area and air velocity in the duct.

— *Angle of rotation*: rotary actuators typically have a maximum angle of rotation of just over a right angle. This angle may be adjusted to suit the required rotation of the valve or damper.

— *Running time*: as for linear actuators.

3.2.2 Electrical connections

An actuator requires some or all of the following connections:

— *Power to power the drive*: may be 230 or 240 V AC, 24 V AC, 24 V DC; 230 V is becoming an EU standard.

— *Control signal from the controller*: 0–10 V and 2–10 V DC are the most common. 4–20 mA is used in process control applications. 0–20 V phase cut may be used for magnetic actuators. 24 V AC pulsed is also found.

— *135 Ω potentiometer*: used by the Honeywell 90 series for both control input and positional feedback.

— *Position indication*: a 2–10 V DC signal to provide positional feedback or indication. Position feedback may also be provided by a potentiometer. End switches are used to provide positive open/close position indication.

The actuator may be fully modulating, where the position of the actuator is proportional to the control signal, or tristate, used for floating control, where the motor may be driven in either direction or stopped. Many actuators exhibit some degree of hysteresis and the relation between control signal and actuator position depends on the direction of travel. Most actuators have the facility to provide a positional feedback signal, indicating the actual position of the actuator. This may be used to drive a remote position indicator, or be incorporated in a control loop to provide positive positioning of the actuator; this overcomes any problems caused by hysteresis. In some cases where positive positioning is required, the position indicator may be mounted on the controlled device itself, e.g. damper. End switches may also be used in simple sequencing applications to divert a signal to another device when the first device is fully closed. The actuator may be configured so that either end of the travel is corresponds to a zero control signal. The spring return which operates on power failure may return the actuator to either the spindle extended or spindle retracted position. All actuators are fitted with a manual override, to allow for manual positioning of the actuator and control device during commissioning or maintenance.

3.2.3 Pneumatic actuators

Pneumatic actuators comprise a piston or diaphragm to which air pressure is applied to provide a linear displacement. A mechanical linkage is required where it is desired to produce a rotary movement, e.g. for damper control. The construction of the actuator and its method of connection to the valve or damper determines the direction of operation, i.e. whether increasing control air pressure results in opening or closing of the valve or damper. Most pneumatic actuators are of the single-action type where the force on the diaphragm is opposed by a spring and the net force applied to the valve or damper is the difference between them. When the air pressure is removed the spring will return the valve to the selected extreme position and this may be used for fail-safe requirements.

When a straightforward pneumatic actuator operates against large or variable forces the position of the actuator spindle may not be proportional to the signal pressure from the controller. To overcome this a pneumatic relay, known as a positioner, is fitted to the actuator; this uses main air line pressure to power the actuator and provide the operating force, but incorporates an all-pneumatic control to ensure that the actuator is correctly positioned for a given signal pressure. To do this a positive feedback of actuator position is used.

Pneumatic controllers provide reliable and fast operation and are still used extensively in the HVAC industry. For new installations they have been largely supplanted by DDC and pneumatic systems are now installed only in special situations. The necessity to provide a clean dry air supply can lead to maintenance problems. Where an existing pneumatic control system is being upgraded to electronic DDC control, it is possible to retain pneumatic operation of the actuators by using hybrid electro-pneumatic transducers which use pneumatic power to provide the operating force, but whose position is controlled by a standard electronic signal.

3.3 Valves

3.3.1 Hydraulic flow

Fluid temperatures used in commercial buildings are classified into five broad ranges (Table 3.8).

In SI units, pressure is measured in pascals. The bar is commonly used, where:

1 bar = 100 kPa

It is sometimes helpful to visualise pressure in terms of head of water:

1 bar = 10.5 m head of water

Table 3.8 Working fluid temperature ranges

Classification	Temperature range / °C
Chilled water (CW)	5–10
Low temperature hot water (LTHW)	20–90
Medium temperature hot water (MTHW)	95–120
High temperature hot water (HTHW)	120–200
Steam	< 16 bar

Flow is properly measured in m^3/s in SI units. This results in small values which are awkward to handle and it is common to quote flow rates in litres per second (l/s) or m^3/h, where

$$1 \text{ l/s} = 3.6 \text{ m}^3/\text{h}$$

A control valve is subject to three types of pressure:

— *Static pressure*: this is the maximum internal pressure of the hydraulic system and for open systems will usually be governed by the height of the cold water tank in the roof above the lowest point of the system. The body of the valve and the gland through which the spindle moves must be able to withstand the maximum pressure of the system, which is equal to the static head of the system plus the pump pressure.

— *Differential pressure*: valves should always be installed so that the plug closes against the flow; installation in the wrong direction could result in unstable operation with a danger of the valve snapping shut. The pressure produced by the pump in a circuit has to be capable of meeting the pressure drops at design flow rate produced by the resistance of all fittings, pipes, boilers valves etc. However, in some circuits using two-port valves, it is possible for a large differential pressure to be developed across a single valve under part load conditions; three-port valves nominally have the same pressure drop for all positions of the valve. The actuator must therefore be capable of driving the valve against a differential pressure equal to the maximum pump head. By the same token, the maximum differential pressure rating (MDP) of the valve must be greater than the maximum pump head.

— *Pressure drop*: there is a pressure drop across the valve in normal operation. This is an important part of valve selection and is discussed below under valve authority.

3.3.2 Types of valve

Valves may be classified by their function:

— *Regulating*: a valve which is adjusted during commissioning to provide a fixed resistance in a fluid circuit to give the design flow rate and ensure a correct balance. The adjustment is normally manual. A double regulating valve is provided with indicated positions of the valve opening and has an adjustable stop, so that the valve can be closed to isolate a circuit and reopened to the previously set position.

— *Commissioning*: a regulating valve which incorporates a calibrated orifice and pressure tappings for flow measurement during commissioning.

— *Flow limiting* (also known as automatic or dynamic balancing valves): valves which maintain a constant flow independently of the differential pressure across them. This constant flow is maintained over the regulation range of differential pressure, which is typically 10:1 or more. Valves are available with preset control cartridges for a predetermined flow rate, or can be externally adjustable for commissioning.

— *Differential pressure control*: a valve which automatically adjusts to maintain a constant differential pressure across part of a circuit.

— *Modulating*: a valve which is adjusted by the control system via an actuator to regulate hydraulic flow.

— *Safety shut-off*: a valve that is designed to close under spring pressure on power failure, critical condition (e.g. fire) or out-of-range process variable.

Modulating valves form the main subject of interest in this Guide. The complete valve assembly consists of:

— *actuator*: which converts the output signal from the controller into mechanical movement

— *spindle*: which transmits the actuator movement to the moving part of the valve

— *valve body*: containing the flow control device.

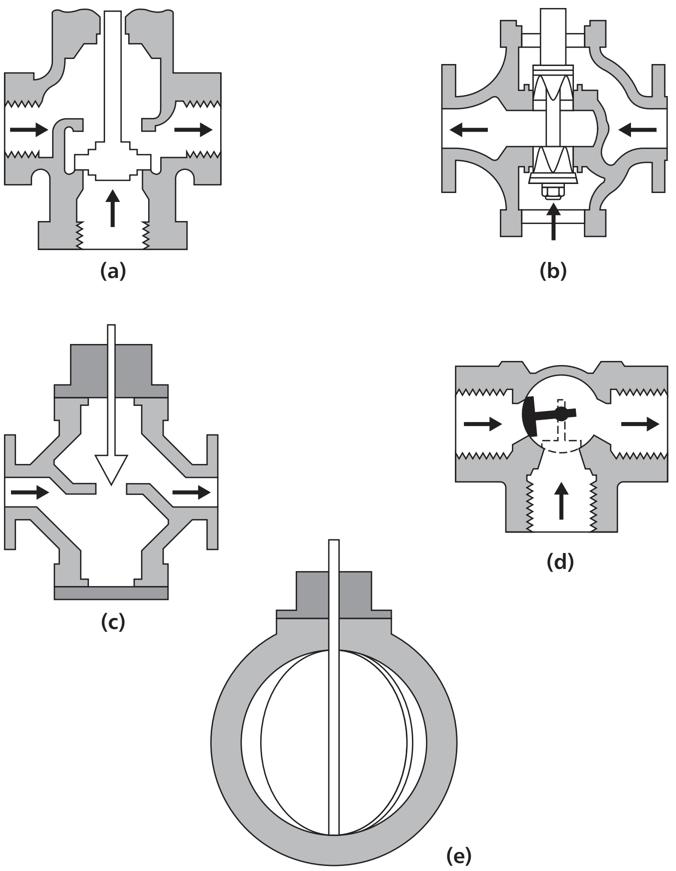


Figure 3.1 Common valve types: (a) plug and seat valve: three-port mixing valve, single seat; (b) plug and seat valve, three-port mixing valve, double seat; (c) two-part plug and seat valve; (d) rotary shoe valve; (e) butterfly valve

Several types of valve body are used and are illustrated in Figure 3.1:

— *Butterfly valve*: the simplest form of valve. The internal disc is aligned either in line or across the flow and is used for on/off control.

— *Rotary shoe valve*: commonly used on chilled and LPHW systems because of their compact size. In action, a rotating shoe is moved over the ports by a rotary actuator and provides modulating regulation, which may be characterised.

— *Plug and seat valve*: the most common type. They are available in a wide range of sizes and can be used for all heat transfer media. The valve plug is moved on and off the valve seat by linear movement of the spindle. The spindle moves through a gland, which must allow free movement and yet not leak under the static pressure of the system. The shape of the valve and seat determine the characteristic of the valve. They are also known as lift and lay, or globe valves.

Valves are available in two-, three- or four-port configurations. Three-port valves have found widespread application in HVAC systems. Used with constant-speed circulation pumps they offer a range of well-established and trouble-free control solutions. A four-port valve performs the control function of a three-port valve but includes an internal bypass to produce compact connections; see Figure 3.2.

A three-port valve is provided with two inlet ports and one outlet port, when it is described as a mixing valve, or, less commonly, with one inlet and two outlet ports, when it is described as a diverting valve. Both mixing and diverting valves may be incorporated in a circuit for either mixing or diverting application. These terms may cause confusion and Figure 3.3 illustrates the meaning of the terms. In general, three-port valves available in the building services industry are designed to be used as mixing valves and are not suitable for use as diverting valves. Where a diverting valve is required, i.e. one inlet and two outlets, a double seated or shoe type valve should be used to avoid the out-of-balance forces which would occur with a single-seated globe valve. Connecting a mixing valve as a diverting valve is likely to lead to unstable operation, since water pressure acts to slam the plug against the valve seat. Mixing applications are

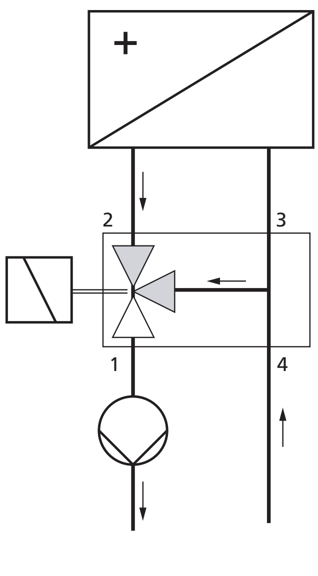


Figure 3.2 Four-port valve. A four-port valve incorporates the bypass and tee connections in the valve body giving compact installation

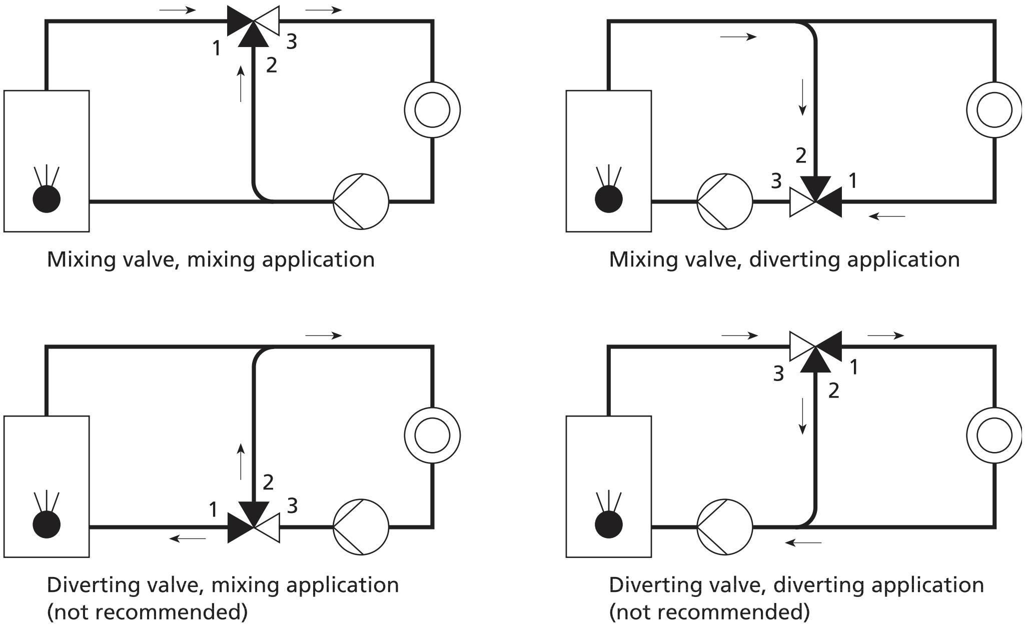
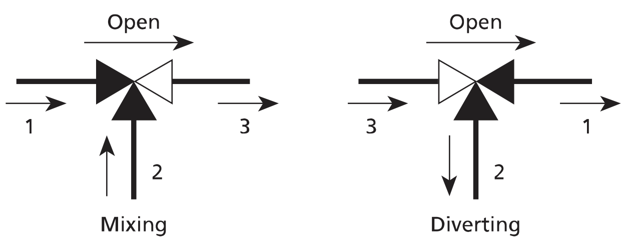


Figure 3.3 Three-port valves in mixing and diverting applications

typically constant flow, variable temperature loads, such as a compensated heating circuit. Diverting applications are typically variable flow, constant temperature circuits, such as heater batteries. Correct connection of a valve is important and may be crucial. There is not a consistent terminology for identifying valve ports. Figure 3.4 illustrates the more common conventions. This Guide refers to the ports as control, bypass and common and describes a three-way valve as open when the flow is between control and common ports, with the bypass shut. This applies to both mixing and diverting valves.

Two-port valves are used to throttle flow in a circuit. In a complex circuit the independent modulation of two-port valves can produce balancing problems and pressure variations throughout the system. However, when used with a variable-speed pump and with proper attention to system design, two-port valves offer reductions in both first cost and the cost of pumping. Suitable hydraulic control circuits are given in chapter 5.



Port	Name	Alternative	USA	Europe
1	Control	Load	A	E
2	Bypass	Bypass	B	L
3	Common	Common	AB	C

Figure 3.4 Three-port valve terminology, showing designation of ports

3.3.3 Valve design

3.3.3.1 Characteristic

A control valve is one link in a chain of control, running from the error signal which is input to the controller to the change in output of the emitter; an example is shown in Figure 2.1. While not essential, a linear relation between the change in output from the controller and change in heat output from the emitter makes for a well-behaved and stable system. For most heat emitters, there is a strongly non-linear relation between the flow rate of the heat transfer fluid and heat output from the emitter, with output rising rapidly as the flow increases from zero, then flattening out at higher flow rates. For example, heat output from a radiator rises rapidly as hot water is admitted at low flow rates, but once the body of the radiator is hot, increasing the water flow rate will produce little increase in heat output. This is illustrated in Figure 3.5; the curves for a heating or cooling coil are similar. A valve which produced a flow rate proportional to spindle lift would therefore result in a non-linear system, operating over a narrow range of spindle movement and possibly resulting in unstable operation.

Valves are therefore often designed so that the resultant heat output from the emitter is approximately proportional to the spindle movement. This is done by shaping the plug so that the free area, and hence flow rate, is a defined function of spindle lift. This relationship is termed the valve characteristic. The most commonly encountered characteristics are:

— *linear*: where the orifice area is directly proportional to the valve spindle movement and the flow varies linearly with spindle lift

— *characterised V-port*: with a characteristic falling between linear and equal percentage

— *equal percentage, or similar modified parabolic*: where equal increments of valve spindle lift provide an equal percentage change of the area

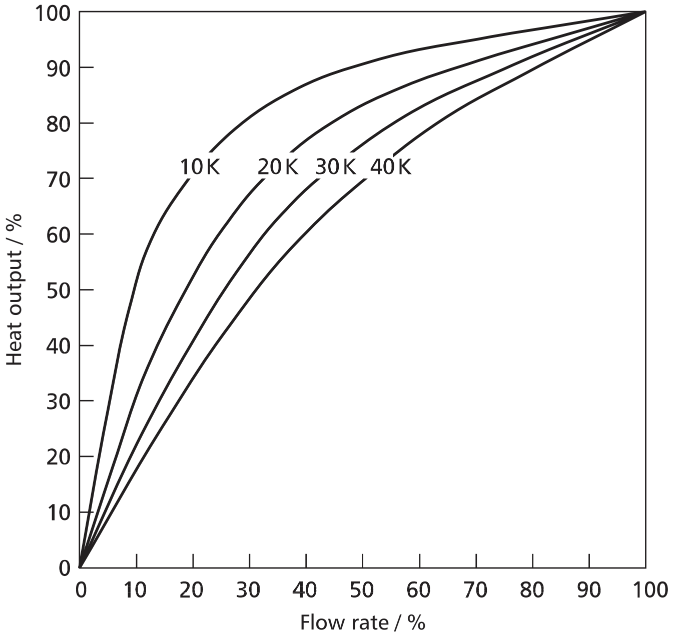


Figure 3.5 Radiator heat output as a function of flow rate, with temperature drop as parameter. Heating and cooling coils show a similar relationship

— *quick opening*: where the flow increases very rapidly from zero for a small spindle movement, with a fairly linear relationship between flow and spindle movement. Such valves are used primarily for on/off service.

Figure 3.6 shows in stylised form the basic characteristic curves for the four types described above. The static characteristics are measured by measuring the flow as a function of valve position for a constant pressure drop across the valve. In a real circuit, the characteristic is modified by the authority of the valve; this is discussed further below.

Equal percentage valves have a theoretical characteristic which may be expressed as an equation relating flow through the valve to the degree of opening, measured at constant pressure drop. The degree of opening of a valve is variously referred to as the spindle lift, stem position, or percentage of full stroke:

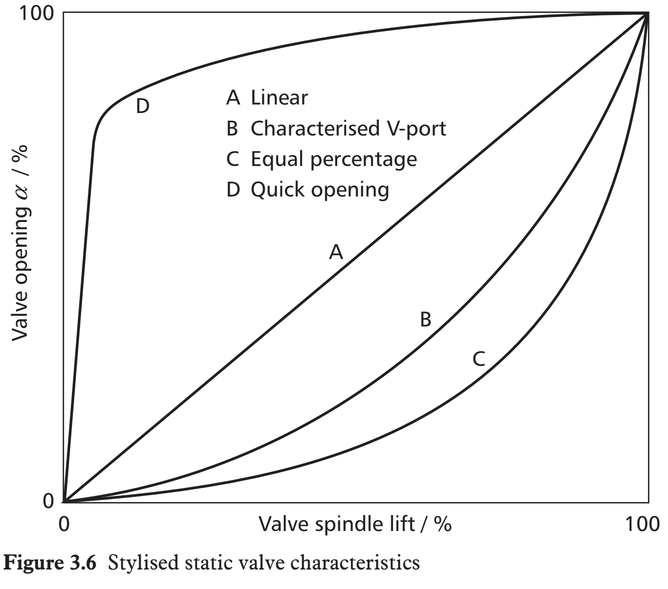


Figure 3.6 Stylised static valve characteristics

$$Q = Q_0 \exp (S\, n) \tag{3.1}$$

where Q is the flow through valve (nominal units), Q_0 is the theoretical flow though valve at $S = 0$, n is the valve sensitivity and S is the spindle lift (1 = fully open).

The sensitivity n is the percentage change in flow through the valve produced by a 1% change in stem position. A typical value is about 4. The theoretical flow Q_0 though the valve at zero opening is a mathematical convenience and does not represent the actual flow when the valve is closed. Real equal percentage valves can be made to follow the theoretical characteristic reasonably well, but depart from it at low openings. A practical equal percentage valve has a characteristic of the form shown in Figure 3.7. Q_{min} represents the minimum flow at which the valve still provides reasonable control. Below this flow, the flow falls off rapidly and cannot be controlled reliably. Valves are normally designed to shut down rapidly below the minimum controllable flow. If the valve does not provide a tight shut-off, the residual flow is termed 'let-by'. The ratio of the maximum controllable flow to the maximum flow is known as the rangeability R, sometimes referred to as the practical rangeability to distinguish it from the theoretical rangeability. A rangeability of 25 indicates a valve which will control according to its defined characteristic down to 4% of its maximum flow. The practical rangeability definition holds for all types of valve. For equal percentage valves it is possible to define an ideal rangeability

$$R_{ideal} = Q_{max}/Q_0 = \exp (n) \tag{3.2}$$

The ideal rangeability is directly related to the sensitivity.

Good rangeability is required when valves are required to control at low flow rates. This occurs in some circuits using two-port valves. Situations where valve authority is low will require operation at low spindle lifts. It is conventional to regard valves as having 'good' rangeability as follows:

— *terminal unit valves*: rangeability of 25:1

— *screwed plant valves*: rangeability of 50:1

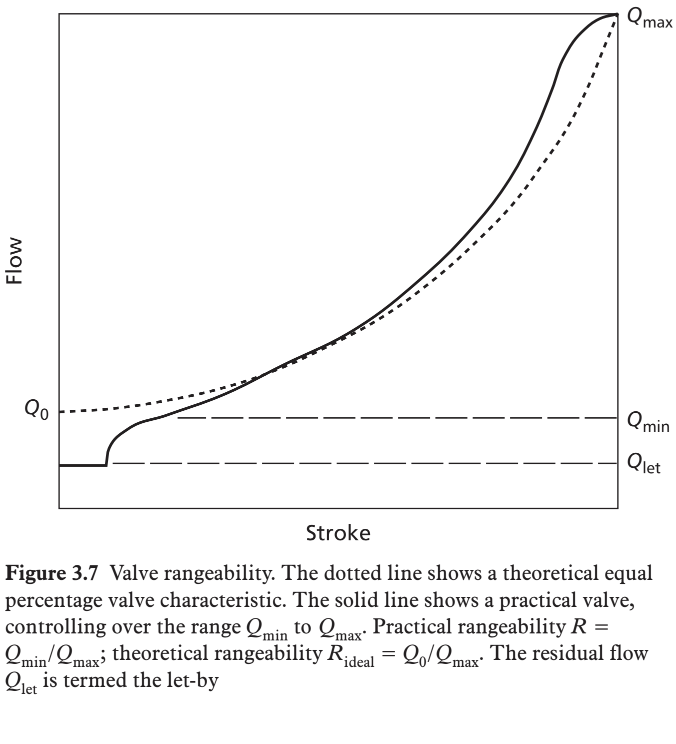


Figure 3.7 Valve rangeability. The dotted line shows a theoretical equal percentage valve characteristic. The solid line shows a practical valve, controlling over the range Q_{min} to Q_{max}. Practical rangeability $R = Q_{min}/Q_{max}$; theoretical rangeability $R_{ideal} = Q_0/Q_{max}$. The residual flow Q_{let} is termed the let-by

— *flanged plant valves*: rangeability of 50:1

— *magnetic solenoid valves*: rangeability of 500:1.

Good control at low strokes requires an actuator that can position the valve accurately.

3.3.3.2 Flow coefficient

The size of a valve is described by the flow coefficient, which determines the rate of flow of fluid through the valve as a function of the pressure drop across it. The flow of fluid through a constriction is proportional to the square root of the pressure drop across the constriction. The flow coefficient of a valve is defined in SI units by the equation:

$$V_m = A_v \left(\frac{P_m}{\rho_{fm}} \right)^{0.5} \tag{3.3}$$

where V_m is the volume flow rate (m^3/s), P_m is the pressure drop across valve (Pa), ρ_{fm} is the fluid density (kg/m^3) and A_v is the flow coefficient of valve (m^2).

Manufacturers often quote the capacity of a valve as the capacity index K_v. This is equivalent to the flow coefficient, but applied to water flow, with the flow rate measured in the so-called continental units of m^3/h and pressure drop in bars. The flow equation becomes

$$V_m = K_v P_m^{0.5} \tag{3.4}$$

where V_m is the volume flow rate of water (m^3/h), P_m is the pressure drop across valve (bar) and K_v is the flow coefficient of valve.

The older imperial unit C_v (equivalent to A_v) may also be met. The conversion factors and units are summarised in Table 3.9. It may be noted that 1 bar $\cong$ 1 kgf/cm^2. Manufacturers usually produce a range of valves with K_v values rising in geometrical progression, with each value of K_v 60% greater than the preceding one in the series.

Table 3.9 Valve flow coefficients

System	Symbol	Flow	Pressure units	Fluid density	A_v
SI (BS 4740)	A_v	m^3/s	Pa	kg/m^3	
Continental	K_v	m^3/h	bar	Water	$28.0 \times 10^{-6} K_v$
Imperial	C_v	gal/min	psi	Specific gravity	$28.8 \times 10^{-6} C_v$
US	C_v	US gal/min	psi	Specific gravity	$24.0 \times 10^{-6} C_v$

3.3.3.3 Steam valves

Valves used for steam are a specialist application of two-port valves for compressible fluid flow. If a small constriction is introduced into a pipe carrying steam, it has the effect of increasing the velocity of the steam passing through the constriction and reducing the steam pressure downstream of the constriction. The net result is that there is little effect on the overall flow of steam in the pipe. As the size of the opening is decreased, this effect is maintained until a maximum critical steam velocity is reached, when, for dry steam, the downstream absolute pressure is 58% of the inlet pressure. Further reduction of the area of the constriction results in reduced flow of steam. Thus, in sizing steam valves, the valve pressure drop may be assumed to be 40% of the absolute pressure at full load, immediately upstream of the valve. Using this figure and the given duty, the valve may be sized from manufacturers' tables. If the inlet pressure is below 100 kPa, applying the 40% rule gives unsatisfactory conditions downstream and, in such cases only, it is necessary to assume a smaller pressure drop, ignoring any possible loss in degree of control. Guidance on these reduced pressure drops is normally given in manufacturers' literature. Additional pressure drops due to pipe runs, isolating valves etc., mean that control valves must be sized on their inlet pressure at full load and not on the boiler pressure.

It is important to ensure that the heat exchange surface which is supplied by the valve is adequate to handle the full design load when the pressure at the inlet of the heat exchanger is 60% of the of the absolute pressure at the inlet of the control valve; any other pressure losses in pipework and fittings need to be taken into account. Care must be taken to ensure that suitable stream traps are incorporated. Failure to do so will result in unacceptably poor control under light conditions.

3.3.4 Valve selection

3.3.4.1 Authority

To provide good control, a control valve must be sized in relation to the circuit it controls so that the pressure drop across the valve is of the same order as that round the rest of the circuit. If the valve is too large when open, the resistance to flow in the circuit is dominated by the resistance of the rest of the circuit. Throttling the valve would initially have little effect on flow; control would then only be obtained over a small range of spindle lift when the valve is nearly closed. The control system is then operating under high gain conditions and instability may result. Conversely, too small a valve may have an unnecessarily high resistance and additional pump head would be required to maintain flow.

The relation of the valve size to the circuit is expressed quantitatively in terms of the valve authority. The concept of authority is first discussed with relation to two-port valves. In the simple circuit of Figure 3.8, a constant-head pump circulates water though a load and the flow rate is controlled by a two-port valve. At design conditions, the valve is fully open and the pump pressure is distributed between the differential pressure across the valve P_1 and the pressure drop round the rest of the circuit. The relation between valve lift and flow in the circuit depends on the resistance of the valve in relation to that of the rest of the circuit. This is expressed quantitatively by the authority N_{des}. The subscript 'des' emphasises that the authority is defined at design flow conditions; this is of significance in more complex circuits.

$$N_{des} = P_1 / P_{close} \tag{3.5}$$

where P_1 is the pressure drop across the valve in the fully open position at design flow (Pa) and P_{close} is the pressure drop across the valve in its fully closed position (Pa).

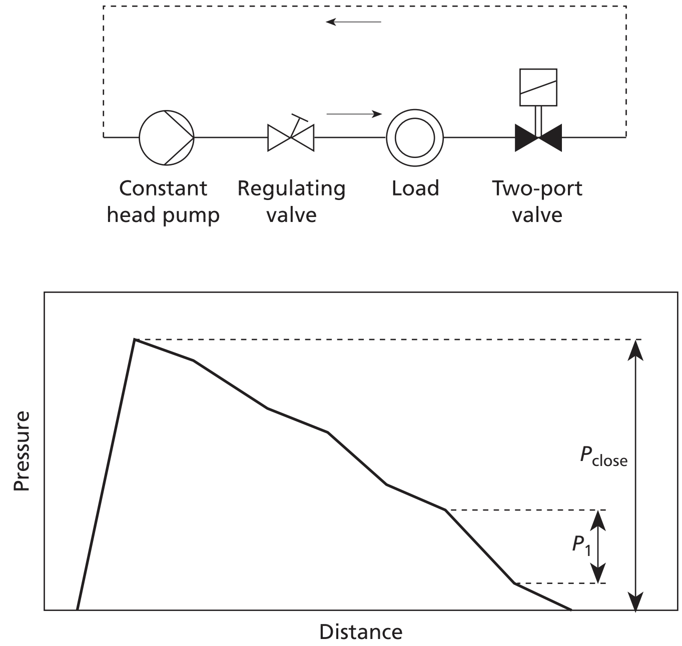


Figure 3.8 Valve authority in simple throttling circuit. Diagram shows pressure drop round a simple throttling circuit at design flow. The circuit has been drawn with a zero pressure drop in the return leg. Valve authority $N_{des} = P_1/P_{close}$

For the simple circuit shown, P_{close} is the pump pressure. Figure 3.9 shows the relation between flow in the circuit and valve lift for both linear and equal percentage valves. Reducing the valve authority distorts the valve characteristic, making control more difficult at low flow rates. A minimum authority of 0.5 is acceptable. Below an authority of 0.5 the characteristic is increasingly distorted away from the required shape. In other words, at design conditions the pressure drop across the fully open control valve should be about half the total locally available differential pressure.

Where the hydronic circuit has several branches, it is necessary to take into account the influence of control action taking place in other branches. Figure 3.10 shows several branches controlled by two-port valves, arranged in a ladder circuit. The valve authority of a single branch is calculated as described above, but with an extension to the definition of Pclose, as follows: 'P_{close} is the pressure drop across the valve in its fully closed position, with all other branches remaining at design settings'.

However, when the circuit is actively controlling, the valves in all branches act independently under the influence of their own control loops. In the worst case, all other branches may close down and the pressure across the branch under consideration rises towards the full pump pressure. In practice the pump head is a function of flow rate; the consequences of this for control are discussed in chapter 5. This increase in pressure at the branch has the effect of reducing the valve authority. To reflect this, the minimum authority is defined as

$$N_{min} = P_1/P_{max} \tag{3.6}$$

where P_1 is the pressure drop across valve in the fully open position at design flow (Pa) and P_{max} is the maximum pressure drop across the valve in its fully closed position (Pa), obtainable with any combination of valve positions in the rest of the circuit.

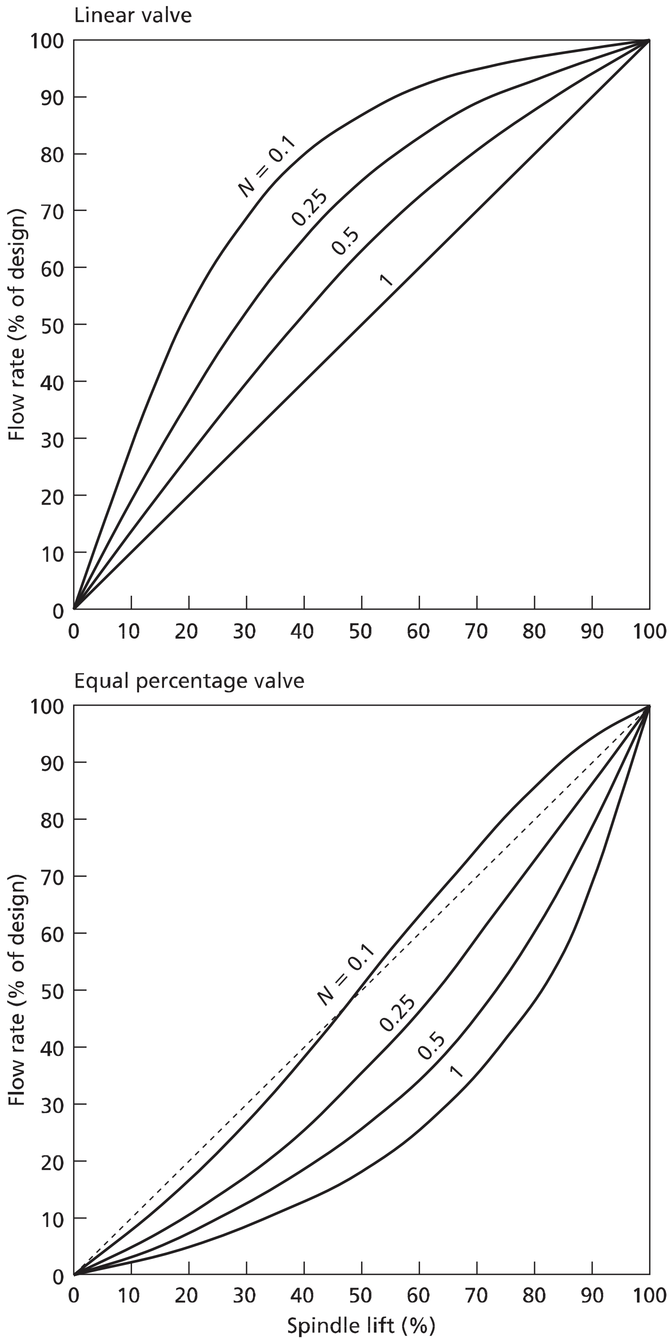


Figure 3.9 Flow through a control valve as a function of spindle lift, showing the effect of valve authority

In general with all other valves shut, flow through the system drops towards zero and the pressure across the control valve under consideration rises towards the pump head P_{pump}. If automatic valves are fitted, P_{max} may be less than the pump head.

Valves should be selected so that:

$$N_{des} \geq 0.5$$

$$N_{min} \geq 0.25$$

The treatment of three-port valves follows that of two-port valves. Figure 3.11 shows a three-port mixing valve in a circuit which is balanced to provide a constant flow though the heat exchanger as the valve modulates. The valve is said to be open when the flow is across the top of the tee, when the pump delivers water directly from the heat source to the heat emitter without recirculation

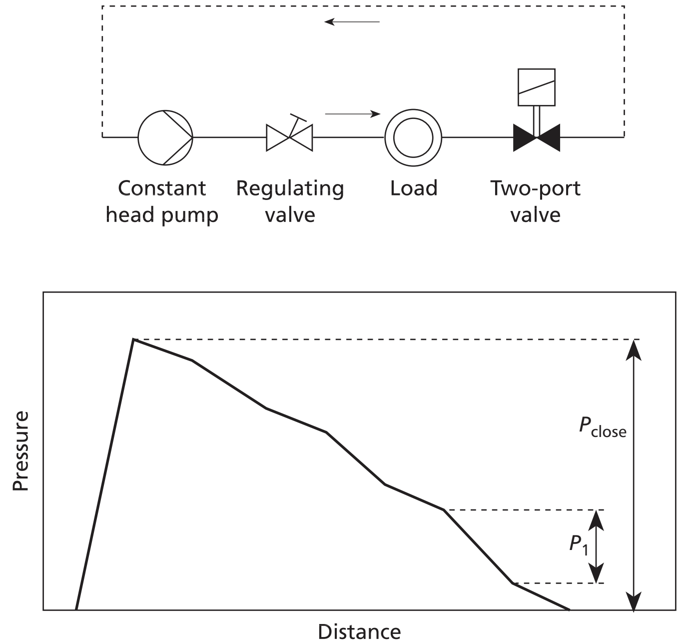


Figure 3.10 Authority in a multi-branch throttling circuit. Schematic three-branch throttling circuit, showing authority of valve in branch 3, which has a design pressure drop of P_1. Design authority $N_{des} = P_1/P_{close}$, minimum authority $N_{min} = P_1/P_{max}$

through the bypass leg. The pressure drop across the valve in the closed position (i.e. full bypass flow) is denoted by P_3 and the authority is defined in the same way as for the two-port valve.

$$N_{des} = P_1 / P_3 = P_1 / (P_1 + P_2) \tag{3.7}$$

where P_2 is the pressure drop round the variable flow part of the circuit (Pa), including the heat generator and associated pipework, but not the bypass or balancing valve, and P_3 is the pressure drop across the valve in the closed position (Pa).

P_3 is constant because of the constant flow through the heat emitter.

The authority is equal to 0.5 if the pressure drop across the three-way valve when fully open is equal to the pressure drop in the variable flow part of the circuit, excluding the bypass.

The circuit shown in Figure 3.11 gives a variable flow through the heat generator which reduces to zero if there is no demand from the heat emitter. This has obvious practical problems which may be obviated by employing a separate pump in the primary circuit as shown in Figure 3.12. The bypass forms a virtual heat generator with almost no pressure drop. The authority of the three-way valve is now:

$$N = P_1/(P_1 + P_4) \tag{3.8}$$

where P_4 is the pressure drop round the variable part of the circuit, i.e. round the bypass pipework. P_4 is therefore small and the valve has an authority close to unity.

Where a three-port valve is used in a diverting application, as in Figure 3.13, the authority is defined in the same way. As before, it is the pressure drop round the controlled, i.e. variable-flow, section of the circuit that is used in the calculation of authority. The above definitions of authority and the recommendation that the designer should aim at a design authority of 0.5 and a minimum authority of 0.25 will assist in the selection of an appropriately sized valve. It will not guarantee good control, especially where a number of variable flow branches interact. Where there is uncertainty a network analysis is recommended. Further details are given in the literature(6–8).

A three-port mixing valve is commonly used to provide a constant flow through the load in a circuit such as the one shown in Figure 3.11. The incorporation of a balancing valve

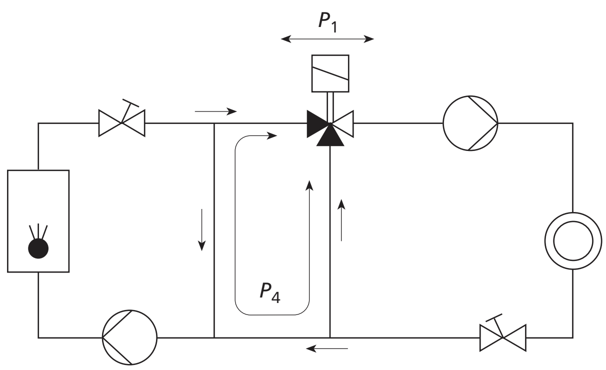


Figure 3.12 Mixing circuit with primary pump and bypass. The authority of the three-way mixing valve $N = P_1/(P_1 + P_4)$ and is close to unity

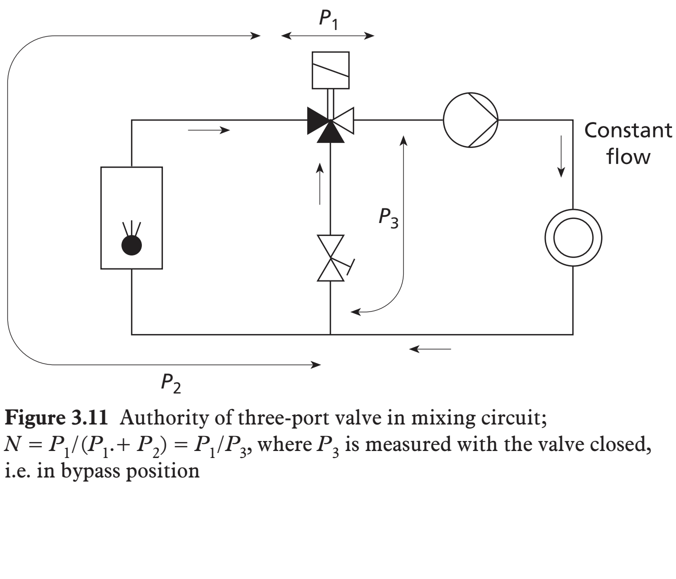


Figure 3.11 Authority of three-port valve in mixing circuit; $N = P_1/(P_1 + P_2) = P_1/P_3$, where P_3 is measured with the valve closed, i.e. in bypass position

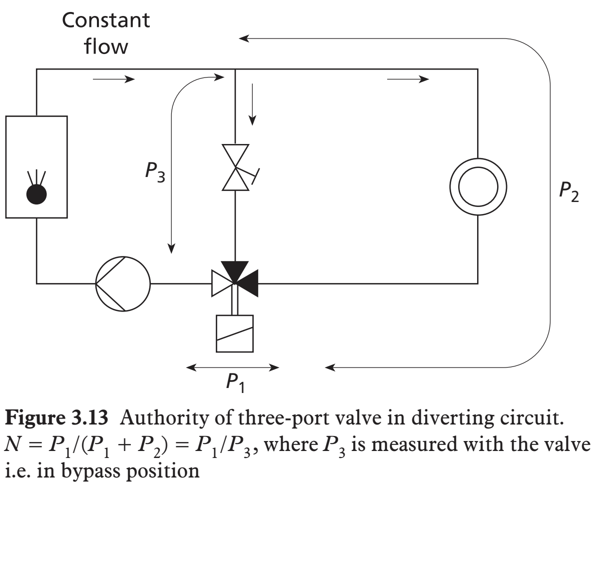


Figure 3.13 Authority of three-port valve in diverting circuit. $N = P_1/(P_1 + P_2) = P_1/P_3$, where P_3 is measured with the valve closed, i.e. in bypass position

in the bypass leg allows the resistance of the bypass leg to be set equal to the resistance of the heat generator circuit. In this way, the resistance seen by the pump is equal whether the three-port valve is fully open or fully shut and the flow is the same in both positions. However, to ensure constant flow at all positions of the valve, a further design parameter associated with three-port valves must be considered, the symmetry of the internal ports. Symmetrical design means that both control and bypass ports in a mixing valve have the same characteristic and the control and bypass connections may be reversed without affecting the control behaviour of the valve. However, when the ports both have an equal percentage characteristic, the total volume flow through the valve is not constant at all opening positions. This is illustrated in Figure 3.14, where it is seen that the common flow is reduced at intermediate opening positions. This is unsatisfactory for some situations and the solution is to use an asymmetrical valve to achieve constant flow. An asymmetrical valve has its internal ports designed so that the control port provides the desired operating characteristic, while the port connected to the bypass is designed to compensate to maintain a constant total flow through the valve independent of valve opening; see Figure 3.15. The ports of an asymmetrical valve are not interchangeable.

