

CHAPTER 39

OPERATION AND MAINTENANCE MANAGEMENT

<i>Operation and Maintenance as Part of Building Life-Cycle Costs</i>	39.1
<i>Elements of Successful Programs</i>	39.2
<i>Automated Fault Detection and Diagnosis (AFDD)</i>	39.5
<i>Documentation</i>	39.7
<i>Staffing</i>	39.8
<i>Managing Changes in Buildings</i>	39.9

EFFECTIVE operation and maintenance is essential for cost-effective provision of the built environment that humankind enjoys today. To derive the greatest return on existing building stock, and to ensure future generations will continue to enjoy these benefits, the built environment must be sustainable. A significant component of the sustainable facility is the way the structure and its systems are operated and preserved for the long term. This chapter presents several strategies, methods, procedures, and techniques for operation and maintenance management programs that minimize asset failure and preserve system function to deliver their intended purpose.

Evolving building system complexity and increasing operating costs demand that equipment and systems providing thermal comfort and beneficial indoor air quality be properly maintained to achieve energy efficiency and building owners' reliability requirements. These factors clearly imply that a highly organized, systematic approach for properly and effectively functioning building assets is necessary to achieve a successful maintenance program. Maintenance management is the formal effort required to plan, design, and implement a maintenance program tailored to the specific needs of the facility.

Traditionally, considerable focus has been devoted to minimizing first costs (i.e., capital investment) of construction. However, choices made regarding operation and maintenance (O&M) can have a greater effect on costs of ownership over a facility's entire life (NIBS 1998; Yates 2001).

1. OPERATION AND MAINTENANCE AS PART OF BUILDING LIFE-CYCLE COSTS

Operation and maintenance are major contributors to the total cost of ownership over the life of a facility. It is useful to compare maintenance costs to the total costs of facility ownership. The major categories of the life-cycle cost of facility ownership include design and construction; operations and maintenance; acquisition, renewal, and disposal; and employee salaries and benefits. Figure 1 represents the major categories of facility life-cycle costs as pillars supporting a building. Within each category, examples of the typical elements that make up the foundation of the category are shown.

Several studies [e.g., Romm (1994); Yates (2001)] state that the costs of operations and maintenance exceed the costs of design and construction. For example, Yates finds that "operational resource costs account for approximately five times construction costs over the 60 year life of a building." Accurately quantifying the life-cycle cost of building components through a statistically significant sample is difficult [see, e.g., Whitestone (2012)], given the availability of data, the timeline required to collect the data, and the varying lives of buildings.

The preparation of this chapter is assigned to TC 7.3, Operation and Maintenance Management. Significant content on fault detection and diagnostics was provided by TC 7.5, Smart Building Systems.

Figure 2 (NIBS 1998) categorizes life-cycle costs to include design and construction, operations and maintenance, and employee salaries and benefits. Other studies find similar values: over a 30-year period, design and construction costs account for about 2% of the life-cycle cost, whereas operations and maintenance costs are about 6% and personnel salaries are 92% (Romm 1994). Figure 3 (BOMA 2008) further defines operations and maintenance costs for a typical office building and shows that operations and maintenance costs most directly related to HVAC (i.e., maintenance and repair and utilities) make up over 50% of the operations costs for a building.

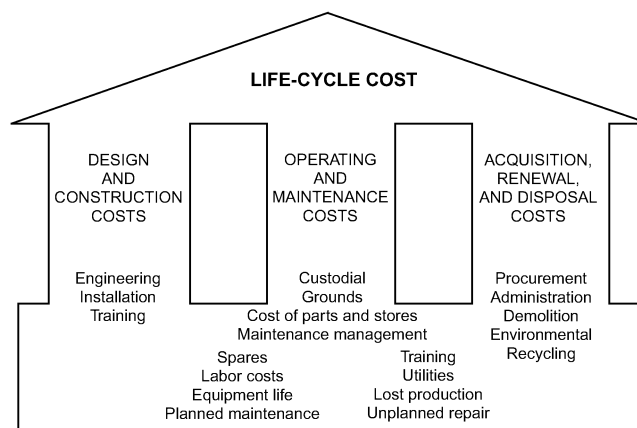


Fig. 1 Three Pillars of Typical Life-Cycle Cost with Cost Elements

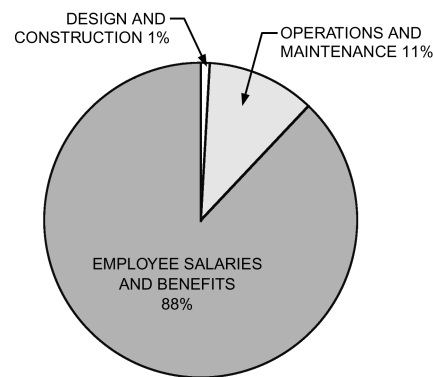


Fig. 2 Life-Cycle Cost Elements: Business Costs for Nonresidential Buildings, Including Salaries and Benefits to Occupants (Adapted from NIBS 1998)

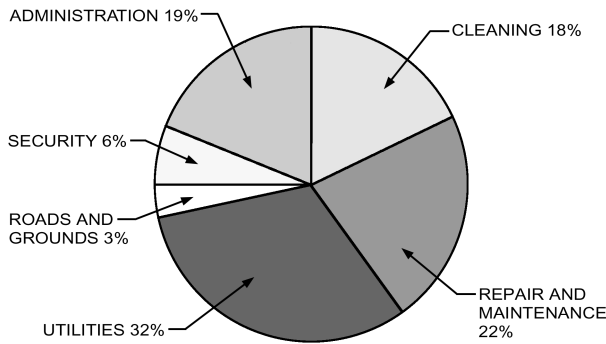


Fig. 3 Operations and Maintenance Cost Elements for Typical Office Building
(Adapted from BOMA 2008)

An alternative approach comparing the cost of design and construction to the cost of operation and maintenance over the building life cycle is to consider the **current replacement value (CRV)** as a percentage of the cost of construction of the building. CRV is calculated considering the cost of maintenance and repair (M&R). M&R includes routine maintenance, repairs, replacement, and the correction of deferred deficiencies, but not operations costs (which include custodial, grounds, and utilities costs). CRV is the estimated cost to construct a replacement building containing an equal amount of space that is designed and equipped for the same use as the original building, and meets current commonly accepted construction standards and environmental and regulatory requirements (Kaiser 2009). CRV does not include costs for routine maintenance, repairs, component or equipment replacements, or the correction of deferred deficiencies. It is calculated as

$$\text{Current replacement value} = (\text{Gross building area}) \times \left(\frac{\text{Construction cost}}{\text{Unit area}} \right)$$

A study by the National Research Council (NRC 1990) suggests that a range of 2 to 4% of CRV (excluding cost of land and major associated infrastructure) is an appropriate budget allocation for annual M&R, with the higher end of the range necessary when a backlog of maintenance and repair exists. If only operations costs are of interest, use 1.55% of the CRV for budget allocation (IFMA 2009a).

For buildings built using green design principles, a 2% investment can result in an average of a 20% life-cycle cost savings (Katz 2003). Given the life-cycle cost of a facility, the operations and maintenance staff should be involved with the predesign, design, and construction phases of the facility. During each phase, life-cycle costs, occupant comfort, energy efficiency, and maintenance strategies should be considered as key factors in the decision-making process. For example, any first-cost compromises made during the construction phase must consider the long-term effects on both life-cycle cost and ability to satisfy occupant thermal comfort while maintaining indoor air quality with efficient energy use. For a detailed discussion of life-cycle costs specific to operating and maintaining buildings, see [Chapter 37](#).

