62. The Smart Building

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62.1 Background

The worldwide energy used to heat, cool, ventilate, light, and deliver basic services to buildings was, on average, approximately 2.4 TW ($= 2.4 \times 10^{12}$ W) in 2004. A further 5.6 TW was attributed to industrial plants, with a large fraction of these housed in buildings such as factories, power plants, and other manufacturing facilities [62.1]. In developed countries, buildings can be responsible for as much as 50% of total energy use. These dramatic statistics coupled with the fact that human beings spend most of their lives inside buildings make this application of critical importance to the well-being of our planet and its global population.

There are many different types of buildings, ranging from simple places of shelter to highly complex ecosystems that provide a range of specialized services to support specific functions. One common purpose of buildings is to create a modified environment that is comfortable for occupants even when outside conditions are unfavorable. Comfortable conditions are maintained through the operation and coordination of mechanical and electrical systems and through the conversion of energy from one type to another. The control of indoor environmental conditions is the most common and widely exploited application of automation technologies.
technologies in buildings and will be the main focus of this chapter. Factors that affect the indoor environment are air quality, temperature, and humidity, as well as lighting, and safety from fire and security threats.

For a building to be smart it must have some form of automatic control system. Building control systems vary widely in complexity from simple mechanical feedback mechanisms to a network of microprocessor-based digital controllers [62.2]. At the latter end of the spectrum, the network of controllers is often known as the building automation system (BAS). A BAS needs to interface with physical systems in order to effect desired changes on the building, and the interfacing is usually made through means of sensors and actuators. Buildings can contain many types of physical systems, the most common of which are described in more detail below.

**HVAC and Plumbing.** In terms of energy, the most important systems in buildings are those used to heat, cool, and ventilate the indoor environment. These systems are collectively known as the heating, ventilating, and air-conditioning (HVAC) plant. The HVAC plant is used to condition the psychrometric properties (temperature and humidity) of the indoor environment as well as air quality. HVAC systems range in complexity from simple residential units that may have only heating units to advanced systems for high-performance buildings such as clean rooms and chemical laboratories [62.3]. Plumbing systems are closely associated with the HVAC plant but are often handled by a different group of companies and contractors on a building project. Plumbing serves the HVAC systems with water supplies used for heating and cooling and also handles distribution of potable and waste water. Plumbing and waste disposal systems are critical elements in ensuring occupant health [62.4]. Automatic control is widely used in HVAC systems and ranges from simple feedback loops to complex sequences of operation that manage scheduling and interactions between systems.

**Lighting Systems.** Lighting systems are responsible for a large fraction of building energy use, close to that used by HVAC for the commercial sector. Most buildings have both artificial and natural lighting and the interaction between these sources is important in creating the right level of illumination. In most buildings, both artificial and natural lighting are operated manually using electric switches and window shades. However, automated lighting systems are available and are starting to be used in modern buildings. For these systems, sensors measure illumination levels in a space and also whether a space is occupied and this information is used to regulate artificial light levels and control shades on windows.

**Fire and Security.** Fire systems are found in large buildings and include fire detection and alarming as well as sprinkler systems for abatement. Security systems are used to control access to buildings and internal areas and trigger alarms when unauthorized access is detected. Both of these systems are evolving rapidly largely due to the availability of more advanced sensor technology and imaging devices. The additional and richer sensor information available from these systems is creating new opportunities for intelligent responses to particular situations. For example, having knowledge of where people are located in the case of a fire can be used to manage evacuation routes, improve emergency response team planning, and also provide input to the HVAC system to mitigate the spread of smoke.

**Specialized Systems.** Many buildings require specialist services to support specific tasks and functions. For example, a hospital might require oxygen supply and distribution and fume hoods for extracting dangerous and toxic chemicals. In common with other building services, these systems require piping or ducting for containment and distribution, and pumps/fans, valves, and dampers for fluid movement and control. Localized power generation and combined heat and power plants that use waste heat from electricity generation to power heating and cooling systems are also found in some buildings or campuses. These systems may include renewable sources of energy such as solar, wind, and geothermal, and other power generation technologies such as fuel cells and microturbines. Specialized systems, and in particular those that are packaged, often have dedicated embedded controls, but in some cases the BAS might be deployed to provide some higher-level control and supervision.

**Supporting Infrastructures.** Modern buildings contain systems powered by electricity and an increasing number powered by natural gas. Buildings therefore need to have a distribution network for these energy supplies. Key components include wiring, switch panels, circuit breakers, transformers for electricity, and valves, piping, and various safety devices for gas. Another key infrastructure in modern buildings is that associated with information technology (IT). The IT infrastructure in a building is usually considered to be separate from the other systems mentioned so far because it is han-
A building is made smart through the application of intelligence or knowledge to automate the operation of building systems. In modern buildings, the intelligence or smartness of building operation is encapsulated in algorithms, which are implemented in software on microprocessor-based computing devices. Many of these computing devices are part of the building automation system, which can be decomposed into the following four main components:

- **User interface** – allows exchange of information between a human operator and the computer system
- **Algorithms** – methods or procedures for performing certain tasks such as control and automation
- **Network** – includes information transmission media (e.g., wiring), routers, and appropriate encoders and decoders for sharing information among devices
- **Sensors and actuators** – these represent the interfaces between the computing systems and the plant.