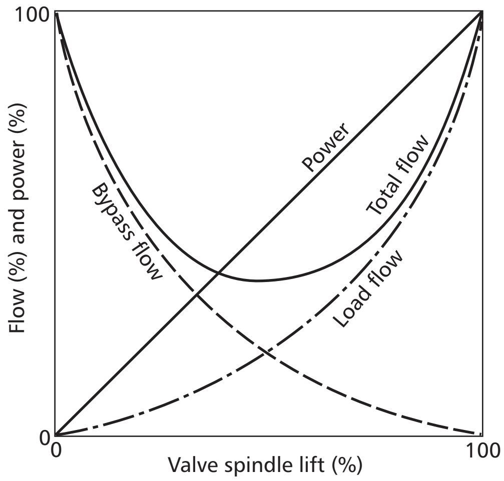


Figure 3.14 Curves for symmetrical three-port valve selected for power linear output

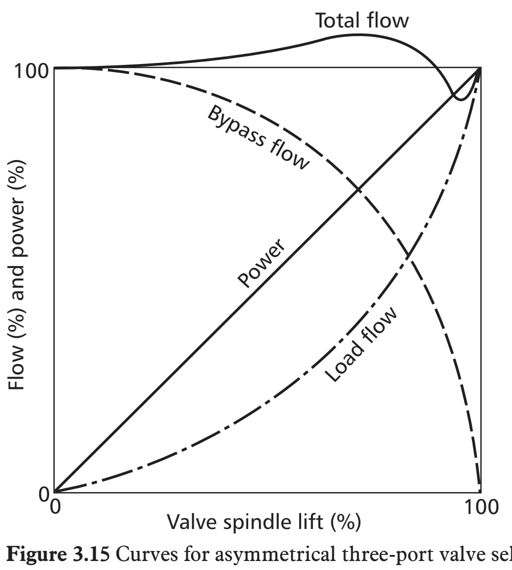


Figure 3.15 Curves for asymmetrical three-port valve selected for power linear output

3.3.4.2 Sizing

The relationship between valve position and heat output may be illustrated using the graphical construction shown in Figure 3.16. The upper right quadrant shows the relation between valve stroke position and flow for two types of valve characteristic for different authorities. The valve authority modifies the characteristic curves shown in Figure 3.6, which are drawn for a constant pressure drop across the valve, i.e. for an authority of unity. The bottom right quadrant shows the relation between flow through the heater emitter and heat output. Together, these allow the construction of the curve in the bottom left quadrant, which shows the relation between valve position and heat output. Two example curves are shown. Curve 2, representing an equal percentage characteristic with authority $N = 0.7$, gives an almost linear change of heat output with valve position. Curve 5, a linear characteristic valve with authority $N = 0.8$, is highly non-linear and shows why this type of valve is unsuitable in this application.

It is the task of the controls specialist to size and select control valves suitable for the HVAC system under consideration. Once the circuit has been designed and the valve authority decided, the valve size can be selected from the pressure drop across the valve and the flow rate through it, both when the valve is fully open. Valve sizes are specified as the K_v value, see 3.3.3.2. The required valve size is given by the equation:

$$K_v = V_m / P_m^{0.5} \qquad (3.9)$$

where V_m is the flow through open valve (m^3/h), P_m is the pressure drop across open valve (bar).

This may be rewritten as:

$$K_v = 36\, V_{ml} / P_{mk}^{0.5} \qquad (3.10)$$

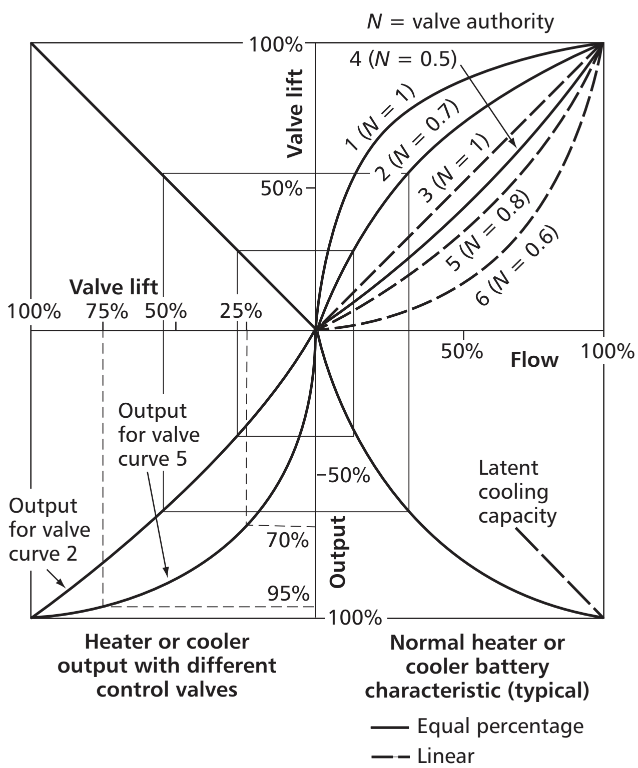


Figure 3.16 Stylised valve authority and power output characteristics

where V_{ml} is the flow through open valve (l/s) and P_{mk} is the pressure drop across open valve (kPa).

The required valve with the nearest K_v value may be selected from a manufacturer's list. Choosing a valve with a lower K_v value will increase the authority. It must be emphasised yet again that the system design has a great influence on the possibility of designing effective controls. System design and controls should be considered together from the concept stage of the project. The design of hydraulic circuits is considered in more detail in section 5.

3.3.4.3 Cavitation

When a fluid flows through a restriction, its velocity increases and in consequence the static pressure decreases. The reduction in pressure may be sufficient to cause the formation of vapour bubbles. When these bubbles collapse, they create noise in the system. In addition, intense microjets of liquid are formed which can damage the surface of the valve and pipework. The condition for cavitation to occur is defined in terms of the pressure drop across the valve:

$$P_{max} = K_m (P_{in} - P_v) \quad (3.11)$$

where P_{max} is the maximum allowable pressure drop across open valve (kPa), K_m is the valve recovery coefficient, P_{in} is the absolute inlet pressure (kPa) and P_v *is* the fluid vapour pressure at inlet temperature (kPa).

Values for K_m are a function of the valve construction, but are typically between 0.6 and 0.9. Values of water vapour pressure as a function of temperature are shown in Table 3.10. In general, cavitation problems are unlikely to be encountered if the pressure drop across the valve is less than 70 kPa, or if the fluid velocity is below 3 m/s.

3.3.4.4 Valve selection checklist

On water circuits, first decide whether two- or three-port valves are the most suitable and select a reliable control strategy. The following points should be taken into consideration when selecting a valve:

— Is the valve body suitable for the temperature and pressure of the fluid system? Remember the pressure is the sum of static and dynamic head.

— Ensure that the valve will pass the required flow at a pressure drop within the maximum differential pressure rating of the valve.

— Check for out-of-balance forces, particularly during closure of a two-port valve.

— Check whether tight shut-off is required; this is not usually possible with a double seated valve.

— Check there is sufficient pump head to provide the pressure drop across the valve at the specific duty.

The above rules apply to all valves, including two-position on/off. For modulating valves, the following additional considerations apply:

— Select an equal percentage valve characteristic unless there is good reason to select an alternative.

— Ensure pressure drops though heat exchangers and associated pipework are known before control valves are selected.

— Select valves to provide an authority of at least 0.5 for diverting applications and 0.3 for mixing applications.

— Where possible, use heat transfer curves of flow against output to check possible anomalies and confirm the correct characteristic has been chosen.

— Ensure that the rangeability of the selected valves is large enough to provide stable control under low load conditions.

— Three-port valves with asymmetrical port characteristics should be used to maintain flow conditions.

Before finalising the selection:

— Check whether there have been changes to the specification of heat exchangers and pipework since the original design.

Table 3.10 Vapour pressure of water

Water temp. / °C	Vapour pressure / kPa
10	1.2
20	2.3
30	4.2
40	7.4
50	12.3
60	19.9
70	31.1
80	47.3
90	70.1
100	101
110	143
120	199
130	270
140	361
150	476
160	618
170	792
180	1003
190	1255
200	1555

3.4 Dampers

3.4.1 Damper selection

Dampers are used to control air flow in ducts in a manner analogous to the use of valves in hydraulic circuits. The damper chosen for a particular situation must satisfy both the physical requirements of the application and also provide suitable control characteristics. The practice of simply selecting a damper to fit the available duct dimensions can lead to unsatisfactory control operation. The majority of dampers used for modulating control have a rectangular cross-section and provide control by rotating a set of blades. The blades may move in parallel or opposition to each other. Figure 3.17 shows different types of damper. Round dampers normally have a butterfly type blade and are used to control flow in ducts that have high static pressure and high velocity characteristics. Dampers

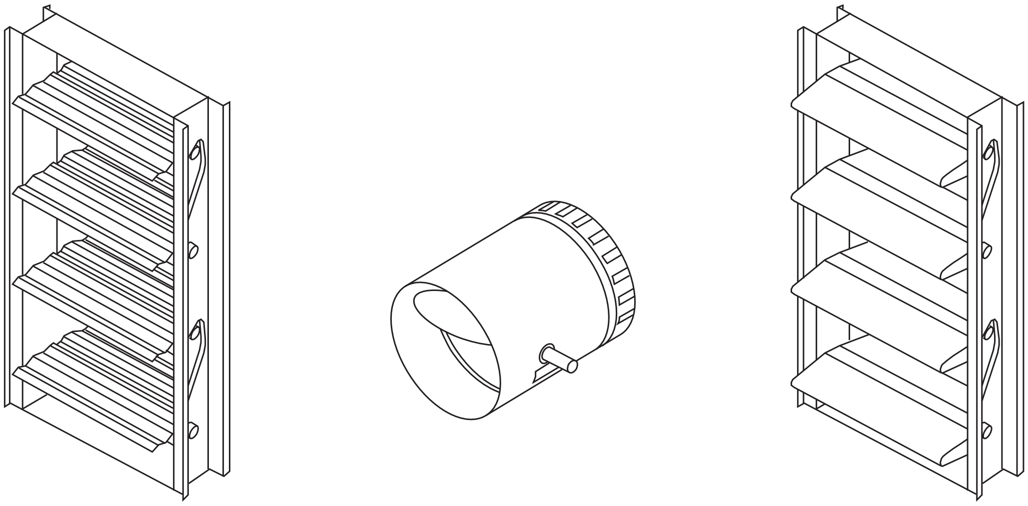


Figure 3.17 Types of damper

may be installed for the control of fire and smoke. Smoke dampers have to meet relevant criteria and are normally installed and operated independently of the HVAC control system; they are not considered further in this Guide. It is possible to obtain smoke and control dampers, which are capable of operating as modulating dampers, while retaining the necessary smoke control criteria after many operations. Damper sizing is covered in more detail below. Other factors to be taken into account when selecting a damper are as follows:

— *Leakage rating*: leakage through the damper in the closed position may be critical in such applications as fresh air intakes in cold climates and the design should specify the maximum acceptable leakage. It is difficult to achieve good shut-off with a damper and it is necessary to specify low leakage construction where required. Different classes of leakage are available and leakage is specified in terms of leakage volumetric flow per unit damper area at a specified pressure difference. Low leakage is obtained by the provision of seals and the use of stiffer blades; this may require a higher closing force from the actuator.

— *Velocity and turbulence*: as the air velocity in a duct increases, the damper blades experience higher forces, which may be sufficient to bend or twist the blade, or cause problems with the bearings and linkage. Dampers are given a velocity rating to indicate the maximum velocity in the duct; ratings may need to be reduced in turbulent conditions. Moderate turbulence may be found downstream of duct transitions or elbows. Severe turbulence can be found near the discharge of a fan and this can be sufficient to prevent satisfactory operation of a damper.

— *Pressure*: the maximum static pressure that can be developed across a damper occurs when the blades are closed. Dampers are given a maximum static pressure differential; operation above this value may give rise to excessive leakage and possible damage.

— *Torque requirements*: two conditions must be considered when establishing minimum torque requirement of a damper. One is the closing torque which is needed to achieve the required maximum leakage rate. The other is the dynamic torque needed to overcome the effect of high velocity air flow over the blades. This will affect actuator selection.

— *Mixing*: parallel blade dampers alter the flow direction of air passing through them. By directing the air flow to one side of the duct, they may cause stratification. In some cases, the change in direction of the air stream may be used to promote mixing where it joins another air stream.

3.4.2 Modulating dampers

The most common type of modulating damper has a rectangular cross-section, with a set of blades that may be rotated by a linkage connected to an actuator, to restrict the flow of air through the damper. The blades are linked to each other and may have parallel or opposed motion; see Figure 3.18. The relationship between damper blade rotation and flow through the damper for a constant pressure drop across the damper is shown in Figure 3.19. This is termed the inherent characteristic of the damper.

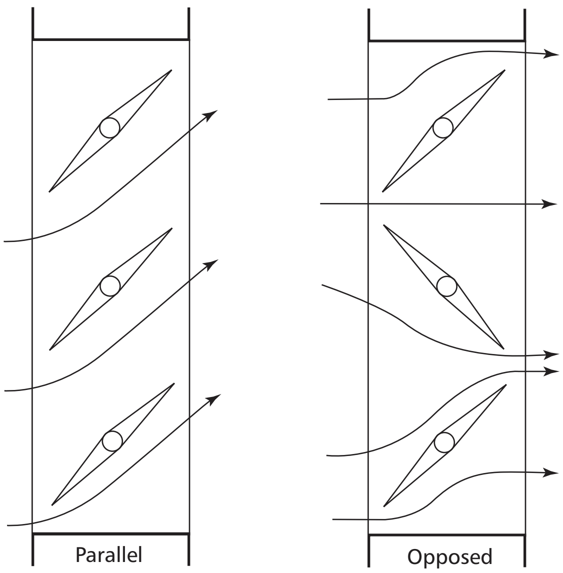


Figure 3.18 parallel and opposed operation of damper blades

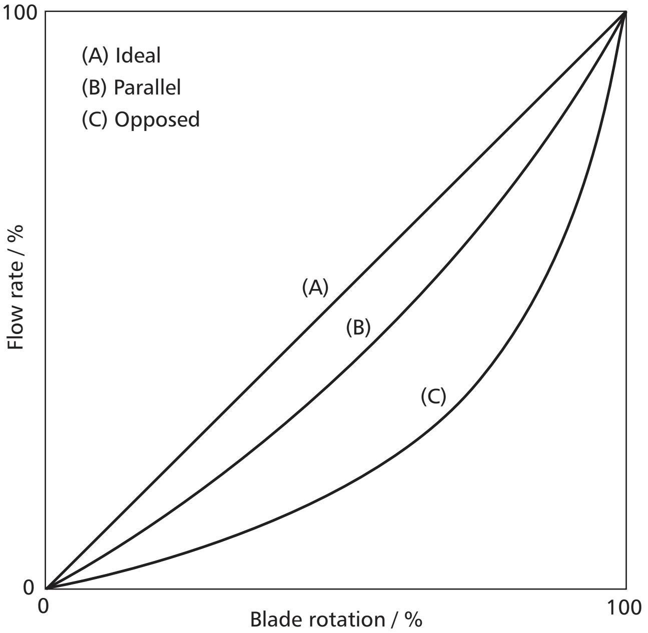


Figure 3.19 Inherent characteristics of damper types

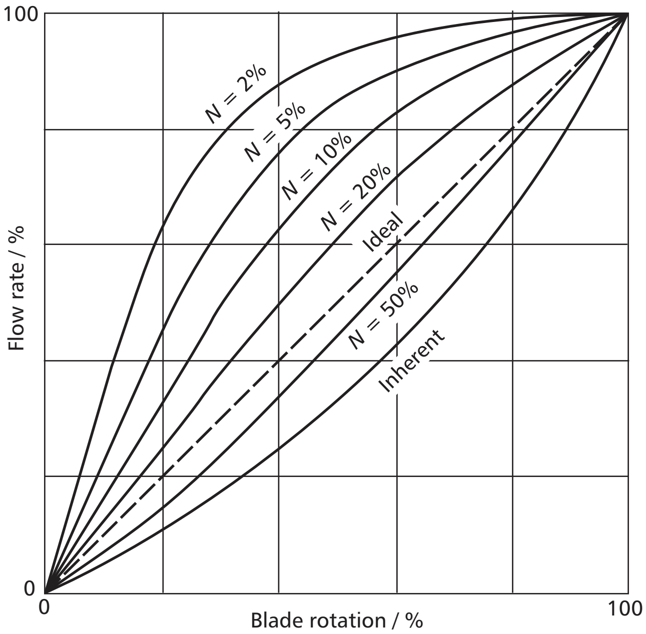


Figure 3.21 Installed characteristic of parallel blade damper

The 'ideal' damper characteristic would result in a linear relation between actuator movement and heat delivered to the conditioned space. The distribution of heat by air differs from that by water in that air systems are essentially open and all the energy in the air stream can be considered as delivered to the conditioned space. A linear damper characteristic is therefore desirable. Systems controlled by modulating dampers normally have a fan running at constant speed with a constant pressure drop across the system. In the simple ducted air system of Figure 3.20, where air is supplied by a fan running at constant pressure, the total pressure drop across damper and plant is constant and so the pressure drop across the damper increases as the damper is closed; when fully closed it is equal to the static pressure of the fan.

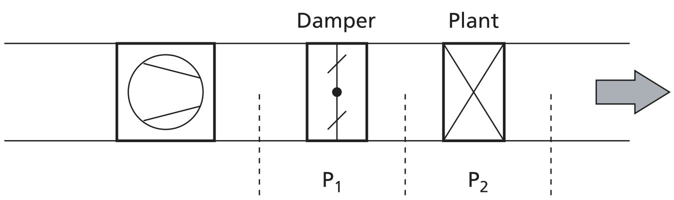


Figure 3.20 Damper authority $N = P_1 / (P_1 + P_2)$

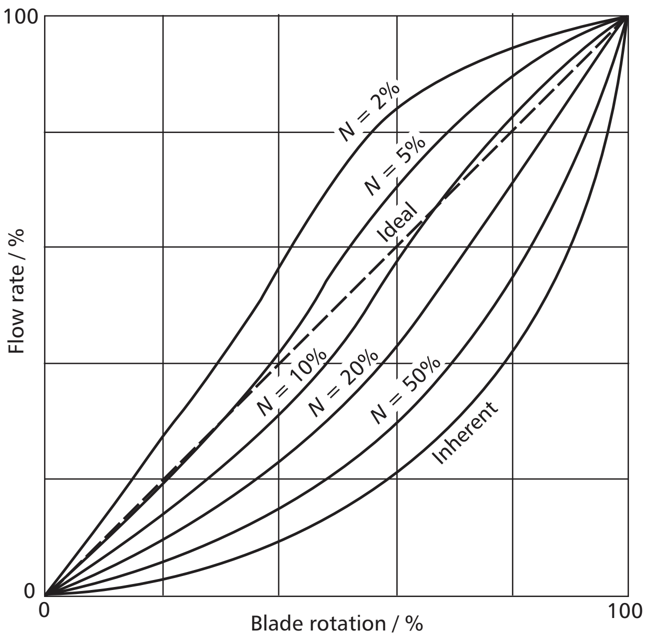


Figure 3.22 Installed characteristic of opposed blade damper

The changing partition of pressure drop across damper and load as the flow changes results in dampers having an installed characteristic different from the inherent characteristic. The installed characteristic is affected by the size of the damper, described by the damper authority. This is defined in a similar way to that of valves, where the authority is given by:

$$N = P_1 / (P_1 + P_2) \tag{3.12}$$

where P_1 is the pressure drop across the damper in the fully open position (Pa) and P_2 is the pressure drop across the rest of the circuit (Pa).

In many cases $(P_1 + P_2)$ is constant and equal to the pressure developed by the fan. American usage may refer to the damper characteristic ratio (α or sometimes δ) defined as:

$$\alpha = P_2 / P_1 \tag{3.13}$$

The installed damper characteristic curves may be derived from a knowledge of the inherent curve and the authority. The pressure drop developed across a fitting is proportional to the square of the air flow through it and it is straightforward to show that for any intermediate opening position:

$$N = \frac{(1 / F_a)^2 - 1}{(1 / F_i)^2 - 1} \tag{3.14}$$

where F_a is the ratio of actual flow in the intermediate position to actual flow at the fully open position and F_i is the ratio of flow in the intermediate position to flow through the fully open damper for the inherent characteristic.

Damper characteristic curves are supplied by damper manufacturers and typical examples of installed characteristics are shown in Figures 3.21 and 3.22.

It can be seen that for an opposed blade damper the closest approach to linearity occurs with an authority N = 5–10%, while for parallel blade dampers it occurs when N = 20%. The implication is that for a given pressure drop across the damper and system, the pressure drop across a parallel blade damper will be four times that across an opposed blade damper, with correspondingly higher energy consumption. Opposed blade dampers are therefore recommended in general for control purposes.

It is poor practice to choose a damper size based on duct size and convenience of location. This frequently results in oversized dampers with inadequate authority to provide proper control. The correct damper will often have smaller dimensions than the duct, giving additional benefits in reduced damper and actuator costs, together with lower leakage in the closed position. Where the damper is smaller than the cross-section of the ductwork, it may be installed with a baffle or blanking plate to take up the additional area. If the blanked off area exceeds about 30% of the total cross section, it may be advisable to use a reducing section of ductwork to avoid turbulence caused by the sudden restriction at the baffle.

3.4.3 Applications

In general, parallel blade dampers are used where there is little resistance to flow in series with the damper, and opposed blade dampers where the controlled section contains restrictions of any sort (Table 3.11). Useful treatments of damper applications are to be found in the literature[9,10].

3.4.3.1 Return air mixing

A common application is the control of return air shown in Figure 3.23. The system delivers a constant flow of air to the conditioned space; the dampers are used to vary the proportion of air that is recycled. The pressures at P_s and P_e are therefore constant and so for sizing purposes each damper may be considered separately in its own subsystem. The inlet and exhaust subsystems include the series resistance of weather louvres and bird screens and an opposed blade damper should therefore be chosen to give an authority of between 5 and 0%; Figure 3.22 shows that this will produce an approximately linear installed characteristic. Where louvres and screens are absent at inlet and exhaust, the lack of their resistance increases the authority of the damper and it may be appropriate to select a parallel blade damper to give a more linear characteristic. The return air path has little resistance other than the damper itself, and so the damper operates at a high authority. The correct choice here would be a parallel blade damper.

Table 3.11 Damper applications

Control application	Damper type
Return air	Parallel
Outdoor air or exhaust air	
— with weather louvre or bird screen	Opposed
— without louvre or screen	Parallel
Coil face	Opposed
Bypass	
— with perforated baffle	Opposed
— without perforated baffle	Parallel
Two-position (all applications)	Parallel

3.4.3.2 Face and bypass control

A common application of dampers controlling the flow of outside air uses two dampers in a face and bypass configuration, as shown in Figure 3.24. The system is designed to provide a constant pressure drop and hence constant combined flow rate, while the proportion of air flowing through the coil is varied by operating a linked pair of dampers. Since the pressure drop across the bypass damper is constant, a parallel blade damper is used to

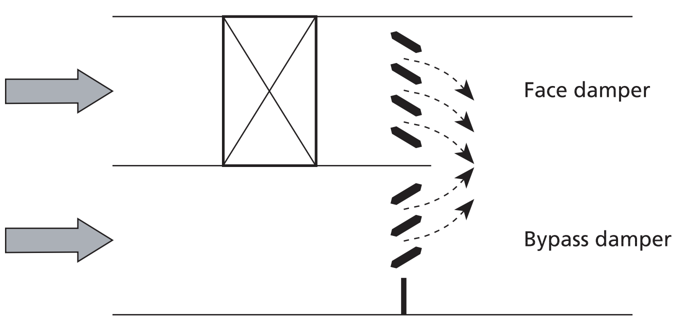


Figure 3.24 Face and bypass damper system, showing use of parallel blade dampers to assist mixing

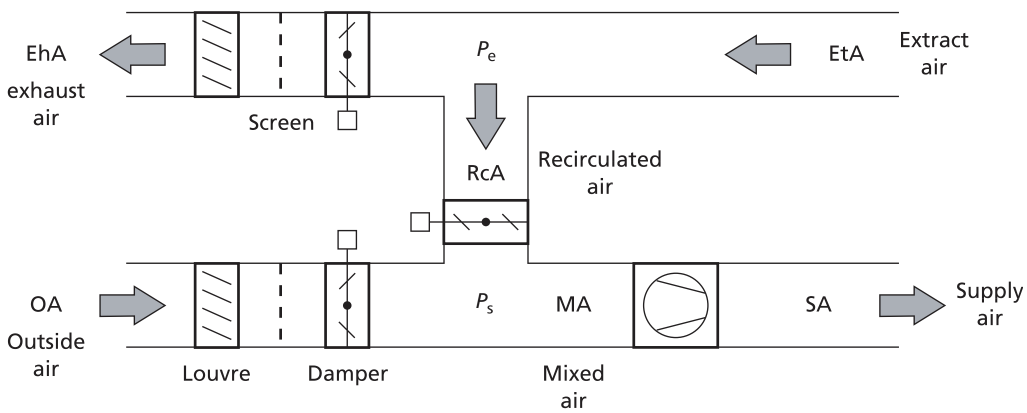


Figure 3.23 Damper selection for a recirculated air mixing circuit

provide a linear characteristic with minimum pressure drop at full flow. Since the face damper has the resistance of the coil in series, an opposed blade damper is used of the appropriate authority to provide a linear characteristic. Starting with the known resistance of the coil, the face damper will be sized to give an authority of between 5 and 10% and the bypass damper then sized so that its resistance is equal to that of the combination of face damper and coil; this will give an approximately constant flow though the system at all operating positions. Consideration may be given to the use of parallel blade dampers for both sets to aid downstream mixing, as shown in the diagram.

3.5 Motors

3.5.1 Energy efficiency

Motors are major users of electricity and account for almost half the total electricity use in the UK. Table 3.12 suggests some ways of reducing the energy consumption of motors. By far the most common type of motor used in HVAC applications is the three-phase squirrel cage induction motor. Three-phase power is supplied to the field windings in the stator, the fixed part of the motor which encloses the rotating rotor. The current in the field windings produces a rotating magnetic field which induces currents in the rotor conductors and pulls the rotor round with it. There are no electric connections to the rotor. The speed of rotation of the rotor is somewhat slower than the frequency of the applied field by an amount known as slip, expressed as a percentage of the synchronous speed, hence the description of the motor as asynchronous. Within the operating range of the motor, speed is approximately constant. The treatment here refers to 3-phase induction motors, unless otherwise stated.

Table 3.12 Energy saving checklist for motors

Item	Check
1	Is the equipment still needed? — Check that changing requirements have not eliminated the need
2	Switching the motor off — Time the switching according to a schedule — Monitor system conditions and switch off when motor is not needed — Sense the motor load and switch off when idling
3	Reducing the load on the motor — Is the transmission efficient? — Is the driven equipment efficient, e.g. gearboxes and belt drives? — Is the control system effective?
4	Minimising motor losses — Specify higher efficiency motors where feasible — Avoid oversized motors — Check power quality
5	Slowing down the load — Use variable speed drives where possible, for both control and regulation — Use multiple-speed motors where 2, 3 or 4 distinct duties exist — Check pulley ratios for belt drives

3.5.2 Starting

The low ohmic resistance of the field windings of an induction motor means that if a stationary motor is connected directly to the supply, it will draw a heavy starting current until the motor develops sufficient speed to produce a balancing back EMF. This starting current may be up to eight times the full load current and can produce problems for the electrical services within the building. Several methods have been developed to limit the starting current and provide controlled start-up of motors. The associated topic of variable-frequency drives is covered in 3.5.3.

3.5.2.1 Direct on-line (DOL)

In some situations it may be possible to simply connect the motor to the supply. This will produce a high peak starting current and in most cases a high starting torque. The control gear and contactors must accommodate the starting current. Switchgear designed to BS EN 60947-4-1[11] is based on a starting current of 7.2 times normal full load current. DOL starting is simple, but it use is limited to applications where:

— low power motors are used and the supply can cope with the start current

— the load driven by the motor can cope with mechanical shock produced by the high starting torque

— a high starting torque is needed.

3.5.2.2 Star–delta starter

With this form of starter, the three-phase supply voltage to the stator windings can be switched between star and delta configurations. On starting, the supply is connected in star configuration, when the starting current is typically between 1.5 and 2.6 times the normal full load current and the peak starting torque is between 0.2 and 0.5 times the nominal operating torque. Under this condition the motor will accelerate to about 75% of full speed, when the connections are switched to delta configuration, allowing the motor to achieve full performance. The switchover is controlled by a timer, whose operating time is set during commissioning. It is normal to introduce a small delay before the delta connection, to avoid any arcing or transient currents. Its features are:

— low starting torque

— access to both ends of stator windings required.

3.5.2.3 Primary resistance starter

Starting current is limited by connecting a resistance bank in series with the motor windings. Once the motor has run up, the resistance is switched out and the motor is directly connected; the changeover is normally controlled by a timer. Starting current and torque are controlled by the choice of resistance; typically a peak starting current of 4.5 times full load and a peak starting torque of 0.75 operating torque. This form of starter is suitable for applications such as ventilator fans, where the load torque increases with speed.

3.5.2.4 Autotransformer

The motor is started at reduced voltage supplied from an autotransformer. This is a specialised solution, used for large motors above 100 kW.

3.5.2.5 Electronic soft start

Introduced relatively recently, this form of starter is rapidly growing in use. An electronic circuit is used to produce a gradually increasing voltage to the motor to produce a steady smooth acceleration. The units employ a thyristor bridge and by varying the firing angle of each set of thyristors, it is possible to control the output voltage. The supply frequency is unchanged and soft starters do not behave like inverter drives.

3.5.3 Speed control

The use of variable-speed drives (VSD) on motors for pumping fluids or moving air can lead to substantial energy savings. The recent development of variable-frequency inverter drives has expanded the application of variable-flow systems, with attendant changes in control system design. This section summarises the main methods of motor speed control, concentrating on inverter drives.

3.5.3.1 Eddy current coupling

The eddy current coupling is an electromagnetic coupling which fits between a standard constant-speed AC induction motor and the load. The relative rotation of the motor and load generates the eddy currents to provide the coupling and so the maximum output speed is less than the motor speed. This form of speed control is well proven and reliable. It can produce high torque at low speed, though this is not often a requirement for HVAC applications.

3.5.3.2 Switched reluctance drive

This system requires a special motor with more stator than rotor poles. It is powered by a solid-state switched reluctance drive controller, which provides controlled DC pulses to the motor. While the components are similar to those used in inverter drives, the principle of operation is different. Sophisticated motor control is possible, with control of maximum and minimum speeds and acceleration rates. Control of starting conditions is available, making the use of a separate starter unnecessary. The number of suppliers is more limited than for inverter drives; the maximum motor size is about 75 kW.

3.5.3.3 Variable-voltage control

Speed control by varying the input voltage by a transformer is not normally recommended. The range of speed regulation is limited and efficiency is poor. Electronic variable-voltage drives are available which use phase angle control thyristors to provide a variable-voltage input to the motor. The cost of the drive is lower than an inverter drive, but the control and efficiency is poorer. A special motor matched to the controller is used and this form of control is only recommended for small pumps with built-in variable-speed drive.

3.5.3.4 Multi-speed motor

Multi-speed motors are available which are basically standard induction motors with additional windings which may be switched in or out, effectively changing the number of poles of the motor. The motor speed will therefore change in coarse steps, from 3000 rpm for a two-pole configuration to 750 rpm as an eight-pole configuration, less slippage. Two- or three-speed motors are common, with four-speed available. Multi-speed motors are simple and low cost and are found incorporated in small multi-speed pumps and fans. They are normally only available in fractional kilowatt sizes.

3.5.3.5 Inverter drive

Variable-speed inverter drives supply power of controlled frequency and voltage to the motor. Standard induction motors are used without modification and with recent developments and cost reductions this is now the most popular method for fan and pump speed control. The inverters produce a limited starting current for a soft start, making the use of a separate starting circuit unnecessary. Various types of speed control are available. There are three main types of inverter:

— pulse width modulation (PWM)

— pulse amplitude modulation (PAM)

— current source inverter (CSI).

Pulse width modulation inverters

The principle of the inverter is shown in Figure 3.25. Three-phase mains current is rectified and fed to a DC link circuit, which provides some smoothing. The rectifier may be either uncontrolled, using diodes, or controlled, using thyristors. Uncontrolled rectifiers produce large disturbances and losses in the mains and the use of controlled rectifiers is generally recommended. The DC link contains induction coils and capacitors to provide a reservoir of smoothed current for the output stage. Recent developments have allowed the elimination of the DC link by the employment of a matrix inverter in the rectifier, which is a combination of power transistors controlled in such a way as to give a smooth output and eliminate the need for the DC link. This reduces the space requirement and also reduces the size of the EMC filter[12]. The output bridge circuit uses transistors to supply a train of pulses. The output bridge operates at a switching frequency which must be substantially higher than mains frequency. By controlling the width and spacing of the pulses it is possible to produce a near sinusoidal supply to the motor of controlled frequency and amplitude; the frequency varies from a minimum of a few hertz to a maximum of mains frequency to give maximum rated motor speed. The higher the operating frequency of the output

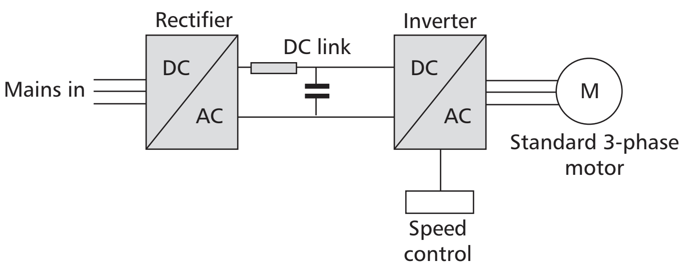


Figure 3.25 Principle of PWM inverter for motor speed control

bridge, the more closely will the motor current approximate to a sine wave. With a low switching frequency (<5 kHz) the motor current waveform will not be smooth and the result may be undesirable motor noise. A higher switching frequency, now available up to 20 kHz, produces smoother running but requires more attention to EMC performance.

The inverter is controlled by driver and control circuits. The control circuit of the variable-speed drive ensures that the amplitude of the output is matched to the frequency; the output voltage is reduced at low frequencies to prevent excessive winding currents being drawn. Highest efficiencies are achieved when the voltage–frequency characteristic is matched to the type of load. The control gear also provides a soft start capability.

The processor may also incorporate localised control functions. The processor takes overall control of the inverter such as up/down ramping of the frequency, start/stop signal, motor protection and error handling. At the same time the processor may also take care of the control task, e.g. pumping application. The processor controls the inverter using a built-in PID regulator and a signal from a pressure sensor, to produce a constant pressure to the system. All adjustments to and communications with the surroundings are controlled by the processor, which also collects the data to be communicated to the user.

Types of control for inverter drives are as follows:

— *Open loop control*: open loop control operates without feedback. The inverter supplies the voltage and frequency which is expected to produce the desired speed. While adequate for many applications, this form of control is not suitable for sustained low speed operation, nor with fluctuating loads.

— *Voltage vector control (VVC)*: this is a sophisticated form of PWM inverter, in which the control circuit of the inverter monitors the output to the motor and digitally controls the timing of the output pulses to produce a high quality sine wave output matched to the motor type and load. It claims better speed control and efficiency than a simple pwm inverter.

— *Flux vector control*: by obtaining information about the speed and position of the rotor, it is possible to calculate the torque and flux demand of the motor instant by instant and control the output bridge accordingly. This makes for a very accurate control of speed with rapid response to input signals. However, it is more expensive than the other varieties of PWM controller and requires some form of tachometer or position encoder on the motor, obviating the advantage of being usable with standard motors. It is not normally justified for building services applications. Sensorless vector control is a form of flux vector control which dispenses with the need for speed feedback from the motor by deducing the rotor behaviour from the winding current.

Pulse amplitude modulation inverters

The pulse amplitude inverter is similar to the PWM inverter in its basic principle, except that the output waveform is constructed from pulses of varied amplitude. With pulse amplitude modulation the output bridge of the inverter constructs an approximately sinusoidal voltage output of variable frequency. The output is made up from either six or 18 pulses per period; the six-pulse inverter gives a rather poor output waveform.

Current source inverter (CSI)

This is a simple low cost inverter, but has the disadvantages of producing harmonic disturbances on the mains and is of lower efficiency than other types of inverter. CSIs are not normally recommended for building services applications.

3.5.4 Variable-speed motors

The frequency inverter has become the standard form of variable-speed drive. Inverters are available as stand-alone units and extend up to the megawatt range. A stand-alone inverter drive offers the greatest choice of drive and speed control system, and when used with a feedback encoder gives great accuracy of torque and speed control. This is important for some process control, but not required in HVAC applications. The term 'variable-speed motor' is now generally used to imply a motor with integrated inverter drive. Such motors are available up to about 10 kW, though the upper limit is increasing. The choice between a variable-speed motor with built-in VSD and a separate inverter will be based on the following considerations:

— Variable-speed motor:
  - (*a*) inverter and EMC filters built in, giving lower installation cost and reduced wiring runs
  - (*b*) suitable for fan and pump speed control, less suitable for constant torque applications
  - (*c*) simple product selection
  - (*d*) inverter may be top or non-drive end mounted
  - (*e*) PID controller for pressure or temperature control can be incorporated.

— Stand-alone inverter[12]:
  - (*a*) more accurate control possible with use of feedback encoder
  - (*b*) available in large sizes, up to megawatts
  - (*c*) smaller bulk of motor may suit available installation space
  - (*d*) suitable for all types of load.

3.6 Pumps and fans

The specification of pumps and fans is outside the responsibility of the controls engineer. A single pump may not be able to satisfy the full design flow and yet provide economical operation at part loads. The designer must also ensure that the pump motor is not overloaded under any possible operating condition. Several possible pump arrangements are available to the designer:

— multiple pumps in parallel or series
— provision of a standby pump
— pumps with two-speed motors
— variable-speed pumps
— distributed pumping, including primary, secondary and tertiary circuits.

This brief discussion is included to emphasise the importance of the chosen method of flow control to overall energy consumption. For a fan or pump operating in a fixed system with flow of constant density:

— volume rate of flow is proportional to speed of rotation
— pressure varies as the square of the speed
— absorbed power varies as the cube of the speed.

Regulation of flow by the use of dampers or valves will therefore in general be less efficient than by the use of variable-speed drives, see Figure 3.26. The use of VSD in control applications will be considered in more detail in chapter 5.