2. ELEMENTS OF SUCCESSFUL PROGRAMS

A successful O&M management program preserves the performance of building assets and enables them to be used effectively to meet owner and occupant requirements for thermal comfort, indoor air quality, and energy efficiency. Success requires

- Understanding and appreciation of the quantitative and qualitative benefits of O&M management

- A written program with clear goals and objectives that are directly tied to owner and occupant requirements
- Proper budget and resources, including people, training, and tools
- Regular evaluation of the program, including adjustments when necessary

O&M management is a team effort. It requires the participation of the building owner, occupant, facility manager, and various staff. For the team to be successful, values must be shared. When each team member recognizes and values the advantages of well-functioning building systems, each will work toward fulfilling the goals of the O&M program.

For goals and objectives to be shared, they must first be communicated through documentation. The level of detail should allow each team member to comprehend his/her individual role, responsibilities, and objectives, as well as how his/her contributions complement others. This helps ensure that everyone is working toward a common goal, and facilitates continuity when members leave or join the team. An essential aspect of the written program is that the proper functioning of building assets be specifically tied to building productivity. This makes it easier for management to make budget and resource allocation decisions that support O&M objectives.

The O&M management program should be considered a living document. Over the life of a building, performance objectives are likely to change (e.g., when building tenants change or building systems are upgraded). At regular intervals, and especially during significant changes, the O&M management program should be reevaluated to ensure that it is still aligned with and meeting building owner and occupant objectives.

Creating and Implementing an Effective O&M Program

Effective maintenance provides the required reliability and availability at the lowest cost by identifying and implementing actions that reduce the probability of failure to an acceptable level. This strategy involves identifying and implementing actions that cost-effectively reduce the probability of significant performance degradation and failure. In general, businesses preferentially invest in assets that contribute directly to their mission. However, buildings they occupy may not be considered mission critical, and investments in buildings are often a lower priority.

Appropriate levels of maintainability seldom occur by chance. They require up-front planning, setting objectives, disciplined design implementation, and feedback from prior projects. If adequate measures for cost-effective maintainability are not integrated into the design and construction phases of a project, reliability and/or uptime are likely to be adversely affected and total life-cycle costs increased significantly. It is vital to identify critical maintainability and production reliability issues and integrate solutions to them into facility project designs to achieve long-term facility owning and operating benefits.

The frequency of maintenance depends in part on system run time and type of operation in the facility. ASHRAE *Standard* 180 provides maintenance frequencies for air distribution systems, chillers, boilers, condensing units, cooling towers, dehumidification and humidification, engines, microturbines, fan coils, pumps, rooftop units, and other HVAC systems.

A maintenance plan should include an inventory of maintained assets, the program goals and objectives, and implementation procedures of the maintenance program. The maintenance plan should be written for the size, scope, age, and complexity of the specific systems and equipment serving the facility. The plan describes all required tasks, their frequency, salient condition indicators, and the parties responsible for performing the work, documentation, and program monitoring tasks. Important concepts to consider when developing a maintenance plan include the following:

Maintenance management is the planning, implementation, and review of maintenance activities. Specific levels of maintenance rigor should be established, ideally determined by cost-effectiveness, health, and safety concerns. Cost-effectiveness is the balance among system effectiveness, including maintenance levels, equipment and system availability, reliability, maintainability, performance, and life-cycle costs.

Performance objectives are stated as desired outcomes, which can be measured in terms of equipment and system deliverables such as thermal comfort, energy efficiency, and indoor air quality. Other measures of performance include uptime, mean time between failures, mean time to repair, and normalized cost data. The program should include the source of the objectives.

Condition indicators rely on descriptions of unacceptable equipment and system conditions, which can be based on physical condition and/or performance output. In general, condition indicators are measurements and observations of conditions known to lead to equipment and system failure or performance degradation. Presence of these conditions is a signal that remedial actions should be expedited to avoid failures or larger repair costs later on.

Inspection and maintenance tasks are developed to minimize the risk of equipment and system failure to achieve operating performance goals for the facility. When abnormal conditions are found, the cause must be investigated and remedied. In general, maintenance tasks comprise a series of activities such as cleaning, adjustment, service, or replacement as conditions warrant. Arguably, unacceptable conditions require more significant repair work.

Task frequency for inspection and maintenance of new equipment and systems is initially established based on the manufacturer's recommendations. Based on the rate of asset condition or performance degradation, the task frequency can be adjusted to provide cost-effective assurance that the asset is in acceptable condition. The monitoring and review elements of a maintenance program are important for keeping maintenance costs in control. For maintenance programs established for equipment and systems in service past the warranty period, task frequencies based on O&M staff experience or advice from a maintenance engineer may be used.

Documentation is a critical element of any maintenance program and includes identifying the asset's capacity, its location, the list of inspection and maintenance tasks and their frequencies, results of inspections and maintenance, and verification that inspection and maintenance tasks have been carried out. Archived results of prior conditions and maintenance are key factors in determining whether task frequencies can be adjusted.

A facility's operating plan dictates when equipment and systems can be shut down for inspection and maintenance. For systems in which continuous operation is a critical requirement, outages must be scheduled in advance or workarounds must be developed to enable maintenance to be performed. In some cases, redundant capacity may be needed to allow off-line maintenance without interrupting operation of the equipment or system. This is demonstrated through task intervals or procedures that are developed to eliminate or minimize asset downtime.

Setting Clearly Defined Maintenance Goals

Maintenance management goals are interdependent with facility operating goals and objectives. The maintenance program must account for building operating plans, procedures, and the criticality of equipment and systems. In general, the maintenance program is established to mitigate asset degradation and failure while enabling assets to deliver the required performance. In other words, maintenance goals focus on equipment performance, reliability, and uptime. These goals must consider expected funding and human capital resources, age of equipment and systems, and capital projects planned for the near term.

Clearly defined goals should be measurable to allow adequate management of the maintenance program. These goals serve to align the facility maintenance and maintenance management staff with the facility operating strategy, required resources, and acceptable levels of risk. When defining goals for any situation, it is helpful to understand the interrelationship between several terms that are related to asset performance. Common descriptors of desired operational outcomes include the following:

Availability is the amount of time that machinery or equipment is operable when needed. Often referred to as *uptime*, availability improvements lead to increased production for manufacturing and industrial companies. Availability is often confused with reliability, which is a component of availability.

Capability is the ability of a system to satisfactorily provide required service. It is the probability of meeting functional requirements when operating under a designated set of conditions. An example of capability is the ability of a heating system to meet the heating load at the winter design temperature. Capability must be verified by commissioning, recommissioning, or retrocommissioning periodically and whenever functional requirements changes are made.

Deliverability is the total amount of production delivered to users per unit of time. High deliverability is clearly supported by levels of the other concepts.

Dependability is the measure of a system's condition. Assuming the system was operative at the beginning of its service life, dependability is the probability of it operating at any given time until the end of its life. For systems that cannot be repaired during use, dependability is the probability that there will not be a failure during use. For systems that can be repaired during use, dependability is governed by how easily and quickly repairs can be made.

Durability is the average expected service life of a system or facility. Table 3 of Chapter 37 lists median years of equipment service life. Individual manufacturers quantify durability as design life, which is the average number of hours of operation before failure, extrapolated from accelerated life tests and from stressing critical components to economic destruction.

Maintainability is the ease, accuracy, safety, and economy of performing maintenance. The purpose of maintainability is to improve the effectiveness and efficiency of maintenance to maximize uptime. Maintainability is an important design consideration and contributes to availability.

For some industries, maintainability is quantitative, corresponding to the probability of performing a maintenance action or repair in a specified period of time using prescribed procedures in a specified environment. For others, maintainability is simply the ease with which maintenance actions can be performed.