The user interface, network, sensors, and actuators are critical components of a **BAS**, but these are all enabling technologies that only provide the means by which the intelligence inherent in the algorithms can be applied. The algorithms fundamentally determine the operational behavior of the controlled systems and are the source of the smartness. In a typical building, numerous objectives can be defined suitable for the application of control methods. Examples are regulating a room temperature to a set level, turning off systems at a certain time, and controlling access to a room based on information read by a card reader. Controlling a variable, such as temperature, to a set level is probably the most common control objective and is most often carried out using feedback. Feedback is a fundamental building block of control and automation and its application in buildings will be discussed in more detail in Sect. 62.2.

Recent technological advances in information technology, including networking, computing power, and sensor technology, have meant that the number of controllable devices in buildings has proliferated. Not only are there more devices to control, but information can now be shared more easily between disparate systems. Information is more easily accessible both within system groups as well as across different groups. The **HVAC** group of systems is particularly notable in making information available to the **BAS** from multiple types of subsystems including boilers, chillers, fans, pumps, cooling towers, and measured by numerous types of sensors. Opportunities abound within just the **HVAC** group of systems for applying control strategies that take advantage of the available data to improve overall system performance.

The idea of combining information from different systems to implement new and smart control and automation strategies extends easily to system groups that traverse traditional boundaries. The example of combining data from the fire and access control systems to provide improved emergency response information and also more effectively manage evacuation was cited earlier. Another example is in utilizing access control data to estimate the number of people in a building and then using this estimate to operate the **HVAC** systems more energy-efficiently. Although huge potential exists for coordinated system operation, the reality today is that the handling of interactions is limited and in most cases ad hoc. However, despite the primitive nature of
Building operation is not the only way in which buildings have been made smarter. The lifecycle of a building includes its planning, design, construction, installation and commissioning, operation, maintenance, retrofit and remodeling, and destruction. Each of these tasks not only consumes energy and resources, but affects subsequent tasks. For example, a building will only operate energy-efficiently if it has been correctly designed and constructed. New and smart technologies are being utilized at each stage in the lifecycle to improve the overall process. A prime example is in being able to simulate the performance of a design before it is built [62.5]. This is a powerful technology that can lead to cost and energy savings for a project. The ability to simulate building systems is also enabling the development of innovative algorithmic smart technologies such as automated design and optimization [62.6].

It is also important to mention the significant energy and resources used during the construction phase of a building. Energy is used at every step; from the production of the building materials, to their transport to site, through to the operation of machines for excavation and assembly of the materials. The businesses devoted to this one phase of the building lifecycle are numerous, diverse, and employ various forms of automation to enhance efficiency. The term smart is frequently encountered in various construction technologies including prefabricated components, advanced supply chain and project management, and on-site machinery, to name only a few examples. However, the term smart buildings has come to mean smart operation more than anything else, and for this reason the operation phase will be the focus of this chapter. The smart operations, enabled by technological advances, guarantees cost savings in construction and operations, and improved functionality [62.7].

### 62.1.2 Historical Perspectives

Modification of the environmental conditions inside buildings is not new, with records showing that the ancient Egyptians used aqueducts for cooling as long ago as the second millennium BC [62.8]. Heating systems were also used by the Romans in 100 AD in their northern territories based on underfloor distribution of air heated by furnaces [62.9]. From the perspective of the building plant, evolution had been slow until the advent of commercially viable electrical air-conditioning systems in the first decade of the 1900s. The origin of these systems can be traced to discoveries by Michael Faraday in 1820 on how to create a cooling effect by compressing and liquefying ammonia, but it was the commercial success of the early electrical air-conditioners that triggered a new interest in the indoor environment and its control. Activity in this area was probably at its height in the first half of the 20th century. During this period, the field of heating, ventilating, and air-conditioning (HVAC) would have been considered a high-technology field that posed some of the most interesting engineering challenges of the time [62.10].