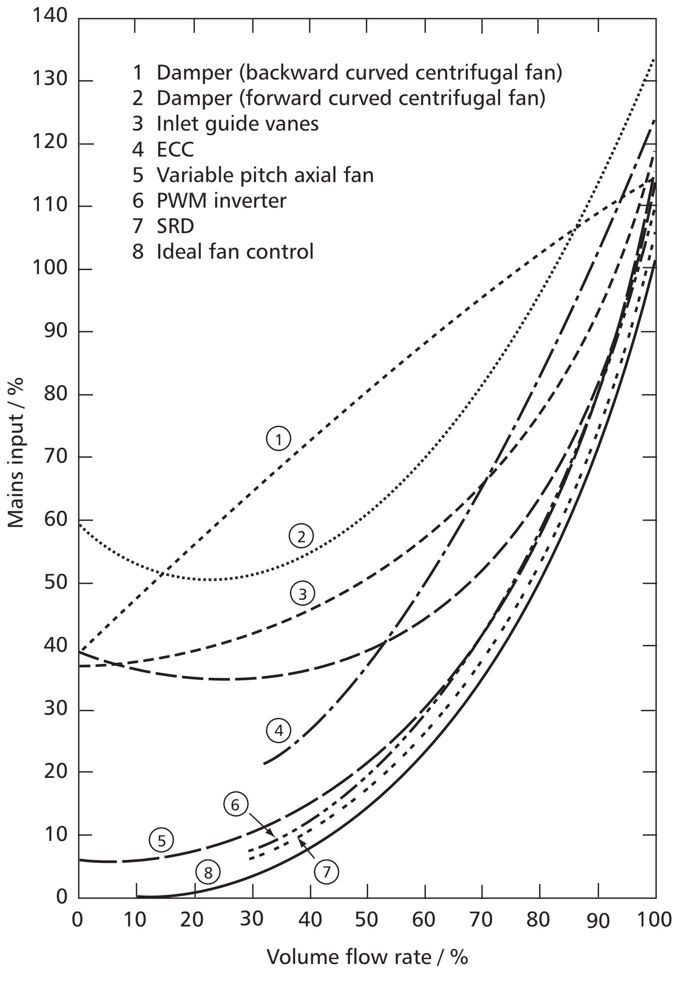


Figure 3.26 Comparative efficiencies of variable-flow methods

3.7 Control panels and motor control centres

It is standard practice to group together low and medium voltage (e.g. 240 V single-phase and 415 V three-phase) control equipment and mount it in an enclosed cabinet. This gives protection for the equipment and operating staff and allows convenient connection of hardwired interlocks. Thus the cabinet will contain such equipment as relays, contactors, isolators, fuses, starters and motor speed controllers. Meters may be mounted in the surface of the cabinet as required. Control panels are classified as follows(13):

— *Form 2*: this is a conventional cupboard type box, with an isolator linked to the door. Opening the door of the cabinet isolates all components, which are commonly mounted on a DIN rail. There is no requirement to shroud connections.

— *Form 3*: the door of the cabinet is lockable but not interlocked to an isolator. All connections are shrouded and individual items of equipment, such as motor starters, have their own covers and isolators. This type of panel is used where several items of plant are served from the same control panel. One item may be isolated and serviced without switching off the rest.

— *Form 4*: the control centre consists of several separate cubicles, each serving a separate item of plant and with its own door and interlocked isolator. The construction serves to contain an explosion and allows work on individual plant items. The separation of electrical equipment also reduces EMC problems; see 4.3. The cubicle construction tends to restrict access for work. An alternative version mounts the equipment on withdrawable racks. This allows the equipment to be withdrawn for servicing or exchange.

With the increased use of inverter drives, there is a move to decentralise motor control, placing the inverter and associated control gear adjacent to the motor being controlled. Several variable-speed drives incorporate their own local controller, which may be connected to the BMS. Inverters require to be air cooled and placing several inverters in a control cabinet will require fan cooling. Control panels usually have a separate section with its own door for the extra-low voltage (ELV) (e.g. 24 V) control system, which is not isolated. It is therefore possible to obtain access to the control wiring while the plant is in operation. There is normally a facility for plugging in a laptop PC or other interface for diagnosis and servicing. It is good practice to allow only ELV control cables to enter or leave the control centre. In particular, LV interlock cables should not enter the box, since they could remain live even when the box was nominally isolated. Some plant provides 240 V interlock signals, e.g. for boiler lockout. A relay at the plant should be fitted to provide a voltage-free contact for use by the control system.

Control panels and motor control centres are normally constructed by specialist subcontractors and delivered to site with internal wiring complete. Further information may be obtained from the regulations set out in BS EN 60439(13).

3.8 The intelligent outstation

The intelligent outstation, or universal controller, is at the heart of the contemporary building management system (BMS). Known variously as a field processing unit, distributed processing unit, freely programmable controller or simply as a controller, it combines a standalone control capability with the ability to communicate over a network with the head end supervisor. Controllers are available from many manufacturers and share the characteristic of being highly versatile, able to accept a range of inputs, to drive different output devices and to be programmed to carry out most common control tasks. Where the controller is dedicated to suit a particular piece of plant, such as a VAV box or chiller unit, it is termed a unitary controller or dedicated function controller.

Controllers incorporate all or most of the following components and can usually accept additional modules as plug in units:

— *inputs*: a module accepting a range of different types of input

— *outputs*: voltage and current outputs, plus relay closures

— *communications*: the ability to communicate with the supervisor and other controllers

— *processor*: a microprocessor to perform the control operations

— *configuration modules*: a range of software modules which can be linked to carry out the required control functions

— *clock*

— *power supply*

— *local display*: either a built in display or provision for a plug in display unit

— *local supervisor*: provision to plug in a supervisor.

Table 3.13 IP protection numbers (IEC 144)

IP	Foreign body protection against:	Water protection against:
0	None	None
1	Large foreign bodies	Vertical dripping water
2	Medium sized foreign bodies	Angled dripping water
3	Small foreign bodies	Fine water spray
4	Granular foreign bodies	Heavy water spray
5	Dust deposit	Water jet
6	Dust ingress	Water flow
7		Immersion
8		Submersion

The components are housed in a case which is normally designed to be tamper proof. Protection against harsh environments is categorised by the ingress protection system. The degree of protection is categorised by the two digit IP number(14) (Table 3.13). The first indicates the degree of protection from dust, running from 0 (no protection) to 6 (dust tight). The second digit indicates water protection, running from 0 (no protection) to 8 (submersible). Controllers may operate in an electrically noisy environment and electromagnetic compatibility (EMC) is discussed in 4.3.13.

3.8.1 Configuration

The controller must be configured before it can be put into operation. This may be divided into:

— system configuration

— hardware configuration

— strategy configuration.

3.8.1.1 System configuration

The controller is part of a larger system, communicating with the supervisor and other controllers. Other devices may communicate with the controller, either to interrogate it for information or to download software or alter control parameters:

— local display panel

— remote display panel

— local or central supervisor

— another controller.

In addition, the controller can originate messages which are transmitted to other devices:

— alarms which can be received by the supervisor, printer or display

— communications transmitted to another controller.

A supervisor is a computer which allows an operator access to data held within controllers and also allows modification to the software held inside the controller. On a large BMS, there is a head end supervisor, which has access to the entire BMS network. It is normally possible to use a portable PC connected locally to a controller, which may be restricted to communicate with that controller alone. The supervisor may communicate in four modes, to restrict unauthorised access to the BMS configuration:

— *Read only*: the supervisor may be used to interrogate controllers and to display values and produce reports. No changes may be made to any system parameters.

— *Supervisor mode*: this mode enables the operator to change set points and operating times. It is normally password protected.

— *Configuration mode*: this mode enables the engineer to change parameters or set up and fundamentally modify the control strategy resident in the controller.

— *Upload/download*: this mode enables the operator to take a copy (i.e. upload) of the strategy defining file from the controller memory and then store on floppy disc. In the unlikely case of loss of memory in the controller, it is possible to download the file from the supervisor to the controller.

3.8.1.2 Hardware configuration

Typically, a controller is hardwired to a number of inputs and outputs, and communicates with the rest of the BMS over some form of network. These have to be set up correctly.

Inputs

Controllers can accept a range of analogue and digital inputs. Each input channel must be configured to match the connected input. Depending on the type of controller, this may be done by physically changing input modules, changing links or components. A universal input channel may accept any form of input, but still requires configuration by changing internal links. The range of analogue inputs includes the following:

— *Voltage*: this is usually 0–10 V DC to match the standard output of a sensor transducer.

— *Current*: this is usually 4–20 mA DC to match the standard.

— *Passive*: some controllers can be configured to accept thermistors or resistance thermometers wired in directly to the input channel. Measurement circuitry is incorporated in the controller.

— *Digital*: this operates on a voltage-free contact closure and is used to monitor plant status. The controller provides a 24 V DC supply to energise the input signal.

— *Pulse*: this accepts pulses from pulsing energy meters, with defined minimum pulse width.

Outputs

Controllers provide a range of analogue and relay outputs, including:

— *Analogue voltage*: usually 0–10 V. This signal may be used to control most actuators without further amplification. In some cases an intermediate driver module may be required.

— *Relay output*: changeover relays, used to energise controlled plant.

— *Time proportioning*: a relay output with variable mark/space ratio.

Table 3.14 Typical controller software modules

Module	Example
Timer functions	Scheduling, time zones
Optimum start stop	Self-adaptive
PID control	Self-tuning control loop
Data logging	Stores input and output data
Metering	Utility energy metering from pulsed meter
Load management	Load cycling and maximum demand control
Actuator drivers	Time proportioning
Lighting	Presence or absence detection, dimming
Maths functions	Log, square root, enthalpy, sensor scaling
Knob	Input settings
Logic	Timers, counters, hours run
Pulse counting	Energy measurement
Sequencing	Controls module operation sequence

— *Pulsed*: 24 V AC pulsed operation, required by some actuators.

— *Resistive*: 0–135 Ω potentiometer output.

— *Network address*: the network node address of the controller must be identified by a by a unique number. This may be set either by a switch within the controller or during software configuration.

— *Communications*: setting up the communications interface depends on the network.

3.8.1.3 Strategy configuration

Controllers are pre-programmed with a number of software modules. The modules exist as 'firmware' within the controller memory and are not re-programmable. In order for the controller to perform the desired function, the modules are brought into action by linking them together by so-called 'soft wiring'. In addition to the firmware, advanced controllers allow the writing of custom control routines in the controller's own programming language. The whole process is known as strategy configuration. Configuration is carried out using a proprietary program running on a PC. Each controller manufacturer has its own high level programming tool, which normally consists of a pictorial representation of the firmware modules contained in the controller, which may be linked on screen by 'soft wiring'. In addition to the interconnections of the modules, values of control parameters may be keyed in at this stage. The complete configuration may be downloaded into the controller. The program remains available for use in other controllers. A controller contains some or all of the software modules listed in Table 3.14.

3.9 Summary

The selection and correct use of appropriate components is essential to produce a reliable and satisfactory control system. The types of sensor available are summarised and advice given on selection. Sensors must be mounted in a position that is representative of the quantity being measured and which gives access for maintenance and calibration. Experience shows that incorrect installation is the major cause of problems with sensors.

Actuators convert the output from a controller into the mechanical movement of a valve or damper. The actuator chosen must have sufficient force to operate the controlled device; it is important to select an actuator with the required degree of positioning accuracy, particularly if the controlled device has to operate over its whole range. Modern actuators incorporate microprocessor control which gives accurate positioning and feedback of position to the control system.

Control valves for hydraulic circuits should be chosen to give adequate authority and a characterisation appropriate for the output device. The aim is to provide a final controlled output which is nearly linear with valve position; this will assist in providing satisfactory control.

The same considerations apply to dampers. The section gives guidance on the choice between parallel and opposed dampers and emphasises the need to provide sufficient damper authority; this may require the damper area to be smaller than the duct. It is now possible to use standard induction motors with variable-speed drives. The use of

VSD and two-port valves can lead to substantial savings in pump and fan energy consumption. The design of hydraulic systems incorporating two-port valves demands care to avoid problems at part load.

Lastly, the intelligent controller is described. This is the workhorse of most control systems. It provides local control of subsystems while communicating over a network with the building management system. Controllers contain a comprehensive range of pre-programmed control functions, which require to be configured for particular applications, using proprietary programming software provided by the controller manufacturer.

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4 Systems, networks and integration

Summary

Chapter 4 describes the ways in which components are linked together on networks and so form a building services control and monitoring system. Systems integration allows communication between different building services control and monitoring systems with consequent advantages of more efficient operation and potential reduced cost. Networks, the electromagnetic interference, the 'head ends' and the user interface are discussed.

4.1 General

The term 'building management system' (BMS) (along with the terms 'building automation system' (BAS), and 'building energy management system' (BEMS), which are also in common use) encompasses a wide range of control systems, ranging from dedicated controllers hardwired to the equipment they control, to large-scale distributed systems extending over several sites and maybe internationally. The development of larger integrated systems depends on the existence of communication protocols which allow devices from different sources to communicate with each other. The organisation of building automation systems and the networks on which they depend is the subject of this section.

4.2 BMS development history

4.2.1 Introduction to conventional controls

Electronic control systems were first developed using analogue signals to carry information between parts of the system and to provide the control action. Controllers were based on operational amplifiers, which are now replaced by microprocessors. The sensor could be connected directly to the controller, in which case the controller required the appropriate input circuitry to handle the signal input. Greater flexibility could be achieved by using a transducer to convert the sensor output to one of the several standard signal forms. This has the additional advantage of providing a stronger signal where transmission over a distance is required, where a small signal such as a thermocouple EMF, might become corrupted. Outputs from the controller are standardised and are connected directly to the required actuator. Voltage-to-pressure and pressure–to-voltage transducers allowed the use of pneumatic actuators with electronic controllers.

Controllers based on analogue inputs and outputs still form the basis of control systems for the simplest of buildings. Each controller is linked by direct connection to the controlled output device and performs a single function, i.e. a single control loop. Several independent control systems may coexist within a building, e.g. a boiler control incorporating time switch and flow temperature control plus independent zone temperature controllers. Conventional controllers share the following characteristics:

— single function controller, hardwired to sensor and actuator
— analogue inputs and outputs
— sensor signal conditioning required for long cable lengths
— standardised controller output
— no central supervision
— cost-effective for simple buildings.

4.2.2 Centralised intelligence, the first micro-processor based building control system

The use of microprocessors in the 1980s allowed the development of direct digital control (DDC) systems for buildings. The controller function is carried by a software program, which can be written to execute any desired control characteristic. Many control loops can be handled by the same processor. Changes to the control function can be made by changes to software alone, without any requirement to change hardware.

The development of adaptive and self-learning control algorithms becomes possible.

The first systems using DDC employed a centralised controller (Figure 4.1) incorporating all the processing capability in one unit, known as the central processing unit (CPU). The CPU is connected to some form of user interface known as a 'dumb' terminal, which allows the operator to view the status of the system and change control parameters. All sensors are brought back to the central unit. Where the path lengths are long this will normally require signal conditioning at the sensor. The signal conditioner combines a transducer, which converts the sensor output to a standard form, and the transmitter

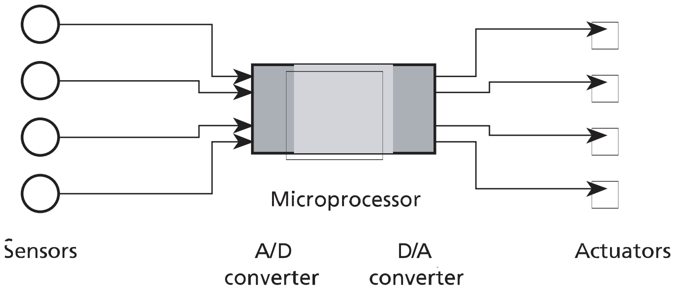

Figure 4.1 DDC with centralised controller and hardwiring

which amplifies the signal for transmission over long distances of wire. At the central controller, the incoming signal is conditioned by an input card, and converted to digital form by an analogue-to-digital converter before being sent to the microprocessor for processing. The treatment of the output signal from the controller follows the same pattern in reverse. The output from the microprocessor is converted to analogue form, and rendered into a standard format before being sent to the transducer at the controlled device.

In control systems with centralised intelligence:

— all sensor inputs are wired to the central controller
— control functions are executed digitally
— software may be changed without hardware change
— reporting and parameter changes are made via the supervisor
— the wiring cost is high
— the system is vulnerable to controller malfunction.

4.2.3 Central intelligence connected to a 'dumb' outstation

The provision of separate wiring for each sensor and actuator is expensive and this has led to the introduction of local outstations, also known as data-gathering panels. Sensors are connected into the outstation which performs signal processing and communications functions. A so-called 'dumb' outstation (Figure 4.2) does not carry out any control function. Connection to the central controller is by a data transmission cable. The CPU is required to address each point in turn; this is known as polling and in a large system results in slow operation. The features of a 'dumb' outstation are:

— sensors and actuators are connected to local outstation
— outstation contains signal conditioning and communication circuits
— outstation performs no control function
— CPU polls each point in turn
— outstations vulnerable to CPU failure
— CPU has to handle large amounts of data.

4.2.4 Programmable universal controllers

While the use of dumb outstations reduces the wiring requirements for a large BMS it is vulnerable to a failure in

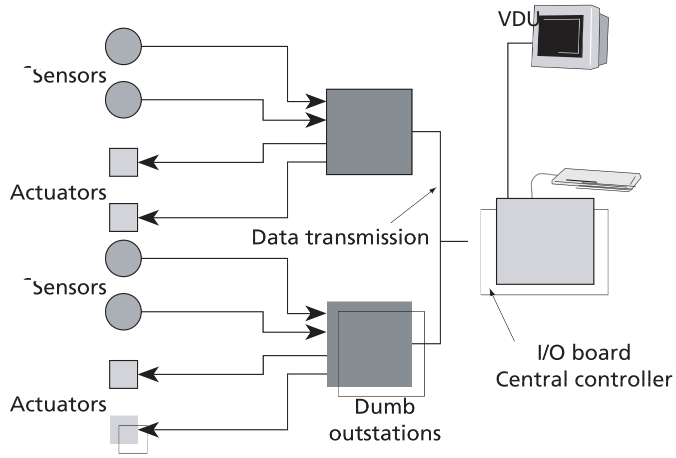

Figure 4.2 Centralised controller with dumb outstations

the CPU. It is now the general rule to use programmable controllers or intelligent outstations (Figure 4.3) which incorporate their own microprocessor and carry out local control functions, which will operate in the event of a CPU problem. Communication with the supervisory computer is for the purpose of supervision, fault reporting, data collection.

The field device that connects to the sensors and actuators incorporates its own microprocessor and carries out local control functions, which will operate in the event of a local area network (LAN) or supervisory computer problem. Communication with the supervisory computer is for the purpose of servo-manual supervision, fault reporting, data collection, monitoring and the ability to change control parameters as necessary. Communication between outstation and supervisor normally uses some form of local area network; this may employ a proprietary protocol or one of the standard or 'open' systems discussed in section 4.3.

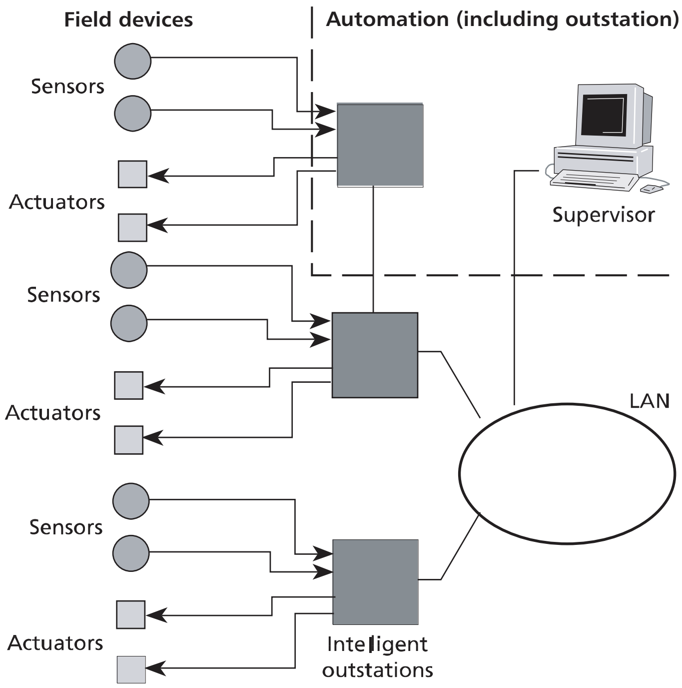

Figure 4.3 BMS with intelligent outstations (two-level system)

The intelligent outstation is the building block of the modern BMS and is discussed in section 4.2.6. The freely programmable outstation (Figures 4.3) spawned many program types and forms, one each per supplier and each with a particular network protocol per supplier.

The main features are:

— control function is incorporated in outstations, outstations function independently of any supervisory computer or CPU

— supervisory computer accepts reports and fault alarms; may alter set points and other parameters.

— controller designed to control a specific type of plant, e.g. a VAV box or fan coil unit.

— controllers and the outstation communicate via a network and also to the supervisory computer.

These can be described as 'two-level' systems, see section 4.3.7.

4.2.5 Extension of old systems and integration of old systems with new systems

The history of BMS architecture development evolved to join together disparate suppliers' own equipment for operational benefits. This approach maintained the integrity of the supplier's system and in various technical ways the supervisory layer (over and above the management layer) communicated with the management layer in software. A standardised protocol is now available in the ASHRAE-developed BACnet®.

BACnet® was published in 2003 as ANSI/ASHRAE 135: *BACnet® — A Data Communication Protocol for Building Automation and Control Networks*(1) and has since been adopted as an International, European and British Standard, BS EN ISO 16484-5(2).

The benefit of these protocols is that they enable new systems to be connected to existing systems that have developed over many years.

An upgrade to these systems for integration is to use the internet and modern programming languages (servers providing this functionality often being incorporated into routers in the case of LonWorks), e.g. XML. In this way access to data is more available on more devices in more places. The use of the web as a vehicle for presentation of information and for override control at the supervisory computer level is the next stage of evolution from the intelligent outstation.

These can be described as 'three-level' systems, see Figure 4.4 and section 4.3.6.

4.2.6 Standardised controllers and network protocols

The development from programmable universal controllers and intelligent outstations, and the pre-programmed or 'unitary' controller, is towards combinations of unitary controllers on standard 'open protocol' networks.

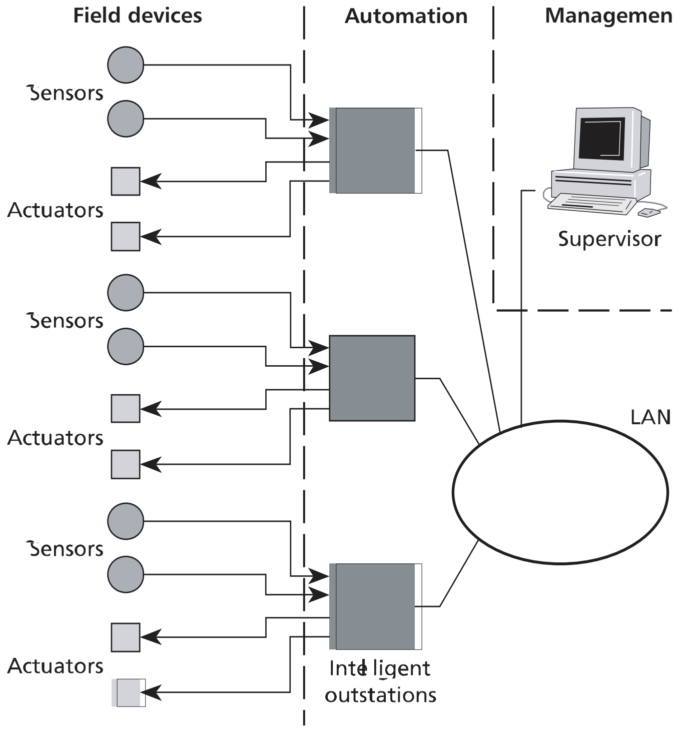

Figure 4.4 Three-level system

For example, Figure 4.5 shows a 2-level BMS architecture provided with greater intelligence at the lowest level and direct routing using the Ethernet TCP/IP protocol.

The standards for these protocols are BS EN 14908-1: 2005(3) and BS EN 14908-2: 2005(4). Further parts are under development.

The systems compliant with these standards are those offered by the members of LonMark International and the KNX Association. KNX is a royalty-free, platform-

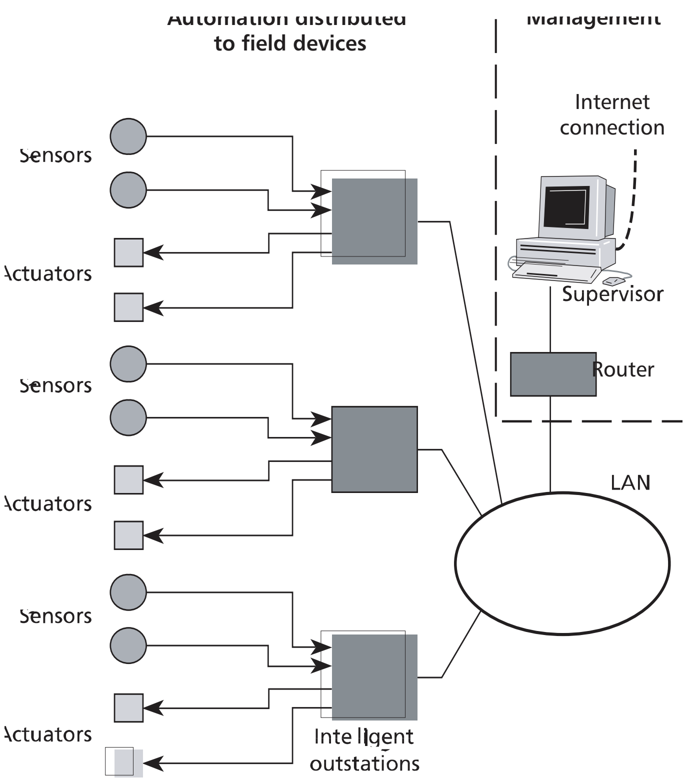

Figure 4.5 Two-level architecture BMS with direct routing using Ethernet TCP/IP protocol

independent protocol for building controls, which has been adopted as a European and British Standard, BS EN 50090: *Home and Building Electronic Systems (HBES)*(5) and as an International Standard, ISO/IEC 14543: *Information technology. Home electronic system (HES) architecture*(6).

A KNX-compliant installation consists of a set of devices, connected to the internet or a local network. Every facet is realized in and through the devices, which adhere to a number of logical standard node architectures. for devices harbouring resources and implementing the protocol. These vary according to node capabilities, management features and configuration modes, and to the device's role in the network, e.g. application (end) device, configuration master, router, gateway etc. KNX also standardises certain general purpose device models, such as for net coupling units (BCUs) or net interface modules. (BIMs) mainly used in combination with the programming tool and downloadable application programs. Application programming interfaces are defined. Together with the characteristics of the configuration modes, these device models are all laid down in the profiles and thereby allow suppliers to adhere to the standard.

LON links directly with BACnet® in a 3-level architecture via gateways. This allows legacy connectivity and interoperability with other systems.

4.2.7 Packaged plant

HVAC plant, such as multiple boilers or chillers, may be supplied as a packaged unit complete with factory installed unitary control system (see Figure 4.6). In the example of a multiple boiler unit, the fitted controller would incorporate all safety cut-outs, ignition procedures, boiler sequencing and the control of ancillary devices such as flue dilution fans. Such a unit will control itself independently. The standalone controls will allow the required flow temperature to be set directly at the local controller. The BMS will need to interface with the packaged plant controls and the packaged plant supplier will need to confirm how this can be achieved.

The main features are:

— packaged plant with factory-installed unitary controller is often an economical solution

— there may be a limited interface with a BMS

— volt-free contacts are used

— package plant may be supplied with LonMark, KNX or BACnet® components which allows direct network connection to the open 2-level system, rather than through a field controller or a gateway device.

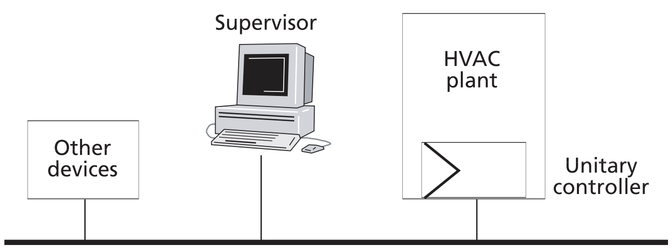

Figure 4.6 Factory-fitted unitary controller

4.3 Networks

4.3.1 Architecture

The organisation of the various control elements into a comprehensive BMS is termed the system architecture.

4.3.2 Description

The term 'network' implies that a number of devices are connected with each other via a communications system. A communications network consists of two essential parts:

— a physical medium, which is used to transport the signals (e.g. wire, optical fibre, radio link)

— a protocol, which is the set of common language rules for the communication signals.

Devices communicating over a segment of the physical medium and using the same protocol form a 'local area network' (LAN). Separate LANs, which may employ a range of physical media and protocols, can communicate with each other with the help of routers, forming a 'wide area network' (WAN). The components of a WAN may be widely separated, communicating via satellite if necessary. The manner in which networks are arranged and interconnected is termed the 'network topology', see section 4.3.5.

4.3.3 IT infrastructure

'IT infrastructure' is the term used to describe not only the network, switches and routers, but the servers, software, system management, maintenance and housekeeping.

Essentially, the use of the IT infrastructure by a BMS, or other low voltage systems that utilise digital communication (e.g. images, speech, data), represents a bringing together of computer systems and controls technology. There is a trend towards convergence of these technologies, and the distinction is becoming blurred, particularly in the building environment. While previously there was perceived to be a ideological difference between the function of a network in a real-time control system and that in a business computer, they are now both regarded as information carriers. In the past, the system functions were seen as independent and unrelated but now they are seen to be interdependent at least and, in some businesses, as critically related. In this situation the need to justify the use of the IT infrastructure by the BMS has been marginalised. However, there are a number of issues that a designer should be aware of and these are discussed in the following sections.

4.3.4 Network data

It will always be the case that the IT traffic (i.e. flow of data) on most building networks will differ from the BMS traffic. The IT traffic is essentially non-time-critical and 'spiky' with occasional heavy peaks when large files are being moved whereas the BMS traffic will generally be lighter but will have time-critical data. When using dedicated networks, BMS and low voltage systems have operated at relatively low data rates (in the region of 9600–19200 baud) because the time constants of the systems controlled have been in the order of seconds. Putting the BMS traffic on high speed networks (i.e. 10–100 Mbaud) will generally have little or no detectable effect. While experience generally demonstrates that the load imposed on a network by a BMS is inconsequential, a BMS designer should as a matter of course co-operate with the network designer/supplier in undertaking traffic analysis/calculations and in the development of an appropriate network management system specification

An issue that is generally beyond the control of the network designer is the timing of the installation of the IT network. Traditionally this is seen as a fit-out, rather than part of the building infrastructure. In order to support the BMS it is essential that the system is installed as part of the building 'base-build'.

4.3.4.1 Data handling

As discussed in 4.3.3, there was initially some resistance amongst IT managers to the use of IT networks by a BMS, due in part to a perception that the supporting software was less easily subject to their approval. While this perception has altered over time, the 'health' of the software, which will be some proprietary applications developed by the BMS provider, remains an important issue. At the time when the BMS was a standalone item the effects of software 'bugs' (however few) were generally minimised (or hidden) by the suppliers by resolving them under the maintenance contract. However, within an IT infrastructure the effects are unpredictable, and it will be important for the designer to provide the client's IT manager with formal assurance that the BMS software can meet appropriate standards. Software validation and the commissioning and handover of the system must be robust. Consideration should be given to the use of relatively inexpensive protocol analyses to demonstrate to the IT manager the traffic characteristics from the building control network(s). It should be noted that the IT industry measures its network operating performance, which allows the performance of the service provider to be measured and thus managed. Where any extra low voltage (ELV) system, including a BMS, shares the IT infrastructure, performance measurement can be applied to it with consequent improvements in performance and cost effectiveness.

4.3.4.2 Data storage and retrieval

There are two categories of data to store:

— the operating software for the BMS

— the data produced by the BMS as it monitors equipment and operating parameters.

The former needs to be secure and protected in order to preserve the supplier's warranty, and accessible only by the supplier and/or the system administrator, in the same way as the IT infrastructure.

4.3.4.3 The internet

The internet represents the furthest extent of IT infrastructure, moving it beyond the individual building or business. It is now the norm for most business IT infrastructure to include facilities to connect to the internet and the building control systems can be designed to take advantage of this. Accordingly, the designer needs to be aware of the additional engineering features that this will entail. These include the following:

— *Graphical user interfaces*: web browser technology provides a simple method of providing designated individuals direct access to the building control systems. Depending on their access privileges, this will range from passive viewing of key parameters (e.g. the conditions local to their desk) via intranet access only, to direct control of key operations via the internet.

— *Security*: providing access to the internet poses a risk of intrusion. When the building control systems include the building security system this risk becomes physical. It may be assumed that the building IT infrastructure will include electronic intrusion protection in the form of a firewall, and that the building control systems are effectively inside the firewall. There is a general supposition that a firewall and associated virus protection software that satisfies the requirements of the IT infrastructure for intrusion protection will be more than capable of protecting the building control systems. This supposition should be tested by the designer of the building control systems.

4.3.5 Network topology

The manner in which devices and their interconnections are laid out is termed the topology of the network. The chosen topology will affect the amount of cabling required and the flexibility of layout. It will also have an influence on the technical aspects of communication, such as signalling rate and reliability. Figure 4.7 illustrates the main topologies. These are as follows:

(*a*) *Point-to-point*: devices are connected directly to each other. Features are:

- only one connection affected by a fault
- simultaneous transmissions are possible
- wiring costs are high
- there is no automatic interconnection between devices.

(*b*) *Star*: each device is directly connected to a central unit. Features are:

- failure of one device does not affect others
- failure of central unit gives system failure
- cabling costs are high.

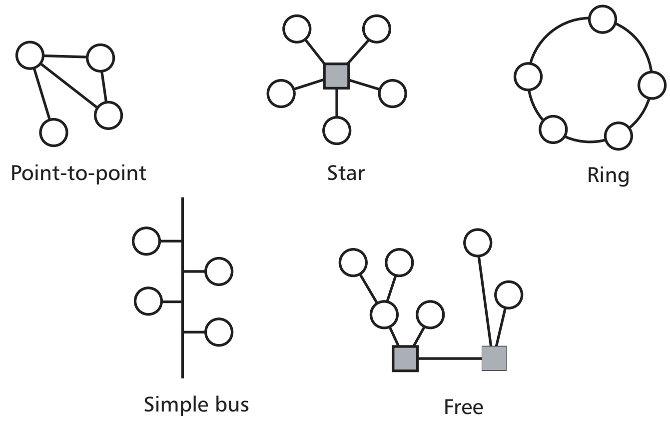

Figure 4.7 Network topologies

(*c*) *Ring*: bus devices are interconnected in a ring structure. Each device communicates with its neighbours and passes messages on. It is possible to incorporate watchdog relays, which bypass individual nodes when a device is powered down; this retains the integrity of the ring. Features are:

— cabling cost is modest and expansion is easy

— failure of one device leads to system failure.

Example: Arcnet.

(*d*) *Bus*: all bus devices communicate over the same transmission path. Features are:

— any device can communicate with any other

— failure of one device does not affect communication between other devices

— cabling cost is low and expansion is simple

— bus can only handle one message at a time.

Example: Ethernet.

(*e*) *Free*: free topology is a combination of the topologies described above. Information sent to a root is passed upwards to all devices sitting on the relevant branches, which are connected as a bus structure. The devices at the roots of the network serve to amplify and send on messages received from other branches, or may act as gateways, converting messages from one transmission medium to another. Features are:

— aids organisation of subsystems

— no direct connection between all bus devices

— failure of one device does not affect others

— failure of the root leads to system failure.

Example: LonWorks.

The most common topology used in the major field network systems is a form of tree structure, whereby local bus topologies may be connected together using couplers or routers at each root. By this means, subsystems using different communications media may be coupled together and operate using the same protocol.

4.3.6 Three-level architecture

The standard approach to BMS network architecture since the 1980s is the three-level model. This was formally defined the European Committee for Standardisation (CEN) which divided the communications within a building into three levels:

— *management level*: e.g. supervisor to supervisor and to communicating outstation (DDC)

— *automation level*: e.g. DDC controllers and to the field controllers e.g. sensors in next level

— *field level*: e.g. sensors and actuators from the field controllers.

Information which is needed locally is not passed upwards to higher levels, thereby reducing the traffic on the system. Communication with sensors and actuators takes place at the field level. Intelligent controllers sit at the automation level, to which the supervisory computer connects and which has access to the outstations at this level. The management level accesses information from the automation level in the PC and has access to a local area network, so that it can exchange management information with systems in the same or other buildings. The control function at management level is limited. Interfaces between levels are used to:

— restrict low level traffic from passing to the level above

— translate from one protocol to another.

The three-layer structure organises network traffic at the respective operational levels and requires the complication of linking the three levels where data need to move between those levels. A single network level of this three-level structure may carry all communications sufficient for many applications; slightly larger systems may operate at the two lower levels of a three-level system, further expansion can lead to a third or even forth level.

4.3.7 Two-level architecture

The current approach to BMS network architecture is 2-level. The reasons for adopting 3-level architecture were cost and security/reliability of the technology with respect to processors, memory and transceivers. These reasons no longer exist; controllers can now use the same twisted pair wire as can actuators and sensors. Falling prices and improved security/reliability mean that web devices can be directly connected.

Intelligent devices in the control system incorporate their own microprocessor and communications ability. Devices are connected by a free topology network which allows communication between all devices using a well-defined protocol. Each device is individually addressable and programmable; e.g. an intelligent temperature sensor at the field level will transmit a message onto the network identifying itself as well as providing a temperature reading. A controller or other device on the network may then use this message.

In order to limit total traffic on a network, a network will be divided into segments connected by routers, which can transmit only messages destined for outside the segment. Connection between networks at different levels is via the same routers or by 'tunnelling' through Ethernet, and therefore standard business enterprise networks, or the worldwide web.

The characteristics of a net system are :

— all devices communicate using standard protocol

— all devices are individually addressable

— devices communicate directly with each other as required

— the system is decentralised

— interoperability between different manufacturers is standard.

The two-level system uses a range of modular units, each of which is programmed to control a specific item of plant to an internationally agreed control profile. All the modules communicate on the same twisted pair net system.

Installation and configuration are simple; the control modules are pre-programmed and are self-tuning, so virtually all the installation that is required is hardwiring to the plant that is to be controlled, and the commissioning of the module's address. Systems can be built incorporating several hundred modules and remote supervision is possible. There are some variations between the two international standards KNX and Lon (see section 4.2.6).

Protocols that can utilise the more robust network topologies will tend to perform better in mission-critical applications such as operating theatres, clean rooms or life systems such as fire alarms. In these cases the network topologies available can make these less prone to single points of failure than is required under the current standards (BS 5839: 2002[7,8]).

With smaller controllers often located in the field the chance of a controller failing remains the same as for a larger controller but the effect of the loss is significantly less, e.g. the control functions associated with 10 or 20 points as opposed to, say, 50 or more. There may be less cable installed with the smaller controllers since they can be located closer to their actuators and detectors. This provides a small additional reliability benefit.

DDC controllers rely on a copy of the program held in the controller's random access memory (RAM) in order to operate. For this reason most manufacturers provide some form of battery backup, or a special form of RAM that does not need an external energy source. This must be sufficient to cover situations when power may not be available (e.g. failure of external power supply or planned shut-down for maintenance). On occasion this may apply for 48 hours or more. In some cases, control may need to be restored within a prescribed time following the restoration of power (e.g. power management/load shedding etc. in a hospital). In such cases the time taken for the controller's processor and network becomes important; some controllers take 10–20 seconds (and some a few minutes) to restore functionality.

4.3.8 Communications media

Communication between devices takes place over a local area network (LAN). This has two aspects: the network protocol and the physical embodiment in the communications medium. Several communications media are available for BMS purposes, see Table 4.1.

Achievable transmission rates are steadily increasing. Coaxial cable and fibre optic cable have very high data carrying capabilities and can transmit data over long distances. They require specialist installation and are used in many IT systems. Despite their relatively high cost, fibre optic cables and radio are often used between buildings for building control systems because of their excellent electrical isolation properties preventing inadvertent electrical connections and widespread damage from lightning strike. The most widely used medium for a BMS network is twisted pair copper wire. The use of cables such as those used in structured cabling installations, e.g. category 5e, with highly twisted conductors will reduce the effect of electrical interference.

As with other communication cable installations, building control systems communication cables should be segregated from sources of radiation. Where it is difficult to run cables, it is possible to use power line carrier or radio systems but with reduced speed.

Low power radio systems operating in the UHF band may be used without a licence for telemetry and data transmission[9]. They have the advantage of low infrastructure cost, low installation cost and flexibility in use. National authorities have issued specifications for licence-exempt radio transmission, which define the maximum permissible RF power, the frequency and bandwidth of the transmission and the number of channels. Standards differ between continental Europe and the UK. In Europe the relevant standard is ETSI EN 300 220-1[10].

Table 4.2 gives the classification of data cables[11]. Category 6 cabling is the current standard for data cabling.