Operability is the efficient conversion of labor, raw materials, and energy into product for which the value of the ratio of output to input is optimal. Maintainability and reliability contribute to availability. High levels of availability minimize the input required for a given output, thereby contributing to high levels of operability.

Reliability is the probability that a system or facility will perform its intended function for a specified period of time when used under specific conditions and environment. Issues affecting reliability include operating practices, equipment and system design, installation, and maintenance practices. Reliability contributes to availability.

Sustainability is "providing for the needs of the present without detracting from the ability to fulfill the needs of the future" (ASHRAE 2010). Sustainable maintenance management includes identifying and reducing a building's detrimental environmental impacts during its operating life. Sustainability in buildings cannot be achieved simply through sustainable design practices, but also requires sustainable operation and maintenance.

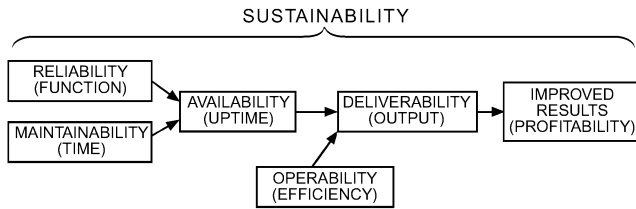


Fig. 4 General Interrelationship of Concepts

There are multiple perspectives of the interrelationship among maintainability, reliability, and availability. Maintainability and reliability are often grouped together, because they deal with essentially the same design concepts from different perspectives. Reliability analyses often serve as input to maintainability analyses. In this chapter, maintainability and reliability are considered independent concepts, both of which contribute to availability. Increased availability and operability can significantly improve profitability. Figure 4 shows these relationships: reliability and maintainability combine to yield availability, which then combines with operability to yield deliverability. Improvements in any area (all else being equal) ultimately lead to improved results or profitability, because these concepts are interrelated. For example, good reliability and availability may minimize or eliminate the need for installed spare capacity, reducing a facility's footprint and resource consumption. Good operability increases efficiency and reduces energy use. As shown, all these concepts contribute to sustaining the facility.

The facility operating plan should stem from a strategy that incorporates the preceding concepts, which can be described in measurable outcomes that support achieving the goals of the maintenance program. The effectiveness of a maintenance program can be measured by its influence on profitability. Cost-effective improvements to any of the concepts shown in Figure 4 contribute to the maintenance program's profitability and effectiveness. In addition, goals may be established to indicate how efficiently the maintenance program is implemented. Good maintenance management monitors progress toward achieving goals over time. As progress is monitored, trends are more important than the incremental values. Comparing recent with historical data on condition and performance provides valuable input for an effective maintenance program. Clearly defined maintenance goals align the maintenance program with the business strategy of the enterprise and the resulting operation systems of plant and equipment. Clear definitions help develop goals that are measurable, and therefore manageable, and contribute to improving facility performance.

Choosing the Best Combination of O&M Strategies

Operation is the processes and methods used when the building is working correctly, in contrast to maintenance, which is the processes and methods necessary to repair and replace equipment. Operation of a building includes a set of procedures and standards to keep systems and equipment operating as designed. Daily or weekly walkthroughs of mechanical rooms, roofs with mechanical equipment, and other locations with mechanical equipment should be performed to help identify equipment conditions that adversely affect equipment operation.

A **building automation system (BAS)** is an important tool to measure, benchmark, and analyze energy consumption and other operational data over the building life. To use a BAS to track whole-building, system, and equipment performance, it is important to make sure the BAS has been properly commissioned, has an appropriate number of alarms set, and has properly set-up logs to collect necessary data. For more information about benchmarking and analyzing energy use, see Chapter 36.

There are three basic maintenance strategies. In **run-to-failure maintenance**, minimal or no resources are invested in maintenance until equipment or systems break down (i.e., fail). **Preventive maintenance** is scheduled, either by run time or by the calendar. **Condition-based and predictive maintenance** uses predictions of future equipment condition to optimize maintenance actions. Other maintenance strategies include corrective, planned, and unplanned maintenance. Within each strategy, the skills and management tools required can vary from simple to complex. Maintenance programs may incorporate features of all three approaches into a single program. Many arguments can be made about the cost-effectiveness of each of these programs. Operation and maintenance costs represent a significant portion of a facility's total life-cycle cost (see Figure 2). Therefore, the cost effectiveness of maintenance management is paramount.

Run-to-Failure and Repair. Failure is the inability of a system or equipment to perform its intended function at an acceptable level. Run-to-failure is applied when the cost of maintenance or repair exceeds the cost of replacement or losses in the event of failure. Only minimum maintenance, such as cleaning or changing filters, is performed. The equipment may or may not be monitored for proper operation, depending on the consequences of failure. This is a highly reactive approach to deal with abnormal conditions. For example, a window air conditioner may be operated although it is vibrating and making noise, then be replaced rather than repaired (a failure-triggered response in which operation is fully restored).

Preventive Maintenance. Preventive maintenance classifies available resources to ensure proper operation of a system or equipment under the maintenance program. Durability, reliability, efficiency, and safety are the principal objectives. Preventive maintenance is scheduled based on run time or by the calendar.

Condition-Based and Predictive Maintenance. Condition-based maintenance uses measurements of the performance of equipment and systems to guide maintenance activities. As performance degradation or operational faults are identified through measurements, they are addressed through corrective actions or deferred for correction until future condition measurements indicate sufficient degradation to warrant maintenance action. In essence, condition-based maintenance uses condition and performance indices based on measurements to optimize maintenance intervals. Maintenance is then performed on the basis of the actual conditions monitored and the interpretation of them. By basing maintenance actions on measurements of conditions, both excessive and too-infrequent maintenance can be avoided, thereby optimizing plant reliability and maximizing maintenance personnel productivity.

The supplemental training and instrumentation required to implement condition-based and predictive maintenance have costs. These costs must be included in an evaluation of the cost effectiveness of these approaches to compare them to the current maintenance approach used in a building and other methods under consideration, such as preventive or run-to-failure and replace.

Measurements can be taken continuously or periodically (e.g., weekly, monthly). Continuous monitoring provides continual information, enabling identification of catastrophic failures (e.g., failure of a motor or compressor) as they occur. Faults and performance degradation are detected by comparing the monitored indicator of performance with expected values, based on benchmarks (e.g., manufacturer specifications, historical performance, values from models). In some cases, alarms based on measured values of conditions exceeding known threshold values (e.g., maximum acceptable temperature, tabulated values of acceptable vibration) are used to notify operations and maintenance staff that action may be warranted to correct conditions. For complex systems, it may be necessary to monitor several conditions (e.g., temperatures, vibration, load) to assess the overall system condition. Trending over a period of time, using measurements of conditions either at intervals or

continuously, can be used to track gradual deterioration, and remedial work can be performed when deterioration reaches a critical level or planned in advance based on the rate of deterioration using a predictive approach.

In the case of air filters in a variable-air-volume (VAV) system where the supply fan draws air through the filter and is controlled to a fixed static pressure, the criterion for replacing the filter is a function of the maximum differential pressure the fully loaded filter can withstand without bursting and the energy consumption of the fan as the filter loading increases. It may be more economical to change the filter before the bursting pressure is reached if the rate of loading is slow. Continuous monitoring with a building automation system rather than changing filters on a fixed time schedule makes it possible to detect rapidly accelerated dust loading (e.g., by nearby construction work), so that the system alerts building staff before filters are overloaded and could potentially burst.

In a constant-volume system, assuming the main fan draws air through the filter, the filter change criterion is a function of the maximum differential pressure the filter can withstand without bursting and the drop in flow rate that can be tolerated by the system. As the filter becomes dirty, energy consumption increases and filter efficiency decreases. A fixed time interval for filter bank changing or cleaning may not be optimum. Changing the filter based on a monitored condition optimizes filter life and minimizes labor costs.