The application of automation technology to buildings has paralleled its application to other industries, with the idea of feedback playing a central role. The feedback concept is a fundamental element of automation and has a history of its own dating back to the water clocks of the ancient Greeks and Arabs [62.11]. The Dutch inventor Cornelis Drebbel is credited as creating one of the first feedback temperature controllers for a furnace in the early 1600s [62.12]. The first thermostats for space temperature control using heating plant appeared in the late 1800s. The thermostat feedback system is an implementation of an intelligent human concept, or procedure, to solve the problem of temperature regulation. These early applications of automation thus led to the creation of the first smart buildings. Implementation of feedback and other control methods originally used mechanical transmission of information, such as pneumatics. These systems were replaced by electrical devices with controllers first being implemented using analog circuits. Today, most analog controllers have given way to digital devices where earlier feedback strategies are now implemented as algorithms in software.

The feedback concept has remained central in building automation. It is the most common type of control strategy and is used to control everything from air-conditioning to lighting to fire and security to toilet flushing. Although the common room thermostat principle is still widely used, building automation systems now encompass an evermore sophisticated array of control algorithms that not only provide regulation of individual variables to setpoints, but also provide high-level coordination and management of building assets.
62.2 Application Examples

Possibly excepting certain types of chain stores, every building is different, having a unique mix of structure, geometry, orientation, location, number of people, and types of building plant. The control and automation systems mirror this bespoke nature and are usually specific to each particular building. Finding common elements of control logic that run across all building types is therefore a challenge. This problem is particularly exacerbated at the higher levels of control logic hierarchy that are used to coordinate the operation of different systems. The aim of this section is to identify and review a sample of control strategies that are generic and found in buildings of different types. Although these strategies are outnumbered in practice by ad hoc and rule-based logic, they usually have a better scientific basis and are more easily adapted and scaled across different buildings.

62.2.1 Control without Feedback

A very simple and yet effective form of building automation is to operate systems based on a time clock: for example, a heater in a building could be turned on at a certain time every day and turned off at another time. These times can be determined from some expected behavior that is known to be linked to time, such as people coming in to work, or even the sun rising and setting. This kind of control logic can be used to control everything from building access, lights, and HVAC. Time-based control is also a type of event-triggered logic where the event being monitored is time of day. The strategy does not contain feedback because time is unaffected by the action of the systems being operated. Time-based operational scheduling is commonplace in modern buildings as an overriding or supervisory logic even when more advanced control and building management strategies are employed. The logic is usually implemented as rules such as: IF TIME = 9.00AM TURN ON CHILLER; IF TIME = 5.00PM TURN OFF CHILLER.

Closed-loop control is synonymous with feedback control. Open loop refers to the case where no information associated with the controlled variable is used in deciding how to adjust the manipulated variable; the loop is thus open. In the HVAC industry, reference is sometimes made to open-loop operation. In most cases this involves having an operator make adjustments to a manipulated variable manually. However, if the operator is making adjustments in response to observations of the controlled variable, this is not truly open loop because the operator is providing the feedback mechanism. An example of this is when a room in a building has a heating device that can be either on or off but only activated by a human operator. When the room is too cold the person will turn on the heater and when it is too hot they will turn it off. Manual operation of this sort is common in buildings and may be carried out by a dedicated building operator who oversees plant operation. In many situations, preexisting automated feedback systems may be overridden by the operator because of lack of confidence or trust. The operator then manually adjusts things such as control valves and dampers to maintain comfort conditions.

62.2.2 Feedback Control

Single Loop

Feedback control is the most widely used automation concept in buildings, with the temperature thermostat being the vanguard of this strategy. Early examples of these devices were based on pneumatics and mechanical transmission of information [62.13]. Modern buildings use thermostats that contain a temperature sensor and a small integrated circuit that determines when the temperature is outside an acceptable range. The thermostat triggers a switch to operate a device which is then expected to bring the temperature back into its acceptable range. Thermostatic temperature devices usually require specification of a setpoint and a control band. A device would be switched either on or off whenever the measured temperature was outside of the control band, which surrounds the setpoint. Figure 62.1 shows an example thermostatic control strategy for a heater in a room with a setpoint of 20°C and a control band of 1°C. There is a trade-off between the closeness of control, determined by the control band, and the wear and tear on the equipment resulting from cycling between on and off states. Some equipment types may also have constraints on how long they can remain in an on or off state and these are called minimum on and off times. The maximum cycle frequency is the reciprocal of the sum of the minimum on and off times.

Thermostatic control is an example of single-loop feedback control where the controller is a switch or relay-type device that has infinite gain. The switching of the controlled device causes oscillations to occur in the controlled variable around its setpoint. These oscilla-
tions are usually undesirable, especially if the amplitude is large due to minimum on and off times being large relative to the dominant time constant of the controlled device. One way to avoid oscillations is to use a physical device whose output can be modulated. Instead of being only on or off, the device output can be modulated by manipulating an input between 0 and 100% of its range. Having a manipulated variable that can be varied opens the way for finite-gain controllers to be used in feedback loops. Modulated systems make up about two-thirds of controlled devices in buildings, with switched systems representing the other third.