Table 4.2 Data cable classification

Category	Description
1	Basic telephone cable for voice
2	Data cable for use to 4 Mbit/s
3	LAN cable characterised up to 16 MHz (Class C link)
4	LAN cable characterised to 20 MHz
5	LAN cable characterised up to 100 MHz (Class D link)
5e	LAN cable characterised up to 100 MHz
6	LAN cable characterised up to 250 MHz
7	LAN cable characterised to 600 MHz

Table 4.1 Communication media

Communications medium	Transmission rate	Application
Power line carrier	14–85 Mbit/s	Primarily domestic or retrofit
ISDN telephone line	2 × 64 kbit/s	High capacity
Unshielded twisted pair (UTP) (e.g. category 5e)	10/100/1000 Mbit/s	The most common medium for voice and data communication. Four-core cable may be used for digital signalling
Shielded twisted pair	16 Mbit/s	Offers higher capacity than UTP but is bulkier and more expensive
Coaxial cable	10 Mbits/s	High capacity data transmission. Basis of older Ethernet systems
Optical fibre	10/100/1000 Mbit/s and 10 Gbit/s	The highest data transmission capacity. Immune from EMC problems. Unsuitable for multiple local connections
Radio :		Short range licence-exempt radio provides flexible operation
— 802.1/a	54 Mbit/s	
— 802.1/b	11 Mbit/s	
— 802.1/c	54 Mbit/s	

Several protocols have been developed, not all of which have been exploited for use in BMS systems. Table 4.3 summarises some of the bus protocols that are in use.

4.3.9 Structured cabling

The increasing use of IT in business operations has required developments in the cabling infrastructure that interconnects the many terminal devices. Networks require sufficient capacity to deal with demands such as video conferencing; network loads of 1 Gbit/s have been reached and are projected to increase. The consequence is that the IT cabling in a building may rapidly become inadequate, with the consequent expense and disruption of upgrading.

The concept of structured cabling, also known as universal cabling, aims to install a cabling infrastructure in a building or group of buildings that will meet the requirements of all potential users of the building during its lifetime, without the need for re-cabling. Personal computers (PCs) and other terminal devices, including BMS components, are plugged into local terminal outlets. The initial installation aims to provide sufficient terminal outlets to accommodate future internal rearrangements and variations of work requirements.

The cabling topology is illustrated in Figure 4.8. Three levels of installed cabling are involved, plus a patch cable to connect each device to the local terminal:

— *Horizontal cabling*: each work area of the building, typically a floor or part floor, has a floor distributor, also known as the 'patch frame', mounted in the telecommunications closet. Direct cabling, normally category 5, 5e, 6 or 7, runs from the floor distributor to each of the local terminal outlets in the work area. The outlets are typically floor boxes containing an RJ45 socket, installed at sufficient density to allow for future needs. The length of horizontal cabling is normally limited to 90 m.

— *Building backbone cabling*: within a building, each floor distributor is connected to the building distributor via building backbone cabling. This cabling is also termed 'building riser cabling', since it commonly interconnects floors of a building. The cabling is typically category 5, 5e, 6 or 7 or fibre optic.

— *Campus backbone cabling*: where several buildings share the same network, campus backbone cabling is used to connect building distributors with the campus distributor. Fibre optic cable is commonly used for this purpose.

— *Work area cabling*: individual devices, such as PCs, printers, telephones and BMS components, are connected to the terminal outlets via work area cabling, also known as 'patch cabling'. Each device which is to be connected to the network is provided with a jack plug compatible with the terminal outlets.

For BMS purposes, the use of an 8-pin RJ45 plug and socket is recommended. Thus, where a BMS system is to share a structured cabling system, it would be specified that all control components (e.g. actuators, controllers, VAV boxes) would be provided with a fly lead terminated by a standard jack plug. The structured cabling system must be specified to provide a large number of sockets in suitable locations, in service ducts and plant rooms, which will be adequate for present and future needs.

Where structured cabling is specified, the cabling system is designed as a complete system to incorporate all data transmission needs. The wiring is then installed by a single contractor. This eliminates many problems of coordination and commissioning, and is claimed to lead to cost savings. However, any decision to incorporate the BMS with a structured cabling system should be considered carefully.

Flexibility is not normally a high priority with HVAC and BMS systems, since major repositioning of plant is an unusual event and is likely to be associated with a major refurbishment in the building. Sharing communications networks may introduce contractual problems over installation, commissioning and maintenance, which should be resolved at an early stage. For some BMS applications, the current-carrying capacity of the cable used in an IT network may be inadequate.

4.3.10 Standardisation

Components of a network communicate with each other using a common communication protocol. The communication medium itself may take a number of physical forms, but is typically a low voltage twisted pair cable. When required to do so, a device transmits a message onto the bus, containing such information as the identification of the sending device, the information to be transmitted, e.g. a temperature value, the address of the device for which the message is intended and additional information needed

Table 4.3 Some network protocols

Protocol	Standard	Comment
ARCNET	ANSI 878.1[12]	High performance LAN with data exchange up to 2.5 Mbit/s. Used widely in industrial applications
BACnet MS/TP	ANSI/ASHRAE 135[1]	Master Slave/Token Passing serial communications using an EIA-485 signal.
Ethernet	ISO/IEC 8802-3[13]	Data transmission up to 1 Gbit/s. The most common IT medium.
KNX	BS EN 50090[5]	Uses twisted pair at 9.6 kbit/s
Point-to-point	TIA 232[14]	Serial communication between two devices. Typically used for dial-up communication using modems
LonWorks	ANSI 709.1[15]	The Lon network is based on the proprietary Neuron chip and can be applied to a wide variety of physical media. Typically operating at 78.5 Kbit/s or faster using fibre optic cable.
TCP/IP		Transmission Control Protocol/Internet Protocol: encompasses media access, packet transport, session communications etc. TCP/IP is supported by a large number of hardware and software vendors. Several Internet protocols deal with aspects of TCP/IP. The most important have been collected into a three-volume set, the *DDN Protocol Handbook*[16]

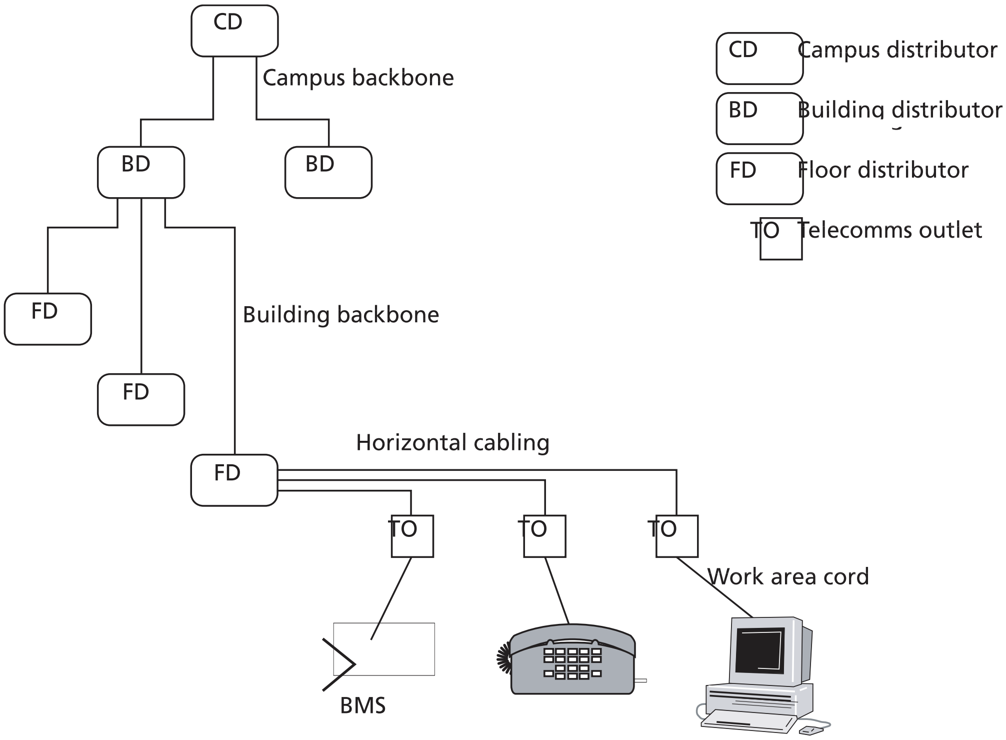

Figure 4.8 Topology of structured cabling installation

for error checking. Each device therefore requires a microprocessor to handle message coding and the transmission and reception of messages to the bus; this must include procedures to deal with message prioritisation and the avoidance of message collision when several devices are attempting to transmit at the same time.

The rules for message formation form the protocol. Historically, manufacturers have developed their own proprietary protocols, but there is now a strong move to the adoption of standard protocols. A major advantage of using a BMS network with a standard operating protocol is the degree of compatibility that may be achieved between different pieces of control equipment. Three levels of compatibility can be distinguished:

— *Compatibility or coexistence*: devices from different manufacturers may use the same communications network without interfering with each other, but can only communicate within their own subgroup of devices.

— *Interoperability*: all devices on the network share the same communications protocol and so may communicate with each other, e.g. one maker's light switch will operate another's light fitting.

— *Interchangeability*: devices are completely standardised, both physically and operationally, so that devices from different sources may be freely interchanged.

Substantial progress has been made towards the goal of producing networks with interoperability. This implies that devices from different manufacturers which conform to the required standard can be plugged into the BMS network and operate with devices from other manufacturers. This development has depended on the development and acceptance of the necessary protocols, which are well defined sets of rules by which devices identify themselves and transmit and receive messages. Several protocols have been developed by national and international bodies and by manufacturers. Full interchangeability is rare. It would benefit users in that more than one source of supply would be available, offering the benefits of competition. However, the requirement that the devices should be operationally identical would hold back developments.

4.3.11 Standardising bodies

A well-defined protocol is essential for a bus system if it is to find wide application and allow devices from different manufacturers to operate together. A bus system requires the following properties:

— a governing association

— a sufficient range of published standard protocols

— a testing procedure

— a certification procedure.

These requirements have been undertaken in two complementary ways, these are:

(*a*) protocol specific certification organisations: e.g. LonMark international® for LonWorks®, BACnet® Manufacturers Association® (BMA) for BACnet®, KNX; these are considered in section 4.3.12.

(*b*) The European Committee for Standardisation (CENELEC) took on the task of defining norms for BMS protocols and started by classifying communications within a building into three levels (see Table 4.4).

Table 4.4 Levels of communication within a building (CEN TC247, WG4)

Level	Example	Standards
Management	Supervisor to supervisor	BACnet
Automation	DDC controllers	BACnet, FIP, Lon, KNX
Field	Sensors, actuators	Lon, KNX

The management network exists to allow data to be collected for the management of facilities and energy and financial reporting. It can be used to connect complete systems together. The automation network operates at the level of controllers and user interfaces. This is the level at which most BMSs operate, e.g. the connection between an intelligent outstation and the head end supervisor. Interfaces to related services such as lighting, fire or security, take place at this level. See also section 4.4.

The field network is the low level network used to connect small devices such as unitary controllers, sensors and actuators. The major standards are considered below.

The International Organisation for Standardisation (ISO) has developed a design model which all protocol development should reference. It is called the Open Systems Interconnection (OSI) Basic Reference Model and is also known as the seven-layer model (see Table 4.5). The model represents an effort to make the communication problem manageable by breaking it down into a series of smaller problems, each of which can then be tackled independently of the others. This has been done by defining a hierarchy of functions arranged one on top of the other in seven layers where each layer deals with one or more of the issues. The seven-layer model is independent of the CEN three-level hierarchy; each of the CEN levels contains a protocol which can be analysed in terms of the OSI model.

Table 4.5 Open Systems Interconnection Basic Reference Model

Layer	Name	Task performed
Layer 7	Application	User interface
Layer 6	Presentation	Common language
Layer 5	Session	Opens and closes dialogue sessions
Layer 4	Transport	Network optimisation
Layer 3	Network	Data packet transport round network
Layer 2	Data link	Message structure
Layer 1	Physical	Communication medium and signalling

For example, the bottom two layers of the stack are the physical and data link layers. According to the OSI model, these layers concern the type of physical interconnection of computers, the electrical signalling, addressing, error detection scheme, and medium access method. The selection of these characteristics, taken together, constitutes what is commonly referred to as a local area network or LAN. The next layer up is called the network layer and describes the characteristics of protocols designed to allow multiple LANs to be connected together. The transport layer optimises the actions of the network level and represents a link between the lower and higher layers. The session and presentation layers deal with wide area networks. The presentation layer provides for a common language for the entire network, so that devices using different protocols may communicate with each other. Finally, at the top, is the application layer which addresses the communication requirements of specific applications, for example, building automation and control. An application layer protocol defines the specific format and content of the messages that two or more computers, each cooperating in a particular application, will use in conversing about their common activities.

Several bus networks are in widespread use for building management systems. Major systems are described in the following sections. The systems share many concepts, though may use different words to describe them. This guide uses the term device to describe a whole physical piece of equipment that is connected to the net; the device contains the necessary communications processing power as well as the hardware necessary for it to carry out its function. The term object may have slightly different meanings in different systems, but is normally defined in terms of the software function of a component or a device.

4.3.12 Standard systems

4.3.12.1 BACnet®

BACnet is an acronym for Building Automation and Control Network. It was developed under the aegis of the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) to provide an open system specifically designed for the requirements of BMSs. It is now formally defined in ANSI/ASHRAE standard 135-2004[1]. BACnet focused on defining a method for communications for the functions commonly found in building automation. BACnet is administered by a standing committee and is designed as a high level protocol which may use a number of transmission protocols at the field bus level. Table 4.6 shows the organisation of BACnet in terms of the OSI model; the commonly used media are in italic type.

Table 4.6 OSI model of BACnet protocols

Layer	Examples
Application (OSI 7)	*BACnet application*
Simple network (OSI 3)	*BACnet network layer*
Data link (OSI 2)	*ISO 8802-2 Type 1*; MS/TP; *Dial-up*; *LON*
Physical (OSI 1)	*Ethernet*; Arcnet; RS 485; *RS 232*; *LON*

Note: layers 4–6 refer to wide area networks; layers 1 and 2 constitute the LAN

In terms of the OSI model, therefore, BACnet is a four-layer protocol stack consisting of an application layer protocol, a network layer protocol, and several data link and physical layer protocols. BACnet's simple network layer allows multiple BACnet networks to be connected in order to create a BACnet internet work. This capability is most often used in order to allow networks employing different data link layer technologies to be linked together through routing devices. For example, a large building could have multiple programmable controllers and operator work-stations connected by an Ethernet network, and each programmable controller could be connected to low cost application-specific controllers using a master-slave RS 485 bus or other low cost bus. This could be described as integration by network linking. The controllers from various systems communicate with each other via gateways and the application layer. This has the advantage of separate systems being integrated providing the head end or application layer software is integrated. Only fully integrated systems can take advantage of the cable and controller saving from the fully integrated approach.

BACnet was defined from the start for use with HVAC and other building services. BACnet defines 25 standard object types, and the number is increasing, where an object is an abstract representation of a control system element. Object types are defined for analogue and binary inputs and outputs, control loops, schedules and so on, chosen to facilitate the modelling of DDC systems; further objects will be added to deal with other building management functions such as fire. The BACnet standard is currently being extended to add other access control and CCTV objects to deal with security. Each object consists of a set of properties, where each property contains a value of some specified data. All objects have the properties of an object identifier, and object name and an object type. In addition, there are other properties such as present value, status and so on. BACnet carries out operations by invoking a set of standard services which govern the rules by which messages are constructed and tasks performed. For example, BACnet services exist that define how equipment share data by reading and writing properties, notification of alarms, change of value events, and so on.

The BACnet standard also defines standard profiles for BACnet devices using BACnet 'interoperability building blocks'. These explicitly define the characteristics of a BACnet device as required by the standard and are used by the manufacturer of the device in the protocol implementation conformance (PIC) statement to define which BACnet objects (and properties), services and networks are supported.

In order to achieve BACnet listing, manufacturers submit their equipment, along with the PIC statement to an authorised BACnet testing laboratory where the performance is independently verified.

4.3.12.2 LonMark®

LonWorks is the general name for field bus systems based on the LonTalk protocol, which is physically implemented in the 'Neuron' chip. This is a programmable integrated circuit developed to handle network and input/output functions. The aim of LonWorks is the establishment of interoperable systems, whereby devices using the LonTalk protocol, from different manufacturers, can freely communicate with each other over the LonWorks network. To this end, an independent association, LonMark International, has been set up, which is responsible for establishing standard specifications for the functionality of devices which are to be connected to the network.

In the language of LonWorks, a device such as a sensor, controller or actuator has an abstract representation as an object. Each object has a strictly defined functional profile, which sets out the inputs and outputs that the device exchanges with the rest of the network. As well as issuing functional profiles, LonMark International offers means for conformance testing of products. Products conforming to the guidelines are issued with the LonMark logo as a warranty for interoperability.

LonWorks is capable of employing several different communication media. It is possible to build a fully distributed HVAC control system in which the components of a control loop exist as physically separate objects, from different manufacturers, communicating with each other over the building's field bus network.

Figure 4.9 illustrates the components of a LonWorks network. Individual devices are connected to the bus at

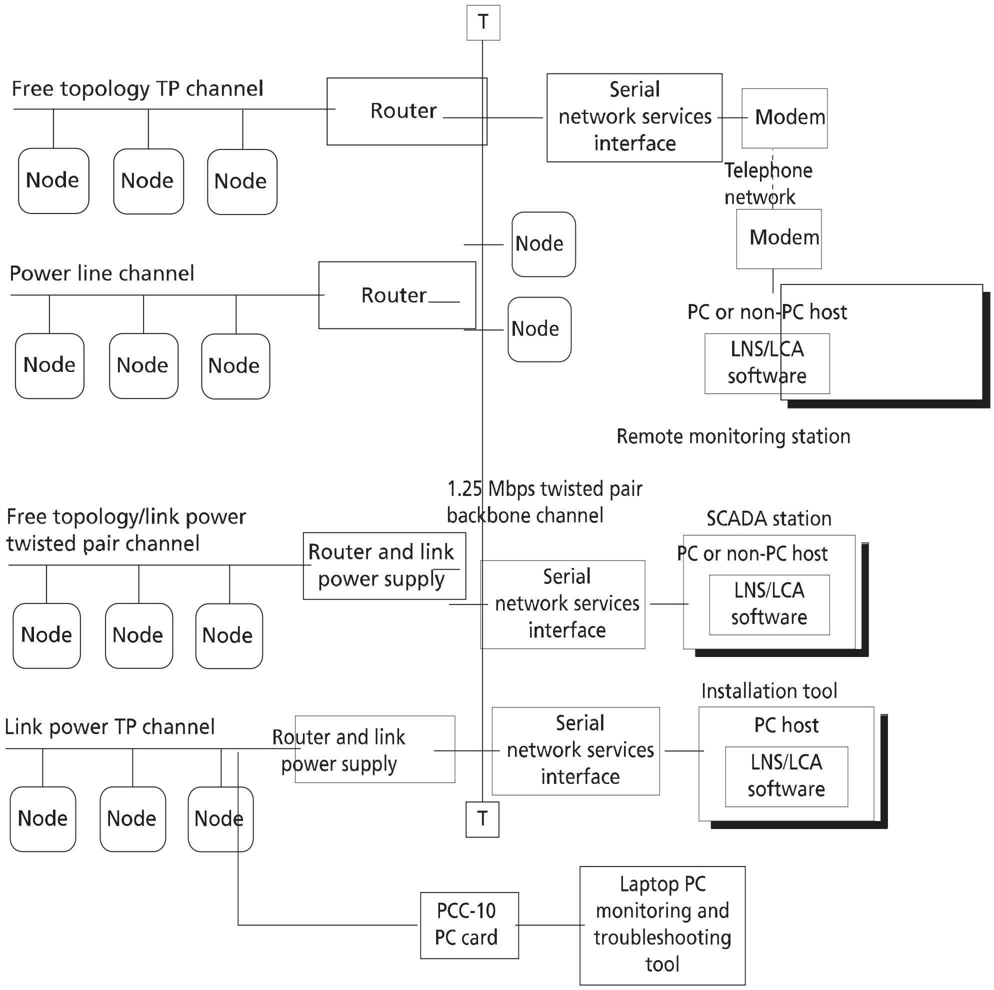

Figure 4.9 Components of a LonWorks network

nodes. The term 'device' is used to imply a physical device such as a controller or sensor. The protocol treats the system as a collection of objects. Objects are well defined building blocks of the system, with a defined set of properties. For instance, a sensor object has properties which identify its type, its individual identity and its output, e.g. temperature, together with several other optional properties. A physical device, such as a controller, may consist of several objects. Each device must contains the processing power necessary for it to communicate according to the protocol. Each device must contain a transceiver, which sits between the Neuron chip and the bus. Transceivers are available for several media, including twisted pair, power line carrier, wireless, fibre, coaxial and infrared.

Figure 4.10 illustrates the components of a temperature sensor. The A/D converter conditions the temperature signal from the temperature sensor into a form that can be recognised by the processor. The function of the processor is to generate a signal which will follow the strict protocol of the network, identifying the sensor and transmitting a temperature value that can be accessed anywhere else on the network. This signal is then converted to a form appropriate to the local communication medium. Depending on the application, the device may be powered from the network or from an external supply.

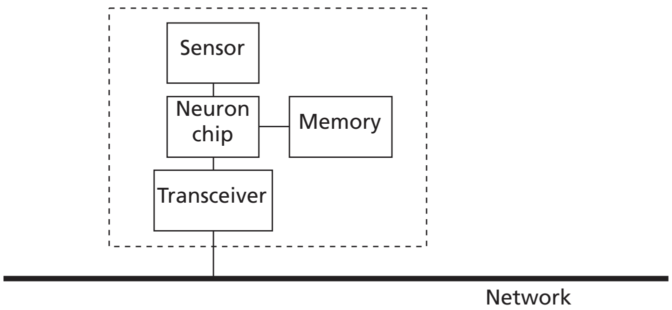

Figure 4.10 Components of a LonWorks temperature sensor

The nature of the system is such that each object performs a well-defined function. For instance, a sensor, controller and actuator driver may be physically separate devices and attached to the bus at different points, but bound together by addressable software and operating as a single controller.

The various protocols define a large number of objects which together cover most requirements of a BMS. It is not necessary that the operation of a device be transparent to the network and in many cases it is more practical to have a complex device, such as a VAV controller, built into the equipment with hardwired sensors and actuators. Such a unitary device may be connected to the net using a limited protocol which allows the supervisor to know the operational status of the controller and alter the set point if necessary; however, the supervisor has no knowledge of the inner workings of the controller. Integrating the controller into the equipment allows more off-site construction to take place.

Different communications media may be used within the same network by the application of routers. Routers also serve the function of partitioning sections of the network from traffic in another area, so that information that is only required within one area is confined to that area and not transmitted over the entire network. In addition, interfaces are available that allow a LonWorks application to run on a non-Neuron host. Thus a PC can become a node on the network. The use of an interoperable network for BMS allows information to be exchanged between subsystems that might otherwise present problems of intercommunication. For instance, an infrared presence detector could send output to lighting, security and HVAC subsystems over the network.

One of the advantages of LonWorks is that many functional profiles have been developed; this aids reliability using industry standard programs and reduces the time needed by the integrator to write these programs. If a functional profile does not exist the protocol is flexibly written to allow the integrator to produce one, and these are often developed to form the basis of new functional profiles.

It is possible to design an interface with a LonWorks field network so that the controller may communicate with the rest of the system. This offers advantages to both customer and manufacturer: the customer receives detailed information on the performance of the plant to assist effective management of the plant and the manufacturer produces an inexpensive gateway to existing plant management software. This is a significant advance on the volt-free contacts often offered by manufacturers in the past. Examples include pumps, electrical metering, air handling units and air conditioning systems.

4.3.12.3 KNX

The KNX Association has members drawn from the major manufacturers of electrical installation equipment in Europe and its aim is to guide development of a highly reliable bus system for BMS systems that will be available all over Europe. KNX is independent of individual companies; it sets out the technical directives for the KNX system and lays down quality requirements. Members who pass its tests may use the KNX mark.

KNX has been developed as a simple and reliable system which may be installed without special skills by an electrical fitter. The bus itself consists of an unshielded twisted pair, which is normally installed adjacent to the power supply cables, sharing the same trunking. Devices sitting on the bus communicate by sending event-driven telegrams. A relatively low information rate of 9.6 kbit/s is used. The choice of frequency makes installation less critical. There are no restrictions on the layout; branching is permitted. Each device on the system comprises a bus coupling unit (BCU) and an application unit (AU). The AU may be some form of sensor or actuator. In the case of a sensor, the AU sends information to the BCU, which encodes it and transmits a message onto the bus. In the case of an actuator, the BCU receives a message destined for the AU, decodes it and instructs the AU on the action to perform. The BCU is programmed during the set-up phase of the installation. This is done using a PC plugged into the system using standardised software tools.

The smallest KNX system consists of a bus line, some bus devices and a power supply, which provides 28 V DC to the line. Up to 64 bus devices may be connected to a single bus line, which has a maximum length of 1000 m. Up to 15 lines may be interconnected using line couplers to form an area. If further expansion is required, up to 15 areas may be connected to a backbone line. Each device is characterised by its physical address of area, line and device number.

Line couplers act to control traffic. When setting up the system, devices are bound together by giving the source and target address. The coupler will pass line-crossing telegrams but all other messages are confined within the line boundary, thus reducing the amount of traffic on the network. A PC may be connected to the bus by a gateway, to provide head end supervision. A laptop PC is also used during the commissioning period with appropriate software. Protocols are now defined for KNX over internet protocols.

4.3.13 Electromagnetic compatibility

The extensive wiring of a control system makes it susceptible to interference from the many sources of electrical noise present in and around buildings. Since the control system operates continuously in real time, it is vulnerable to interference. A malfunction that may be tolerable if it involves a temporary deviation in HVAC performance becomes intolerable if it represents a threat to safety or security.

The possibility that a BMS will suffer from interference depends on:

— the levels of electromagnetic radiation

— the immunity that has been designed into the individual components that make up the BMS

— the way that the BMS, as a networked system of controllers, has been installed.

Ambient electromagnetic noise levels can be high in modern commercial buildings with their high densities of electrical and electronic equipment, and in HVAC plant rooms containing heavy electrical plant. Industrial processes can produce substantial interference and there may be sources of electromagnetic noise external to the building. As far as possible, these problems should be tackled at source at an early stage. The prime responsibility of the controls specialist is to select equipment that complies with the immunity and emissions limits in the EMC product standards and to install them in accordance with good practice. The BMS installation should then have satisfactory reliability and comply with the UK regulations. For further information see CIBSE Guide K: *Electricity in buildings*[17].

4.3.13.1 The Electromagnetic Compatibility Directive

The EMC Directive[18] sets out the two requirements: that equipment should neither suffer from, nor cause, electrical interference. Compliant equipment carries a CE mark and it is an offence to sell or bring into service non-compliant equipment. It should therefore be possible to assume that control products meet the essential requirements of the Directive. In the UK, the Directive is implemented by the Electrocompatibility Regulations 2006[19]. Most products are self-certified by the manufacturer, based on tests in their own or third-party test houses. For a bespoke product, such as a control panel, where the expense of testing would not be justified, it is possible to meet the regulations by the preparation of a technical construction file, where an approved third party certifies that the construction complies with the objectives of the Directive.

4.3.13.2 Installation

The use of approved components is not sufficient to guarantee freedom from interference. The EMC of an installation depends also on the degree of coupling to noise sources; BMS systems, with their extensive signal cabling, are especially vulnerable. There is a balance to be made between the costs of providing protection by using high immunity components or by using lower immunity products which may require special installation measures to prevent interference.

4.3.13.3 Location

EMC should be a major consideration, along with ease of access, in the location of controllers and other components of a control system. While placing control components close to the equipment being controlled has advantages, it may expose them to high levels of disturbance. Controllers and cabling should be placed as far away as practicable from sources of electrical noise; these include switched loads such as relays and contactors, lifts, air-handling units, chillers and variable-speed drives. Transformers, busbars and lift control equipment can be strong sources of 50 Hz magnetic fields, which can cause disturbance to computer display screens; a separation of up to 5 m may be necessary to avoid wobbling images.

There may be sources of interference external to the building. It is advisable to carry out an EMC survey in advance of construction if the planned site is near to radar installations, radio transmitters, electrified railway lines or heavy industrial plant. It may be necessary to install special mains-conditioning units to provide clean power to the BMS. In extreme situations, it is possible to incorporate architectural screening to screen rooms or even the entire building against interference[20].

4.3.13.4 Power supply and earthing

Power supplies in HVAC plant rooms should normally be adequate for BMS controllers that comply with the relevant immunity standards. However, power supplies may suffer from a wide range of disturbances and the risk of interference will be minimised if supplies from electrically noisy circuits are avoided. If practicable, field controllers should be supplied via a separate ring or spur circuit from the local distribution board. The earthing of electronic equipment and signal cabling can introduce problems. Earth systems in a building provide the functions of:

— safety

— lightning protection

— electromagnetic compatibility.

Safety earthing provides protection against electric shock by connecting exposed metalwork to the earth lead in mains wiring. Lightning protection for a structure is provided by lightning conductors mounted at the top of the structure, connected by down leads to earth electrodes. Transients induced in external cables, lightning conductors and other metalwork can propagate throughout a building; remote strikes to power and data cables can generate transients that propagate by conduction down the cable before entering the building. For this reason it is desirable for fibre optic cabling or radio connections to be used to link separate buildings, these reduce the effect of lightning strike to one building. Lightning protection of buildings is covered by BS 6651[21] and BS EN 62305[22–25]. With a properly designed lightning protection system, the risk to components conforming to the EMC Directive should be low. BMS cables running outside the building should be buried; screened twisted pair cable in metal conduit may be used for short distances. To improve reliability, surge protection devices may be installed where external cables enter the building or run in fibre optical cable/utilise wireless technologies. For advice on earthing practice, see *Earthing Practice*[26].

4.3.13.5 Cabling

The cabling that connects components of a control system is susceptible to interference from adjacent power cables and from radio frequency interference. Techniques for avoiding interference include the use of screened cables, care with routing cables, segregation of power and signal cables and correct earthing practices.

Many types of screened cable are available. A comprehensive treatment of data and other types of cabling is given in *Electric Cables Handbook*[27]. Table 4.7 gives an indication of the performance of different types of cable in attenuating magnetic and electric fields. It is important to remember that screening with a conductive material, such as copper, is effective at attenuating high frequency electromagnetic fields, but has little effect on power frequency magnetic fields. To attenuate 50 Hz magnetic fields it is necessary to shield with a magnetic material such as steel, or to use twisted-pair cables.

Table 4.7 Screening cables against 50 Hz magnetic and radio frequency (RF) electromagnetic fields

Code	Cable type	Noise reduction	
		50 Hz	RF
Plain	Plain, no screen, no twists	None	None
	Plain in steel conduit or trunking	Good	Good
	Plain with braid or metal tape screen	None	Good
UTP	Plain two-core unscreened twisted pair	Good	None
STP	Braid-screened twisted pair	Good	Good
FTP	Foil-screened twisted pair	Good	Good
MICC	Mineral-insulated copper clad	None	Good
	Twisted-pair MICC	Good	Good
SWA	Steel wire armoured	Good	Good

In practice, a low cost, foil-screened twisted pair cable is suitable for most BMS applications for frequencies below 1 MHz. For IT and data communication circuits operating at frequencies above 1 MHz, such as Ethernet, the cable type will normally be specified by the equipment supplier. It may be coaxial cable or suitable twisted pair. The use of coaxial cable is not recommended for low frequency use as noise induced in the screen will be added to the signal.

BMS signal cables should be kept as far away as practicable from sources of interference. In particular, untwisted cables should not be exposed to magnetic fields from high current equipment such as transformers. BS 7671[29] permits signal and power cables to share the same conduit, providing the signal cable has adequate insulation. The regulations are written from the point of view of electrical safety, and do not concern interference. Sharing a conduit or trunking makes for economical installation and some field bus systems, e.g. KNX, are designed so that this will not introduce any EMC problems. However, in general, it is recommended that signal cables without screening should be separated from power cables by a minimum distance of 150 mm. Ideally signal and power cables should be routed in separate trays or trunking, and cross at right angles where they meet. Table 4.8 presents general recommendations for different types of screened signal and power cables; manufacturers' recommendations should be followed where appropriate. The control system specification should lay down what standard of installation is required.

Table 4.8 Separation between power and signal cables[28]

Signal cable type	Separation from stated type of power cable (/ mm)		
	Twin and earth	Steel wire armoured	Mineral insulated
Plain	150	125	Touching
High frequency	75*	50	Touching
	125†	50	Touching
Screened	Touching	Touching	Touching

* below 100 MHz
† above 100 MHz

The earthing of circuits and cable screens can present problems. Correct earthing depends on the type of cable, the signal frequency and whether the signal is single ended or differential. In a differential circuit, neither of the pair of signal wires is at earth potential; induced potentials from interference are induced onto both wires, and the input of a differential amplifier is able to reject common-mode disturbances. Most BMS analogue and digital circuits are low frequency and single ended, with the ground line at earth potential. For such cables, both the ground line and the screen of the cable should be connected together and earthed at the controller end of the cable only. Earthing the screen at both ends of the cable creates an earth loop, which can cause large 50 Hz currents to be induced, which in turn can induce unwanted noise in the signal cable. Some communication circuits employ differential amplifiers. Neither signal lead is earthed and the screen should be connected to earth at one end only. Cabling for a standard system should follow manufacturer's advice. High frequency cables above 1 MHz behave rather differently and the outer screen is earthed at both ends and perhaps at several points along its length.

4.3.13.6 Control panels

Control panels must comply with the EMC Directive. This may be achieved by constructing the panel entirely from CE-marked components, in which case each component must be installed in accordance with instructions supplied with the component. Alternatively, the complete panel may be tested as a unit for compliance with the relevant standards, in which case the panel itself will have a CE mark. Unauthorised modifications made after installation could invalidate the CE mark.

BRE Digest 424[30] summarises good practice in the design of control panels, including the following points:

— Sources of broadband electrical noise, such as contactor solenoid coils and switch contacts for external inductive loads, may need suppressors.

— Metal cabinets with low impedance bonding between separate parts provide good screening against radiated electromagnetic disturbances.

— Mild steel cabinets give good protection, while metal-coated plastic enclosures may be inadequate against low frequency magnetic fields. Conductive gaskets may be required where a high level of interference is expected, such as near a transmitter or radar installation.

— Use a Form 4 control panel cabinet, which is divided into cubicles with each motor drive in a separate cubicle.

— Interfacing relays may be mounted in either the drive or controller section. If in the controller section, they should be in a separate area from the controller or separated by a metal screen.

— Cables entering the panel should preferably be led to a termination strip mounted on the cabinet, rather than to the controller itself. Connections within the cabinet should be routed wherever possible along a metal surface.

— Variable-speed motor drives should be carefully installed in accordance with the manufacturer's instructions, which may require the use of a designated VSD enclosure and screened power cables.

4.4 System integration

The term 'systems integration' describes a system in which several building services systems and building systems are brought together into a single cooperative management system. These are able to communicate with each other and take appropriate action. For example, information on occupation level derived from the access control system can be used as an input to the ventilation controller. The increasing use of standard protocols makes communication between systems easier; gateways can be used where it is necessary to bridge between different protocols. All building services may be controlled from a single supervisor.

Modern buildings incorporate a range of building services other than HVAC. Such systems have in the past been developed by different manufacturers and in operation they worked completely independently of each other. There are great potential benefits if the different systems can communicate with each other and work cooperatively. The term 'systems integration' is used to describe the bringing together of equipment from different sources and the combined working of different building services systems, bringing about some or all of the following benefits:

— *Savings in installation costs*: the integrated systems may share the same physical network for communication, see Figure 4.11.

— *Greater choice for the designer*: devices from different manufacturers use the same protocols and can be used with the same network.

— *Simpler building operation*: all building services systems can be supervised from the same central interface. Where appropriate, systems can be accessed from other points in the network.

— *Integrated operation*: where fully implemented, systems integration allows systems to interact, giving intelligent operation of the whole building.

— *Maintenance costs*: savings in revenue/maintenance costs and improved environmental benefits.

From the point of view of the user, a major benefit of systems integration is that the entire BMS may be operated from a single head-end PC, so that operating staff have to learn only one set of operating software. This benefit can be achieved by the use of a neutral head-end, see below.

4.4.1 Implementation

Systems integration can be implemented at different levels:

— *Within a system*: the term systems integration is sometimes used to describe the ability of devices from different manufacturers to use the same communications network. This is better described as interoperability rather than as full systems integration.

— *At the head-end supervisor*: the separate systems act independently of each other, but are all brought to a common supervisor, known as a neutral head end, which incorporates gateways allowing it to communicate with all the systems. Thus all systems may be controlled using a common interface with a consistent look and feel. Information from the different systems may be combined into reports and operating schedules may be set in common. It differs from full integration in that there is no direct communication between different systems; if data is to be passed from one system to another, it has to be sent via the supervisor.

— *Full integration*: information is exchanged between all systems, which are programmed to respond appropriately.

A modern building will have many networked systems running in parallel, including:

— IT network

— telephone network, paging and fax

— security and access control

— fire and emergency systems

— closed circuit television (CCTV)

— lifts

— lighting

— HVAC

— energy management.

It is possible for all systems to share a common IT network for communication with evident savings in cabling costs;

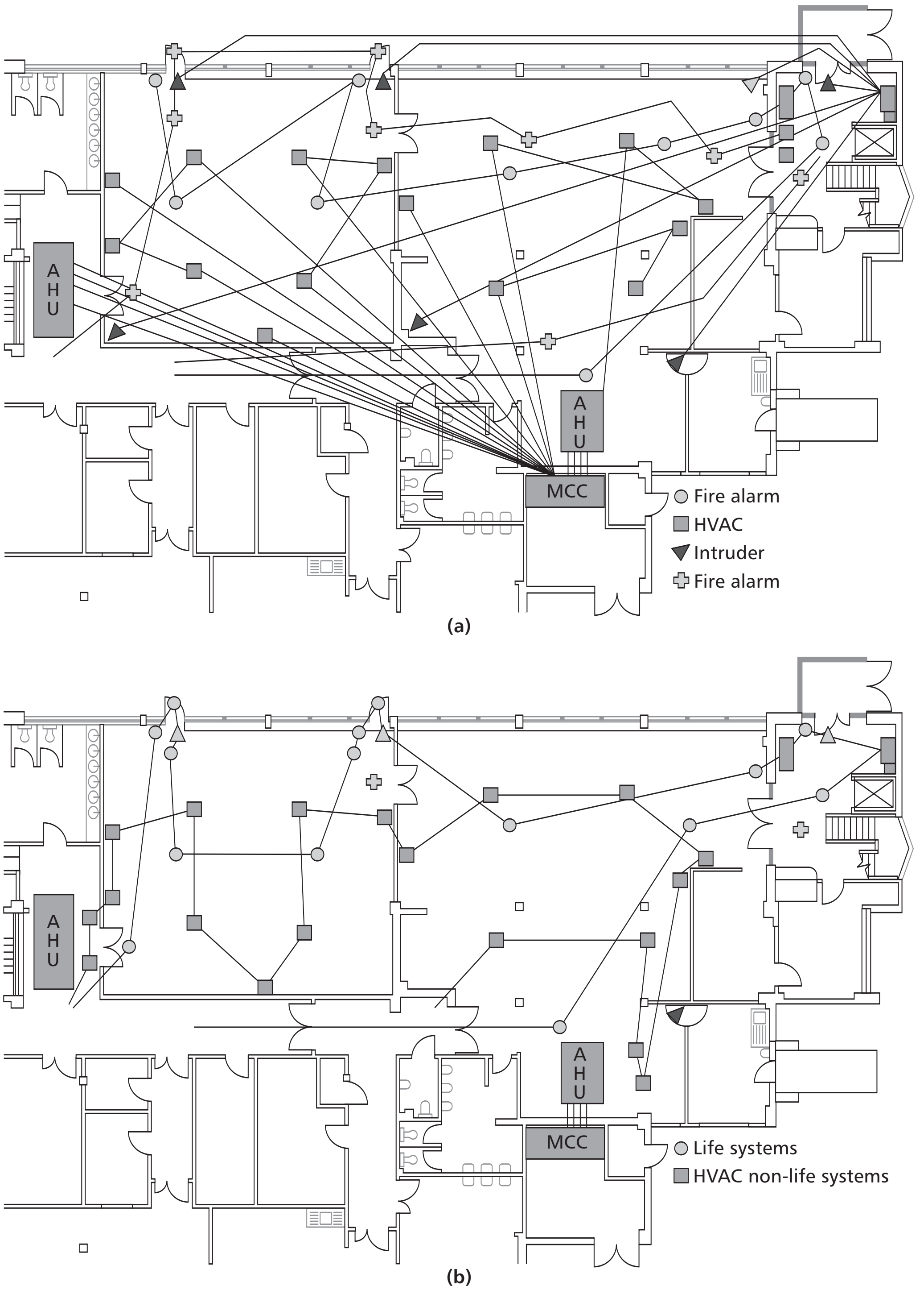

Figure 4.11 Typical installation for control and monitoring systems (normal lighting control not shown); (a) traditional cabling, (b) integrated cabling

the practical considerations are dealt with further in section 4.3.8.