Routine operating plant inspection conducted by the technician during regularly scheduled plant tours can be an effective condition-monitoring practice. A technician's knowledge, experience, and familiarity with the plant are valuable for plant diagnostics. Plant familiarity, however, is valuable only when based on a solid knowledge of the underlying physical principles, and is lost with frequent technician staff changes.

Many physical parameters or conditions can be measured objectively using both special equipment and conventional building automation system sensors. One such condition is vibration on rolling element bearings. Vibration data are captured by computers. Special software is used to analyze the data to determine whether shaft alignment is correct, whether there are excessively unbalanced forces in the rotating mass, the state of bearing lubrication, and/or faults with the fixed or moving bearing surfaces or rolling elements. Not only can this technique be used to diagnose faults and determine repair requirements at an early stage, but it can also be used after completing a repair to ensure that the underlying cause of fault has been removed.

Other techniques include (1) using thermal infrared images of electrical connections to determine whether mechanical joints are tight, (2) analyzing oil and grease for contamination (e.g., water in fuel oil on diesel engines), (3) analyzing electrical current to diagnose motor winding faults, (4) measuring differential pressure across filter banks and heat exchangers to determine optimum change or cleaning frequency, and (5) measuring temperature differences, such as correct control valve response, chiller operation, and air handling.

In some cases, multiple parameters are required. For example, to determine the degree of contamination of an air filter bank in a VAV system, it is necessary to measure the differential pressure across the filter and interpret it in terms of the actual flow rate through the filter. This can be done either by forcing the fan on to high speed and then measuring the differential pressure, or by combining a flow rate signal with a differential pressure signal.

With predictive maintenance, indicators of performance degradation are extrapolated into the future to predict when an unacceptable degree of degradation will be reached and repair or maintenance should be performed. The extrapolation is based on a statistically valid approach that accounts for uncertainty of future projections. The resulting projections of the time to failure (or unacceptable performance) can be used to plan maintenance in advance. Predictions

can be based on nearly any indicator of performance degradation (e.g., pressure drop across a filter) that changes gradually over time. Several techniques are frequently associated with predictive maintenance, including nondestructive testing, chemical analysis, vibration and noise monitoring, and routine visual inspection and logging.

Additional Maintenance Strategies

Corrective maintenance classifies resources (expended or reserved) for predicting and correcting conditions of impending failure. Corrective action is strictly remedial and always performed before failure occurs. An identical procedure performed in response to failure is classified as a repair. Corrective action may be taken during a shutdown caused by failure, if the action is optional and unrelated.

Planned maintenance classifies resources invested in selected functions at specified intervals. All functions and resources in this classification must be planned, budgeted, and scheduled. Planned maintenance includes preventive and corrective maintenance.

Unplanned maintenance classifies resources expended or reserved to handle interruptions in the operation or function of systems or equipment covered by the maintenance program. This classification is defined by a repair response.

3. AUTOMATED FAULT DETECTION AND DIAGNOSIS (AFDD)

An emerging set of tools known as **automated fault detection and diagnosis (AFDD)** software can keep O&M staff more informed on the condition of HVAC&R equipment and systems and assist in performing system- and building-level maintenance management. AFDD can automatically and continuously monitor system performance and detect faults as they occur, enhancing the ability of O&M staff to remain informed on the condition of equipment and systems they manage. This section describes what AFDD is, types of AFDD tools, characteristics of AFDD systems, AFDD in practice, and the benefits of detecting and diagnosing system and equipment faults. For further information about AFDD, see [Chapter 62](#).

The primary purpose of an AFDD system is early detection of faults and diagnosis of their causes, enabling correction before additional damage to the system, loss of service, or significant energy waste and increased costs occur. AFDD interprets values and trends in measured parameters to automatically reach conclusions about the presence of faults or degree of performance degradation. This enables performance monitoring to be performed continuously for a large inventory of equipment, which is not possible manually.

In AFDD, software automatically compares measured and expected system performance and determines the causes of discrepancies (i.e., symptoms or indicators of faults, caused by the faults themselves). **Fault detection** is the process of determining whether the monitored system deviates from normal operation, and **fault diagnosis** is the process of isolating the detected fault(s) from other possible faults. These processes are based on a thorough knowledge of the physical principles underlying the operation of HVAC systems, equipment, and components. Measurements provide data on actual performance at the time they are taken, and models that capture normal operational behavior are generally used to provide values of the same variables when the system is operating properly. Models used include engineering models based on first principles, purely empirical models based on past performance, gray-box models that combine some engineering modeling with empirical data, and various statistical approaches. These methods differ primarily by the type of model used, the methods used for detecting differences between measured and expected performance, and methods used to distinguish among diagnostic outcomes. These methods are

then coded in software to automate execution on measured data as they become available.

The ability to detect unacceptable conditions in HVAC&R systems has existed for some time and has been used primarily in safety devices intended to protect expensive equipment from catastrophic failure and for alarms tied to occupant comfort. These techniques were generally based on the value of a parameter exceeding a pre-defined threshold (e.g., a maximum acceptable pressure, above which a relief valve opens or equipment shuts down). They have also been used for alarms in building automation systems to alert operators to unacceptable conditions (e.g., a chilled-water temperature that is too high). In recent years, motivations for AFDD include increasing energy efficiency, improving indoor air quality, and reducing unscheduled equipment downtime (Braun 1999). At the same time, AFDD capabilities have expanded to detecting and diagnosing faults based on many different variables.

The benefits of AFDD capabilities have been validated in part by studies that documented a wide variety of operating faults in common HVAC equipment (Breuker and Braun 1998; Breuker et al. 2000; Comstock et al. 2002; House et al. 2001a, 2003; Jacobs et al. 2003; Katipamula et al. 1999; Proctor 2004; Rossi 2004; Seem et al. 1999). Faults included economizers in packaged air conditioners and heat pumps not operating properly; low (and high) refrigerant charges; condenser and filter fouling; faulty sensors; electrical problems; chillers with faulty controls, condensers, compressors, lubrication, piping, and evaporators; and air-handling units with too little or too much outdoor-air ventilation, poor economizer control, stuck outdoor-air dampers and other problems.

Types of AFDD Tools. **Portable service tools** can evaluate the performance of packaged and unitary vapor-compression systems and guide servicing to address problems. Self-contained, micro-processor-based portable hardware is used during a service visit for data acquisition and analysis. The sensors for making measurements and evaluating system performance may be installed temporarily or permanently. Data are usually collected for a relatively short period of time (minutes) while the equipment operates at steady-state conditions.

Local controllers with embedded AFDD include fault detection and diagnostic algorithms as part of the control software code. Embedded AFDD software can access data at the controller's short sampling interval; because they perform analysis locally on controllers, embedded AFDD tools can also reduce control network traffic. Computational and memory limits, however, may place practical restrictions on the complexity of algorithms embedded in local controllers.

Central workstation AFDD tools use dedicated software to detect and diagnose HVAC system faults using data from a building automation system or dedicated sensors or sensor networks. This software usually resides on a computer that is part of a building automation system, or has access to stored data from a BAS. A key strength of workstation AFDD software is its ability to detect system-level faults arising from interactions among components.

Workstation AFDD software may require extensive effort for configuration. In particular, mapping points from the building automation system to the AFDD tool can be labor intensive and costly, depending on the number of measurement and control points used by the AFDD tool.