Proportional, integral, and derivative (PID) action controllers are the most common type of finite-gain controllers used in building feedback loops. These controllers modulate the input to the controlled device based on the difference between the setpoint and the controlled variable, and the theory behind the algorithm is well established \[62.14\]. Proportional-only (P) controllers are still common in buildings where control exactly to setpoint is not critical. As is well known, these controllers yield a steady-state offset from setpoint and, when this is not desirable, proportional–integral (PI) controllers are used. This complexity of feedback control works well for most building control loops that are dominated by one time constant. The integral action of the controller ensures that the error signal can be maintained at zero and proper tuning allows good control without oscillations for most loops. Adding the derivative action can yield better results for common applications such as room temperature control, but the drawback is that tuning is more difficult.

PI(D) controllers can also be used in buildings to control switched devices. This is achieved by using an element in the control loop that converts the output signal from the controller (usually between 0 and 100%) to a pulse train (either 0 or 1). Pulse-width-modulation (PWM) logic can be used to provide this conversion, as illustrated in Fig. 62.2. PWM and other variants have been applied to HVAC system applications with promising results \[62.15\].

Although the PI algorithm is well established and almost ubiquitously deployed for building control, it has been recognized for some time that control performance is often poor in practice. One reason for this is that many plant items in buildings are nonlinear. When a PI controller is used to control a nonlinear system, its performance will vary with operating point. In severe cases, the control might be too aggressive, causing oscillations at one point and yet be too slow at another. These kinds of performance problems can jeopardize comfort and energy use and also wear out equipment. There are several methods for counteracting nonlinearity that are used in nonbuilding applications, such as gain scheduling and model-based control \[62.16\]. The research community has investigated using some of these methods in buildings including generalized minimum-variance control \[62.17\] and model-based control \[62.18\]. However, the industry has been reluctant to adopt these methods because of the extra time (and money) required for setup and tuning. More successful approaches in the building industry have been those that are self-tuning or automatically adaptive to changes; examples include neural networks \[62.19\] and pattern-recognition adaptive control \[62.20\]. The latter method of Seem has been commercialized and is applied.
Multiloop feedback control strategies are used in buildings, with the most common being cascaded control. In these configurations, there is an inner loop that controls a fast variable and an outer loop that controls the setpoint of the inner loop based on the feedback of a slower variable. An example is the control of variable-air-volume (VAV) boxes for regulating room temperature, as illustrated in Fig. 62.3. These boxes are supplied with conditioned air from a central air-handling unit and they can control the flow of conditioned air to a room by means of a damper. In the inner loop, the controlled variable is the airflow rate entering the room. In the outer loop, the controlled variable is the room temperature. The outer loop tries to control the room temperature to its setpoint by modulating the setpoint for the airflow in the inner loop. In turn, the inner loop tries to meet the airflow setpoint by modulating the VAV box damper. Cascaded control allows a control problem to be separated into two parts, one with slow dynamics and the other with fast dynamics. Each type of fast and slow disturbance is then handled by a separate controller, with improved performance compared with having just one controller. A general guideline for cascade control is that the inner loop should be at least three times faster than the outer loop. Further guidelines for implementation can be found in [62.14].

Multivariable control in the sense of having centralized controllers that are multiple-input multiple-output (MIMO) is not typical in building applications. The most common situation is to have multiple feedback controllers that do not share information with each other. For example, a large open-plan office space might have several controlled temperature zones that have separate feedback controllers. An obvious problem with this approach is when there are interactions between zones due to effects such as interzonal airflow. Poor performance in one zone can then propagate to other zones if interactions are strong. Current practice involves trying to minimize interactions by positioning sensors away from each other and making sure that control zones are separated.

There is generally significant interaction amongst building systems and in many cases operation could be improved through application of multivariable control methods. Model-based approaches are one way of handling multivariable systems and these methods have been investigated and applied to buildings, e.g., [62.21].
Optimum start and stop strategies are often combined with night-setback. Instead of just turning all systems off during unoccupied periods, night setback control maintains closed-loop control on space temperatures but at different setpoints. During the heating season, for example, temperatures inside the building would be kept lower during the unoccupied period, but only low enough that recovery time would be rapid enough and losses of energy stored in building materials minimized so that this stored energy can be carried over to the next day to reduce overall energy use. Various algorithms have been proposed for predicting the night-setback setpoints and startup and shutdown times based on models and optimization and the use of thermal storage systems, e.g., [62.23, 24]. Integrated optimum start and stop with night-setback algorithms are available from some control vendors, and tuning and setup requirements depend on the particular algorithm that is offered and the systems that are targeted for control.