Intelligent building operation is achieved when the different systems are able to communicate with each other directly and take appropriate control decisions. Some examples will make this clear (see Table 4.9).

4.4.2 Fully integrated systems

A fully integrated building management system offers considerable advantages to the building user. However, there are difficulties in achieving this, which may be classified as technical and contractual.

Table 4.9 Examples of integration between systems

Integrated systems	Features
Access and HVAC	Access control system informs the HVAC system of the number of occupants in an auditorium, which adjusts ventilation rate accordingly
Security and CCTV	If a visitor is denied access, CCTV and PA systems are activated, allowing the supervisor to see and speak to the person and take appropriate action
Energy management and HVAC	The energy metering system reports that maximum demand limit may be exceeded, so that the HVAC controls may shed load
Lighting and security	Occupancy detectors in the lighting control system inform the security system of the position of occupants during out-of-hours working

4.4.2.1 Technical

At the field level, interoperability requires that all devices conform to the protocol standard being used. An example is the LonWorks set of definitions of Standard Network Variable Types, which defines the protocol for devices ranging from temperature sensor to VAV controller. In situations where the required device either does not match the standard, or the standard has not yet been defined, it will be necessary to provide a customised solution, both for the device in question and any other devices on the network that need to receive the message.

Network technicalities are discussed in section 4.3.4, but there may be problems with widely different systems sharing the same communications medium. Most building services operate in real time, sending relatively small amounts of information at frequent intervals. The building user's IT system, however, is designed for the needs of the business and is likely to transmit very large files at irregular intervals. There are difficulties in ensuring that all systems achieve their required traffic access. This situation can be improved by confining control traffic to a segment of the network, or sub-LAN, by the use of a bridge or router to connect it to the rest of the internetwork. Local traffic is confined to the segment and only information which is destined elsewhere is allowed out via the bridge.

Under current legislation fire systems can be integrated with other systems providing the integrity of the life safety system is not compromised. With the advanced cables now available, bandwidth is no longer considered to be a problem. Advanced cables can maintain their integrity for over 2 hours at 900 °C at bandwidths of up to 100 Mbits. There are several ways to achieve the integrity of a network designed around safety critical system; for example redundant routers, which can switch to alternate data paths around the system. Another example would be to use a network protocol which can distribute the intelligence network. This makes it very resilient to a single point of failure. Using a network that is shared with other systems decreases the down time, as any failure is detected almost immediately; with conventional life safety systems failure may be discovered only when the system is tested. When considering the use of networked safety-critical devices a truly open protocol has the advantage that the devices can communicate with each other. For example, if a break-glass unit were activated, the fire message would be sent out along with the zone number and relevant fire information. This would be recognised by smoke dampers, which would respond directly to this command. This gives greater integrity, and the message would also be received by other devices such as sounders, fire panels, lifts etc.

BS 7807[31] sets requirements for the design, installation and servicing of integrated fire detection systems. In principle, it allows a considerable degree of integration between fire and other systems, providing the requirements of BS 5389-1[7] are met. The suitability of cabling should no longer be the limiting factor for integrating systems as a wide range of standard and enhanced grade cable is available at a reasonable cost.

4.4.2.2 Contractual

Systems integration requires the bringing together of equipment and systems which have in the past been handled as independent contracts. Where an integrated network is planned care must be taken to ensure that clear lines of responsibility are laid down. It may be that a single company, possibly a systems integrator or one of the suppliers, should be responsible for providing the communications network and coordinating all other companies that are to use it. Not only must there be clear responsibility for design, installation and commissioning, but there must be a responsibility that extends throughout the operating life of the integrated system.

Some standards require a central database to hold all information on the network topology and linking software. There must be clear ownership of the database and arrangements for its upkeep. There are technical advantages to be gained by the integration of security systems with the BMS, e.g. the presence detectors used for lighting control can feed information to the security system.

Potential conflicts of responsibility may be avoided as far as possible by creating sub-networks for primary systems so that each can be fully installed and tested for independent functionality before adding the interoperable functions. Any problems occurring on integration will overlap two or more networks and be the responsibility of the systems integrator to resolve.

4.4.3 Integration with IT systems

Systems integration moves the BMS closer to the IT system. The term information technology is used to cover a number of meanings. Information systems may be regarded as belonging to three generic areas:

— *user information systems*: voice, text, image and data networks used by the occupants of the building for business purposes

— *building information systems*: for the control and supervision of building management, energy, fire and security systems

— *miscellaneous information systems*: public address, closed circuit TV, paging and signage, which span or fall between the first two categories.

Modern organisations usually have an extensive IT system, which necessarily incorporates a network covering the building. IT networks are designed to carry very large amounts of information and it may be possible to use the network for some of the purposes of the BMS.

The current trend is to avoid the 'all fully' converged position in favour of a 'part all' converged system, see Figure 4.12.

However, providing there is compatibility of products irrespective of the system employed and which share the same technology and protocol, then a converged system is desirable and practical. Fire, access, security, emergency lighting, general lighting and HVAC can all share the same infrastructure and the interoperability between devices and systems is seamless and transparent.

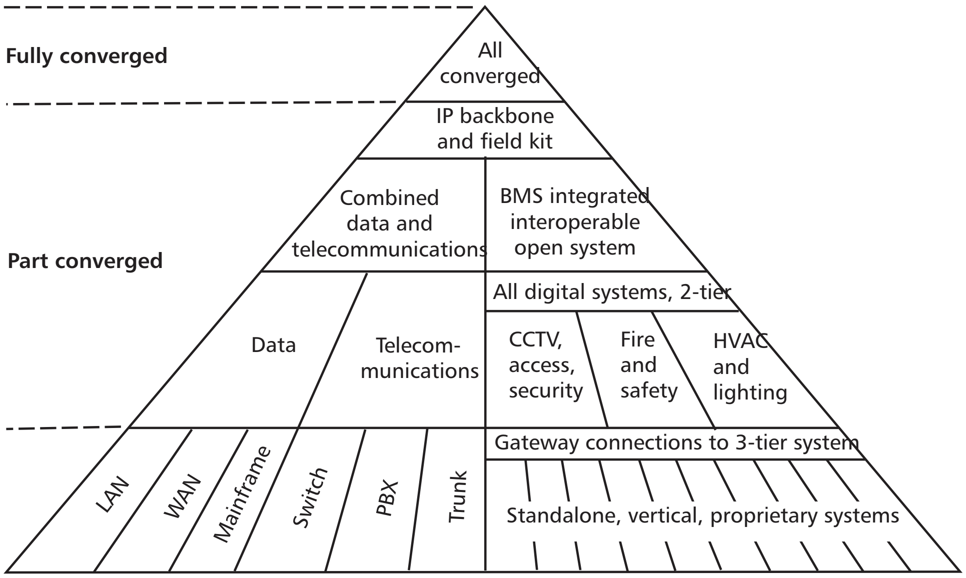

Figure 4.12 Controls and IT integration heirarchy

4.5 User interface

Modern building management systems are controlled by means of software operations. Control is no longer by knobs and switches, hardwired to the device to be operated. The use of computers as central supervisors gives the designer almost total freedom to design the operator interface. The ability to control and monitor every aspect of the building's operation has in turn increased the amount of information to be handled by the supervisor with a corresponding increase in complexity. Since a building service installation will be operated by a range of users with disparate responsibilities, qualifications and experience, it is vital to design operator controls which can be used at the appropriate level by a wide range of users.

4.5.1 Levels of operation

Interaction with the BMS may take place at all levels of the system and at each level there may be different requirements for different classes of operator, see Table 4.10 and Figure 4.13.

Table 4.10 User interaction with BMS

Level	Operator	Function
Management level	Facilities manager	Reporting
	System administrator	Energy M&T Off-line data analysis
Operations level central supervisor	Non-technical personnel (security, caretaker)	Response to alarm messages and instructions
	System operator	Rescheduling, parameter adjustment, monitoring
	Specialist engineer	Reprogramming, fault finding, expansion
Service tools	Specialist engineer	Monitoring, reconfiguration, fault finding
System level outstation	Non-technical personnel	Some local control of conditions
	Specialist engineer	Parameter adjustment, reprogramming, fault finding
Zone level local control	Occupants	Set point adjustment

Large systems contain all levels of operation. Management level activities are primarily information gathering and data analysis, without active control of the system. The management level computer can communicate with several remote sites or even countries. In many systems, the management and operations level functions are housed within the same computer. Some supervisory programs will carry out both management and control functions, e.g. interoperation between disparate systems.

4.5.2 Hardware

4.5.2.1 Zone level: standalone controllers

Small HVAC systems may operate without a BMS, using a number of dedicated controllers, each of which is designed to perform a particular function. Each controller is hardwired to the relevant plant and does not communicate with other controllers. Examples are compensators, optimisers and three-term temperature controllers. Such controllers are small in size and incorporate their own user interface. Typically, this consists of a liquid crystal display plus a keypad or a number of multi-function knobs and buttons. They are capable of sophisticated control functions and require careful setting up by a trained operator. It may be possible to disable the set-up functions, leaving the main

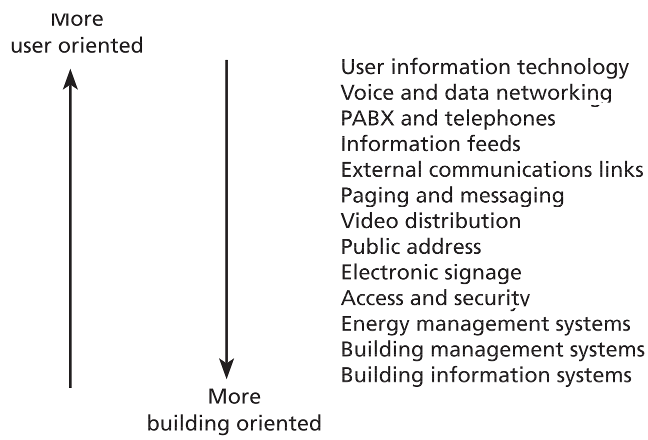

Figure 4.13 The range of information types found in a modern building

set point, e.g. room temperature, available for change by unskilled staff. Alternatively, the setting knob may be mounted remotely from the controller in the occupied space, with the controller itself in a protected space such as the plant room.

The limited size of the display puts great demands on the ergonomic design of the interface. Much use is made of symbols and menus. However, it is rarely possible to make the full range of user adjustments self-explanatory. It is advantageous if abbreviated instructions be kept with the controller behind a drop-down cover or elsewhere. It is essential that the instruction book be kept in a place where it will be found when required at a later date.

4.5.2.2 Operations level: plug-in keypad

A simple keypad may be plugged into a BMS outstation to review point values, receive alarms and provide some parameter adjustment. The keypads have a small LCD display and a limited number of keys. The device may be permanently mounted on an outstation or be used as a portable readout. Alarms may be directed to the keypad, which contains a built-in buzzer. Some types of keypad may be mounted on a motor control panel and be used to view data and make changes to parameters for all the controls mounted within the panel.

4.5.2.3 Systems level: touchscreen and networked PCs

A PC can sit on the network, providing either full or reduced input and output capacity compared with the main supervisor. However, subject to access control, it can have access to the entire network. The user communicates with the display by touching the screen display, which may consist of pictures, graphs, knobs, dials and text. The screen takes up less space than a PC. It has no moving parts and is suitable for wall or panel mounting. A typical use is to provide limited control of local plant operation by a minimally trained user. The display screens can be specially designed for the intended function.

4.5.2.4 Operations level: supervisor

The supervisory computer, also known as the 'head end' supervisor, commonly consists of a PC together with a printer. By the use of appropriate gateways and interfaces, the PC can communicate with control and bus systems employing a variety of communications protocols, and if desired, with other building management systems such as fire, lighting, security etc. The head end supervisor is the prime interface between the system operator and the BMS. Where the BMS operates over a LAN or bus system, it will normally be possible to access the system from anywhere on the network using a PC and appropriate software. The use of a portable supervisor is of great value when performing commissioning or maintenance. Use is, of course, dependent on access control.

4.5.3 Users

The enormous power and flexibility of the PC-based supervisor means that the software must be carefully chosen to allow appropriate operation by different levels of user. This may include access at varying levels of the system either through the 'head end' server router or direct to the controllers in the field from one or many PCs depending on customer requirements. There are three levels of operation:

— *Operation by unskilled personnel*: when the building is unoccupied, or the operator is absent, unskilled personnel such as a caretaker or security guard can monitor critical alarms from the BMS. The supervisor should display or forward only alarms requiring action and also give instructions to allow the action to be carried out.

— *Operation by trained personnel*: in a large system, the supervisor will be operated by a person trained in its use, but who will not necessarily be a building services engineer. The operator's responsibilities include monitoring the plant for satisfactory operation, resetting parameters or time schedules as required. All alarms must be responded to; a well designed supervisor requires confirmation of the action taken before allowing an alarm to be turned off.

— *Operation by the controls engineer*: the supervisor may incorporate software which allows reconfiguring of the control system, and uploading and downloading of software to outstations.

4.5.4 Software

Several software packages for supervisors are available and may be expected to include some or all of the following features:

— *Graphics*: graphic displays of plant operation contain diagrams of the plant with live point values displayed, giving on-screen displays of temperatures, flows etc. plus the operating state of items of plant. Set points may be adjusted directly and plant items switched on and off.

— *Data logging*: point values, analogue and digital, are routinely recorded in the system database. If widespread data logging is available every one to two minutes, this becomes a very powerful tool for tracing intermittent faults with the plant or the system. This technique takes advantage the relative cheapness of data storage devices. Data may be displayed graphically, either as a real-time trend graph of the present situation or a review of historical data.

— *Alarms*: certain points may be assigned alarm levels and alarm priorities. When an alarm event occurs, the supervisor software takes appropriate action, typically:

  — displaying an alarm message on screen

  — sending an alarm message to another network

  — relaying an alarm message via e-mail, pager or fax

  — updating the alarm log, which includes acknowledgement and action taken.

  Alarm management logging of the number of standing alarms (of each grade) should be favoured.

— *Reports*: reports are predefined summaries of historical data, which may be printed automatically or on demand. They may also be transferred to a spreadsheet for off-line analysis.

— *Time scheduling*: time schedules determine the operation of building services on working days, weekends, holidays and maintenance periods. The supervisor software incorporates a calendar function which allows advance time scheduling including a master holiday scheduler linked to all time schedules for systems that are not used on public holidays.

— *Security*: access to the supervisor must be controlled to prevent unauthorised use. Each user is assigned a password which has an access level associated with it. Typical access levels are as follows:

(1) *Alarms only*: allows viewing and printing of alarms.

(2) *View*: allows viewing of all graphics.

(3) *Read/write*: as view, but allows changing set points and time schedules.

(4) *Supervisor*: as read/write, plus changing system parameters and passwords. For additional security, all accesses to the supervisor are logged. In addition, the supervisor may contain additional software relevant to the operation of the BMS, such as monitoring and targeting or maintenance management. A suitable drawing package will allow the production of the system graphics.

4.6 Summary

Conventional controllers are hardwired to the systems they control and do not communicate with each other. They can provide satisfactory and economical control of small buildings. The modern programmable controller contains a microprocessor and performs local control of a piece of plant or subsystem and exchanges information with the rest of the building management system. The programmable controller is the workhorse of most BMSs and can be configured to perform a wide range of control functions. Packaged plant is usually supplied with its own hardwired dedicated controller, which has limited communications with the main BMS.

Communications within a BMS take place at three levels: management level for supervisors, automation level for controllers and field level for sensors and actuators. Local area networks may be organised in a variety of topologies. The most common is free topology. Devices on the same branch communicate freely with each other over a field bus. Routers at the root of the branch filter messages and translate to a different protocol or communications medium as required. A BMS network may therefore include different communications media and protocols.

The most common cable used by a BMS is the unshielded twisted pair, which is cheap and simple to install. Fibre optic cable is used where the BMS shares a network with IT and high data transmission rates are required. Telephone lines or radio links may be used to link physically separated parts of a wide area network.

The use of standard communications protocols allows devices from different manufacturers to communicate with each other, and the major protocols are described, including BACnet and LonTalk. Components and installation practices should meet the requirements of the EMC Directive to prevent problems arising.

The philosophy of systems integration brings building services systems together, so that such systems as HVAC, lifts, lighting, security may share information and be controlled from a common supervisor. This leads to improved efficiency of operation, but integration requires careful planning to ensure clear lines of responsibility.

The complexity of a large system places demands on the user interface design. The supervisor should be arranged so that access is possible at several controlled levels, from simple supervision to fault location and reconfiguration.

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6 Control strategies for buildings

Summary

This chapter deals with control strategies for whole buildings. The strategy for a complete HVAC system must take into account the interaction between subsystems. The system may operate in several different modes and the condition of each subsystem in every possible mode must be specified. Practical and theoretical design techniques are described which may be used to predict control performance under a range of conditions. The major HVAC systems are summarised with advice on avoiding conflict between subsystems and the successful incorporation of user control. The chapter ends with some case studies to illustrate successful applications.

6.1 General

A complete HVAC system consists of an assembly of plant modules, many of which interact with each other. Similarly, the control strategy for a whole building includes the strategies of individual plant modules and must take into account all the possible interactions between subsystems. Failure to consider these interactions may result in:

- system instabilities
- high energy consumption
- compromise of safe operation.

6.2 Operating modes

The descriptions of subsystem control strategies in the previous chapter indicated many of the interactions which should be included in control strategies. In the design of the HVAC and control system for a new building, there are inevitably combinations of subsystems that have not previously been documented and it is essential that the design is theoretically challenged with a range of 'what if ' scenarios. A variety of possible, likely and unlikely situations should be drawn up and predicted responses of the control system followed through, to ensure that there are no unexpected effects. The BSRIA *Library of Control Strategies*(1) uses a number of operating modes in which a HVAC plant could operate at different times. Possible modes include:

- low outside air temperature interlock (for plant protection)
- low return water temperature interlock (for plant protection)
- low zone temperature in the conditioned zone (for building fabric and contents protection)
- plant shut-down
- fan overrun for air systems, pump overrun for water systems
- optimum start heating (OSH), boost heating
- optimum start cooling (OSC)
- night cooling
- fire
- normal operation during the occupied period, subdivided into: heating; cooling; natural or mechanical ventilation (mixed mode); thermal storage operation.

The number of modes will depend on the nature of the hvac system. A mixed mode system involving heating and cooling, plus mechanical and natural ventilation may have several distinct operating modes during occupancy. The operation of all control strategies in these modes should always be specified unambiguously. Documentation of a complete control strategy consists of the following:

- schematic diagram of plant
- description of plant
- control strategy
- specification clauses
- BMS points list
- summary of plant operation
- control flowchart.

For reasons of space it is not possible to present a range of full control strategies in this manual. Control strategies may be obtained from a number of sources. Large consultancies maintain their own libraries of strategies which have been found reliable in practice and which may be modified to meet the needs of new design projects. Some of the major manufacturers publish control strategies, which are often of general application(2,3). The major published source of strategies in the UK is the BSRIA *Library of System Control Strategies*(1). This is a comprehensive document, presenting a large number of control solutions with descriptions of plant operation and control strategy. A standard specification clause is provided with each strategy, together with a full points list. The expectation is that the *Library* will provide a set of standardised solutions that will enable control systems to be designed, configured and tested in less time than would be required designing from scratch. This Guide has drawn heavily on the *Library* for the control strategies summarised in the previous chapter and BSRIA references have been given where applicable.

It is important to choose an HVAC system and control system that are appropriate for the requirements of the building and the operations it supports. There is no advantage in having a sophisticated BMS nor in accumulating information that is not needed and will not be used. Where simple controls, perhaps packaged controllers supplied by plant manufacturers, will perform adequately, they should be used unless there is good reason to install a customised control system. Large modern buildings benefit from a full BMS; the various options for system architecture are dealt with in chapter 4. The power and flexibility of a modern BMS allows virtually any control strategy to be implemented, and later modified. Changes in user requirements, developments in HVAC technology and evolving policies on energy conservation ensure that innovation and change in building design is a continuing process. Few buildings are identical in their needs to others. This has the consequence that the controls designer is faced with buildings that cannot be satisfied by off-the-shelf solutions. The control strategies for subsystems set out in chapter 5 have been chosen to be representative of best current practice, but must always be evaluated for suitability for any given building and environmental control system.

The requirements of energy conservation and the desire to reduce or eliminate the need for air conditioning have led to building designs which are intended to operate at the limit of their capabilities during conditions of design weather conditions; it is no longer acceptable to insure against problems by oversizing the plant. This has led to a wide range of buildings, ranging from fully air conditioned sealed buildings to full natural ventilation. In many cases, however, it has been found necessary to introduce ancillary equipment to deal with particular weather or operational conditions. This gives rise to potential control problems in operating the various systems and avoiding conflicts. Practical examples are given in the case studies.

6.3 Design techniques

Various techniques are available which will assist the designer in assessing the performance of possible HVAC plant designs and associated control strategies. The various techniques differ in their methods and application and are described below. The information that may be expected from their use includes:

— performance of building under different operating conditions, especially hot weather

— information on practical problems of installation and operation

— energy consumption

— evaluation of control strategies

— prediction of control performance.

6.3.1 Full scale mock-up

A full scale mock-up of a representative section of the building is constructed. As far as possible it should use the actual materials and items of plant that will be employed in the actual building. The mock-up is placed in a large environmental chamber that can simulate external conditions, including the effects of solar radiation; several such chambers exist in the UK. The effects of indoor activities are reproduced by placing suitable heat sources in the mock-up room. Suitable instrumentation has to be provided to monitor the internal conditions produced. The mock-up is then subjected to a range of external conditions, representing extreme design conditions and a number of intermediate conditions. The HVAC installation is used to control the indoor conditions, which are recorded and evaluated. The procedure allows the designer to:

— show the visual appearance of the finished internal space

— investigate the performance of the HVAC system

— evaluate the control system and its strategy

— ensure that all components can be installed as planned and so obviate problems on site.

Where the cost of a mock-up can be justified, it has proved beneficial to all parties involved in the building project. The use of mock-ups is usually restricted in practice to room-height sections. Where it is required to predict the performance of tall atrium type structures, recourse must be made to analogue or mathematical modelling.

6.3.2 Analogue modelling

Air movement in convective flow may be modelled in a water tank, using salt solutions of varying concentration to represent air at different temperatures[4,5]. The model is operated upside down; dense salt solution moves down through water in a way analogous to the upward movement of warm air. A scale model of a section of the building is constructed out of Perspex and mounted upside down in the test tank. Coloured salt solution is injected to represented heat sources and its movement under convective flow is recorded. The technique has been used successfully to evaluate the performance of natural ventilation systems and their control by opening and closing vents[6] but has not received widespread application.

6.3.3 Mathematical modelling

Computer-based mathematical modelling may be used to simulate the performance of a building in considerable detail. Several software applications are available and may be purchased or used via a bureau. General advice on the application of models is given in CIBSE AM11[7]. The first step is to input a geometrical model of the building. This includes the building dimensions, thermal properties of the constructional elements, and the orientation and location of the building. The HVAC plant is added; separate modules exist which model the performance of common plant and control systems. Internal heat production and occupancy schedules over the year are set up. The model may then be run to produce predictions of temperatures and energy flows, using detailed weather data for the location and season of interest. Air movement is modelled using the technique of computer fluid dynamics (CFD). This has found considerable application in the investigation of naturally ventilated buildings. The models usually operate in time steps of 1 h and so cannot be used to investigate the finer points of control dynamics. The models are most useful in predicting building performance in extreme weather conditions and establishing whether internal conditions will be found acceptable in hot weather. The ability of the models to allow for the effects of thermal mass on peak temperature is of particular value in this context.

Control strategies may be evaluated using mathematical models. It is sometimes found that control criteria may be relaxed without causing any appreciable discomfort, due to the stabilising effects of the building thermal mass. This can lead to worthwhile savings in energy consumption. Models have also been found of real value in establishing effective night cooling strategies and the operation of mixed mode systems.

6.3.4 Emulation

An emulator for a building energy management system consists of a simulation of a building and its HVAC system which may be connected to a real BMS. The real BMS controls the simulated building as if it were real, transmitting control signals and receiving simulated information back as the simulated building responds to its actions. Since an actual BMS controller is used, with its own time characteristics, it is necessary that the simulated building responds at the same rate as the real building. An emulation run therefore operates in real time, e.g. it will take a week to emulate a week's building operation. An emulator can be used for:

— evaluating the performance of a BMS

— training of BMS operators

— assisting in the development of new control algorithms

— fine tuning the control parameters.

An advantage of using an emulator is that a BMS may be tested with any type of building and HVAC system for which a simulation model is available, and tests can be run on different BMS under identical conditions. Since a real BMS is used, it is not necessary to know the algorithms employed, so that products from different manufacturers may be compared without compromising any proprietary information about the control strategies. The building simulation model is of fundamental importance for the emulation technique. As well as modelling the thermal response of the building, the dynamic behaviour of the controls and actuators must be modelled realistically; this is a more stringent requirement than is found with the mathematical models described in 6.3.3 above. Operation of plant is described in great detail and the emulation exercise may be used to predict reversals and travel of actuators as an indicator of potential maintenance costs. Six emulators were developed for an IEA exercise and are described by Lebrun and Wang[8]. They worked well but have not yet found widespread application.

6.4 Whole-building HVAC systems

Table 6.1 lists some major types of HVAC system used in modern buildings with some of their characteristics. Many variations on the basic systems are possible. Control strategies for the subsystems involved have been dealt with in chapter 5. The designer must consider how the different components of the HVAC system may interact under different operating conditions and ensure that the control system will maintain economic and effective operation under all conditions.

6.4.1 VAV and perimeter heating

This is a widely used combination. Conditioned air is supplied to all parts of the space via the VAV boxes. The proportion of recirculated to outdoor air in the air supply is controlled to ensure that the correct amount of ventilation air is maintained against variations in supply air volume. Temperature control in the zone supplied by a group of terminal units is provided by varying the air flow though each box. Heating may be provided via the terminal unit by fitting the box with a reheat coil, which is supplied with LTHW. The relevant control strategies are set out in chapter 5. It is common to provide heating by conventional LTHW radiators or other room heat emitters. This has advantages:

— There is no water supply in the ceiling.

— The heat is supplied where required to counteract perimeter heat loss, especially under windows.

— There is better heat distribution from radiators than from the ceiling, especially at low air flow rates.

The control strategies for the combined system present no great problems. The perimeter heating LTHW flow should be weather compensated. It may be necessary to fit separate controls on different facades where there are large differences in heat loss or insolation. Thermostatic radiator valves will give extra control if required; they may be fitted in addition to, but not instead of, compensated flow temperature. Given effective control of the perimeter heating, it is not necessary to interlock the VAV cooling and the heating to prevent simultaneous operation. With a deep building, perimeter heating may be necessary to maintain comfort in the perimeter zone while the central zones require cooling. Boost heating during optimum start is provided by setting the perimeter heating flow temperature to maximum, with the VAV system off or on full recirculation.

6.4.2 Fan coil units

Fan coil units are available in a wide range of configurations, including underfloor units, console units designed to go on the wall or under windows, to the common type installed in a ceiling void. Units are connected to a supply of hot and chilled water. The distribution of water round a building is simpler and takes less space than the distribution of conditioned air. This makes the installation of fan coil units more flexible than that of a VAV system. FCUs are to be found in all types of building and control systems range from a local thermostat controlling fan operation to a fully integrated whole building system.

Table 6.1 Major HVAC systems

Feature	VAV and perimeter heating	Fan coil units, four-pipe	Chilled ceiling displacement vent	Natural ventilation	VRF
Component:					
— heating	LTHW radiators	FCU	Perimeter radiators	Radiators	Indoor unit
— cooling	VAV box	FCU	Ceiling or beam	None	Indoor unit
— ventilation	Central AHU, mixed air	Central AHU, full fresh air	Central AHU, full fresh air	Natural	Mechanical ventilation
Spatial impact:					
— plant space	High	Average	Average	High	Good
— riser shafts	High	Average	Average	High	Good
— floor space	High	Average	Low	High	High
— ceiling depth	High	Average	High	High	Average
Performance:					
— temperature	Good	Good	Satisfactory	Poor	Satisfactory
— air distribution	Adequate	Adequate	Good	Adequate	Poor
— noise	Good	Adequate	Excellent	Good	Adequate
Cost:					
— capital	High	Average	High	Average	Low
— operating	Low	Average	Average	Low	Average
— maintenance	Average	High	Average	Low	High
Flexibility:					
— rearrangement of partitions	Good	Good	Good	Poor	Poor

Control of individual FCUs was dealt with in 5.10; here, we consider the implications of integration.

The FCUs themselves recirculate room air, heating or cooling as required to maintain the room air set point. Ventilation air is provided by a central air handling unit which supplies 100% outdoor air at controlled temperature and usually controlled humidity. Incorporating the temperature of the primary supply air in the control strategy allows energy savings to be made by controlling the operation of the heat exchanger to exploit free cooling. Fan coil units have no provision for dehumidification other than moisture condensing on the cooling coil. Fan coil units must therefore always be provided with a condensate tray and a means to remove any condensate. In general, it is best to avoid running an FCU with a wet coil, especially when the unit is mounted above a false ceiling where the results of any failure of the condensate removal will be a problem. The preferred method is to deal with the latent load by dehumidifying the primary outdoor air to control room humidity at the desired level; this will normally be sufficient to prevent condensation on the FCU cooling coil. The usual practice is to duct the primary supply air to each FCU, where it is mixed with the recirculated room air by the unit fan. It is also possible to distribute ventilation air through independent terminals. This may have advantages where it is required to maintain maximum flexibility for possible repositioning of the FCUs at a later date, or where the FCUs are only used during the cooling season.

In an integrated system, each intelligent fan coil unit incorporates its own controller which communicates with the BMS. Room temperature set points and time schedules may be set remotely for each unit or group of units acting together. Once of the disadvantages of fan coil units is the potential degree of maintenance required and the disruption involved in identifying and servicing faulty units which are distributed throughout the occupied space. The BMS is used to give warning of any failures or routine maintenance needed, such as the need for a filter change. A fan coil system incorporates many small water control valves, which are susceptible to sticking or blockage. It is possible to incorporate checking routines in the BMS. Each valve is driven fully open and closed in turn, and the appropriate response of the discharge air temperature is checked.

Figure 6.1 shows an air handling unit for a fan coil system, which supplies 100% outdoor air to all room units. A heat exchanger is incorporated to transfer heat between exhaust and outdoor intake air. The air is supplied at constant flow rate during the occupancy period; the extract fan is interlocked to operate at the same time. The supply air humidity is controlled to maintain the zone humidity at a level which will provide comfort and prevent, or at least minimise, condensation on the fan coils. This is typically controlled using an RH sensor in the extract. Supply air temperature may be controlled to be near the desired zone temperature, or scheduled to the outside air temperature; this will allow full advantage to be taken of any free cooling. A suitable schedule is that the supply air temperature should have a maximum temperature of 22 °C when the outside air is at 12 °C or below, and a minimum temperature of 14 °C when the outside air is above 21 °C, with a linear relation in between these values. The heat recovery is operated according to the strategy in Table 5.5 for maximum efficiency.

Further economies may be made by resetting the flow temperatures of the LTHW and CW to the coils. This strategy requires information to be made available to the BMS on the position of the heating and cooling valves on each FCU. The temperature of the LTHW is reset so that at least one heating valve is fully open while maintaining the required room temperature in all zones. Similarly, the chilled water flow temperature is reset so that at least one cooling valve is fully open. This strategy ensures that the water being circulated to the coils is neither hotter nor cooler than required to maintain the desired conditions. Some care must be exercised when employing this type of strategy, which depends on a large number of logical criteria all being

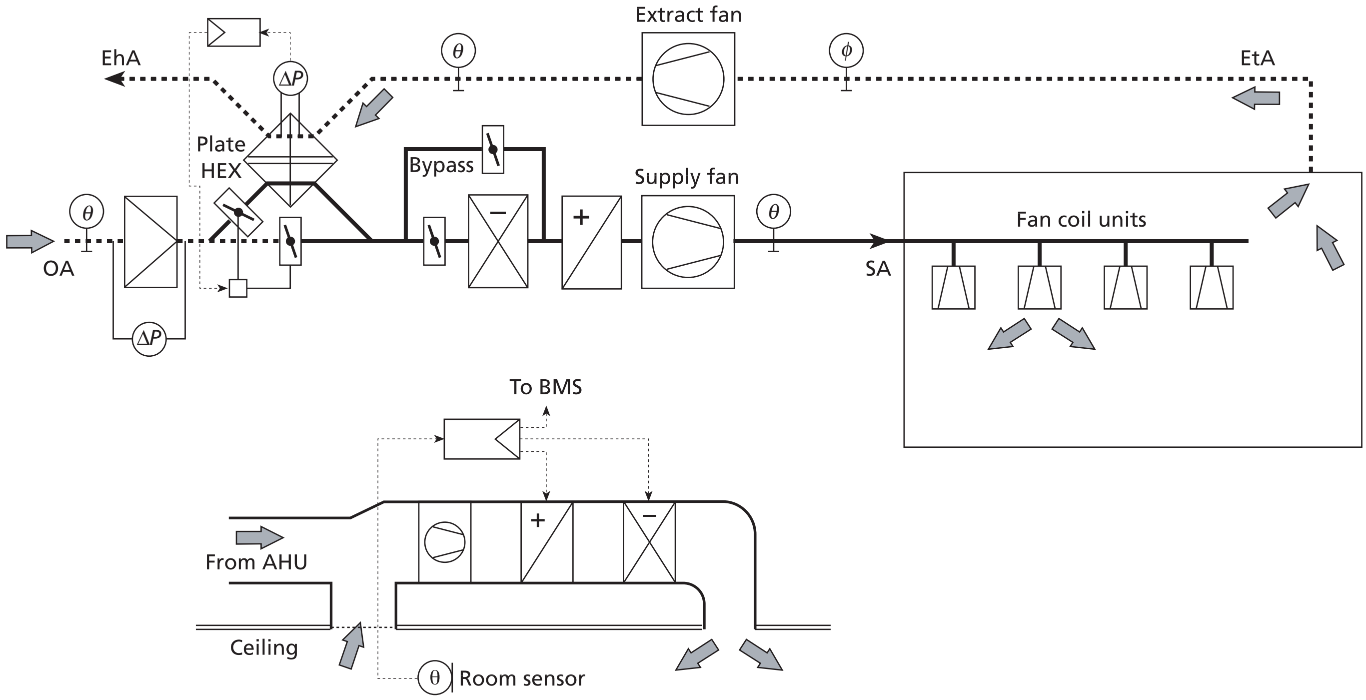

Figure 6.1 Integrated fan coil unit system. The supply air temperature is scheduled to outside temperature. Control connections not shown

satisfied. A single sensor failure or incorrectly adjusted set point will prevent satisfactory operation. A full control strategy for a fan coil unit system is given in BSRIA *Library of System Control Strategies*, 3.16.3[(1)].

6.4.3 VRF systems

Variable refrigerant flow systems provide zone heating and cooling by means of indoor units which are connected via refrigerant lines to the group outdoor unit. Control strategies for VRF systems were set out in 5.13.1. The VRF indoor units do not provide ventilation air and this has to be provided separately. For some applications, such as hotel rooms, it may be adequate to use simple extract ventilation. In general it is better to provide full mechanical ventilation with controlled supply and extract. Manufacturers of VRF systems provide mechanical ventilation with heat recovery (MVHR) systems which may be used in conjunction with the indoor units to provide both temperature control and ventilation. The MVHR unit contains supply and exhaust fans, a cross-flow heat exchanger, filter and a bypass damper which can allow the air to flow straight through and bypass the heat exchanger. The unit is fully ducted and the supply air may be led to conventional diffusers or connected to the indoor units, where it mixes with the recirculated room air being heated or cooled. Each MVHR unit provides sufficient air for several indoor units.

When operating as an independent ventilation system, the unit has its own controller, offering a selection of fan speeds and heat exchange or bypass operating modes. The mode may be selected manually or automatically, based on the outdoor air and extract temperatures. Where the unit is connected to the indoor VRF units, the control may be integrated with the VRF control system, using the manufacturer's proprietary network. The modular nature of VRF systems means that the system may be extended to provide temperature control and ventilation for a large building. Humidity control is not provided in the ventilation units; some dehumidification is provided by the room units when cooling in conditions of high humidity.

6.4.4 Chilled ceiling and displacement ventilation

The range of systems coming under the general description of chilled ceilings can be divided into three groups, with different operating characteristics:

— *Chilled panels*: a chilled ceiling panel presents a flat surface to the room below. The rear surface of the panel is insulated and there is no requirement for air circulation behind the panel. Cooling is over 50% by radiation.

— *Passive chilled beam*: the chilled beam contains a cooling coil designed to cool air flowing down through it. Room air circulates up behind the beam and down through it by natural convection. Higher cooling loads are possible than with chilled panels and cooling is about 80% convection. Some beams are designed to present a cool surface to the room, enhancing the radiant proportion.

— *Ventilated chilled beam*: the beam contains an air duct which supplies the room ventilation air. The supply is 100% outdoor air and is cooled and possibly dehumidified. High velocity nozzles inject air into the beam, which induces additional room air flow thorough the cooling coil. This increases the cooling capacity of the beam over that of a passive beam.

Chilled ceilings and beams provide an effective way of producing comfort cooling in buildings with modest heat loads. Ventilation air is provided independently and this gives the opportunity of introducing mixed mode ventilation, where natural ventilation can be used at appropriate times. Mechanical ventilation with conditioned outdoor air is provided in the heating and cooling seasons; natural ventilation may be used if desired when the outside conditions are suitable. The usual form of mechanical ventilation is a form of displacement ventilation, where the air is introduced at floor level; the use of swirl diffusers ensures that air velocities fall rapidly away from the diffusers and do not cause draughts. In an ideal displacement ventilation system, the air moves steadily up through the occupied zone, taking heat and pollutants with it, to be extracted at high level. By this means, a high ventilation efficiency, potentially greater than one, can be achieved. An air temperature and air quality gradient can be achieved, whereby the occupants are in the clean cool part of the gradient, with air quality worsening at high level. This is in contrast to mixing air distribution, which gives average conditions over the whole space.

In practice, true displacement ventilation is difficult to achieve with a radiant ceiling and impossible with a chilled beam. The chilled beam provides convective cooling, with cooled air falling back into the occupied zone and mixing with the incoming ventilation air. The effect is less marked with a radiant ceiling, which cools largely by radiant exchange with the warmer surfaces in the room[9,10]. Some typical chilled ceiling combinations are shown in Table 6.2, with relevant outline strategies.

Chilled ceilings are normally arranged with a separately controlled perimeter zone. Perimeter heating using conventional LTHW radiators is used to counteract perimeter heat loss and any downdraught from windows and is controlled using weather-compensated flow temperature as described in 6.4.1 for VAV systems. A large space will require perimeter heating at the same time as central zone cooling to maintain comfort near windows. Where the radiators are compensated, it will not always be necessary to interlock the perimeter ceiling and radiator to prevent simultaneous heating and cooling. Where a ventilated beam is used incorporating heating coils, an interlock must be present.

6.4.5 Natural and mixed mode systems

The design of mixed mode and naturally ventilated buildings is closely integrated with that of the building itself. Provision of air flow paths, control of solar gain and the need to provide adequate thermal mass, all influence the building shape and layout. Mixed mode and naturally ventilated buildings tend to be one-off designs, with unique control solutions. Such buildings are likely to include a number of controlled devices, relating to solar control, lighting, heating and mechanical ventilation and perhaps cooling. These controlled devices are operated by a combination of automatic and occupant control. There is a danger, borne out by experience, that subsystems may interact in such a way to give unsatisfactory control and excessive energy consumption. Every attempt must be made to anticipate and design out potential problems.

Full occupant control is only feasible in small cellular offices, where the control choices have limited effect on the rest of the building. The use of a weather-compensated heating circuit will avoid the worst excesses of the ‘window open/heating on’ problem, and simple timeswitches and presence detection will limit excessive use of lighting. Most naturally ventilated buildings incorporate openable windows and other forms of occupant control. Direct control is appreciated by occupants and should lead to greater satisfaction. However, not too much should be expected of occupant control as regards optimum operation of a large building. Operation of a controlled device may have an effect remote from the occupant who, by reasons of proximity, has ‘ownership’ of the controlled device. For instance, the opening of leeward windows is necessary for cross-ventilation in a large building, but will have little effect on comfort nearby. There is therefore little incentive for anyone near the window to open it. While it is desirable to delegate as much control as is practical to occupants, it is not reasonable to expect them to take responsibility for the efficient operation of the whole building. The ability to take an action in response to discomfort, perhaps by opening a window, is valued. The requirement to operate windows for the benefit of staff in a remote part of the zone is unlikely to be carried out efficiently.