Web-based AFDD software may obtain data from a BAS, independent data acquisition system, or controller-embedded AFDD software. In this case, wired and/or wireless Internet connections using the Internet for data acquisition allows gathering data from many buildings and supports enterprise-wide reporting. Because AFDD processing is done by software on the web, updating of software is simplified, and all users have access to the latest version. Web-based systems are emerging for detecting and diagnosing faults in individual equipment and whole-building energy

consumption (Brambley et al. 2005). A significant challenge for web-based AFDD is Internet security, which may require additional hardware and software administration.

Characteristics of AFDD Systems. Inherent characteristics of AFDD systems can be adjusted to suit a variety of applications and users.

Sensitivity is the lowest fault severity level required to trigger the correct detection and diagnosis of a fault. This characteristic is vital for monitoring safety-critical systems. For non-safety-critical applications (which cover most HVAC equipment), the sensitivity threshold can be higher so that faults have significant performance or cost impacts before operators are alerted.

False alarm rate is the rate at which an AFDD system reports faults when they do not actually exist (i.e., when operation is normal). A high false alarm rate could result in excessive costs from unnecessary service inspections or stoppage of equipment operation.

The challenge is to establish a balance between adequate AFDD system sensitivity and minimizing false alarms. Take care to achieve the right balance, because false alarms can defeat the purpose of installing AFDD. One technique used for critical systems, installing redundant sensors, mitigates excessive false alarms while maintaining desired fault sensitivity. Redundant sensors, however, are unusual in HVAC systems because of their additional cost.

Additional characteristics that affect the performance and usability that should be considered when selecting an AFDD tool (House et al. 2001b) include

- Number of sensors and control signals used
- Amount of design data used
- Training data required
- User-selected parameters

Users should seek a balance among these considerations that is appropriate for the intended application.

AFDD in Practice. Figure 5 shows an example of an operation and maintenance process using AFDD comprising four distinct functional processes. The first two steps in this process are fault detection and, if a fault is detected, fault diagnosis. After diagnosis, the software can analyze the various consequences of the faults detected. Human operators can then evaluate the results from the automated fault impact analysis to arrive at an integrated assessment of overall fault significance (based on operational requirements for safety, availability, cost, energy use, comfort, health, environmental impacts, or effects on other performance indicators). Once fault evaluation is completed, the operators determine how to respond (e.g., by taking a corrective action). Together, these four steps can alert operations and maintenance staff to problems, help identify the root causes of problems so that they can be properly corrected, and help prioritize maintenance activities to ensure that the most important problems are attended to first. This forms the basis for condition-based maintenance.

Benefits of Detecting and Diagnosing SYSTEM and Equipment Faults

Since 1995, many studies of the effects of O&M show that maintenance intended to preserve equipment performance and condition also accrues beneficial energy and operating cost savings. Operational savings exceed the cost of AFDD and servicing, particularly when considering optimizing service task scheduling, reducing unnecessary on-site inspections, and decreasing the peaks and valleys of seasonal work (Li and Braun 2007a, 2007b, 2007c; Rossi 2004). Building owners and operators should carefully evaluate the cost and benefits of implementing and using AFDD technology in their specific situations.

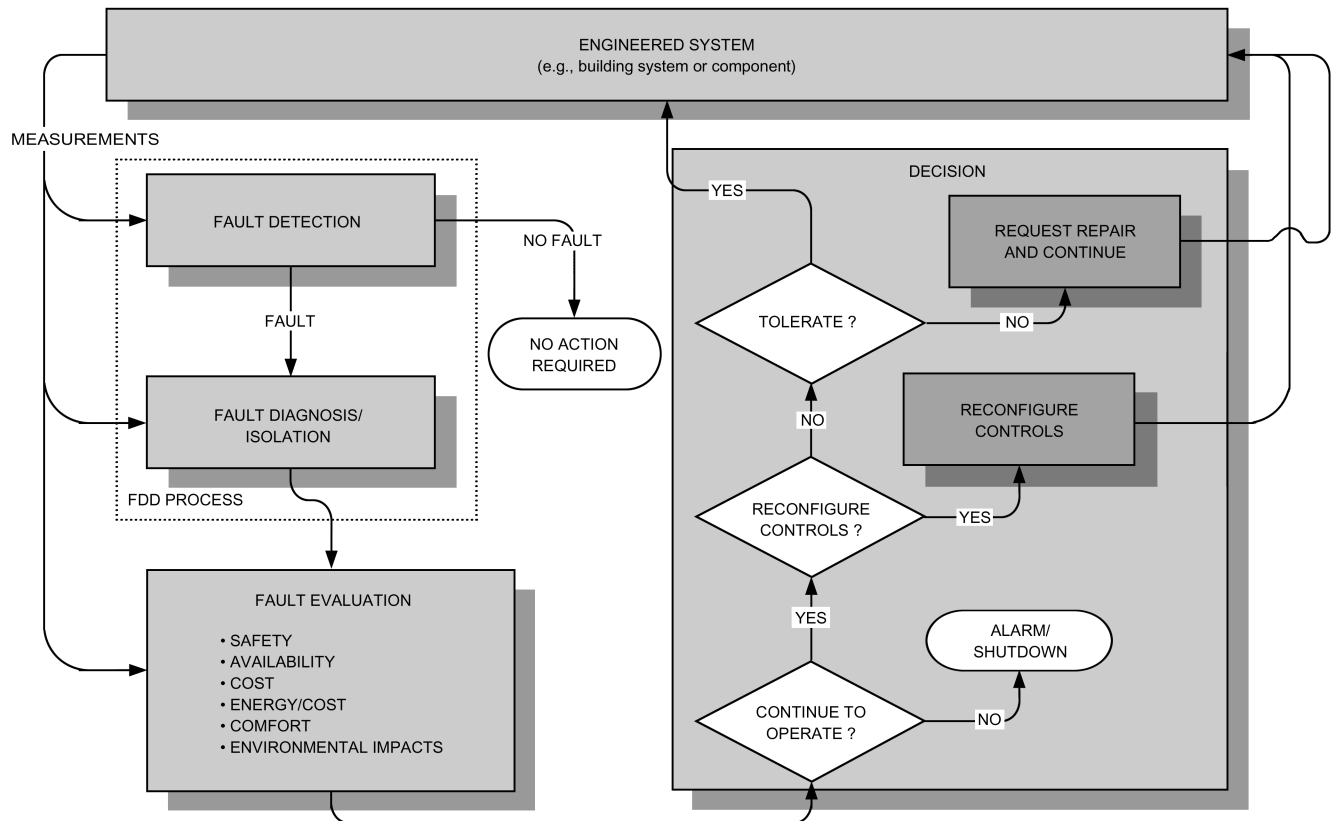


Fig. 5 Generic Application of AFDD to Operation and Maintenance of Engineered Systems

[Adapted from Katipamula and Brambley (2005)]

4. DOCUMENTATION

Information on the facilities, equipment, and intended operation procedures is essential for planning and performing maintenance efficiently, documenting maintenance histories, following up on maintenance performance, energy reporting, and management reporting. For these reasons, documentation is a critical element in a successful maintenance program. Prepare operation and maintenance documentation as outlined in ASHRAE *Guideline 4*.

For new construction, establish operation and maintenance documentation requirements as part of the project requirements. Deliverables should support the expected maintenance strategy, skills of the maintenance and operations staff, and anticipated resources to be committed to performing operations and maintenance. The requirements for maintenance programs developed for existing facilities are the same; however, the operations and maintenance staff may be more involved with developing the documents.

Operation and Maintenance Documents

Information should be compiled into a manual as soon as it becomes available. This information can be used to support design and construction activities, commissioning, training of operation and maintenance staff, start-up, and troubleshooting. In addition to providing the operation and maintenance manual to the construction team, set aside an appropriate number of manuals for the building owner's staff after construction turnover. It is critical that all information required to operate and maintain the systems and equipment be compiled before project turnover to the owner's staff and be available to the entire facilities department.