Another higher-level control strategy that uses feedforward is setpoint reset, where the setpoint of a feedback loop is adjusted based on a feedforward variable; for example, the setpoint of the main supply of conditioned air to a building can be made a function of the outside air temperature. The setpoint would be adjusted to be higher when the outside air temperature is low and made to be lower if the outside temperature is high. The setpoint of cold and hot water supplies generated by building chiller and boiler plant are other variables that are sometimes linked to reset strategies based on outside air temperature. Most of these algorithms adjust setpoints between two specified limits as the outside air temperature varies between upper and lower bounds. Setup and tuning of these reset strategies usually requires specification of the upper and lower values for the setpoints and the outside air temperature.

Feedforward control can also be used to supplement feedback control in situations where disturbances such as changes in airflow and outside temperatures can be measured in systems such as air-handling units [62.25]. The advantage of supplementing feedback with feedforward is that the effect of disturbances can be mitigated when they occur instead of having to wait for their effect to be revealed in the feedback variable. It is unfortunate that many disturbance signals in buildings are in fact measured but not used in the control strategy. The number of potentially useful signals is also increasing as more types of systems become integrated in the BAS; for example, signals from lighting occupancy sensors could be used to improve the control of the HVAC systems by adjusting capacity based on anticipated changes in loads.

Economizer control is a very common energy-saving strategy, particularly in the USA, that is used to reduce cooling loads by switching the air source to the main air-handling systems between recirculated (with a mix of minimum outside air) and 100% outside air. An economizer strategy evaluates the temperature or enthalpy of the two potential air sources and issues control signals to dampers to provide an air supply to cooling heat exchangers with the aim of reducing required cooling capacity. This control method is usually part of sequencing logic that is used to coordinate the operation of heating, cooling, and recirculation systems. The energy saving potential of economizer control has been shown to be as high as 52% [62.26], but results depend on climatic conditions. Both temperature and enthalpy measurements are meant as proxies for the eventual cooling load. Improved results could thus be obtained by using more accurate methods for predicting loads, e.g., by using thermodynamic models of the cooling plant. Today, control vendors normally only offer a choice between temperature or enthalpy economizer strategies. In most cases, enthalpy-based strategies will yield more energy savings, but results can be inconsistent because most humidity sensors, which are used to calculate enthalpy, are notoriously inaccurate.

Peak load management is an aspect of energy management that has received increased attention in recent years. This is mostly due to the fact that utility companies often tie energy tariffs to peak demand statistics, thereby creating incentives to minimize peaks and flatten the load profile. The strategy is commonly termed demand limiting and involves shutting down the operation of certain plant items to keep demand below target levels. The concept is illustrated in Fig. 62.4, which shows how building demand is kept below a target level by shedding loads. The objective of this strategy is to control peak demands while at the same time minimizing the disruption to control objectives such as comfort conditions within the building [62.27]. Unresolved research issues are how to set the targets and how to determine the order and time over which equipment
loads should be added and removed. Currently, the algorithms available from control vendors for demand limiting require the user to set targets based on expert knowledge, which leads to very variable results from these strategies.

The discussion so far has focused on energy management and control of HVAC systems. The reason for this focus is that this group of systems usually represents the only example of where algorithms with more sophistication than simple scheduling and feedback can be found in contemporary buildings. Although more sophisticated system types are being integrated into the BAS network, the control strategies for these systems are normally primitive and frequently just provide a means for centralized manual operation. However, the potential for more sophisticated control and coordination of systems such as lighting, fire, and security has been recognized for some time and examples of specialized buildings with more sophisticated control strategies can be found. Some of the ideas implemented in these showcase buildings are beginning to trickle down to the rest of the building stock but the rate of adoption is slow, mostly because of cost constraints. Lighting systems are one example of where the use of more sophisticated control can overcome cost constraints by reducing energy use. Traditionally, lights have been controlled manually as a form of open-loop control. However, studies have shown that the implementation of automated feedback signals such as occupancy measurements and outside light sensors can be very effective for control and energy reduction [62.28]. More advanced control is also starting to appear, making use of additional controllable elements such as shading devices that can be used to regulate the inflow of natural light into a space [62.29].

This section has only provided a brief overview of a sample of energy management strategies in buildings. Further examples related to HVAC can be found in [62.30]. The demand for these kinds of strategies is growing in response to higher energy prices and increased environmental concerns, and the computing and networking infrastructure needed to perform this kind of plant-wide control is becoming more widely available. Most energy management strategies are implemented as supervisory logic on top of lower feedback control loops. In controls terminology the combination of this kind of supervisory logic with low-level feedback control is known as hybrid control. Design of hybrid control strategies in buildings is becoming more formalized due to the availability of new software design tools; for example, the lower-level control strategies might be designed using block diagrams and transfer functions and the supervisory logic designed using state-machine logic diagrams. Modern software programs also allow control logic to be simulated before being implemented, which greatly improves reliability and lowers development costs.