Most mixed mode buildings are of complementary design and are designed to operate under a concurrent or changeover strategy[11]. A concurrent system uses permanent mechanical ventilation which runs continuously to provide sufficient outdoor air for ventilation purposes. Occupants are free to open windows to provide additional cooling when needed. The natural and mechanical systems complement each other and simultaneous use is possible

Table 6.2 Chilled ceiling systems

		Chilled panel	Passive beam	Ventilated beam
Cooling	System	Chilled panel	Coil in beam	Coil in beam
	Chilled water	14°C	14°C	14°C
	Control	Water flow on/off	Water flow on/off	Modulate water flow
Heating	System	Radiators	Radiators	Coil in beam
	Control	Compensated flow	Compensated flow	Modulated flow
Ventilation	System	Floor diffusers	Floor diffusers	Duct in beam
	Air supply	18–22 °C	18–22 °C	14–18 °C
	Control	Constant volume	Constant volume	Constant volume
Interlocks	Heat/cool	No	No	Yes
	Windows or presence	If desired	If desired	If desired
Condensation prevention	All systems	Raise chilled water temperature above dewpoint or dehumidify ventilation air; plus condensation detection		

without conflict. A changeover mixed mode strategy aims to operate the building using the most efficient combination of available systems. The BMS selects the appropriate operating mode and enables or inhibits the relevant systems. There may be several modes, depending on season, use of building or time of day. The BMS must change from one operating mode to another in such a way that continuous control is provided and without being obvious to the occupant. Control of particular devices may be passed from manual occupant control to automatic control and this must be done without antagonising the building users. Control decisions made by the BMS must be acceptable to the occupants and appear sensible; if not, the building users may expend considerable ingenuity in outwitting the BMS. Locking windows which shut when external air temperature exceeds internal temperature may not be acceptable to the occupants in the building. Situations where the BMS promptly overrides an action taken by an occupant will be disliked and lead either to the abandonment of any involvement in environmental control or an antagonism to the building and the organisation which it represents(12).

6.5 Case studies

The control solution adopted for any individual building is likely to have its own particular characteristics. Choices are made by the designer to resolve problems or take advantage of opportunities presented by the project. It is therefore impossible for this Guide to list a comprehensive selection of whole-building control strategies that would cover all, or even most, BMSs. The remainder of the chapter presents some case studies of building management systems that have been successfully applied to actual buildings. The studies cover a range of building types and HVAC systems. The description of the control systems, while brief, serve to demonstrate the wide range of BMS applied in practice and serve to bring out some useful lessons.

6.5.1 Retrofit using a modular control system

Building: Greenway School, Horsham

Type: Junior School

Greenway School in Horsham teaches four hundred 7 to 11-year-old children in a group of buildings, comprising a main building and six classroom huts. Heating and hot water to the main building are provided by three gas-fired boilers and independent gas-fired convectors are used to heat the classroom huts. It was decided to keep the existing heating system and upgrade the controls to provide overall control from a single position, but allow individual teachers some flexibility in setting temperatures.

A modular control system was installed, consisting of one master and eight-slave zone controllers, plus a boiler sequence controller and the necessary sensors and actuators. All components are interconnected via a simple two-wire bus, employing the LonWorks protocol. The master zone controller is located in the school secretary’s office and is used to set the time schedule and temperatures for all zones. In addition, the controller provides optimum start and weather compensation. The individual zone controllers in each classroom give a temperature display and allow limited alteration of set point.

The control system provides central control of time scheduling, bringing the entire system under central control and preventing any individual heaters being left on by mistake. No specialist knowledge is required for operation.

The modular controls chosen proved easy to install using the bus system. The straightforward interface allowed operation by non-technical staff.

6.5.2 Remote control of a group of homes for the elderly

Building: 10 elderly people’s homes, Clwyd

Type: Residential homes

Clwyd Council operates a centralised BMS bureau and energy monitoring and targeting service, which has been successful in producing an overall reduction of 25% in energy consumption in buildings serviced. It was decided that a group of elderly people’s homes operated by the social services department offered scope for improved control and monitoring. The ten homes are of modern construction and heated by a conventional boiler serving radiators and hot water services.

The energy conservation unit applies a three-year payback criterion for improvement schemes, which required a low cost solution. Each home was retrofitted with a stand-alone energy management system. This provided time and temperature scheduling, optimum start and weather compensation, including room reset control. Boiler operation includes sequencing control and improvement of efficiency by variable minimum off-time control, which increases the off-time during cycling as the flow and return temperatures get closer together, i.e. at light loads. Control of hot water services is also provided. Water heating periods are matched to kitchen operating times and the boiler flow temperature is adjusted as the duty moves between space and water heating. The controllers contain their own datalogging features and a modem, which allows communication between the controller and the BMS bureau over the public service telephone network. The controller can send routine data files automatically to the central PC and initiate alarms messages if required. If desired, alarms can be sent automatically to a fax machine. Staff at the central bureau may remotely view plant status or take direct control of operation.

The previous heating systems were poorly controlled and installation of the improved controllers produced reductions in gas consumption of between 20 and 30%. In addition to the savings produced by improved controller performance, the information provided by the monitoring and targeting service allowed other energy savings to be identified.

Lesson. The use of stand-alone controllers with built-in communication facilities allowed professional energy management of a number of dispersed buildings to be installed at low cost.

6.5.3 Low energy university building with fabric storage

Building: Elizabeth Fry Building, University of East Anglia

Type: Two floors of cellular offices and two floors of lecture and seminar rooms, plus kitchen and dining room

The building is highly insulated and well sealed. No mechanical cooling is provided. Supply ventilation air is tempered by passing though hollow core floor and ceiling slabs. A highly simplified diagram of the system as applied to the office area is shown in Figure 6.2. Gas-fired boilers provide heat to the AHU when required and a high efficiency regenerative heat exchanger is employed for heat recovery. Full fresh air ventilation is used during occupied hours. All windows are openable without restriction on their use. Ventilation to the lecture theatres is by variable speed fan controlled by the CO_2 concentration of the extract air. This compensates for the variable occupancy and gives substantial savings in fan running costs.

The building is thermally very stable and control of zone temperature is achieved by controlling the core temperature (Table 6.3), measured near the air outlets.

The Elizabeth Fry Building has successfully achieved a combination of very low energy consumption and high occupant satisfaction. The hollow core slab system achieves very steady temperatures and comfortable summer conditions without the use of air conditioning.

There were initial teething problems caused by inadequate controls and the lack of a proper BMS, which did not allow the maintenance staff to understand the operation of the various systems. Subsequently, new controls were fitted and integrated into the campus-wide BMS system. The availability of performance data was vital in allowing the control strategy and settings to be fine tuned and simplified. The commissioning and handover period extended over the first two years of occupancy. Cooperation between the building manager, controls specialist and the design team resulted in a well-configured system with a simple control strategy[10,13].

6.5.4 Mixed mode R&D facility using chilled beams

Building: Hewlett Packard, Building 3, Bristol

Type: Three-storey open plan building housing offices and computing laboratories

This building provides a research and development facility for up to 450 staff and was completed during 1998[14]. The three storeys provide two floors of open plan flexible space for offices and laboratories (Figure 6.3). The ground floor contains a presentation area, meeting rooms and a large coffee shop, which provides a centre of social interaction. A central atrium forms a central street; on the upper floors, glazed balustrades surround the central space, giving a feeling of light and openness.

The nature of the business activity produces a relatively high small power load of about 40 W/m^2. This demands mechanical cooling, which is provided by chilled beams. There is no natural ventilation. The building is well sealed, achieving a low leakage value with the assistance of concrete floor and ceiling slabs, which also provide thermal mass. Supply air is provided as 100% outside air through floor diffusers; extract is via air handling luminaires. The supply air is conditioned in the central AHU and delivered to the zones at a constant temperature of 19 ºC, though this may be reset over the range 19–21 ºC if required in hot or cold weather. Full recirculation is used during warm-up. Supply air can be dehumidified to maintain the dewpoint below 12 ºC, to avoid condensation forming on the chilled beams; in this building no facility for humidification is provided. Perimeter heating to offset losses at the windows is provided by LTHW radiators. Additional radiators are fitted at high level in the atrium to prevent cold downdraughts in winter from the atrium roof. There is no external solar shading. Internal venetian blinds are fitted and a central blind controller sets the position and angle of the blinds. In strong

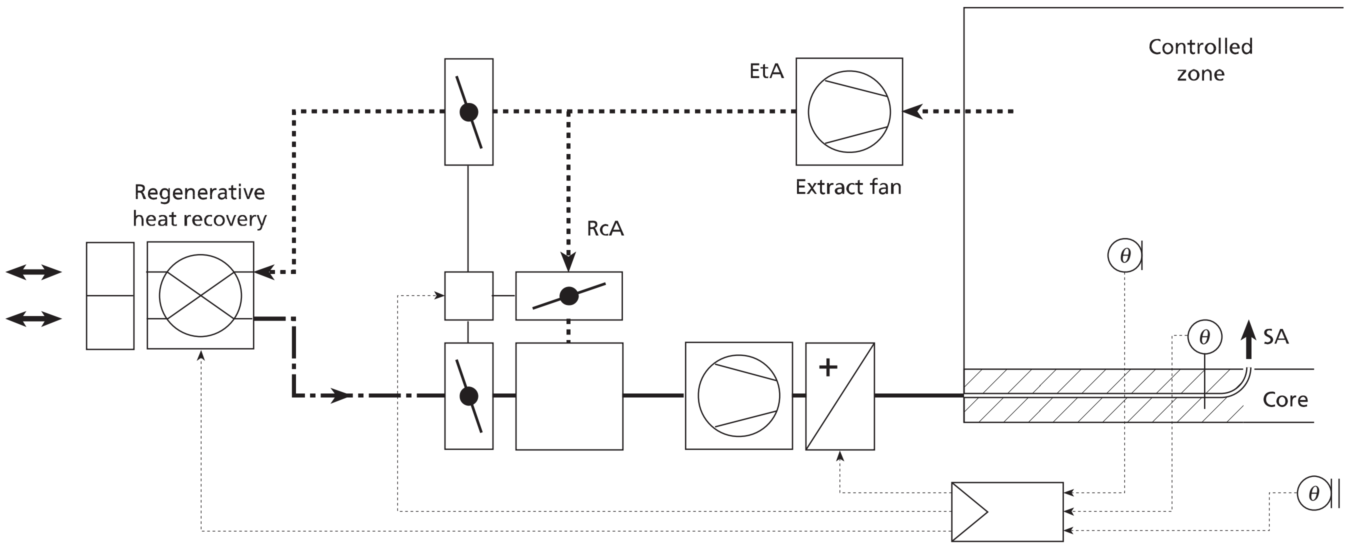

Figure 6.2 Hollow core slab system used in Elizabeth Fry Building. Full fresh air ventilation is used at all times during occupancy. Heat recovery may be deactivated

Table 6.3 Operating regimes for the Hewlett Packard Building 3

Mode	Core temperature	Outside temperature	Heat recovery	Heating coil	Recirculation
Stage 2 heating	T_c < 21.5 °C for 15 min		Yes	Yes	No
Stage 1 heating	T_c < 21.5 °C		Yes	No	No
Ventilation only	21.5 °C < T_c < 22.5 °C		No	No	No
Stage 1 cooling	T_c > 22.5 °C	$T_o < T_z$	No	No	No
Stage 2 cooling	T_c > 22.5 °C	$T_o > T_z$	Yes	No	No
Night cooling	T_c < 23 °C	$T_o < (T_c - 2)$	No	No	No
Night heating			N/A	Yes	Yes

T_c = Core temperature; T_o = Outside temperature; T_z = Zone temperature.

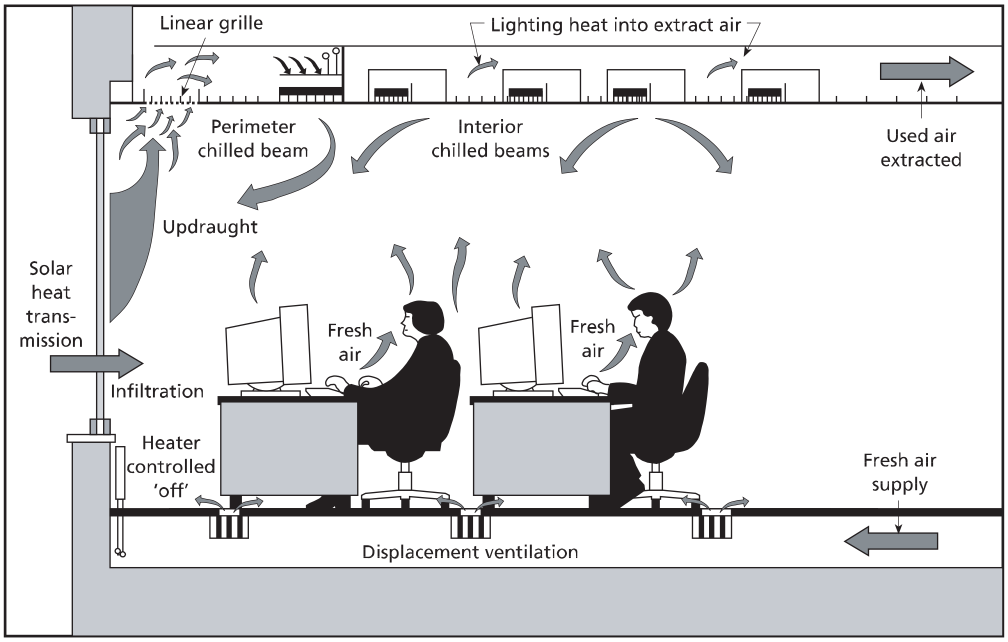

Figure 6.3 Cross-section of Hewlett Packard Building 3, showing chilled ceiling and displacement ventilation[14]

sunshine, the blinds heat up and produce a convective updraught of warm air. To prevent this causing problems for the chilled beams, the perimeter is decoupled from the internal zone by drawing the air through a grille circling the perimeter. The air passes over a large cooling coil and returns to the occupied space. In hot weather, it is possible for hot air to accumulate under the atrium roof and work its way down into the second-floor offices. To prevent this, chilled water can be passed through the high level radiators.

The building has an advanced IT network. This is designed to be innovative and is subject to change. It was therefore decided to maintain the control network entirely independent of the IT system. The innovative nature of the system decided the consultants to construct a full scale mock-up of the perimeter zone to evaluate the control system under a range of operating conditions. These tests demonstrated a potential instability, where the perimeter radiators and chilled beams oscillated between heating and cooling. This was resolved by altering the control set points. Air movement in the atrium was investigated using CFD modelling, which demonstrated the need to use high level radiators, both to prevent downdraughts in winter and to limit overheating in summer. The thorough investigation of control behaviour at the design stage proved invaluable in resolving potential problems.

6.5.5 Terminal 2, Manchester Airport

Building: Terminal 2, Manchester Airport

Type: Large airport terminal

Manchester Airport's second terminal was completed in 1994. It was decided to use an integrated BMS which would provide a facilities management system which, in addition to controlling the extensive HVAC system, would interface with many other systems and provide the following control and monitoring:

(*a*) Control:

- HVAC: VAV systems in terminal, shops and offices
- lighting
- airport services: telephone system, baggage handling, escalators
- runway drainage
- access control: to plant rooms.

(*b*) Monitor:

- energy: electricity, water, gas and provide billing

— life safety: fire fighting, smoke detection
— apron services: ground power, battery charging.

The system is designed to provide full multi-user functionality and operate using the airport's existing fibre optic structured wiring system. It utilises a two-tier network topology. The top tier sits on the Manchester Airport fibre optic network; master controllers are located in plant rooms and workstations in various control rooms are connected directly to the network. The lower tier is then run locally to pick up controllers located in motor control centres, substations or VAV boxes, using coaxial cable or UTP as appropriate.

As far as possible, control systems were designed as generic copies of existing systems, allowing the use of existing reliable software. Commissioning was facilitated by positioning the site team's temporary buildings so that connections could be made to the structured wiring system at an early stage. This provision of a temporary location for the supervisor allowed programs to be downloaded into the controllers as soon as the network was complete. The system has proved capable of expansion. It now comprises over 8000 points and 1000 graphics panels. It can cope with multi-users. Touchscreen display panels are installed in shop and office areas, allowing adjustment of a restricted range of set points and variables.

6.6 Summary

Efficient operation of a building requires that the sub-systems do not interact wastefully. All possible operating modes of the building should be listed systematically together with the operating states of the component subsystems. This will assist in identifying unsatisfactory situations, e.g. where heating and cooling may be operating simultaneously. The involvement of the building occupant in the operation of control devices can bring benefits in increased comfort and satisfaction with the environment. However, concurrent operation of automatic control systems and occupant action may produce dissatisfaction if the user is overridden by the automatic system. Careful attention is required to produce a combination of user and automatic control that is neither wasteful nor over-complex and self-defeating.

Several techniques are available to predict building performance, either analogue modelling, full scale mockup, or various mathematical modelling techniques. Modelling can anticipate potential control problems and allow them to be corrected at the design stage. The chapter summarises the more common combinations of heating, cooling and ventilation and discusses the requirements for them to work together satisfactorily.

Design lessons are illustrated by a range of case studies, which range from simple heating-only classrooms to large complex integrated buildings. The choice of the appropriate system and strategy for the task in hand is emphasised.

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7 Uses of BMS-derived data

Summary

The building management system provides an important source of information, which may be exported to other applications. Building performance and energy consumption are analysed by energy monitoring and targeting software, to assist in effective energy management. Information from the BMS is employed as part of facilities management, including the administration of planned maintenance.

7.1 Energy monitoring

A major justification for the installation of a BMS is the prevention of energy waste. Correct and efficient control of HVAC plant will itself contribute to efficient use of energy but in addition it is necessary that the energy manager receive accurate and up-to-date information on energy use in the buildings for which he is responsible. The approach generally adopted in the UK is termed energy monitoring and targeting (M&T) and is promoted by the Department of Communities and Local Government (DCLG). It is a requirement of the Building Regulations[1,2] that metering of at least 90% of the estimated annual energy consumption of each fuel is to be assigned to the various end-use categories. Detailed guidance on how this can be achieved is given in CIBSE TM39[3]. The term monitoring and targeting does not in itself imply the use of a BMS or indeed any hardware for data collection and analysis. M&T requires that data on energy consumption be regularly collected, summarised and compared with target consumption figures. Computerised collection and analysis of data makes M&T a powerful tool for the control and reduction of energy consumption.

Where M&T data are collected through the BMS other information can be collected. For example, the energy manager needs to know the quantity and the maximum rate of energy use. The maintenance manager also needs this information, along with power factor, voltage, spare capacity and harmonic distortion to enable the electrical installation to be managed. Suitable limits can be set during commissioning (e.g. current at 80% of rating, total harmonic distortion at 10% etc.) and exception reports generated. Metering units are now inexpensive and readily networkable for either TCP/IP or open protocols.

7.1.1 Monitoring and targeting

Monitoring and targeting (M&T) has two major functions:

— the control of current energy use, by monitoring consumption and comparing it against historical data and benchmarks for similar buildings

— improvements in the efficiency of energy use by the setting of future targets.

In large buildings or complexes, effective energy management requires that areas of accountability be established, termed energy account centres (EAC). Accountability implies both responsibility for the energy consumed and the authority to control the consumption. The energy consumption of an EAC should be:

— measurable

— manageable

— reconcilable against a measured activity.

An EAC could be a department, an energy intensive production process, a sublet part of a building or an individual building on a site. A standard energy performance is initially established for each EAC, which relates energy consumption to appropriate variables, such as degree-days or production output. The standard performance provides a benchmark against which energy consumption may be compared, prior to the setting of targets for future improvements. The targets must be realistic and achievable and agreed with the managers responsible for each EAC. The Carbon Trust (www.carbontrust.co.uk) has available a number of Energy Consumption Guides, e.g. ECG19: *Energy use in offices*[4]. Energy consumption benchmarks for a wide range of building types may be found in CIBSE Guide F: *Energy efficiency in buildings*[5].

The monitoring part of the M&T process involves four stages:

(1) *Data collection*: energy consumption data are collected. A comprehensive system will include electricity, gas and water meters located in each EAC, capable of sending data to a central collection point. The availability of other relevant data must be taken into account, e.g. degree-day data or production figures.

(2) *Data analysis*: the data received by the computer are checked for errors and then stored in a form suitable for further analysis. Data analysis is carried out according to the needs of the system; this is likely to include weekly and monthly totals. Any results which indicate a problem or malfunction should generate an immediate warning.

(3) *Reporting*: management reports produced by the system which show the energy consumption of each EAC compared with targets.

(4) *Action*. It is essential that a management structure exists to make effective use of the reports generated by the M&T system.

For an M&T system to be effective, all four stages must be implemented. The collection of data, however accurate, which is not looked at and which prompts no action serves no purpose. Effective M&T requires full management support. As a rule-of-thumb, M&T may be expected to reduce energy bill by about 5%; larger savings are possible where equipment malfunction or gross control failures are identified as the result of metering information. This figure allows an appropriate level of M&T to be chosen in relation to the total energy bill. Energy management systems share many of the characteristics of a BMS. In a building the system installed for energy monitoring and targeting may share hardware with the BMS and may be operated from the same terminal by the same staff. However, the they are not the same. The BMS provides real-time control of the building services, while the M&T system is concerned with data collection and historical analysis.

7.1.2 Planning an M&T system

Energy M&T may be instituted at a simple level, using invoices or manual meter readings and simple manual or spreadsheet analysis. The major factors to be taken into account at an early stage are summarised below. The most important is the total energy bill to be monitored, since it is the potential savings on this bill that fund the M&T system. M&T systems may be classified according to their level of coverage and sophistication.

7.1.2.1 Level of coverage

— *Single site, utility based*: the site is treated as a single EAC and monitored using only utility meters and invoices. Here, a site implies a building or group of buildings served by a single utility meter. It may be possible to aggregate physically separate buildings into a single site for supply and metering purposes.

— *Single site with submeters*: energy is monitored for each of the EACs within a single site by means of submetering.

— *Multi-site, utility based*: a number of sites are monitored using the main utility meters. Each site is treated as a single EAC.

— *Multi-site with submeters*: several sites, each of which is subdivided into EACs and submetered. 7.1.2.2 Level of sophistication

— *Manual system*: meters are read manually and the readings tabulated on paper.

— *Keyboard input system*: meters are read individually, and readings recorded by hand or by a data capture unit. Readings are then entered into a computer for analysis.

— *Automatic input system*: the meters are connected via data loggers or other system to the computer and energy consumption is collected and monitored automatically.

— *Advanced system*: implies more sophisticated data handling, combining energy data with data from other systems or sites. May include automatic control or provide warning messages. Sophisticated bureau services are available using neural network analysis of consumption data to detect energy waste, coupled with an expert system to identify causes.

7.1.2.3 Choice of system

It is important not to choose an oversophisticated system. Not only will such a system cost more to install, but it will demand staff time to maintain it in an operational state and to take action on the results. If the requisite support is not available the system will not fulfil any purpose. The following points should be considered at an early stage in the planning:

— *Cost effectiveness*: any proposed system will be required to meet the organisation's criteria for return on investment. The cost of a system is sensitive to the number of meters installed. Not only does this affect the installed cost, but the analysis, reporting and storage of the increased amount of data will add to the running costs. The rule-of-thumb that M&T should save 5% of energy costs may be used to provide indication of a viable level of investment.

— *Number of meters*: each EAC requires its own meters. Electricity meters will always be required, together with gas meters where appropriate. Water meters are recommended, particularly if there are any water intensive processes. Further submetering may be desirable for particular processes or equipment. The consumption of some areas may be calculated using the concept of a virtual meter, i.e. the difference between a main and submeter.

— *Monitoring period*: this is the period between meter readings. For a fully automated system this should be half-hourly. The use of time-of-day electricity pricing is spreading from large customers to smaller or even domestic customers and half-hourly information will be necessary when considering the optimum policy for electricity tariffs. The additional information given by half-hourly metering is useful for diagnostic purposes, helping to identify reasons for anomalous consumption.

— *Reporting*: the M&T system should produce regular standardised reports, showing performance against target. Weekly and monthly periods are commonplace. There is no point in producing reports more frequently than they will be read. It is important that the information is usable by the intended audience of the report. Ideally management reports should highlight any avoidable waste and define responsibility for improvement.

— *Management organisation*: Figure 7.1[5] shows how M&T operates within the management structure. Each EAC requires a manager responsible for energy performance within the centre, and who will receive routine reports. It is essential that sufficient staff are trained in the operation of the system and a minimum of two staff should be able to operate it. If this is not practicable, the use of a bureau service should be considered. Metered data are read remotely via modem or the internet and the bureau produces the required analysis, reporting and billing as required.

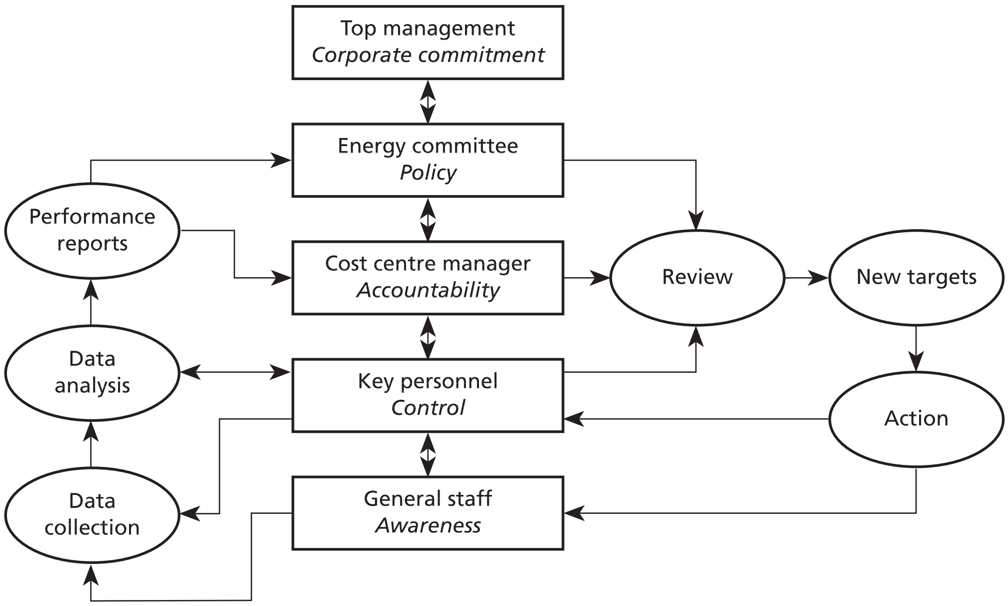

Figure 7.1 Monitoring and targeting management structure

7.1.2.4 Electricity tariffs

The choice of electricity tariff has its own relevance to the design of a M&T system. Since 1994, customers have been free to negotiate a tariff with any electrical supplier. The type of tariff negotiated will have a bearing on the design of submetering and the energy management system. The major factors to be considered are:

— aggregation of sites

— choice of tariff.

It may be advantageous to group separate buildings or sites together so that they are supplied as a single unit through one main meter. The Office of Gas and Electricity Markets (OFGEM) has set out requirements for the main meter. It must comply with the Pooling Settlement Agreement document known as Code of Practice 5 and it must be maintained by an approved meter operator. The meter must record all units used each half hour and transmit the stored readings once per day to the UK Data Collection Service, which then passes the information on to the interested parties. The readings will normally be made available to the building operator.

The customer may install further meters downstream of the main meter; this is known as secondary metering or submetering. Secondary metering is installed for:

— tenant billing

— cost centre accounting

— energy management.

Secondary metering is not constrained by the same level of regulation as primary metering, though any meter used for tenant billing has to be OFFER approved. With the growth in the number of competing electricity suppliers, there are several types of tariff available. The major classifications are:

— *Two-rate*: separate rates are charged for day and night.

— *Six-rate STOD*: the unit rate varies by season and time of day.

— *Disaggregated*: this identifies the components of electricity use which contribute to the total charge, e.g. energy used, maximum demand, power factor.

— *Pool pricing*: the unit charge is based on the half-hourly spot price of electricity.

— *Tariffs requiring the measurement of reactive power*: these are mostly found in industry.

It is outside the scope of this guide to deal with the choice of tariffs. The price of electricity in the pool can vary substantially from half hour to half hour and pool pricing is only suitable for large users where the necessary active management of load can be supported. A disaggregated tariff will be suitable for sites where demand can be managed to reduce costs; this is likely to be true where there are energy intensive processes that can be controlled to contain the maximum demand. The tariff chosen will affect the level of submetering and type of energy management. Half-hourly metering is almost always worthwhile as detailed demand patterns can assist in the identification of problems or identification of excessive electricity consumption. Management of a disaggregated tariff requires information on maximum demand available in real time with some form of warning to enable action to be taken.

7.1.3 Metering equipment

Energy metering hardware in an energy management system consists of some or all of the following components:

— *meter module*: which measures the desired quantity and converts the value to an electrical output, typically pulses; specialist pulse metering cards in outstations are becoming less common as these are being replaced by low cost metering with Modbus or LonWorks bus outputs and are able to measure most properties of electrical circuits.

— *display module*: which displays the present value of the rate of energy consumption, plus other derived quantities

— *data logger*: which accepts pulses from the meter, processes and stores data on energy consumption and transmits data on demand to the central computer containing the M&T software

— *data transmission system*: connecting one or more data loggers to the central computer

— *computer*: containing the analysis software.

Building control systems display the present value of the power consumption. They often have the ability to log and transmit data automatically to the central computer containing the M&T software.

Meter module

A meter module (Figure 7.2) requires simultaneous inputs of current and voltage. In a whole current meter, the entire current is wired to pass though the meter. They are suitable for single-phase applications, up to a current of about 80 A. Otherwise, a current transformer (CT) is used which is fitted around each phase conductor. Standard ring type CTs require the cable to be isolated and disconnected for installation, while split core CTs can be installed without disturbance. Clamp-on CTs are used for temporary connections with portable equipment. The secondary current output of the CT is measured by a low impedance meter; the resistance of the connection between CT and meter must be kept low or an appreciable error may be introduced. Simultaneous measurement of voltage and current is required to give an accurate measurement of power consumption, and is essential for the calculation of kW, kV·A, kV·Ar and power factor. The harmonic content and reactive component of many modern electrical loads can give rise to substantial measurement errors if current only metering is used. However, on sites where the power factor is high and the voltage stable it may be sufficient to employ only a current connection to the meter. Where the aim of energy management is the partition of energy consumption between EACs and the detection of excess consumption, this will normally be sufficient.

Meters often provide a pulsed output in the form of voltage-free contact closures. This is true for gas, water and other meters as well as electricity meters. Where a pulse is used this is typically of about 100 ms duration and is provided each time the meter records an equal increment of energy consumption. The scaling is chosen to give a pulse frequency of around 1 Hz at maximum power. If the pulse duration is too short or the frequency too high for the meter card to detect, the readings from the meter become very inaccurate. It is possible to fit optical meter readers to existing utility meters without any disturbance to their connections. The reader employs a photoelectric device to detect the rotation of the meter disc or dial needle and provides an output pulse which may be handled in the same way as a conventional pulse output.

For most purposes it is sufficient to measure kW·h alone. For larger circuits, or where the consequence of a loss of supply is high, more detail is required. This can be obtained from manufacturers of meters with field bus outputs such as Modbus and LonWorks. These can be specified to measure the following:

- current,
- voltage
- active power
- reactive power
- apparent power
- power factor
- line frequency
- total harmonic distortion
- maximum demand.

If necessary, a portable power analyser may be used to give detailed measurements of power quality. The measurement and display on instantaneous power (kW) can be useful for diagnostic purposes, such as identifying loads in the building and tracking down any 'hidden loads'.

Display module

The meter may incorporate a display or be connected to a local display module. At its simplest, this shows a real-time display of the rate of energy consumption, e.g. kW. More complex displays can select kV·A, kV·Ar and have sufficient memory to show maximum demand and cumulative energy consumption.

Data logger

Meters with field bus network connections are often provided with in-built logging abilities that can be downloaded either automatically or manually via the bus connection.

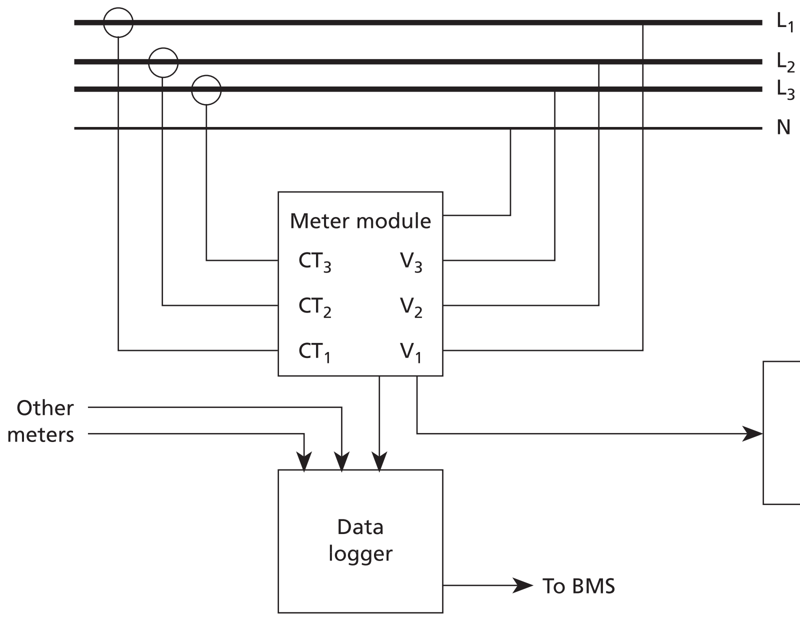

Figure 7.2 Components of an automatic electricity meter

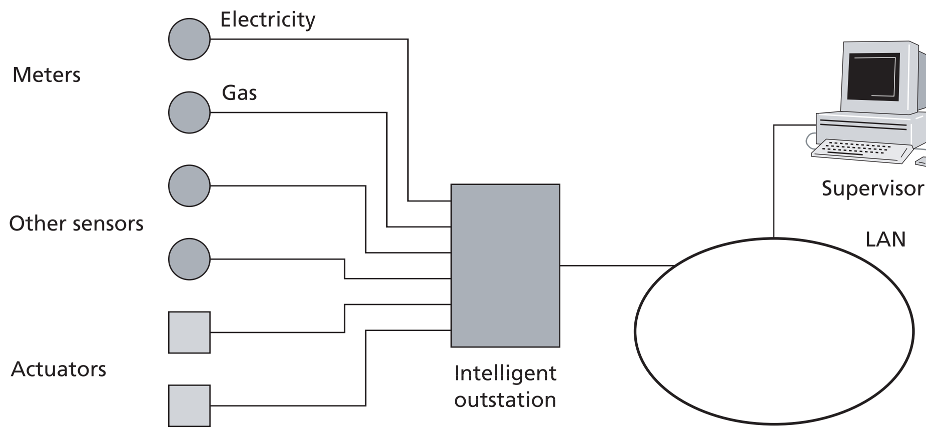

Figure 7.3 Incorporation of metering into a BMS

The output pulses from (non-networked) meters are summed in a data logger module. This will typically have several input channels for different meters. The data logger may be part of a separate energy management system. Alternatively, where the energy management system is an integral part of the main BMS where pulse metering is employed, intelligent BMS outstations are able to accept pulsed inputs for energy measurement purposes (Figure 7.3). The pulses are counted, scaled and stored to give values of energy consumption per half hour for each channel. There must be a real-time connection between the meter and the data logger. Hardwiring is the most common, being simple and reliable. Where the meters are dispersed over a large site, it is possible to use a radio link between the meters and logger. Where the energy management system is separate from the BMS, it may be advisable for the EMS data logger to accept temperature inputs. This makes possible analysis of energy consumption as a function of temperature without any additional data from sources outside the system. Meters are available with built-in communications systems such as RS 485, typically using the LonWorks or Modbus communications protocol. This is preferred to pulsed output where it is required to measure variables other than simple kW·h.

Metering from other sources

The manufacturers of variable speed drives for fans, pumps or other large plant provide field bus connections to Modbus or LonWorks protocols. In addition to electrical information these devices also provide performance and alarm information. In some cases this information allows diagnosis of faults.

Computer

The central computer receives and processes the metered data. The computer may be a separate machine dedicated to M&T or the software may reside in the main BMS supervisor. Where a bureau service is used, the computer is situated off site and communicates via modem or internet. The software can carry out some or all of the following functions:

— retrieval, checking and collation of metered data
— acceptance of data from other sources
— instant access on demand to data from individual meters
— review of data in flexible format, allowing comparison between different time periods and meter locations
— display of additional electrical data such as power factor, frequency, reactive power
— comprehensive input of tariff definitions
— automatic production of sub-billing
— automatic production of routine reports
— immediate warning of exceptions, such as parameters exceeding preset limits
— historical analysis of energy consumptions, e.g. regression or CUSUM.

7.1.4 Data analysis and reporting

For a simple system it may be sufficient to use a spreadsheet for data analysis. However, once there are several meters with half-hourly energy readings, it will almost certainly be better to employ a commercial software package for analysis.

In the UK, maximum demand (MD) is calculated over half-hourly periods and forms the basis for the charged MD for electricity tariffs with a MD charging element. For designers and facilities managers who require a broad indication of transformer or generator loadings, peak maximum demands should be recorded.

7.1.4.1 Data input

The analysis software can only operate properly given a complete set of accurate data. During commissioning of the system, it is important to check that each meter channel is correctly identified and that all scaling factors have been correctly set. During routine operation, the software can be set to carry out routine checks on the incoming data:

— Are the data within preset limits?
— Are any data missing?
— Is the new reading higher than the previous reading?

Invalid readings should be flagged for the operator's attention. If the analysis proceeds with dubious input data, the subsequent reports should be so annotated. Subsequent energy analysis may involve data from other sources, such as degree-days or production figures. This data has to be provided reliably and in a form which is compatible with the metered data, e.g. the periods over which production output and energy consumption are measured must coincide. At some stage the measured energy consumptions should be compared with the fuel invoices. Where an M&T system is installed in an existing building, it is desirable to input historical consumption data to provide a basis for comparison. It may be difficult to provide data in a suitable format to match the new EAC organisation.

7.1.4.2 Routine analysis

The analysis package will be programmed to produce routine analysis every reporting period. The type of analysis will be tailored to individual needs:

- attribution of energy costs to each EAC, including tenant billing
- comparison of energy consumption with target figures.

In addition, further analysis can be undertaken which will be used in reviewing performance and setting future targets. Energy consumption often shows a simple linear relationship with an independent variable such as degree-days or production. A linear regression analysis establishes the slope of the line and intercept on the consumption axis. This can be used to estimate base consumption such as hot water loads, which do not vary with external temperature (see Figure 7.4). Once a historical regression has been established, any new point which falls off the regression line demands attention. A degree-day regression is subject to a scatter of around 10%; the analysis may be improved by refining the choice of base temperature used in compiling the degree-day figures.

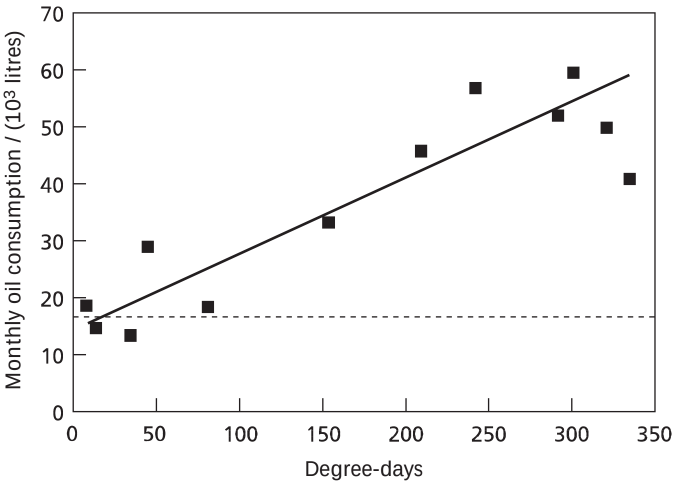

Figure 7.4 Linear regression of energy consumption against monthly degree days, showing the summer base load[4]

CUSUM

The CUSUM technique[6] compares actual performance with target performance for each measurement period and displays cumulative savings. It is necessary to be able to calculate a target consumption for each analysis period; this may be a function of other variables, such as outside temperature. By calculating the cumulative sum of the differences from the target, a trend line can be plotted that gives a clear indication of performance and changes in performance. The value of the CUSUM gives total saving to date and the slope gives the performance trend. A change in performance of the building system will be shown by a change in slope (see Figure 7.5)[7].