A complete operation and maintenance documentation package includes an operation and maintenance document directory, emergency information, an operating manual, maintenance manual test reports, and construction documents. These documents should be available to the entire facilities department.

The **operation and maintenance document directory** provides easy access to the various sections within the document. The O&M manual will serve the facility for the entire use life. During this time, staff turnover will occur many times. A directory that is well organized and clearly organized facilitates quick reference by new technicians and operators.

Emergency information must be directly distributed to emergency response personnel. Including emergency information in the O&M documents that are kept in a single location ensures that this critical information is immediately available when needed. Emergency information should include emergency and staff and/or agency notification procedures.

The **operating manual** should contain the following information:

- I. General information
 - A. Building function
 - B. Basis of design
 - C. Building description
 - D. Operating standards and logs
- II. Technical information
 - A. System description
 - B. Operating routines and procedures
 - C. Seasonal start-up and shutdown
 - D. Special procedures

E. Basic troubleshooting

The **maintenance operating manual** should contain the following information:

- I. Equipment data sheets specific to installed equipment
 - A. Operating and nameplate data
 - B. Warranty information
- II. Maintenance program and procedure information
 - A. Manufacturer installation, operation, and maintenance instructions
 - B. Spare parts information
 - C. Corrective and planned maintenance actions, as applicable
 - D. Schedule of actions, including frequency
 - E. Action descriptions
 - F. History
- III. **Test reports** provide a record of observed performance during start-up and commissioning. The records should be compiled throughout the service life of the facility.
- IV. Copies of **construction documents**, also called record drawings

These documents should be available to the entire facilities department.

Initial system maintenance procedures should be detailed in the maintenance manual, with individual equipment maintenance frequency detailed in manufacturers' literature that was furnished during the initial installation or developed after installation. The maintenance program should be tailored to each specific facility and system type.

Documentation Methods

There are two basic methods for collecting and archiving operation and maintenance documents: (1) a bound written document that is executed and updated by hand, and (2) an electronic, computer-based database management system. The chosen method should be congruent with facility and maintenance program complexity and scope, and with the skill level of maintenance staff. The objective is to enter, archive, update, and evaluate information on building systems and assets efficiently and effectively. Regardless of which method is used, it is important that operations and maintenance staff be provided adequate time to collect and document the required information. Otherwise, the data collected may not be of the quality or accuracy needed to support effective decision making.

A **computerized maintenance management system (CMMS)** is a database software tool to plan, schedule, and track maintenance activities; store maintenance histories and asset inventory information; communicate building operation and maintenance information; and generate reports to quantify maintenance productivity. A CMMS is used by facility managers, maintenance technicians, third-party maintenance service providers, and asset managers to track the status, asset condition, and cost of day-to-day maintenance activities. The number and type of modules used within a CMMS is specified by the facility management team, depending on the facility's needs and the management team's goals. Typical CMMS modules include work order generator and tracking, work order requests, inventory control, planned maintenance, equipment histories, maintenance contracts, and key performance indicator (KPI) reporting.

Although a CMMS is not required to manage maintenance activities, they are becoming more commonly used (Sapp 2008). When implementing a CMMS in a new or existing facility, or upgrading an existing one, the needs of the CMMS and the planning process must be carefully determined. Although using a CMMS has the potential to increase the facility management team's efficiency and serve as a historical maintenance archive, more than 50% of implementations

fail (Berger 2009). One reason for failure is inadequate data population. To overcome this challenge, especially when new buildings and major renovations are designed and constructed using building information modeling (BIM), open information exchanges can be used. A supplement in the ASHRAE Handbook Online version of this chapter provides a brief overview of what open information exchange standards are, followed by a descriptive list of current and developing open information exchange standards. Selecting the right software does not guarantee that using a CMMS will improve maintenance productivity; it is important to evaluate, document, and align facility management processes with how the CMMS will be used. When implementing or upgrading a CMMS, schedule three to six months to design new processes and develop a set of system requirements, using a participatory approach that includes all stakeholders (Berger 2009).

5. STAFFING

Determining the correct number of staff when implementing a maintenance program is a complex exercise. Multiple factors must be considered in order to have sufficient maintenance staff available to do the work. Such factors include but are not limited to skill level of maintenance staff, complexity and criticality of the equipment and systems to be maintained, the rigor of the maintenance program, source of the maintenance staff, available maintenance program funding, labor agreement provisions, business imperatives, and certification credentials required.

The number of maintenance staff working at a facility depends on how the systems and equipment are operated. For example, multiple-shift or 24/7 operations require a larger staff than a typical 5-day, 8-hour business week. The requirements of a maintenance program are a second major influence on staffing levels. The maintenance plan can be translated into expected time to perform a given task, considering both number and frequency of tasks. Staffing levels can be adjusted to account for vacation and staff sick days. Several references, such as APPA (2011), provide standard labor units for maintenance tasks to help develop the projections.

It is important for maintenance staff to be able to provide customer service for requested operations and maintenance work. This means responding to requests and complaints from building occupants. In nonmanufacturing facilities, the level of customer service provided, or the perceived level of service provided, is a key component of a successful maintenance organization.

Training

To be effective and efficient, operation and maintenance management staff must have both technical and managerial skills. Technical skills include the ability to understand how mechanical systems operate and how maintenance of mechanical equipment is performed, as well as the analytical problem-solving expertise of a physical plant engineer. Physical plant engineers require a variety of skills to effectively operate HVAC systems, implement a maintenance program, manage operations and maintenance staff, and meet requirements of the investment plan. Good physical plant engineering solutions are developed while the investment plan is being formulated, and continue throughout the life of the facility. Managerial skills include managing the facility to achieve reliability and efficiency targets to support the business enterprise. Facility management responsibilities may include development of maintenance strategies; determination of program goals and objectives; and administration of contracts with tenants, service providers, and labor unions. Even when specialized contract maintenance companies provide service, the facility manager requires these skills in order to be a smart buyer. With increased interest in sustainable, high-performance buildings, it is also suggested that staff be trained about how to retrocommission or recommission mechanical

systems. Doing so will ensure optimum comfort, efficient system operation, and minimal operation and maintenance costs. The importance of detailed commissioning documentation should be included in the training. This will help staff to effectively consider factors such as energy budgets when addressing building occupants' comfort complaints.

An effective facility manager should be able to manage and train staff, and plan and control a facility's operation and maintenance with the cooperation of senior management and all departments. The facility manager's responsibilities include administering the O&M budget and protecting the life-cycle objectives. There are eleven core competencies of facility management (IFMA 2009b), eight of which apply to operations and maintenance management:

- **Operations and maintenance:** Oversee acquisition; installation; operation; maintenance; and disposition of building systems, furniture and equipment, grounds, and exterior elements
- **Human factors:** Develop and implement practices that promote and protect health, safety, security, quality of work life, the environment, and organizational effectiveness
- **Project management:** Develop facility plans; plan and manage each phase of the project, including construction and relocations
- **Leadership and strategy:** Plan, organize, administer, manage and lead facility's functions; manage personnel assigned to each function
- **Quality:** Manage the process of assessing the quality of services and facility effectiveness; manage benchmarking process and audits
- **Communication:** Communicate plans and processes effectively
- **Technology:** Plan, direct, and manage facility management business and operational technologies, and support the organization's technological infrastructure
- **Environmental stewardship and sustainability:** Management of the built and natural environment using sustainable practices

Training should be an important part a facility management department. The use of technology in buildings continues to increase, making training for all facility teams more important than ever. Training can be done in house or by a contracted third party who provides training as a business. When developing an in-house training program or evaluating training by a third party, make sure these key components are addressed:

- **Personnel:** Who will attend the training; create a list of maintenance managers, supervisors, and trades workers
- **Course content:** Course requirements, type of training, and media required
- **Schedule:** When the training will take place and how it will be coordinated with day-to-day assignments
- **Master training plan:** A written document to record personnel, course content, and time schedule requirements

Self-Perform versus Contract Considerations

For most enterprises with large facilities, maintenance organizations are not usually part of the core business, and economics becomes an important factor in determining whether maintenance will be self performed or done by a contractor. Wage structures, available labor pool, skill level of maintenance staff, and ability to perform specialized tasks are among the characteristics evaluated and compared when making a decision. When reducing operational overhead costs is important, the lowest-cost option tends to be the most attractive. For self performance, another cost factor to consider is the cost of training for development and training for various credentials.