62.2.4 Performance Monitoring and Alarms

Control and operational automation is the most common application of intelligence in buildings. However, recent years have seen a growing interest in intelligent monitoring and analysis of operational performance [62.31]. This has paralleled similar research and application in other industries such as aerospace, chemical processing, and power generation. The most pressing need for monitoring and analysis technologies is to detect faults that could jeopardize performance and, more importantly, safety. The concept of generating an alarm when a critical variable is outside of acceptable bounds is the simplest implementation and is employed quite widely in modern buildings. Although the idea is simple, setting the alarm limits requires intelligence and in some cases may need to be periodically adjusted to cater for changing conditions. A detailed discussion on safety warnings in automation is provided in Chap. 39.

Recent years have seen a demand for more sophisticated performance monitoring and analysis, beyond simple alarming [62.32, 33]. The motivation for this derives from a recognition that control and automation of system operation frequently fall short of expectations. Poor performance can be caused by many things, ranging from faults and deteriorations in the plant, badly tuned controllers, wrongly implemented control logic, to sensor or actuator malfunction. There is also a drive to increase the automation of analysis and operational oversight tasks that were previously carried out manually, not only to reduce costs, but also to help operators deal with the overwhelming amount of data now
available to them through modern building automation systems.

The associated problems of performance analysis and fault detection and diagnosis primarily involve transforming data available from sensor measurements and control actions into variables related to performance that can be compared with expectations, as illustrated in Fig. 62.5. An example of a performance variable is the coefficient of performance (COP) of a chiller, which is calculated from several temperature and power measurements. Fault detection involves comparing performance variables with expectations and making a binary decision as to whether a fault exists or not. Fault detection is therefore very similar to simple alarming except that the variables being monitored are not raw measurements, but derived from them using models, statistics, expert rules or some other transformation method. Fault diagnosis is more complicated and can be broken down into locating the source of the problem, matching symptoms to a cause, and estimating the magnitude of the fault. In a building, a hierarchical approach might start with the detection of higher than normal energy use, get narrowed down to one air-handling system, and subsequently to a valve on a heat exchanger. Finally the fault might be diagnosed as a valve leakage and estimated to be 50% of maximum flow.

The problem of performance monitoring in buildings is also suitable for the application of single-input single-output (SISO) loop monitoring techniques developed for other industries. Measuring the variance of controlled variables and comparing with theoretical benchmarks for example is one method that has been successfully deployed in many industries [62.34]. However, variance of control variables is normally less important in buildings than in other manufacturing-type industries where product quality and profit is directly correlated with control variable variance. One of the biggest problems in buildings lies in detecting problems with the plant such as leaking valves, stuck dampers, sensor failures, and other more prevalent malfunctions [62.31].

### 62.3 Emerging Trends

As mentioned at the start of this chapter, buildings can be viewed as large processes with many interacting and diverse systems operating together to achieve various objectives. In this way buildings are broadly similar to other applications such as chemical processing, power generation or oil refineries. A building has numerous manipulated variables and measured signals like these other systems. The challenge lies in how to connect the variables together and what algorithms and logic to deploy between these linkages. Figure 62.6 illustrates the concept of how algorithms and logic routines link manipulated and measured variables.
One trend that is still emerging in some sectors of the buildings industry but is already mature in other sectors is the deployment of IT infrastructure to provide a backbone that allows all sensors actuators and other devices to be visible on a single network. This is part of a more general trend toward the convergence of the building automation and information technology systems in a building. Having an IT infrastructure in place that links disparate building devices facilitates the development of advanced control and operational management algorithms that take advantage of the plant-wide data. Energy management strategies that were mentioned in Sect. 62.2.3 are one example of algorithms that combine information from different subsystems to attain an overall objective. Application of these types of building-wide optimization is likely to increase in the future with the demand driven by rising energy costs and increasing environmental concerns.

IT infrastructure and networking is constantly evolving, making it easier to connect and redistribute devices; for example, wireless networking is becoming more popular in buildings because it reduces wiring costs and makes it easier to reconfigure spaces and move sensors from one location to another. The general trend is also for a greater diversity of devices to be connected to the network and for each device to contain some level of embedded intelligence. These so-called smart devices are part of a trend toward distributed computing. Distribution of computing functions across devices makes a system less prone to catastrophic failure and allows problems to be broken up into smaller pieces and solved using many low-cost devices rather than one high-cost computing engine.

The development of automation algorithms and control techniques has lagged that of hardware and IT infrastructure. Many opportunities therefore now exist for making better use of the information available from a building automation network to improve operation and control and address higher-level objectives such as minimizing energy use. One particularly underdeveloped topic is that of coordinating the operation of different building systems; for example, taking into account the interactions between lighting and HVAC could potentially yield large energy savings for many types of buildings [62.35]. Another example is food retail buildings that use refrigeration systems to keep products cool. Refrigeration systems generate heat and affect the indoor environment in these buildings but their operation is not usually coordinated with the HVAC plant. Combining information from security and access control systems to predict the number of people in a space for improved climate control is yet another example, mentioned earlier, of how information from one subsystem could be used to enhance the operation of another.