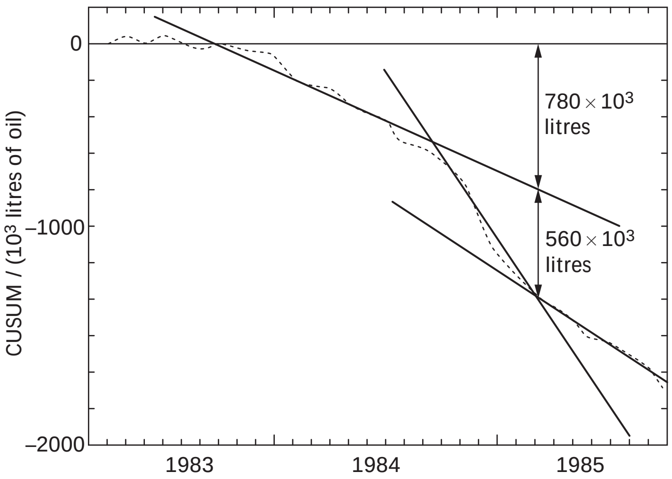

Figure 7.5 Example of a CUSUM plot showing cumulative energy savings

7.2 Fault reports and maintenance scheduling

The BMS can be used to provide information on the total run time and condition of HVAC components, which can be integrated into maintenance operations. Maintenance operation software can also export alarms received from the control system. This enables job cards to be generated, with the message from the control system outlining the alarm condition and, possibly, the fault that generated the alarm. This ensures that the alarm is acted upon without having to rely on human interaction to generate the work instruction.

Ideally, a maintenance policy should be decided for each component of the HVAC system, taking into account risk, technical and cost issues. Five maintenance categories may be classified:

- run to fail
- install redundant units
- preventive maintenance program
- condition-based maintenance
- redesign to reduce maintenance.

The appropriate maintenance policy for each component can be chosen on the basis of the decision tree shown in Figure 7.6.

Preventive maintenance tasks are carried out either at regular calendar intervals or at intervals based on equipment run time. Preventive maintenance ranges from simple lubrication to complete tear down and rebuild of equipment. Selection of the maintenance period is of great economic significance and is usually based on manufacturers' recommendations. Planned maintenance software is available which is used to:

- catalogue maintenance tasks for various plant items
- generate and manage work orders
- manage inventory for spare parts
- store maintenance history
- generate management reports.

The BMS is used to provide information on equipment run time, which is fed directly to the planned maintenance program.

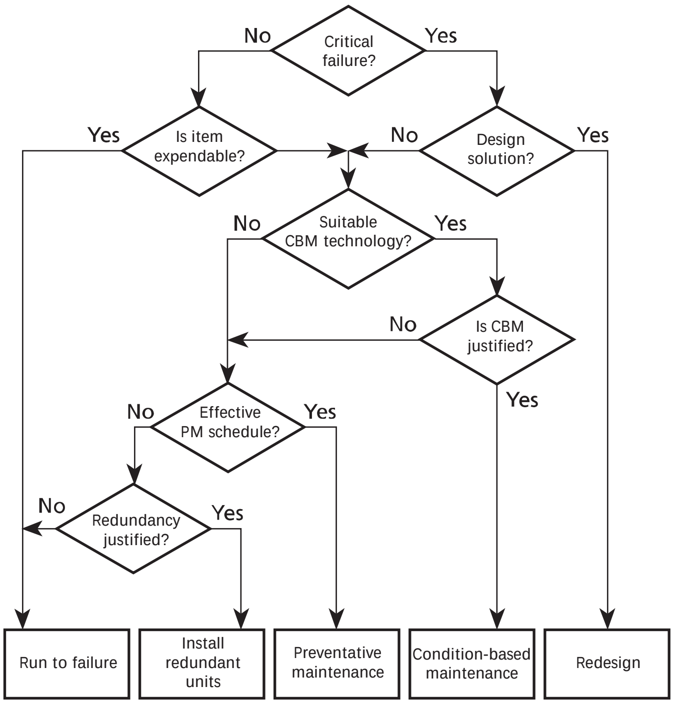

Figure 7.6 Selection of maintenance strategy

Condition-based maintenance

In some situations it is possible to monitor the condition of an item of plant. This provides valuable information on system performance and reliability and can detect early signs of trouble in an item of plant(8), allowing maintenance to be carried out before the plant progresses to failure or when it begins to operate with reduced efficiency. This technique will normally provide greater intervals between maintenance than preventive maintenance carried out at fixed intervals. The economic justification is based on the relation between the increased cost of condition-based maintenance (CBM) balanced against the saving from increased maintenance periods. CBM encompasses a set of techniques used to monitor plant condition. Some may be carried out automatically via the BMS; others require a physical inspection or measurement. Examples of direct monitoring include the following:

— *Pressure drop across filters*: this indicates when they need to be changed. The analysis algorithm will depend on whether the system is constant or variable flow.

— *Efficiency of heat exchangers*: this may be monitored by measuring temperatures and flows, and so detect degradation of performance caused by fouling.

— *Operating variables*: a selection of plant variables, such as temperature and pressure, is logged. A long term change in operating conditions may indicate degradation in the equipment.

Other monitoring techniques are not yet suitable for integration into the BMS, though this may become possible in special situations:

— *Vibration analysis*: used to detect wear in rotating machinery.

— *Infrared thermography*: can detect high resistance connections in electrical equipment, high friction in rotating machinery and failing thermal insulation.

— *Analysis of lubricants*: used to detect wear of gears and other mechanical parts.

— *Motor current analysis*: used in large electrical motors (> 20 kW).

7.3 Summary

The building management system can be used to support energy management and targeting (EM&T) by measuring components of energy consumption and exporting the data to a EM&T applications package. The use of EM&T can save 5% of energy costs; this yardstick may be used to support decisions on the level of investment in metering. Secondary meters may be used for tenant billing as well as energy management. Monitoring via the BMS may be used to support maintenance management. Information on plant run times and condition monitoring is fed into a planned maintenance program which produces maintenance schedules.

References

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8 Management issues

Summary

Effective planning is essential to ensure that the final building is properly controlled. This section describes different variations of the building procurement process, setting out the responsibilities of the parties involved, with emphasis on the part played by the controls specialist. The importance of good planning is emphasised in ensuring that the control system is properly specified, installed and commissioned. Operation and maintenance of the control system subsequent to handover is also dealt with. The financial benefits of the investment in a BMS may be analysed using the life cycle costing methods described in the section.

8.1 Procurement options

The form of procurement chosen by the client can have an important influence on the way in which the controls are designed and installed. Irrespective of the procurement method, we may define the main parties involved in the building process as follows:

— *Client*: the customer for whom the building is procured and who pays the cost.

— *Contractors*: companies that construct the building. There may be firms that manufacture and install specialist subsystems and work as subcontractors to the main contractors.

— *Consultants*: firms that offer design and cost control services and are independent of any commercial interest in construction companies.

The procurement of a large building is a complex process and over the years different forms of organisation and management have developed. *Thinking About Building*(1) identifies four main procurement options. Many variations of these basic structures are possible, and are discussed at length in Turner(2). The major systems may be classified as follows:

(*a*) Design combined with construction:

— design and build

— design and manage.

(*b*) Design separate from construction:

— traditional

— management methods.

The structure of the options is shown in Figure 8.1 in simplified form. The following describes their main characteristics that are relevant to control systems.

8.1.1 Design and build

With design and build, the client places a contract with a single contractor who has responsibility for both design and construction. The client may appoint an adviser to act as employer's agent, to advise on the preparation of the client's brief, evaluation of tenders and to provide independent advice throughout the project. Design and build has advantages:

— The client has single point responsibility from one organisation.

— Because the contractor has responsibility for both design and construction, economies should be possible.

A well-written client's brief is essential to the achievement of a satisfactory controls solution in the final building; an inadequately detailed initial brief may lead to the contractor providing an absolute minimum specification. A variation is known as develop and construct, where the client uses a design consultant to produce a scope design, before obtaining tenders from contractors who develop and complete the design and then construct the building.

8.1.2 Design and manage

A single firm is appointed to design, manage and deliver a project. This is similar to design and build, except that the design and management contractor does not carry out the construction, but places this with a construction contractor. The common variations of design and manage are:

— *Contractor*: a project design and management organisation designs and manages the work, generally for a fee, and delivers the project by employing works contractors to design and or construct.

— *Consultant*: an organisation that is the client's agent designs and manages the work and obtains subcontracts from works contractors who then each enter into a direct contract with the client.

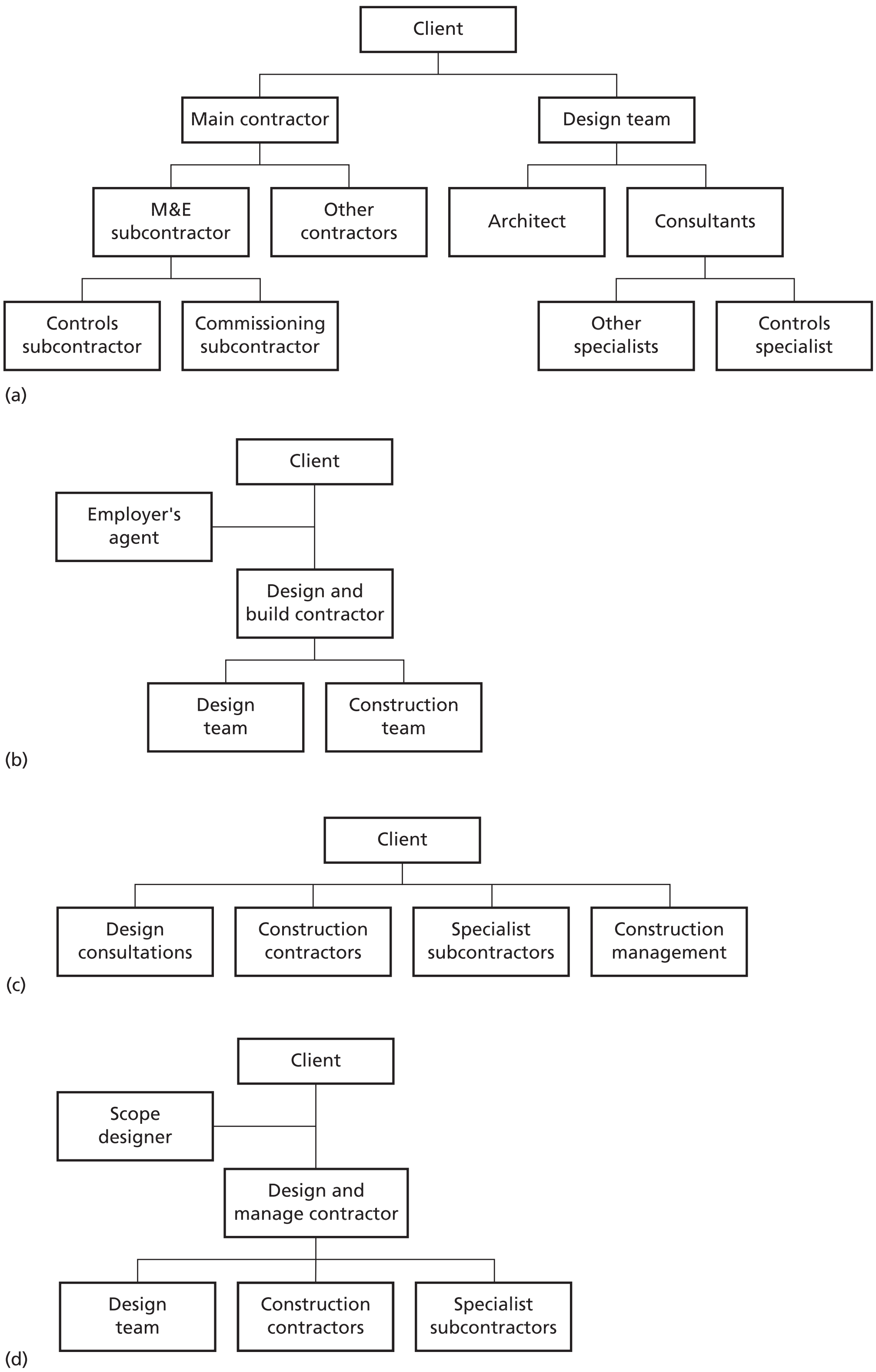

Figure 8.1 Major procurement options. (a) traditional (lump sum) contracting relationships, (b) design and build, (c) construction management, (d) design and manage

8.1.3 Traditional

The traditional procurement method separates design from construction. The client appoints design consultants who prepare a detailed design of the building. The design is put out to tender, following which a main contractor, responsible to the client, is appointed. The main contractor may appoint subcontractors. During construction, the design consultants exercise a supervisory role. This method is well understood in the UK and has the advantages of:

- providing clear contractual responsibility for each aspect of the work
- a well-understood procedure.

From the controls point of view, it has disadvantages:

- There is no involvement of specialist subcontractor at the design stage.
- Modifications to the design during construction are expensive.

8.1.4 Management methods

Management methods separate to a greater or lesser extent the function of management from those of design and construction. They have become associated with projects which are large and complex, and where early completion is required. Management methods give more flexibility to modify requirements during the course of the project and design and construction may overlap. Reduced project times are generally possible by continual re-evaluation of options and reallocation of resources. This allows variations to be introduced more easily than the traditional method but can result in increased costs. This flexibility may make it difficult to assign responsibility in case of dispute. There are two main variations of management methods:

— *Construction management*: design and construction are still separate functions, but a construction manager is appointed to manage the whole process. The manager is appointed by the client; consultants and contractors have a direct contractual agreement with the client.

— *Management contracting*: the appointed management contractor provides the services of managing for a fee all the works contractors by employing them as subcontractors.

8.1.5 Relations between parties

There are many variations of the above, which are summarised in Turner[2]. The traditional organisation still accounts for the majority of new buildings, particularly for the smaller operations. Construction management is still relatively uncommon, except for large complex projects. Design and build is increasing. The form of organisation can affect the process of designing and installing a control system. In the traditional system, the controls specialist subcontractor is at the end of a contract chain, which may mean that available money and time are insufficient to produce the required quality of installation. The exclusion of the specialist contractor from the design process may mean that their experience is not taken into account. Fragmentation of the design consultancy can mean that controls consultants do not have an input into the design of the HVAC system itself, leading to the common complaint among controls consultants that the systems they are presented with are inherently uncontrollable.

The general awareness that procurement practices could be improved led to a review being set up under the chairmanship of Sir Michael Latham to consider:

— current procurement and contractual arrangements

— current roles, responsibilities and performance of participants, including the client.

The Latham report *Constructing the Team*[3] recognised that the efficiency of the British building industry could be increased by improving the interrelationship of the many parties involved. Many of the report's recommendations have been implemented, or are in the process of being set up. However, a subsequent report[4] found that the UK M&E contracting industry lagged well behind that of other countries. Among a number of factors, the report identified the following which are relevant to controls subcontracting:

— lack of project planning and organisation

— poor quality design of services

— lack of approved installation drawings

— inadequate use of prefabrication and pre-assembly.

Further recommendations for improvement in both quality and efficiency were contained in the Egan report *Rethinking Construction*[5], which proposed a target of a cost reduction of 10% per year plus a reduction in defects. The report strongly favoured the use of partnering methods, which are described further below.

8.1.6 Partnering

Partnering is not a different form of procurement organisation, but rather a cooperative approach which has been defined as 'an arrangement whereby people are encouraged to work more efficiently together, including shared problem resolution, continuous improvement, continuity of work, fast construction, completion on time and improved profits'. Two types of partnering are in common use: project partnering, where one-off development is undertaken using a team that agrees to work in partnership, and strategic partnership, where the same team is involved over a series of construction projects. A study by Reading University[6] calculates that savings of up to 10% may be achieved with one-off partnerships, and up to 30% for strategic partnerships. Partnering aims to replace the confrontational system of watertight contracts with a more open approach to resolving problems as they arise. This often involves partnering workshops, where all parties meet on neutral territory to set goals and resolve problems. The workshops may be conducted by a facilitator, a third party skilled in team building and group dynamics.

Since partnering requires a shared approach to problems it is often linked to some form of profit sharing. While partnering may be applied to almost any form of procurement, it is best suited to a situation where the partners learn to work together over a series of projects in a stable market. The client has also an important part to play in creating the conditions where partnering can flourish. Table 8.1 indicates the situations where the partnering approach may be most useful.

The controls specialist will be expected to contribute to the design at an early stage and to take part in partnering workshops to increase the effectiveness of all members of the construction team. This will help contribute to the design of an effective, controllable HVAC system. In return the controls specialist is entitled to expect the main contractor to[7]:

— offer greater predictability of work

— use standard forms of subcontract

— refrain from rebidding to help reduce subcontractor's bid costs

— draw up a preferred list of subcontractors

— honour tender commitments

— reimburse the costs of design.

Table 8.1 Situations where partnering can be used[7]

	Partnering may provide benefits	Good for partnering	Ideal for partnering
Form of contract	Traditional	Management contracting	Construction management
Initiator		Consultant, contractor	Client
Programme of work	One-off	Regular	Programme of similar projects
Project type			High value, high risk
Market conditions	Boom/bust		Stable

Partnering does not normally involve a legally binding agreement, though it is common for everyone to sign up to a partnering charter setting out the declared aims. Care needs to be taken to ensure that a partnering agreement does not fall foul of the laws on restrictive practices or fair competition, which may prevent exclusion of potential bidders or demand that contracts must be awarded on lowest price. Partnering is by no means a panacea and it cannot compensate for other inefficiencies.

8.2 Design and specification of a controls system

8.2.1 Sequence of events

Table 8.2 illustrates the steps involved from design to completion of a building control system. The procedure is based on the traditional building procurement method, but it applies to all methods, with some variations in responsibility. The first step is for the client to set out the requirements for the building as a design concept. The more clearly the client's requirements are set out in the project brief, the better controlled will be the whole process. The outline design process should include consideration of the end user's operational requirements and the general level of control and IT systems. The client may appoint a principal adviser at this stage to supply independent advice now and later in the project. The use of a principal adviser may be crucial to the success of a project where the client has little in-house experience.

Table 8.2 Sequence of events in building procurement

Activity	Person responsible
Concept and design brief of building, including control and associated requirements	Client, architect, principal adviser
Place contract for design with consultants	Client
Produce detailed design of building, HVAC and control systems, which becomes basis for tender document	Architect, consultants, controls specialist
Estimate costs and prepare bid	Contractors
Place contract with main contractor	Client
Main contractor may subcontract controls installation	Main contractor
Prepare and agree description of operation	Controls specialist
Prepare detailed installation drawings	
Obtain items from suppliers and install controls system	
Check operation	
Prepare documentation	
Test and commissioning	Commissioning sub-contractor, with consultant supervision
Staff training	Controls specialist
Acceptance and handover	Client
Fine tuning and maintenance of controls	Separate contract

Once the brief has been agreed, the design work is passed over to consultants, whose job it is to produce the final design which will form the basis of the building contract. For a complex building, the controls design is likely to be done by a specialist consultant, either an independent firm or a specialist group within an M&E consultancy. The level of detail varies from project to project; it may be a complete specification, or a simple performance specification, which leaves the controls specialist to do the detailed design work and select the supplier. It is possible to place the controls design with a manufacturer, who will provide design, supply and installation to the project. This will reduce competition. Large building projects will be constructed by several contractors and subcontractors and it is important that their responsibilities be clearly allocated. Some level of design responsibility is normally allocated to the installing contractor, for instance by an instruction that they produce drawings. The division of responsibilities between contractors must also be made clear in the specification. An example relevant to controls is the provision of cabling. Power and signal cabling may be provided by different contractors and BMS signals may be partially carried by a shared IT network. The specification must detail responsibilities, including the routing of cabling to satisfy EMC requirements.

Potential contractors bid for the contract to construct the building. The successful bidder, the main contractor, is unlikely to provide all necessary specialists in-house, and may appoint specialist subcontractors to supply and install the control system. This subcontractor may need to provide detail design work, depending on the completeness of the controls specification. When the specialist subcontract has been appointed, they may prepare a description of operation. This document sets out how the subcontractor intends to interpret the controls specification and realise it as a practical operating control system. The description of operation is referred back through the contract chain to be agreed by the client and the consultant responsible for the controls specification. This ensures that the specification has been interpreted properly and that the client is clear as to the controls system that will be provided; the procedure also gives some protection to the controls specialist against later disputes arising from any misunderstanding. Commissioning of the HVAC and controls systems may be carried out by an independent specialist subcontractor, witnessed by the controls specialist and the control consultant. Provision of full documentation and training for the staff who will operate the systems is an essential part of the process and is completed before handover of the system to the client.

8.2.2 Design brief

The first stage is for the client to set out the requirements:

- improve productivity both human and process
- reduce lifetime costs to a minimum with respect to the benefits from productivity gains and energy consumption
- provision for future developments
- compliance with any statutory requirements.

The brief should be written in a way that can be interpreted by the design team. The control system of a complex building is essential to the proper functioning of the building. It represents a substantial cost and the design of a BMS should be considered from the start. The design brief produced by the client should include any particular requirements and restrictions on the cost and scope of the controls. The client should consider carefully the intended function of the building and its occupants together with future control and IT requirements. This should include discussions between controls companies and the end user. Experience shows that the best building management systems result from situations where controls specialists and the end user have had direct contact with each other. It is never too early to include the end users, including operators of the BMS and the building occupants. The client, in association with a design consultant, produces a design brief, which forms the basis for the specification. A pre-specification checklist is shown in Figure 8.2.

Where installation of a BMS is being considered for an existing building, planning should start with a thorough survey of the building and its operation. An energy audit will reveal sources of avoidable energy waste, which should be rectified before starting work on the control system. The need for centralised control should be considered critically; for smaller installations, the use of stand-alone controls may be a cheaper alternative compared with BMS.

8.2.3 Specification

The specification forms the basis of bids by contractors and is the basis of the eventual contractual agreement. It is therefore essential that the specification provides a complete and unambiguous definition of the building control system. Changes made to the specification after work has started are likely to be expensive. It is also important that the specification should set out clearly the allocation of design responsibilities to avoid subsequent disagreements. A comprehensive treatment of the issues which should be considered when specifying a BMS is given by Pennycook and Hamilton[8]. To simplify the process of drawing up a specification and to reduce the chance of important items being overlooked, various bodies have drawn up outline specifications which may be used with the minimum of modification. Teekeram and Gray[9] reviewed the situation over several countries.

The objective is to set out the specification in functional terms, rather than prescribing the hardware and software to be used. In a time of rapidly changing technology, functional objectives may be achieved by different hardware and software strategies for different systems. The functional approach should encourage suppliers to offer the most suitable systems on a competitive basis.

A project specification would normally comprise the following:

- *Preliminaries*: referring to the whole project.
- *System specifications*: one for each relevant work section.
- *Reference specifications*: relevant specifications of component parts and materials. These may be relevant to several sections in the system specification, so it is common practice to bind them in a separate volume for easy reference.

The 'Preliminaries' section contains an overall description of the project, together with information on organisation and contractual matters. Specification for the controls system must take its place and be compatible with the specification for the whole project. The preliminaries for the controls system specification must not conflict with the main contract preliminaries, which is the governing document for the whole project.

Each of the systems specifications should be subdivided into three parts:

- *Part 1: System objectives*: descriptive clauses to be written by the specifier, using the following headings:
  - performance objectives
  - design parameters
  - system description
  - control requirements
  - system schematics
  - system drawings.

  The system objectives should provide a complete reference package so that the ideas behind the design are passed on in an intelligible and logical format. The first three parts should start as soon as the client's brief has been received, and kept up to date as the design proceeds. In the absence of a central control system, the control requirements are listed in the system specification for the relevant work section. Where a central control system is to be used, the control requirements may either be listed in the relevant system specification, or else all details of the control system can be listed in the 'Central Controls' work section, with appropriate cross-references from the systems being controlled.
- *Part 2: Selection schedules*: a list of references to the specifications that are applicable to this work section. As well as invoking the relevant specification, the schedule invokes required clauses from component parts and materials specifications.
- *Part 3: Clauses specific to the system*: information specific to the work section.

PRE-SPECIFICATION CHECK LIST

1 GENERAL DETAILS

1.1 Have the detailed operational needs of the end user been fully considered?

1.2 Will the envisaged form of contract allow for the needs of the client/user to be met?

1.3 Is there to be scope for integrating other functions/elements into the BMS? If YES which:
a) Access/security b) CCTV c) Lighting control d) Chillers
e) Boilers f) Variable speed drives g) Others, please specify

1.4 Will any elements of the system need to be acceptance tested at manufacturers works?

1.5 Will the system be required to be expanded and/or upgraded over the next 5 to 10 years?

1.6 Will the BMS supplier have a minimum 4-week tendering?

Section 2 OUTSTATION DETAILS

2.1 Will the motor control units (MCCs) contain the outstations? If 'YES' outstations should be contained in a separate control section
If 'NO' state the distance between MCC and outstation

2.2 What form of MCC will you be specifying?

2.3 Are the MCC s to be a special colour? If 'YES' please specify

2.4 What IP ratings are the MCCs?

2.5 If OUTSIDE the MCCs what IP rating is required for outstations?

2.6 Have you specified the number of points (inputs/outputs) to be covered by the system If 'YES' please indicate:
a) Analogue (resistance b) Digital (open or closed c) Pulse (metering) voltage or current) contacts)
d) Hardware e) Software f) Other (please specify)

2.7 Are the outstations to have any special features? If 'YES' please indicate: Memory battery back-up I/O battery back-up Special cards
Individual I/O override UPS Other features

2.8 Are the outstations to have displays/keypads? If 'NO' please state which are not required. Is a fully functional laptop PC required? If 'YES' please indicate:
a) Door mounted b) Within MCC c) Portable device
d) Specially protected e) on all outstations If 'NO' please specify how many, which, and what functionality

Section 3 CENTRAL SUPERVISOR SOFTWARE & HARDWARE

3.1 Is there to be a central supervisory computer on the project?

3.2 Is the central supervisor dedicated to BMS or also running other programmes?

3.3 Have you specified the hardware and can it cope with the project?

3.4 What size monitor have you specified?

3.5 Have you specified ALL the software that you require for this project?

3.6 Is the central supervisor to be networked? If 'YES' please indicate the type of network.

3.7 Do you require extra computer terminals? If 'YES' how many

3.8 Have you specified how these terminals are to be configured?

3.9 Have you indicated where these terminals are to be located?

3.10 Will remote telephone modem communication be required?

4 INSTALLATION

4.1 Will the BMS contractor be required to supply
a) Computer hardware b) Sensors/actuators c) MCC s
d) Install all the above e) Cable all the above f) Engineer BMS software
g) Supervisor software h) Power wiring i) Commission the above

4.2 Will tendering information accord with the building controls standard method of measurement?

4.3 Will you be applying special conditions to the contract installation? If 'YES' please specify

5 TRAINING

What training will the BMS contractor be required to provide?
Off site On site Other

6 WARRANTY AND MAINTENANCE

6.1 Have you Included for a system service and maintenance contract in your tender documentation? If 'YES' have you specified the type of cover you require
a) 24-hour callout b) Guaranteed response time c) 6-monthly maintenance check-up d) Annual maintenance check up
e) Dedicated spares holding f) Other requirements

6.2 Have you specified the period during which you require maintenance to be provided?

IS THERE ANYTHING ELSE YOU OUGHT TO HAVE THOUGHT ABOUT?

Figure 8.2 Pre-specification checklist

The specification should also make reference to published standards and guidance (e.g. CIBSE Guides and BSRIA publications).

8.2.4 Conditions and tolerances

The specification of the required controlled conditions and permissible tolerances must be considered carefully. Setting unrealistically tight tolerances may result in either an unnecessarily expensive design solution to meet them, or a system which fails to meet the specification, with the attendant risk of litigation.

General comfort criteria are covered in chapter 1 of CIBSE Guide A[10] and by ASHRAE-ANSI Standard 55[11]. The most important variable is the temperature in the occupied space. This may be specified in terms of air temperature, environmental temperature or one of a number of comfort indices. The adaptive model of thermal comfort[12] states that it is permissible to allow space temperatures to rise in summer, since the occupants learn to adapt and minimise discomfort. This has importance for the design of HVAC systems, since it may be possible to reduce or even eliminate the need for air conditioning.

Where this principle is adopted, the acceptable limits of building performance must be understood and accepted by all parties. Where full air conditioning is employed, the required range of air temperature and humidity is specified. The interaction of air temperature, relative humidity and moisture content must be remembered. In general, the moisture content of the air in a building is less subject to variation than the air temperature. Changes in air temperature at constant moisture content may cause the relative humidity to go outside the specified range. People are not very sensitive to the level of ambient humidity and a range of 40 to 70% RH is normally found acceptable. If closer control is required, then the tolerances must be specified in such a manner that they can be realistically met by the HVAC system. Where central control of humidity is used, it may be better to specify humidity in terms of moisture content rather than relative humidity. Similar considerations apply to plant operation. Control limits must be within the capability of the plant and its measurement and control system. When specifying the tolerances for system variables there is no point in specifying unnecessarily narrow limits, even if they can be met. The heat output from a heat emitter may be little affected by a 20% variation in water flow; however, a narrower specification is required for chilled water systems.

8.2.5 Alarm specification

The specification should include the following:

- alarm set points
- alarm actions
- alarm texts
- alarm handling.

These are the principle outputs required to enable the building control system to report an 'out of tolerance' warning (see 8.2.4) or a fault. If these systems are not specified correctly there is little chance that the system will operate as intended, often resulting in reduced productivity and increased energy usage.

8.2.5.1 Alarm set points

If there is an operational or statutory reason for the plant or its components working correctly, the specification should require the plant and its components to be monitored. Alarms set points should be specified and warnings generated if the plant operation deviates from its specified tolerances.

The specification should also require that the alarm set points be checked for errors For example, in an office heated in the winter by radiators it is common for a wall temperature sensor to be installed to report an alarm if the office is too hot or cold. On warm summer days the alarm would report that the office is too hot (a false positive). The specification should require the summer alarm to be disabled, perhaps by linking it with an outside detector inhibiting the alarm if the outside temperature rises to within 3 °C of the 'high alarm' set point.

The reduction of false positives is very important as investigating them wastes large amounts of time and money and reduces user confidence in the building control system.

8.2.5.2 Alarm priorities and distribution

Within an organisation, alarms may need to be distributed to a number of personnel for action and information. The methods include:

- printer
- touchscreen
- e-mail
- pager
- bureau, etc.

The alarm distribution requirements should be tabulated and form part of the specification. The importance of each alarm should also be specified and a priority stated. These could be simply categorised as:

- *Low priority*: e.g. filter change; sent directly to the maintenance team.
- *Medium priority*: e.g. high air supply temperature to a group of offices; sent directly to the maintenance team and if it persists sent to the maintenance manager.
- *Critical*: e.g. the gas supply has failed to a large boiler house; sent directly to maintenance team and manager.

Note some systems have 12 or more message priorities. In practice each of these can be directed to a printer, screen, e-mail etc., the text then defining the severity of the alarm. So in this case a 12-priority alarm system may be inadequate if three priority levels are required and these need to be distributed to more than four recipients (or groups).

8.2.5.3 Alarm texts

The specification should specify how alarm messages are displayed, e.g. the style, if the messages are to be displayed on a screen. The specification should also take account of any limitations of using a particular communication device, these may include:

— printers and screens (including handheld 'personal digital assistants' (PDAs)): limitations with colour, font and text length

— pager or LCD screen: text needs to take account of display limitation, e.g. some 'bleep' systems cannot display spaces, which may make this type of display unsuitable.

8.2.5.4 Alarm handling

The specification should detail the requirements for alarm handling. Some of the issues are detailed below.

Often alarm handling is carried out through the 'head end' PC. Some systems will forward these alarm messages on to other networked PCs (or display, PDA etc.). The alarm handling system is vulnerable to failure due to the 'head end' PC not being available due to maintenance, programming or breakdown (hardware or software), and no alarms will be forwarded during this time. There is often little or no cost penalty for generating and forwarding alarms from routers or controllers in the field, so the effect of a failure is limited to the few points connected to it. This is particularly important where the alarms being handled are 'mission critical' or a more robust method is required, the specification may limit the number of points connected to critical controllers.

The specification should also confirm if alarm messages are to be confirmed or acknowledged. The requirements should be defined in the specification. The following are examples:

— *Acknowledged*: a message is sent to a controller and a acknowledgement is received; this may be used where confirmation is required that an alarm has been received (or, in non-alarm terms, that a message was received by another controller).

— *Request/Response*: a message is sent to a controller when the message has been processed; the response confirms that the alarm was received and understood.

— *Repeated*: a message is sent and re-sent a number of times but no acknowledgement is required, e.g. low priority alarms.

Note that alarm messaging is also useful as a monitoring tool for the reliability of the communications system as a whole. For example, where a known number of messages are sent, these may be compared with the number of messages received to gauge the health of the controllers used for the messaging and the network as a whole.

At the receiving end of the system, where the alarm is displayed and acted upon, the following points should be considered dependent on the desired reliability and the importance of the alarms being handled:

— resilient power supplies

— dual redundant servers

— a resilient IT network (possibly also between sites)

— 'heartbeat' messaging between the handling centre and the controllers generating critical alarms (this can also be generated from the controllers/intelligent sensors)

— software to acknowledge the alarm

— management software to log alarms, including who acknowledged and how long they took

— exception reporting software to report when the 'heartbeat' signal from the field is not present.

Further guidance is given in BS 5979(13); this standard also gives guidance on secure call handling centres.

While alarm handling systems that are required to handle critical alarms, for example, can output to pager/bleeper and PDAs, when specifying such systems the designer should check that the receiving device can return a 'heartbeat signal' to prove that the receiving device is functioning correctly.

8.3 Tendering process

8.3.1 Pre-tendering

In many cases it is advantageous to draw up a short list of potential suppliers who will be asked to tender for the project. The use of a pre-tender brief allows selection of suitable tenderers to be produced, avoiding wasted effort. A pre-tender brief is given to possible suppliers, who are asked to return a questionnaire and are then interviewed to discuss the project in outline. The pre-tender brief contains enough information to indicate the size and complexity of the project, the available budget and the proposed time scale. The brief should contain the following:

— objective of the brief

— project description

— an indication of cost

— project management and form of contract

— building and plant schedules

— questionnaire.

8.3.2 Tendering

The usual documents required for the tendering process are shown in Table 8.3. If the pretendering process has produced a suitable short list and the specification has been properly drawn up, assessment of the tenders should be straightforward. To protect subcontractors against possible bad practices, a *Code of Practice for the Selection of Subcontractors*(14) has been published by the Construction Industry Board.

8.4 Commissioning

Commissioning is defined by CIBSE as 'the advancement of an installation from static completion to working order

Table 8.3 Tender documents

Document	Purpose
Instructions to tenderers	How to complete the tender documents
Form of tender	On which the tender bid is returned
Tender details and summary	Cost breakdown of the tender price. Will provide the basis for any negotiation of variations
Form of contract and special conditions	
Full specification	Full set of standard and particular specifications, together with relevant plans and drawings
Information required from tenderer	Additional requirements needed to confirm details of the tender

to specified requirements (as envisaged by the designer)'. Correct commissioning is vital to the satisfactory operation of the HVAC system and it is essential that sufficient time and resources be allocated to the task. Since commissioning is the last major operation in the building process and the control system is the last system to be commissioned, there is every danger that commissioning the control system will take place under great time pressure or even continue after the building is occupied. Experience has shown only too well that this can create many problems, with an unacceptably high proportion of buildings failing to operate properly, with consequences of high energy consumption and occupant dissatisfaction. This section emphasises the importance of ensuring that commissioning takes its proper place in the procurement process from the start of planning the project.

Commissioning of the control systems is dependent on satisfactory operation of the electrical and mechanical services. The control system may also interact with specialist services such as security, access control and the IT system. The greater the degree of integration, the more planning is necessary and the more care required to define areas of responsibility(15). Sequential records of all stages of pre-commissioning and commissioning of all other aspects of the building must be issued prior to commencement of the commissioning of the automatic control system. Table 8.4 summarises the stages of the procurement process and the activities which are relevant to the commissioning of the controls system.

Table 8.4 Commissioning activities during the procurement process

Stage	Commissioning activity
Brief	Commissioning objectives Appoint commissioning manager
Design	Minimise need for commissioning Design for commissionability
Installation	Pre-commissioning Commissioning
Handover	Witnessing O&M documentation User training
Operation	Monitoring and feedback System proving Fine tuning Recommissioning

8.4.1 Commissioning management

For the traditional UK procurement organisation, the responsibilities for commissioning the BMS are shown in Table 8.5. This arrangement has the advantage of clearly defined responsibilities. However, it does not necessarily produce the most effective commissioning. The controls specialist, who is responsible for installation and commissioning, has little or no input into the design of the BMS, nor the design and commissioning of the plant which will be controlled by the BMS.

Table 8.5 Commissioning responsibilities for traditional procurement

Party	Responsibility
Client	Write design brief Appoint design consultant
Design consultant	Write BMS functional specification Review tenders from BMS contractors Appoint BMS contractor Witness commissioning Approve completion
BMS contractor	Prepare tender Design BMS to meet specification Install BMS Commission BMS

8.4.1.1 Project management

Good project management is essential for large and complex projects and should include the following:

— A detailed commissioning programme should be written and agreed with the main contractor.

— There must be a means of monitoring progress.

— Checklists should be used to monitor progress.

— The controls specialist must have a documentation system in place for dealing with variations to contract.

Project management guidance(16) and BSRIA's Commissioning Guides define responsibilities for the personnel involved in the commissioning process. Duties will vary between projects depending on assigned responsibility. Example roles are detailed below. The project manager has a coordinating, monitoring and controlling role for the project. The responsibilities include the following:

— aiding the client selecting the design team and other appropriate consultants and negotiating their terms and conditions of employment

— setting up the management and administrative structure for the project.

The client's commissioning manager provides the control point for commissioning for the client. The manager will be responsible for:

— arranging the appointment of the commissioning team

— establishing the commissioning objectives

— developing a comprehensive commissioning programme and preparing the roles and job descriptions for each member of the team

— arranging the sessions for user training at the end of the project.

The professional consultants must identify the services to be commissioned and define the responsibilities split between the contractor, manufacturer and client. They are also responsible for inspecting the work for which they have design responsibility (including inspecting the work at the end of the contract defects liability period) and defining the performance testing criteria to be adopted. The site commissioning manager may be a member of the main contractor's team and provides the focus for the management of all the commissioning activities. The tasks may include the following:

— coordinating the professional team members and the client's involvement in commissioning
— ensuring that the contractors' programmes include commissioning activities and that these coordinate with the main construction activity
— acquiring appropriate information from the relevant parties to ensure that the systems can be commissioned in accordance with relevant codes of practice
— witnessing works and site testing of plant, cleaning and commissioning
— demonstrating safety systems to the local authority, fire officer, district surveyor and the building insurer
— providing a focus to collect all handover documentation.

8.4.2 The brief

The original brief will lay down the foundation for the organisation of commissioning. This is the stage at which the organisation of the whole building procurement process is decided. For large projects, the appointment of a commissioning manager should be considered, with the responsibility of ensuring that the requirements of commissioning are considered at all stages. The manager will be responsible for appointing the commissioning team and ensuring that adequate resources for commissioning are built into the specification. Decisions should be taken at this stage whether commissioning should extend beyond the handover of the building and whether provision is to be made for system proving and post occupancy feedback when the building is in operation.

8.4.3 The design stage

Commissioning should be borne in mind at the initial design stage; this applies to both the HVAC system and the control system itself. Two complementary approaches are relevant:

— designing to minimise commissioning
— designing to make commissioning easier.

The amount of commissioning needed can be reduced by appropriate design:

— Design for self-balancing wherever possible.
— Balance pressure drops across sub-branches and terminal units.
— Avoid using different terminal units on same branch.
— Use reverse return pipework layouts.
— Use automatic balancing valves.
— Use variable-speed drives for fan and pump regulation.
— Use computer analysis to give settings for preset valves.

Attention to the needs of commissioning at the design stage will make it easier. Conversely, failing to provide the necessary facilities for commissioning may make it impossible. The following items will assist commissioning:

— Include regulating valves where appropriate.
— Include isolation valves and test points.
— Include flow measurement devices at main branches and major heat exchangers.
— Ensure that the system may be cleaned and vented.
— Ensure access for commissioning and maintenance.
— Provide items of plant with a 'manual/off/auto' switch. The switch can be set to 'manual' for commissioning the plant itself, prior to commissioning the BMS.
— Agree at an early stage a common procedure for allocating mnemonics to identify points uniquely.
— Obtain mid and full load design values from consultant.

The design consultants are responsible for writing the system specification, which includes the commissioning specification. At this stage a commissioning specialist should review the specification.

8.4.4 Installation

Satisfactory commissioning of the BMS is of course dependent on the correct installation and commissioning of the HVAC plant. The commissioning manager will ensure that plant is in a suitable condition before commissioning of the BMS commences and is certified as such. Above all, all water systems must be flushed clean; the presence of debris in water systems is a common cause of problems in the commissioning of valves.

8.4.4.1 Pre-commissioning the BMS

Pre-commissioning is the checking of all the components of the controls system, both on the bench and on site, before putting the system into operation for commissioning proper. As much checking should be done off site before installation; this will normally be faster and allow rapid rectification of any problems that are found. Checking of sensors for accuracy is best done off site under controlled conditions. The on-site pre-commissioning consists in checking that all items have been installed in the right place, the right way round and are wired correctly. Precommissioning tasks include:

— maximisation of off-site testing and precommissioning of control panels, application software etc.

— the checking of all wiring for short circuits, continuity, identification and termination
— the checking of all sensors for correct installation
— proving of all actuators
— proving the presence of outputs and devices on the network bus system.