Owners of one or several small buildings often cannot justify the expense of employing in-house maintenance personnel. Thus, they may decide to contract out all maintenance work. In these cases, it

is important that the contract specifies that the work to be carried out is consistent with the recommendations in this chapter. In particular, it should include periodic operational checks, such as equipment operating schedules, set points, and indoor air quality.

When the owner employs in-house maintenance staff, they should carry out operational checks, in addition to responding to occupant complaints and overseeing corrective actions, as needed. In addition, they should carry out maintenance tasks within their capabilities. At minimum, changing filters, belts, and motors; lubricating bearings; and similar routine maintenance is generally expected. In many buildings, particularly larger ones or campuses, in-house maintenance staff may include specialized expertise, reducing the need to retain contractors. Whenever the operator cannot service and repair the systems or components installed, the owner should ensure that qualified contractors and technicians perform the work. When there are regulatory requirements or certification is required to perform specialized maintenance work, the owner's in-house staff must either have the certification, or the work must be contracted out to someone who has it.

A mix of the two approaches is common: routine inspection tasks are self performed, and repairs to major equipment are more likely contracted out to factory-authorized service providers. This approach can reduce expenses associated with maintaining an inventory of special tools and keeping in-house staff up to date with training for an activity that is usually performed once or twice a year.

Cost-plus service agreements, those in which the service provider is paid for all allowed expenses, plus a fee for profit, are common because they make it easy to begin work when certain required tasks are known but the entire scope is not known, because of unforeseen risks or other factors. In many cases where there are unknown risks, such as emergency repairs, many service contractors favor cost-plus to enable the work to proceed without delay due to task or scope revision. Where maintenance programs are well defined and thus conducive to firm, fixed-price contracts, alternative contracting methods can be used. These agreements may have some form of indefinite-quantity, indefinite-delivery provisions to cover unplanned maintenance or repair requirements. Recently, performance incentives such as savings sharing, extending the contract term, and award fees have been provided to contractors.

6. MANAGING CHANGES IN BUILDINGS

Renovation and Retrofit Projects

Design and Construction Coordination in Occupied Facilities. Retrofit of mechanical systems in occupied buildings requires a level of design and construction planning beyond what is normally required in new construction. Often, owners must keep the building operating during construction, which usually affects system design and phases of installation. It is often helpful to select the construction team before design completion, so that the expertise of all parties can focus on constructability and budget consequences before the design is complete.

Design for Ease of Operation and Maintenance. Operation, maintenance, and maintainability of all HVAC&R systems should be considered during building design. Any successful operation and maintenance program must include proper documentation of design intent and criteria. ASHRAE *Guideline 4* provides a methodology to properly document HVAC systems. Newly installed systems should be commissioned according to the methods and procedures in ASHRAE *Guideline 1.1* to ensure that they are functioning as designed. It is then the responsibility of management and operational staff to maintain design functionality throughout the life of the building.

For new construction or renovation, the building owner should work with the designer to clearly define facility requirements. In

addition to meeting the owner's project requirements, the designer must provide a safe and efficient facility with adequate space to inspect and repair components. The designer must reach agreement with the owner on the criticality of each system to establish issues such as access, redundancy, and component isolation requirements.

Conversion to New Technology

Building systems and equipment are based on the technology available to planners and designers at the time of preparation, construction, and installation. Maintenance, repairs, and operating schemes should be adhered to throughout the required service life of the facility or system. During the service life, new technology (e.g., high-efficiency equipment, smart technology systems, sustainability advances) may become available to increase overall efficiency and affect maintenance, repair, and replacement programs. Potential conversion from existing to new technology must be assessed in life-cycle terms. The conversion to new technology must be assessed for (1) all initial, operation, and maintenance costs; (2) the correlation between service life and the facility's remaining service life; and (3) the cost of conversion, including revenue losses from associated downtime. As facilities and systems are upgraded, facility operations and maintenance personnel must be trained to ensure that new equipment operates efficiently and effectively throughout its service life to maintain the anticipated benefits.

Document and Communicate

As a facility is planned, designed, constructed, and occupied, the documentation and information about the facility increases. To ensure minimal loss of information about a facility, information must be documented and communicated from the early stages of planning through the entire facility life. During planning and design, documentation must include detailed plans and specifications identifying all aspects of the equipment, including physical size, location, system interactions, operating set points (e.g., temperature, humidity, airflow, energy usage, relative pressure), flow diagrams, instrumentation, and sequences of operation. The equipment supplier must provide equipment meeting the specifications, and should also recommend alternatives that offer lower life-cycle costs for the owner and designer to evaluate. The installing contractor must turn over the newly installed system to the owner in an organized and comprehensive manner, including complete documentation with O&M manuals and commissioning reports (e.g., air and water balance, fume hood certification). The design and commissioning team should ensure that a comprehensive systems manual as outlined in ASHRAE *Guideline 0* is provided to the owner, along with training on equipment and systems. The design team and the contractor should also ensure that a complete and correct set of record drawings are provided showing the actual facility as built, including all changes from the initial construction drawings made during the construction process.

Technological advances now allow much of this information to be provided electronically. During facility planning and construction, software and hardware systems can create building information models (BIMs) that can become a resource for the owner throughout the facility's service life. BIMs can be linked into the CMMS, building automation, and other smart building systems to allow building owners, operating engineers, technicians, and other facility personnel immediate access to the information required to maintain, operate, and service the building systems. During the building's life cycle, as modifications and changes are made to the facility, this information must be continuously updated to ensure accurate records continue to be maintained.

Commissioning Through Turnover to Operation and Maintenance

Existing systems may need to be reconfigured and recommissioned to accommodate changes. For existing buildings, the two most common types of commissioning are retrocommissioning and ongoing commissioning. **Retrocommissioning** is the process of commissioning existing building systems that were not commissioned when originally constructed (ASHRAE *Guideline 0*). The process ensures that building systems perform interactively according to the design intent and/or to meet the owner's current operational need. Per ASHRAE *Guideline 0*, **ongoing commissioning** is the process that verifies that building systems remain optimized throughout the life of the building, essentially a perpetual form of recommissioning (commissioning a building that was initially commissioned during construction), with an emphasis of benchmarking historical performance compared with current operation. See [Chapter 43](#) for additional information.