Continuing with the theme of IT infrastructure providing new opportunities for higher level-plant coordination, recent years have also seen the deployment of multibuilding control and operation management [62.27]. The concept here is to tie together several buildings and have operational oversight and alarm management handled in one location rather than in each individual building. This allows for centralized data processing and the possibility for a smaller group of highly qualified operators to spread their expertise over multiple buildings. The approach also opens the way for peer-based benchmarking and performance monitoring that can be particularly advantageous when many buildings are of the same type [62.36].

The discussion so far in this section has identified some potential opportunities for control and operational management that are the result of having more information from multiple diverse systems available on a network. Capitalizing on these opportunities often requires combining ideas and methods from different mathematical disciplines. This has been an emerging trend in recent years with a common example being the combination of statistics and control theory such as when employed in statistical process control [62.37]. Other examples are the use of economic ideas as a way to instigate distributed optimization. The availability of real-time energy prices in certain geographical areas is an example of using economics to encourage distributed optimization of load profiles with the aim of evening out the loads at the power plant [62.38].

The idea of using market-based theories is also beginning to be seen as a viable strategy for optimizing the operation of systems within a building. The way in which building systems are designed and implemented is inherently distributed, with small amounts of processing power usually available locally at each device rather than concentrated in a central location. Furthermore, the number of variables in a building and the complexity of interactions and nonlinear behaviors can make a centralized approach to optimization unviable. The metaphor of each device being an agent working to optimize its own objective function according to constraints and general guidelines is an emerging field of research with the aim being that overall building performance would reach some optimum behavior without the need for centralized optimization. This idea is beginning to be explored for building applications [62.39].
and has already been applied to problems in other applications [62.40].

The expansion of control methods and plant operational management ideas that has occurred in other applications is highly relevant to buildings and many of the most promising ideas are beginning to be explored and adopted. The general subject of plant performance assessment and auditing is one example where advances from other applications are being adopted. Some control vendors now offer automatic trending and benchmarking of performance indices that are not just raw measurements, but quantities derived from physics and/or statistics. The methods of analyzing these performance indices and ways in which they can be presented to a user are emerging areas of research and application. The goal of this work is to be able to quickly detect problems and narrow down the cause so that downtimes are reduced, performance is more consistent, and maintenance can be more proactive and targeted. One popular approach is to group together operational statistics from multiple plant items that are of similar type and look for outliers amongst the set as a way to identify faults. Figure 62.7 illustrates this approach based on actual exponentially weighted moving averages (EWMA) of the setpoint error signal for VAV boxes in a large building [62.41].

An extension of the concepts of detecting and diagnosing problems is to make the control system able to adjust automatically so that the building can become fault-tolerant. Buildings usually have many different types of systems that can be used to compensate for each other; for example, a problem identified with cooling capacity that is affecting the temperature of conditioned air could be compensated for by operating the fans at higher loads to increase airflow. This redundancy is already (inadvertently) used to create fault tolerance in buildings by having multiple closed-loop control strategies that sometimes compete with each other. This creates problems for more conventional methods of fault detection that only check whether setpoints are being maintained because the effects of a fault are masked by the competing closed-loop controllers. Hence, there is increasing awareness that fault detection and diagnosis methods need to share information with the control strategy and be combined for the most effective solution [62.42].

The buildings industry is notoriously fragmented with multiple parties involved in the various lifecycle tasks of, among others: design, construction, occupation, maintenance, and renovation. An emerging area is the application of information management to a building lifecycle. Recent years have seen concerted efforts to standardize various aspects of a building process, ranging from standard data models for building geometry and plant description [62.43] to communication protocols for automation system networks [62.44]. The general goal of these standardization efforts is to improve the efficiency of passing information and also reduce the costs and risk of developing and marketing new products such as software. The proliferation of web-based commerce is testament to how standard (and stable) infrastructure can be an effective stimulant to innovation and technological progress.

### 62.4 Open Challenges

Although buildings can be considered similar to any other large-scale process, there are some unique issues that can hamper efforts to make buildings smart. Primary systemic issues in the building industry are that it is low cost, fragmented, and risk averse. The way in which buildings are financed is geared toward minimization of capital costs. Most contracts are awarded on a lowest-cost basis and this means that the operational costs of a building and other lifecycle costs are deemphasized. The result is that...
operational performance of the building is frequently compromised through poor design and poor-quality installation and maintenance. Several studies have shown that proper commissioning of buildings can lead to large energy savings and improvements in system performance [62.45]. Cost pressures also lead to the installation of low-quality sensors and actuators that detrimentally affect control performance. A related problem is when too few sensors are installed, causing measurements to be inaccurate and control performance and energy use to be affected.