8.4.4.2 Commissioning the BMS

Before commissioning can start, all control hardware must be installed and pre-commissioned. Any unitary controls on plant which is to be connected to the BMS should have been commissioned, or be commissioned in parallel with the BMS. The HVAC plant itself must have been commissioned; all plant items under control of the BMS must have been commissioned and the system flushed clean and vented. All electro-mechanical safety interlocks and fail safe conditions should be implemented and operational.

Commissioning the BMS consists of two major activities:

— checking that the control system works
— setting all parameters and switches to appropriate values, including tuning control loops.

Checking the system

Both the head end supervisor and the controls of particular building services plants have to be commissioned. The supervisor requires commissioning after installation. It may be commissioned in parallel with the outstations which control specific items of plant, when it can itself be used as an aid to commissioning. Full commissioning of the central supervisor requires previous completion of plant commissioning. There are six basic items for specific plant commissioning:

— panel controls
— hardware points
— interlocks
— control loops
— alarms
— supervisor.

This procedure is illustrated by the example of an air handling unit shown in Figure 8.3. Table 8.6 summarises the tasks of the commissioning process.

Setting the values

An important function of a BMS is its operation as a timeswitch, controlling the start and stop operation of many systems throughout the building, including optimisers. All BMS supervisors allow time schedules to be readily altered at the head end. However, experience shows that the initial settings may remain unaltered. Accordingly, the client should supply as much information as possible on required time and temperature schedules, to allow the correct values to be input during commissioning. It is recommended that the controls specialist sends a questionnaire to the client asking for relevant information.

All control loops require to be tuned. While the goal is minimum response time consistent with stability, it must be remembered that the operating gain of a control loop is likely to vary with operating conditions, so that the gain will vary with season. Where possible, the loop should be tuned under conditions of maximum gain; this will ensure stability under all conditions. Various ways of tuning loops including the use of automatic tuning are discussed in 2.4.1.

8.4.5 Handover

Once commissioning of the control system has been completed, it is demonstrated in front of witnesses and a completion certificate issued; the client's representative may attend. The witnessing officer will require a completion method statement which details the arrangements, methods and a list of items to be demonstrated in front of witnesses. Witnessing is just one part of completion. Documentation and training arrangements are also required. Table 8.7 summarises the items to be covered during completion. When all items have been completed to the satisfaction of the testers and witnesses, a certificate to that effect is signed off by both parties and handover takes place. Handover represents change of ownership from contractor to client.

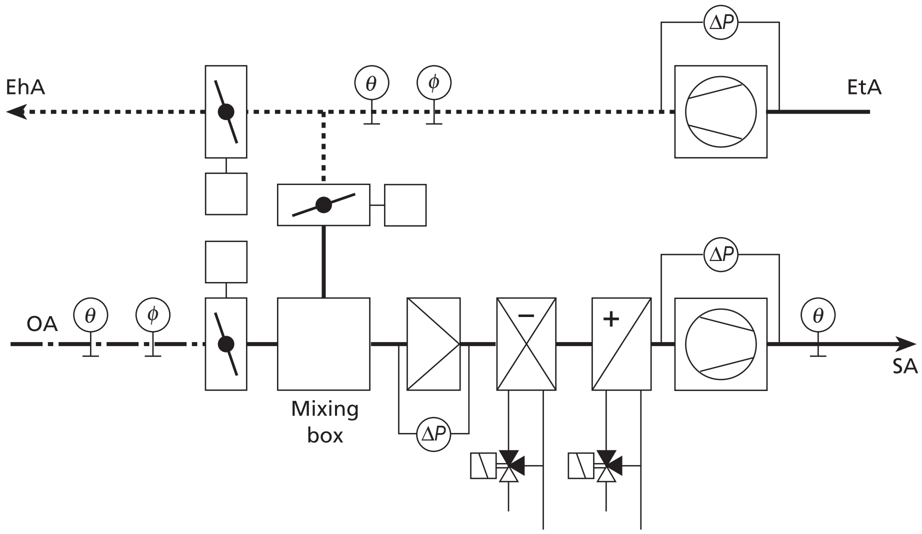

Figure 8.3 Air handling system to be commissioned

Table 8.6 Commissioning an air handling unit

Step	Function	Check
Panel controls	Power	Phases healthy, panel live, BMS power on
	Fire alarm	Reset button, lamp test
	Supply fan	Run, trip, test/off/auto switch, overload range and set
	Extract fan	Run, trip, test/off/auto switch, overload range and set
	Fuses	Correct size, spares in panel
Hardware points	Sensors	Outputs, correct connections
(at pre-commissioning)	Actuators	Full stroke travel
	Connections	Continuity and polarity
Interlocks	Fans	Supply and extract fan interlock
	Dampers	Supply, extract and recirculation dampers synchronised
	Coils	Heater and cooler batteries move to default position on shut-down
	Fire	Appropriate action on fire signal, e.g. close supply and recirculation dampers, open exhaust damper, stop fans
Control loops	Optimiser	Set parameters
	Frost	Set and test frost protection and morning boost
	Control loop	Set proportional and integral constants
		Operation of valves and dampers
		Enthalpy control if fitted
		Run-time totalisation
	Software	Check application software
	Timeswitches	Run through time schedules
Alarms	General	Operation, labelling
	Filter block	Set pressure switch and check operation
	Supply fan	Set pressure switch and inhibit time. Check operation
	Extract fan	Set pressure switch and inhibit time. Check operation
Supervisor	Graphics	Points labelling, plant depiction
		Control functions, correct values

Table 8.7 Completion checklist

Item	Description
1	Audit of cabling and hardware installation
2	Demonstration that sensors and actuators are correctly connected and addressed
3	Demonstration of the physical and logical integrity of the system
4	Demonstration of the sensor calibrations
5	Demonstration of all control actions
6	Demonstration of successful system software commissioning. (This should include loading and subsequent operation)
7	Verification of specified graphics
8	Verification of specified training arrangements
9	Verification of handover of all specified manuals, documentation and drawings
10	Verification of handover of back-up copies of software
11	Verification of handover of consumable spares

8.4.5.1 Witnessing

The organisation of witnessing will depend on the nature of the system and is decided by the witnessing officer. For large projects, there are advantages in a phased approach, so that witnessing of completed subsystems can begin before final completion of the whole system. It is not essential that every point be checked. A sufficient number should be checked to give the witnesses confidence in the overall reliability, using a quality control approach. The method suggested is:

- The BMS controlling the main plant (e.g. boilers and chillers) and other important points should be witnessed completely.
- The proportion of other points to be witnessed depends on the size of the system, e.g. if fewer than 300 points, witness all the points, between 300 and 1000 points, witness 50%, and if more than 1000 points, witness 20%.
- If the failure rate is greater than 15%, the supervising officer should have the right to witness 100% of the points.
- Where there are several similar plants, one can be witnessed in detail and the others on a sampling basis.

A similar approach can be taken when testing alarms. All graphic slides and other displays, including alarm outputs to pagers etc., should be inspected and where data output is required this should be validated as being accurate. After a short period of operation the performance of the management reports should be verified.

8.4.5.2 Documentation

Good operations and maintenance (O&M) documentation is necessary for successful:

- day-to-day operation of the system
- effective maintenance
- system refurbishment.

There is a statutory requirement under the CDM Regulations[17,18] to provide proper documentation in the form of a health and safety file. The client is required to appoint a CDM coordinator, whose function is to ensure that a health and safety file is prepared, to advise the client on the necessary resources required to implement the plan, and to prepare the health and safety file. The health and safety file is a record of information for the end user, which tells those who might be responsible for the building in the future of the risks that have to be managed during maintenance, repair or renovation. Operation, maintenance and commissioning documentation make up part of the health and safety file. The file must include details of hazards and risks, and the safety certificates collected during construction. The documentation must be presented in the format required by the Regulations.

Building Regulations Approved Document L2[19] stipulates that a building log book be prepared, and states that preparing it in accordance with CIBSE TM31: *Building log book toolkit*[20] will satisfy this requirement.

While all building services require proper o&m documentation, the complex nature of a bms, which may have control strategies and other information stored in computer memories, makes it essential to provide written details of what function the bms performs and how it achieves them. Advice on the preparation of O&M manuals is given in Armstrong[21]. The documentation should include:

- written description of plant operation
- control strategy or logic diagrams recording the final version of installed software
- details of system application software configuration
- points list, including hard and soft points
- copies of certificate of compliance with relevant standards
- data sheets for all control components and equipment
- instructions for switching on, operation and switching off, isolation, fault finding and for dealing with emergency conditions
- instructions for any necessary precautionary measures
- instructions for servicing
- instructions in the use of software routines for creating procedures, graphics reports etc., where applicable
- description of user adjustable points
- provision for updates and modifications.

Full system backups should be provided, including databases which should also be updated prior to any modifications to the system.

The file may be in two parts: operating manuals for day-today use and sets of drawings for use during alterations. Copies of manufacturers' data may be incorporated, but are not a substitute for proper instructions. Details of spares and sources of supply should be included. In addition, there should be a complete set of record documents supplied at handover, containing records of all the commissioning values and the checklists completed during commissioning and witnessing.

8.4.5.3 Training

The successful operation of a BMS depends on the skill and knowledge of the operator. The installation of a modern BMS represents a substantial investment and proper operator training is necessary to realise the full value of this investment. The client has to decide who will operate the BMS. In many cases this will be staff, but the contracting out of facilities management services is becoming more common. Training is often part of the contract and so contract completion is not possible until the training has been carried out. This may result in financial pressure to perform the training too early, before the end user is ready or staff have been appointed. It is recommended that training costs should be determined and held as a PC sum outside the main contract, to be paid when the training is completed.

It is recommended that:

- at least two BMS operators attend an 'in-house' training course run by the controls specialist before completion of the BMS
- the BMS operators are invited to attend the commissioning of the BMS
- the BMS operators should be present during the handover period to learn about the system
- all new operators who may subsequently be appointed should also receive proper training.

8.4.6 Costing

The importance of commissioning to the satisfactory operation of the plant and control system has been emphasised. It therefore requires proper provision of time and cost to enable the process to be carried out satisfactorily; allowing commissioning to absorb time and cost overruns is not satisfactory. Effective commissioning has long lasting benefits, which need to be given full value when making out a business case for expenditure; inadequate commissioning is sure to prove expensive over the long run. The benefits of effective commissioning may be summarised:

- increased building value
- improved occupant satisfaction and productivity
- reduced energy costs
- reduced maintenance requirements and longer plant life

— sound database for future refurbishment.

When costing proposals, all activities should be taken into account, including provision for post-occupancy evaluation and fine tuning.

8.5 Operation

8.5.1 Fine tuning

After handover, the building operates under control of the appropriate staff, whether in-house staff, a contract facilities management team or other form of organisation. It is rare that a new building works perfectly without further attention; it would be unreasonable to expect this, since the manner of building use by the occupants cannot always be predicted and it will not have been possible during commissioning to experience the full range of weather conditions. It is therefore to be expected that the BMS will require attention and tuning over a period of at least a year after occupation. Proper provision should be made for this, in terms of effort and cost. This should include an allowance for a return visit at least twice during the first year. In most cases, it will be of great benefit for all concerned if the client installs a dedicated telephone line to allow remote monitoring of the BMS by the controls specialist. As well as assisting in fault diagnosis, the link can be used for training and other purposes.

8.5.2 Maintenance

The designer can dramatically affect the maintenance requirements for the building control system, not only by the way the systems components are installed but also by the quality of components. Careful selection of controllers, sensors and actuators will increase the period between inspections.

The frequency of calibration checks will be reduced if sensors with a small annual drift are installed. By installing low drift, high accuracy temperature sensors the period between calibration checks may be extended from one year to three years[22].

While the microelectronics components in a BMS are in general very reliable, a controls systems contains moving parts which are subject to wear and devices such as sensors which may be subject to physical damage or degradation from their environment. Maintenance is therefore essential to ensure that a BMS stays in efficient working order throughout its life. Maintenance includes updating and maintenance of software and documentation. Maintenance may be obtained from different types of provider:

— *In-house staff*: only large organisations with a sophisticated building are likely to carry the necessary technical staff to provide BMS maintenance. In-house staff may be used to provide the first line of investigation into failures and carry out simple repairs, calling on specialist contractors for more complex work.

— *Maintenance divisions of M&E companies*: many M&E contractors operate specialist maintenance divisions that will undertake maintenance of BMS systems, whether installed by the parent company or not. The maintenance companies are generally autonomous companies, so it should not be assumed that there is a continuity of responsibility between installer and maintenance company.

— *Systems integrators*: many of the larger systems integrators provide comprehensive maintenance and 24-hour bureau services. This may include remote monitoring of plant condition.

— *Specialised maintenance companies*: there is a large number of small specialised maintenance companies, often specialising in a particular range of equipment. Although not having the resources of the large M&E companies, they can supply a service tailored to the customer's needs.

— *Consultants*: an increasing number of engineering consultants offer maintenance services, including training or documentation production, and the management of maintenance on behalf of the building operator.

— *Controls manufacturers*: several major manufacturers offer maintenance contracts of systems using their equipment.

Whichever method is chosen, it is important that the maintenance is specified carefully[8]. As a minimum, a maintenance specification should include requirements for:

— software upgrades

— data back-up and archiving

— checking of sensors and actuators

— arrangements for emergency callout

— performance standard for the building control system, including delivered conditions and operating efficiency.

As with commissioning, it is advantageous if the needs of maintenance are considered at an early stage; various approaches to the organisation of maintenance are reviewed in CIBSE Guide M: *Maintenance engineering and management*[23]. Plant and equipment should be designed and installed in a manner to assist future maintenance; recommendations are given by MoD[22], BSRIA[24], HVCA[25] and Parsloe[26]. Advice on specification and contracts is to be found in Smith[27] and the HVCA's *Standard Maintenance Specification*[25]. Experience shows that the best results are obtained in situations where the BMS is 'owned' by someone in the building operator's organisation. There should be an individual who feels responsible for the proper operation of the BMS and will take whatever initiative is necessary to ensure its successful working.

8.5.3 Recommissioning

Existing buildings may operate below optimum performance and recommissioning the building services may represent the most effective way to bring operation up to the required standard. Recommissioning can often be justified by:

— evidence of occupant dissatisfaction

— high operating costs or energy consumption

— high maintenance costs
— a change in building use
— major plant overhaul or replacement
— repeated system failures.

8.6 Occupant surveys

The experience of the building occupants plays an important part in the evaluation of the performance of a building control system. Building users consistently place good environmental control at the top of the list of desirable features in a workplace. A well-controlled environment not only produces comfort, but contributes to productivity and health as well as influencing the occupants' general opinion of other facilities. The series of PROBE post-occupancy studies of buildings has emphasised the importance of a well-controlled environment and emphasised that the occupants themselves are part of the system. Disregarding the responses of the users will itself create problems, even if the mechanical system is performing adequately. The published summary of the first PROBE series produced a set of key design lessons about the requirements of the occupant[28].

— *Rapid response to changes*: there should be a rapid response to the need for a change, whether this is provided automatically by the BMS or by management intervention.
— *Offer choices and trade-offs*: if ideal conditions cannot be provided, the occupants should be offered a choice of trade-offs, e.g. in hot conditions, openable windows allow a choice between being hot or suffering from external noise.
— *Good feedback mechanisms*: these are essential so that action can be taken quickly. Complaints or problems need to receive rapid attention.
— *Management resources*: these are vital; complicated buildings can outstrip the limited capabilities of the occupiers to run them effectively.
— *Ownership of some problems by the occupants*: this is so that they may participate in the solution without suffering a sense of alienation.
— *Perception of good control*: this is important to occupants, who require simple effective controls or else rapid and effective management response to requests.

The above design lessons emphasise that the users must perceive that they are part of the control system. However good the control system may be in technical terms, if the manner in which it is operated ignores the feelings and responses of the building occupants, then it will not be found satisfactory. The application of the above lessons will result in working methods whereby early indications of unsatisfactory operation of the building control system come to the attention of the building operator. Other indications may come from the energy monitoring and targeting procedures. In any case, it may be advantageous to initiate a regular review of system performance, say one year after installation and at longer intervals thereafter. When it is desired to initiate a proactive review of the operation of the building services operation, a three-level strategy to review building performance is suggested, which can be initiated at any stage of the building's life.

— *Level 1*: review performance, using a help desk or focus groups to obtain the views of occupants. Assess energy performance against targets or benchmarks and ensure that health and safety requirements are met. If there is cause for concern, move on to Level 2.
— *Level 2*: use a more formal procedure to identify any problems. Use occupation satisfaction surveys and energy surveys. If performance problems are established, go to Level 3.
— *Level 3*: employ plant-focused troubleshooting procedures to find the cause of troubles. Systems can then be fine tuned, recommissioned or refurbished as required.

The relation between building controls and complaints of poor indoor environmental quality is set out by Fletcher[29]. Reports of poor conditions are classified into 16 divisions and an action checklist for each is given. The suggested actions only apply if the problem is controls related or can be mitigated by modifying the control set-up. A detailed occupant satisfaction survey demands a formal approach. The use of a standardised questionnaire will provide a satisfaction score for the building that will enable its performance to be compared with national benchmarks, as well as identifying areas of control and management that require attention. The PROBE standard questionnaire is copyright and may be used under licence; this ensures that it is applied according to standard procedures. Formal occupant surveys should be undertaken with caution, both to ensure results that can be compared with benchmarks and to avoid possible staff-related problems.

— The questionnaire should be short and easy to answer in at most 10 minutes.
— In large buildings, a representative sample of occupants should be surveyed, aiming at as high a response rate as possible.
— The provisions of the Data Protection Act must be borne in mind.
— The staff association or other relevant body should be kept fully informed.
— Make the goal of the survey clear to respondents; do not raise unrealistic expectations of improvement in conditions.
— Resolve any questions of confidentiality in advance.
— If the survey is to be conducted by external researchers, resolve questions of ownership of data and possible publication in advance.

8.7 Cost issues

8.7.1 Cost benefit analysis

A comprehensive BMS represents a substantial investment, which is expected to bring a variety of benefits to the client. In order to make a rational investment decision, it is necessary to have some method of comparison between alternative systems. Cost benefit methods of analysis have been developed by economists, which aim to express all costs and benefits associated with a plan of action in a common unit, i.e. money, and to make rational comparisons between plans which may have different size and time scales. One important principle is that the benefits and costs must be expressed from a single point of view, e.g. better indoor air quality may be beneficial to the office worker in terms of health and comfort and it may produce a benefit for the office tenant in terms of increased productivity. However, neither is a direct benefit for the building owner, who may be able to achieve the benefit as an increased rent. Cost benefit analysis is most straightforward where the building owner, operator and employer are the same. Where they are not, it must be borne in mind that the organisation receiving the benefit, e.g. of a reduction in energy consumption, may not be the organisation that paid for the BMS.

The IEA Annex 16 task, *Cost Benefit Assessment Methods for BEMS*[30] set out to produce a coherent analysis procedure which could be used to calculate savings from BMS and assist in making investment decisions. The report concluded that no single model would become accepted; the more common methods of analysis are given in the report and summarised below. More important than the method chosen is the ability to provide good quality input data, particularly where it is necessary to compare different types of costs and savings, e.g. investment cost versus productivity gain. It is recommended that a detailed listing is prepared of the costs incurred and the benefits expected from the BMS. Table 8.8 summarises the suggested headings, which may be expanded into considerably more detail.

In a modern office building, staffing costs are much greater than energy costs. The benefits of improved staff utilisation may therefore be as much or more than the savings in energy consumption. The IEA report quotes estimates which state that the benefits of an intelligent building in terms of energy savings, increased productivity and reduction in building management costs are roughly equal; put another way, this means that the overall benefits of a good BMS may be three times the direct saving in energy consumption. Another rule-of-thumb quoted is that an overall productivity improvement of 2.5% would be enough to pay for the entire BMS.

Table 8.8 Listing of costs and benefits of a BMS

Cost/benefit	Item
First cost	Specification and design Hardware Software Installation, commissioning Training
On-going costs	Maintenance Communication costs Staffing
Benefits	Reduction in avoidable waste Savings in staffing costs Better maintenance and fault detection Improved productivity Tax implications
Life cycle factors	Replacement cost Scrap value System economic life Life of related systems

8.7.2 Life cycle costing

Life cycle costing seeks to extend the cost benefit analysis over the whole life of the project, including final disposal. It has been defined as a method that collects together all tax allowances, capital and revenue costs for each system from original installation to abandonment. As with all such analyses, the quality of the data is of vital importance. For life cycle costing to take place, the tender invitation should include separate price breakdowns as follows:

— installation cost

— annual maintenance cost of components

— cost and rate of increase of maintenance contracts

— cost of replacement items

— economic life of system and components

— minimum guaranteed period that spares will be available

— system training costs.

The relation between BMS lifetime and the lifetime of related systems may be important. IT systems in general have a shorter life than BMS. If the BMS is to be closely integrated with the IT system, there may be implications for the BMS if the IT system is renewed.

8.7.3 Assessment methods

There are several assessment methods available which are to be found in standard economic texts, e.g. Sullivan et al.[31]. It is emphasised again that good quality data is important, and that the costs and benefits should be assessed from the same standpoint. The main methods are summarised as follows.

8.7.3.1 Net cash flow

Cash flow analysis is the basis for all cost benefit analyses. For a number of periods, typically yearly, the costs and benefits of the investment opportunity are written down. The total period may extend up to the expected life of the investment, including disposal costs for full life cycle costing. Thus the cash flow table shows both the total costs and benefits and when they are expected to be achieved.

8.7.3.2 Payback method

The payback period is commonly defined as the length of time to recover the initial investment from the benefits produced by that investment; no account is taken of interest rates. Using the cash flow table described above, the net cash flow is accumulated. The year in which the total benefits equal the total cost is the simple payback period, i.e. it is the time after which the investment cost is repaid. There are several variants on the payback period and it is important to state which one is used when making comparisons. For instance, the payback period calculated by dividing the initial cost by the annual benefits does not take into account the initial period, e.g. construction phase, during which no benefits are received.

In general the payback period fails to consider the time value of money, i.e. the value of money to be received in the future is less than that of money received now, nor does it consider what happens after the payback period, e.g. the magnitude and timing of the cash flows. The payback method tends to favour shorter lived investments. Acceptable values of payback period vary with the type of organisation. Typically, payback period of three years or less are required by industry and up to 10 years by Government projects.

8.7.3.3 Discount techniques

There are several techniques based on discounted cash flow (DCF), all of which use a discount rate in the calculations, reflecting the time value of money[32,33]. The present worth method, also known as net present value, is typical. All future amounts in the cash flow table are discounted back to the start of the project. The discount rate may be thought of as the return available on money from other investments; 10% is typically used. With this method of analysis, it is possible that an investment which shows a positive net cash flow after a few years may show a negative present worth; the implication is that it would be more profitable to invest the money elsewhere. The techniques can be used for life cycle costing; the effect of the discount rate is to reduce the present value of costs and benefits which will occur more than a few years in the future.

8.8 Summary

The procurement process chosen by the client strongly influences the way in which the control system is designed and installed. The traditional procurement process separates design from construction. This provides for clear contractual responsibilities, but means that the controls specialist may be appointed late in the process and have little opportunity to contribute to the design. Design and build brings design and construction together in the same organisation. Partnering methods aim to build a stable relationship between those involved in the procurement process, enabling all parties involved to make a full contribution.

The initial project brief produced by the client is of great importance and the type of control system and the organisation of commissioning should be considered from the start.

Once the HVAC and control systems have been installed, effective commissioning is crucial. In modern complex buildings, the controls system interacts with other systems and care is necessary in planning the commissioning process and assigning areas of responsibility. The original specification should be designed both to reduce the amount of commissioning required and to make that commissioning easier. The design should be reviewed at an early stage by a commissioning specialist.

There are statutory requirements for the preparation of proper documentation, which is necessary for system operation, maintenance and refurbishment.

After the building is occupied, it must be run to provide a satisfactory working environment for its occupants. Prompt response to any user problems is important in producing satisfaction. Where there appear to be problems a survey of the building users can be helpful; standard questionnaires can be used to provide comparison with other buildings.

Decisions on how much to spend on control systems should involve the concept of life cycle costing, taking future running costs, maintenance expenditure and energy saving into account. Standard discounted cash flow techniques can be used to evaluate proposals.

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Appendix A1: Tuning rules

A1.1 The PID control loop

The basic feedback controller is illustrated in Figure A1.1. The error signal x_e is processed by a controller which produces an output signal Y, which in turn drives the controlled device, e.g. actuator and fan coil, resulting in a change in the controlled variable x. In 3.3.3.1 a description was given of how the components of the controlled device, e.g. valve and heat emitter, may be matched to linearise the heat output, resulting in an approximately linear relation between the controller output Y and the heat output to the conditioned space. However, even if the change in the output is roughly linear with controller output, the gain of the system can change with operating conditions.

When a controlled system running in a steady state is disturbed by a change in load, a change in set point or some other disturbance, the system will react. If the system is operating in a stable manner, it will sooner or later settle down in a new stable state. If the system is unstable, it will go into indefinite oscillations of increasing amplitude; in practice the size of the oscillation will be limited by the components of the system and the system will continue oscillating or hunting.

The high thermal inertia of most buildings, coupled with the slow response of traditional heating systems, has usually meant that reasonably stable temperature conditions can be achieved with simple control systems. In some circumstances, it is possible for satisfactorily steady conditions to be achieved in the controlled space even when the HVAC system itself is hunting in an unstable manner. This is bad practice, leading to excess wear of components. The trend towards lighter buildings and the use of air handling systems has increased the responsiveness of systems and so increased the possibility of unstable operation.

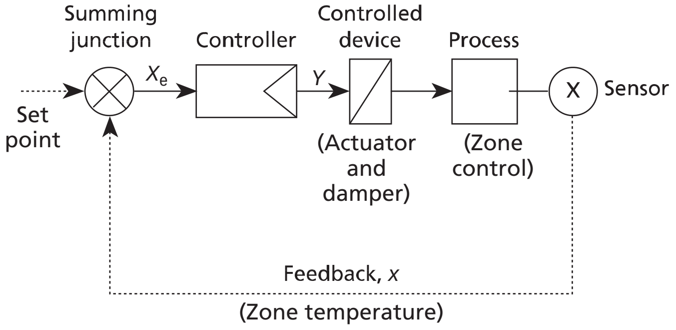

Figure A1.1 Feedback control loop

The general equation for the output of a three-term controller is:

$$Y = Y_o + K_p x_e + K_i \int_0^T x_e \, dt + K_d \frac{dx_e}{dt} \quad \text{(A1.1)}$$

where Y is the output from controller (ND, 0–1), Y_0 is the constant controller output (bias) (ND), x_e is the error (i.e. difference between set point and the measured value) (K), K_p is the proportional gain constant (= 1/proportional band) (K^{-1}), K_i is the integral gain constant ($(K \cdot s)^{-1}$) and K_d is the derivative gain constant ($s \cdot K^{-1}$).

The equation has been written in terms of the controller output as a non-dimensional (ND) quantity scaled from 0 to 1. In practice, the output would be a standard voltage or current output, or else a digital value for DDC. The controlled variable is illustrated as a temperature, but could be any other controlled variable.

The equation may be rewritten as:

$$Y = Y_o + K_p \left(x_e + (1/T_i) \int_0^T x_e \, dt + T_d \frac{dx_e}{dt} \right) \quad \text{(A1.2)}$$

where T_i is the integral action time (= K_p / K_i) (s) and T_d is the derivative action time (= K_d / K_p) (s).

Most controllers are set up this way, with independent adjustments for T_i and T_d, which are usually calibrated in minutes.

The stability of a simple system may be analysed by setting up the differential equations which describe its dynamic behaviour(A1.1). Standard analysis methods, based on Laplace transforms, are then used to check for stable operation. However, most systems are too complex for this analysis to be practical and empirical rules have been derived to assist in setting up a three-term controller to achieve the desired compromise between stability and speed of response. For completeness, the general case of a three-term controller is given. However, in most HVAC applications the derivative term is not required and is disabled by setting the derivative time to zero.

A1.2 Digital control

The above equations are written in terms of continuous analogue quantities. Digital control systems, which constitute the majority of modern systems, operate with discrete sample values of the measured quantities. The general equation for a three-term PID controller becomes

$$Y_{k+1} = Y_o + K_p \left(x_{k+1} + (1/T_i)\sum_{j=1}^{k} x_j \,\Delta t + T_d \frac{x_{k+1} - x_k}{\Delta t} \right) \quad \text{(A1.3)}$$

where Y_k is the output from controller at time step k (ND, 0–1), Y_0 is the controller offset (ND), x_k is the deviation from set point at time step k (K) and Δt is the sampling interval (s).

Equation A1.3 is similar to equation A1.2, but with the symbol changes indicated above.

The discrete sampling of the controlled variable produces some effects not found with analogue controllers. Noise or interference can cause sudden changes in the controller output. Noise affecting a single sampled value will produce a sudden change in controller output due to the phenomenon known as derivative kick; this is caused by the change in value of the derivative term $(x_{k+1} - x_k)/\Delta t$. A change in set point will also produce a derivative kick, together with the associated proportional kick; the kick lasts for only one time step but can cause unwanted movement in the controlled device. While in general a short sampling time increases the accuracy of control, it increases the effect of derivative kick.

Software techniques may be used to reduce the effect of derivative kick. A moving average of the last four sensor values may be used to reduce the effects of noise; logical filters can also be beneficial. It is possible to set an error deadband around the set point. Control action is only taken when the controlled variable moves outside the deadband; this prevents operation of the controlled device due to minor noise signals in a system that is controlling satisfactorily near the set point. Another technique is to apply the derivative calculation to the change in value of the controlled variable, rather than the change in deviation of the controlled variable from the set point as shown above; this avoids any derivative kick when the set point changes. In practice, derivative control is not implemented in most BMS controllers, since the benefits are not sufficient to justify the extra effort of setting up the controller and the risk of introducing instabilities.

Equation A1.3 is termed the position algorithm. The position of the controlled device is related directly to the output signal Y from the controller; a constant position offset Y_0 can be used if required. There may be situations where the error x is large for an extended period of time; this can easily arise during a long warm-up period. The integral term may then become very large. This will cause the controller to overshoot the set point and proper control is not established until the integral term has become dissipated. This phenomenon is known as integral wind-up and may be prevented in software by limiting the integral term to a maximum value, typically that which will produce between 50 and 100% output from the controller.

The problem of wind-up may be avoided by using the incremental control algorithm. This is based on the change between successive values of the controlled variable.

$$\Delta Y_{k+1} = Y_{k+1} - Y_k = K_p \left(x_{k+1} - x_k + \frac{\Delta t}{T_i} x_k \right) \quad \text{(A1.4)}$$

Equation A1.4 has been written without a derivative term, which is not normally used in incremental control. The change in output Y_{k+1} is used to reposition the controlled device, e.g. by holding on an actuator motor for a time interval proportional to Y_{k+1}or by controlling a stepper motor. There is no positional feedback from the actuator. The algorithm has the advantage of avoiding integral windup.

A1.3 Tuning

The aim of tuning a controller is to restore control following a disturbance as quickly as possible and to achieve stable control with a small or zero offset from the set point. These criteria interact; increasing the speed of response risks introducing instability. The controller parameters must be set to values appropriate to the system. A full analysis of the dynamic response of a controlled system is complex(A1.2) and not often attempted in practice. Several methods have been developed to estimate suitable values of the control constants.

The ultimate cycling method, also known as the ultimate frequency method, can be carried out on the intact control system. To use this method, the integral and derivative actions of the controller to be tuned are first disabled. The proportional gain setting is then increased (i.e. the band is reduced) in small steps from a low value; at each value of the band, the system is given a small disturbance by adjusting the set point. At low values of the proportional gain the controlled variable will settle down to a stable value when the set point is changed; as the gain is increased, a value will be reached when the system starts hunting. The oscillations should be steady, with neither increasing nor decreasing amplitude. The value of the proportional gain K_p^* at which this happens is noted, together with the period of oscillation T^*. The settings of the controller may then be obtained using the Ziegler–Nichols method set out in Table A1.1. This method produces a response to a step change in the set point similar to that shown in Figure A1.2. This is also known as the quarter wave method, because the amplitude of the first overshooting wave is four times that of the second.

Reaction curve methods depend on measuring the open loop response. This requires the controller to be taken out of the control loop and the response of the controlled variable to an artificial step change ΔY in controller output to be measured. Most systems will respond with a combination of time delay and first-order response. Figure A1.3 shows how the time delay T_t, time constant T_g and final change in controlled variable x may be estimated

from the reaction curve. These values may then be used to calculate the optimum controller settings. Table A1.2 shows values calculated according to a method developed

Table A1.1 Ultimate frequency method controller settings to produce a quarter-wave response (Ziegler and Nichols); K_p^* is the gain which just produces hunting with period T^*

Controller mode	K_p	T_i	T_d
P	0.5 K_p^*	—	—
PI	0.45 K_p^*	0.8 T^*	—
PID	0.6 K_p^*	0.5 T^*	0.125 T^*

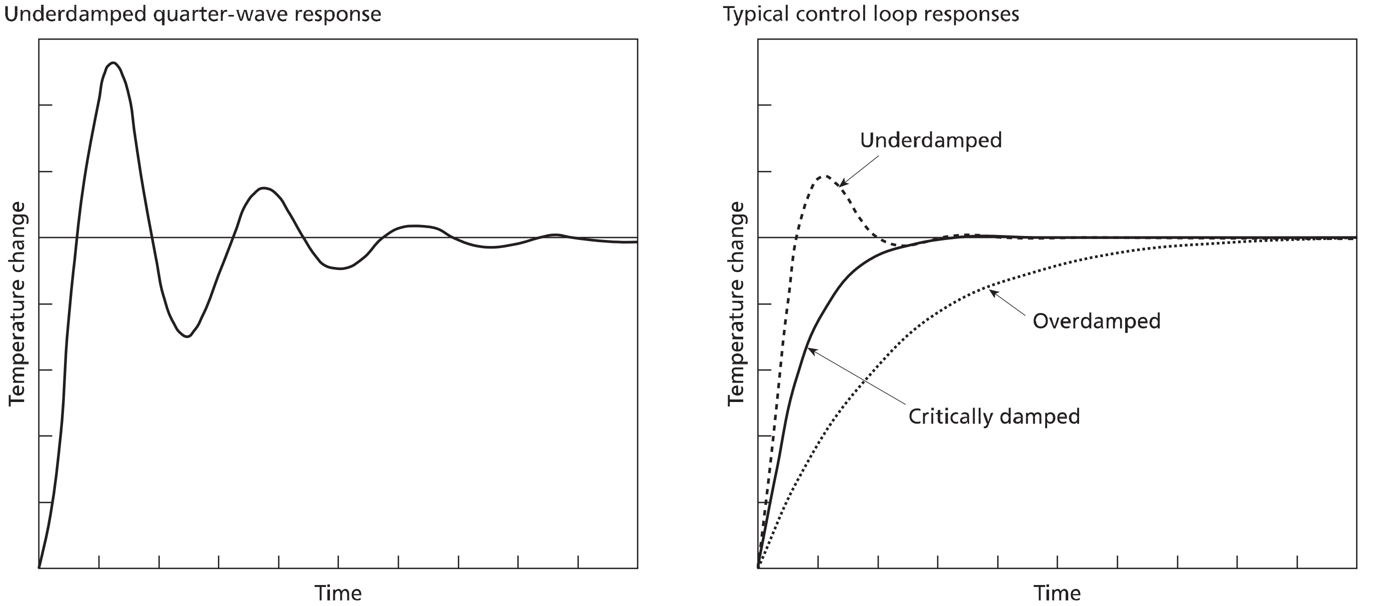

Figure A1.2 Response to a change in set point, showing underdamped and critically damped responses

by Cohen and Coon(A1.3) quoted by Kreider and Rabl(A1.4), which produces a quarter-wave response.

The quarter-wave response produced by the Ziegler–Nichols or Cohen–Coon methods may be considered too oscillatory and a more damped response is often more appropriate in practice. Control settings to produce a critically damped response may be estimated from the open loop response by a method due to Bekker(A1.5) and are set out in Table A1.2. It was pointed out at the beginning of the section that the gain of a controlled system is likely to vary with operating conditions. Control settings should be established with the system in a high gain condition. Setting the controller in conditions of low gain could result in system instability when the conditions move to high gain.

Digital controllers add a fourth setting, the computation time step, which is the interval between digital controller updates. The sensitivity of the integral term increases and the sensitivity of the derivative term decreases as the sampling time interval increases. A long sampling interval means that the controller does not receive information at a sufficient rate to operate properly and may result in unstable control; on the other hand, a very short sampling interval may waste execution time resources.

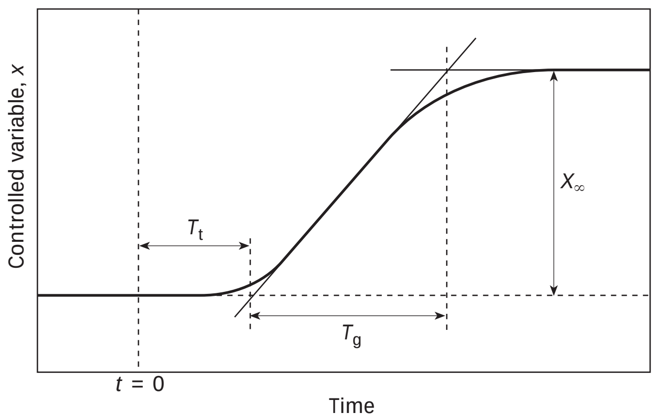

Figure A1.3 Reaction curve. Curve shows open loop response of a system to a step change in controller output ΔY applied at time $t = 0$. The values of time delay T_t, time constant T_g and final change in output x_∞ are estimated as shown.

Table A1.2 Controller settings: open loop reaction curve method. The measured variables are defined in Figure A1.3

Controller mode	K_p	T_i	T_d
Quarter-wave response(A1-4):			
P	$A\,B\,(1 + R/3)$	—	—
PI	$A\,B\,(1.1 + R/12)$	$T_i \dfrac{30 + 3\,R}{9 + 20\,R}$	—
PID	$A\,B\,(1.33 + R/4)$	$T_i \dfrac{32 + 3\,R}{13 + 8\,R}$	$T_i \dfrac{4}{11 + 2\,R}$
Critically damped response(A1-5):			
PI	$0.37\,A\,B$	T_g	—

Note: $A = \Delta Y / x_\infty$, $B = T_g / T_t$, $R = 1/B$

A1.4 Step-by-step tuning procedure

The procedure given below, to be followed for tuning a controller by either of the two methods analysed above, has been adapted from a controller manual. Settings have been quantified in terms of the proportional band, rather than gain, since this corresponds to the settings on most controllers. This description should be read in conjunction with the guidance given in chapter 2. An alternative simplified procedure is given by Borresen(A1.6).

A1.4.1 Closed loop ultimate cycling

This tuning method is carried out on the intact control loop.

(1) Connect a chart recorder to measure the controlled variable.

(2) Set the controller to give proportional action only, by the selector switch if fitted, or by setting the integral time to maximum and the derivative time to zero.

(3) Start with a wide proportional band, i.e. low gain setting.

(4) Reduce the proportional band in steps. After each reduction, make a small adjustment to the set point and observe the response. To start with the loop will stabilise with the controlled variable at a steady value.

(5) Note the proportional band setting X_p^* when the response to a set point change is for the loop to go into oscillation with a steady amplitude. Measure the period of the oscillation T^*.

(6) Calculate the control parameters from Table A1.3.

(7) Set the parameters on the controller and check how the control loop behaves in response to a change in set point. Adjust the parameters if necessary.

Table A1.3 Control parameters, ultimate cycling method

Controller mode	X_p	T_i	T_d
P	$2\,X_p^*$	—	—
PI	$2.2\,X_p^*$	$0.9\,T^*$	—
PID	$1.7\,X_p^*$	$0.75\,T^*$	$0.15\,T^*$

A1.4.2 Open loop response

(1) Connect a chart recorder to measure the controlled variable.

(2) Open the control loop by disconnecting the controller from the controlled device.

(3) Make a sudden change ΔY in the position of the controlled device, either by hand or by applying a constant voltage to the device input to simulate the controller output. ΔY is measured as a fraction of full output.

Table A1.4 Control parameters, reaction curve method

Controller mode	X_p	T_i	T_d
P	$\frac{x_\infty}{\Delta Y}\frac{T_t}{T_g}$	—	—
PI	$1.1\,\frac{x_\infty}{\Delta Y}\frac{T_t}{T_g}$	$3.5\,T_t$	—
PID	$0.9\,\frac{x_\infty}{\Delta Y}\frac{T_t}{T_g}$	$2.5\,T_t$	$0.5\,T_t$

(4) Record the change in controlled variable with time, which will have the form shown in Figure A1.3. Calculate the time lag T_t, the time constant T_g and the final change in controlled variable.

(5) Calculate the parameter settings from Table A1.4.

(6) Reconnect the controller and observe the reaction of the control loop to changes in set point. Adjust parameters if necessary.

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