REFERENCES

- APPA. 2011. *Operational guidelines for educational facilities: Maintenance*, 2nd ed. APPA, Alexandria, VA.
- ASHRAE. 2013. The commissioning process. *Guideline 0-2013*.
- ASHRAE. 2007. HVAC&R technical requirements for the commissioning process. *Guideline 1.1-2007*.
- ASHRAE. 2008. Preparation of operating and maintenance documentation for building systems. *Guideline 4-2014*.
- ASHRAE. 2012. Standard practice for inspection and maintenance of commercial building HVAC systems. ANSI/ASHRAE/ACCA *Standard 180-2012*.
- ASHRAE. 2010. *ASHRAE greenguide: The design, construction, and operation of sustainable buildings*, 3rd ed.
- Berger, D. 2009. 2009 CMMS/EAM review: Power up a winner—How to find the right asset management system for your plant. *Plant Services Digital Magazine*. Available at <http://www.plantservices.com/articles/2009/066.html>.
- BOMA. 2008. *Experience exchange report (EER)*. Building Owners and Managers Association International, Washington, D.C.
- Brambley, M.R., S. Katipamula, and P. O'Neill. 2005. Facility energy management via a commercial web service. Ch. 18 in *Information technology for energy managers*, vol. II: *Web based energy information and control systems case studies and applications*, pp. 229-240, B.L. Capehart and L.C. Capehart, eds. Fairmont/CRC, Lilburn, GA.
- Braun, J.E. 1999. Automated fault detection and diagnostics for the HVAC&R industry. *HVAC&R Research* (now *Science and Technology for the Built Environment*) 5(2):85-86.
- Breuker, M.S., and J.E. Braun. 1998. Common faults and their impact for rooftop air conditioners. *HVAC&R Research* (now *Science and Technology for the Built Environment*) 4(3):303-318.
- Breuker, M.S., T. Rossi, and J. Braun. 2000. Smart maintenance for rooftop units. *ASHRAE Journal* 42(11):41-47.
- Comstock, M.C., J.E. Braun, and E.A. Groll. 2002. A survey of common faults for chillers. *ASHRAE Transactions* 108(1):819-825.
- House, J.M., H. Vaezi-Nejad, and J.M. Whitcomb. 2001a. An expert rule set for fault detection in air-handling units. *ASHRAE Transactions* 107(1): 858-871.
- House, J.M., J.E. Braun, T.M. Rossi, and G.E. Kelly. 2001b. Section D: Evaluation of FDD tools. In *Final report: Demonstrating automated fault detection and diagnosis methods in real buildings*, A. Dexter and J. Pakanen, eds. International Energy Agency on Energy Conservation in Buildings and Community Systems, Annex 34. VTT Technical Research Centre of Finland, Espoo, Finland.
- House, J.M., K.D. Lee, and L.K. Norford. 2003. Controls and diagnostics for air distribution systems. *ASME Journal of Solar Energy Engineering* 125(3):310-317.
- IFMA. 2009a. Operations and maintenance benchmarks. *Research Report 32*. International Facility Management Association, Houston.
- IFMA. 2009b. *Eleven core competencies of facility managers*. International Facility Management Association, Houston. Available at <http://www.ifma.org/know-base/fm-knowledge-base/knowledge-base-details/11-core-competencies-of-facility-managers>.

- Jacobs, P., V. Smith, C. Higgins, and M. Brost. 2003. Small commercial rooftops: Field problems, solutions and the role of manufacturers. *Proceedings of the 2003 National Conference on Building Commissioning*, Portland Energy Conservation, Portland, OR.
- Kaiser, H. 2009. *Capital renewal and deferred maintenance programs*. APPA, Alexandria, VA. Available at <http://certification.appa.org/documents/BOKChapter13-CapitalRenewalandDeferredMaintenanceProgram.pdf>.
- Katipamula, S., and M.R. Brambley. 2005. Methods for fault detection, diagnostics and prognostics for building systems—a review, part I. *HVAC&R Research* (now *Science and Technology for the Built Environment*) 11(1):3-25.
- Katipamula, S., R.G. Pratt, D.P. Chassin, Z.T. Taylor, K. Gowri, and M.R. Brambley. 1999. Automated fault detection and diagnosis for outdoor-air ventilation systems and economizers: Methodology and results from field testing. *ASHRAE Transactions* 105(1):555-567.
- Katz, G. 2003. *The costs and financial benefits of green buildings: A report to California's sustainable building task force*. Available at <http://www.usgbc.org/Docs/News/News477.pdf>.
- Li, H., and J.E. Braun. 2007a. An overall performance index for characterizing the economic impact of faults in direct expansion cooling equipment. *International Journal of Refrigeration* 30(2):299-310.
- Li, H., and J.E. Braun. 2007b. An economic evaluation of the benefits associated with application of automated fault detection and diagnosis in rooftop air conditioners. *ASHRAE Transactions* 113(2):200-210.
- Li, H., and J.E. Braun. 2007c. A methodology for diagnosing multiple-simultaneous faults in vapor compression air conditioners. *HVAC&R Research* (now *Science and Technology for the Built Environment*) 13(2): 369-395.
- NIBS. 1998. Excellence in facility management: Five federal case studies. Publication 5600-1. Facility Maintenance and Operations Committee, National Institute of Building Sciences, Washington, D.C.
- NRC. 1990. Committing to the cost of ownership: Maintenance and repair of public buildings. National Research Council, National Academy Press, Washington D.C. Available from http://www.nap.edu/catalog.php?record_id=9807.
- Proctor, J. 2004. Residential and small commercial air conditioning—Rated efficiency isn't automatic. ASHRAE Public Session, Winter Meeting, Anaheim, CA.
- Romm, J.J. 1994. Lean and clean management: How to boost profits and productivity by reducing pollution. Kodansha USA, New York.
- Rossi, T.M. 2004. Unitary air conditioning field performance. *Proceedings of the Tenth International Refrigeration and Air Conditioning Conference at Purdue*, pp. R146.1-R146.9.
- Sapp, D. 2008. *Computerized maintenance management systems (CMMS)*. Whole Building Design Guide, National Institute of Building Sciences, Washington, D.C. Available at <http://www.wbdg.org/om/cmms.php>.
- Seem, J.E., J.M. House and R.H. Monroe. 1999. On-line monitoring and fault detection of control system performance. *ASHRAE Journal* 41(7): 21-26.
- Whitestone. 2012. *The Whitestone facility operations cost reference 2012-2013, North American version*. 6th edition, p. 292. Whitestone Research, Santa Barbara.
- Yates, A. 2001. *Quantifying the business benefits of sustainable buildings—Summary of existing research findings (extracts); Draft for discussion*. Building Research Establishment (BRE), Waterford England. Available from <http://www.usgbc.org/resources/quantifying-business-benefits-sustainable-buildings-%E2%80%93summary-existing-research-findings-e>.

BIBLIOGRAPHY

- Blanchard, B.S., D. Verma, and E.L. Peterson. 1995. *Maintainability: A key to effective serviceability and maintenance management*. John Wiley & Sons, New York.
- Campbell, J.D. 1995. *Uptime, strategies for excellence in maintenance management*. Productivity Press, Portland, OR.
- Fuchs, S.J. 1992. *Complete building equipment maintenance desk book*. Prentice Hall, Englewood Cliffs, NJ.
- Katipamula, S., and M.R. Brambley. 2004. Methods for fault detection, diagnostics and prognostics for building systems—A review, part II. *International Journal of HVAC&R Research* (now *Science and Technology for the Built Environment*) 11(2):169-187.
- Moubray, J. 1997. *Reliability-centered maintenance*, 2nd ed. Industrial Press, New York.
- NCMS. 1999. *Reliability and maintainability guideline for manufacturing machinery and equipment*, 2nd ed. National Center for Manufacturing Sciences, Ann Arbor, MI.
- National Academy of Sciences. 1998. *Stewardship of federal facilities: A proactive strategy for managing the nation's public assets*. National Academy, Washington, D.C.
- Smith, A.M. 1993. *Reliability-centered maintenance*. McGraw-Hill, New York.
- Stum, K. 2000. Compilation and evaluation of information sources for HVAC&R system operations and maintenance procedures. *Report*, ASHRAE Research Project RP-1025.