At the control hardware level, cost constraints lead to minimal memory and processing power in local controllers and also low-resolution analog-to-digital and digital-to-analog converters. Eight-bit converters are still commonplace and the level of signal quantization can be severe enough to cause oscillations in feedback loops. Quantization can also corrupt signals, which makes later analysis and diagnosis of problems more difficult. Another source of quantization is logic that is included on a network so that data are only sent when there is a change of value beyond a certain threshold. This strategy provides data compression and network traffic minimization but it severely affects the signals being filtered and poses problems when trying to analyze data for control performance assessment and diagnostics [62.46].

The level of education and training tends to be low for building operators, also because of cost constraints. This means that there is often difficulty in understanding the processes in a building, their interactions, and the role of the control system. It is common therefore for operators to quickly shut-off control logic that they do not properly understand. The situation then arises of having many loops in a building left in override mode, leading to suboptimal and effectively open-loop, or no, control of the building systems. The primary objective of most operators is also to keep the occupants comfortable and respond to hot and cold complaints. The energy efficiency of the building is usually secondary and draws little attention. The lack of consideration for energy use is due to the still relatively cheap cost of energy and also the lack of performance indicators that could help identify energy problems.

The discussion so far has centered on barriers, both industry-systemic and technical, that impede the development, application, and deployment of new smart-building algorithms and technologies. However, many of these barriers can be overcome by adapting smart control and operational management methods to the unique aspects of the buildings industry; for example, the problem of too few sensors can be addressed by using models to predict measurements to create virtual sensors based on analytical redundancy. Signal processing methods can be used to reconstruct quantized data, and robust control theory can be used to minimize the effect of slow sampling and potential jitter. Buildings can benefit from the application of methods and algorithms developed in other diverse fields but these methods have to be adapted to the specific issues of the buildings.

Another open challenge is to integrate the diverse array of systems in buildings into a common information-sharing framework. Although this has already started to happen with the advent of open protocols for network communication, the full potential is not yet realized. One reason for this is that buildings contain a very diverse group of systems that are made by many different manufacturers, all with their own embedded controls and electronics. The commoditization of certain building systems such as packaged cooling units has brought down costs, but these systems rarely have external communication interfaces to allow interconnectivity with other systems because of the extra costs this would incur. Although interconnection of building devices is a key to unlocking untapped energy and operational efficiencies, this cannot happen without algorithms and control methods that can take advantage of the newly available information. There is therefore a dilemma because both aspects are needed, and business will be reluctant to invest in development of just one aspect without the other being already available. Possible future avenues that could alleviate some of the barriers to connectivity are solutions such as power line networking, utilization of an existing IT backbone, and general lower-cost solutions for plug-and-play networking.

The issue of energy efficiency has again come to the fore in recent years, and this has led to new legislation and various certification programs being established in several countries around the world to encourage the design and construction of so-called green buildings. Even if financial incentives are lacking, increased concern over the environmental impacts of wasteful energy use within populations is exerting pressure on the construction industry to portray a greener and more energy-efficient image. The most visible sign of a response to these pressures is in the design and construction of modern buildings. There are several examples of new buildings around the world that make such efficient use of sunlight and wind through smart design that they can eliminate the need
for mechanical heating/cooling and ventilation and almost eliminate the need for artificial lighting when sunlight is available. The manufacturers of electrical and mechanical systems are also responding to energy concerns by producing more efficient equipment that is often certified by government or other third-party organizations. However, the challenge is for the automation systems and especially the control algorithms to keep pace with the rapid evolution of buildings and inherent equipment. Failure to keep pace will result in buildings operating well below their intended efficiency levels.

62.5 Conclusions

The operation of many aspects of a building is now automated, ranging from temperature control to fire and security. The general trend is for the operation of more systems and appliances to be automated and for these to be connected to a common network. The availability of common networking infrastructure is also stimulating the demand for more advanced control and operational management methods that take into account system interactions and facilitate the optimization of building-wide criteria such as energy use. However, the adoption of IT infrastructure has in many ways outpaced the development of algorithms and automation methods that can capitalize on these advances. There is also the problem of operators not being able to cope with the abundance of data now available on BAS networks. Again, this problem is exacerbated by the lack of algorithms for processing and reducing the data into more manageable statistics or performance reports.

The complex and bespoke nature of building systems makes it difficult to develop and apply generic algorithms and, on the other hand, it is too costly to tailor algorithms to every building system. This issue is difficult to resolve but is being alleviated by standardization and commoditization of building systems. New model-free algorithmic methods for control and optimization have the potential of being able to adapt to different system types without requiring significant engineering effort or tuning. In combination, these developments may help overcome some of the barriers to the adoption of new technology for improved energy management and control in buildings.

References


