

CHAPTER 40. OPERATION AND MAINTENANCE MANAGEMENT

OPERATION and maintenance management is the organization of people, materials, and funds to allow a building’s infrastructure to fulfill its owner’s and occupants’ requirements for building performance. Operating a building requires dynamic assessment of when to turn systems on; optimization of set points; and monitoring, recording, and responding to **key performance indicators (KPIs)**. Maintaining a building involves tasks designed to ensure that building systems are functionally available at acceptable levels when needed. Occasionally, buildings undergo capital upgrades, which reconfigure or replace significant portions of buildings or building systems. Such upgrades are distinct from, though closely tied to, operation and maintenance. Operation, maintenance, and upgrades all affect a building’s ability to fulfill its performance requirements.

Commonly, performance is defined in terms of energy efficiency and energy cost, but in reality, building performance extends to expectations for reliability, availability, and occupant comfort, safety, and health. Recently, building performance has expanded to include environmental and community impacts. As buildings age, their performance can drift from original design targets, and even new buildings can fall short of design requirements or experience degradation in their first years. Poor performance can be due to errors in design or construction; manufacturing defects in equipment; or human activity (e.g., adjusting thermostat set points, adding plug loads, and leaving things on when not in use). A Lawrence Berkeley National Laboratory study (Mills 2009) found that retro- or recommissioning activities that reset operating parameters to meet current facility requirements can improve performance of an existing building by 7 to 29%. Given the natural tendency toward building system wear and performance drift, it is clear that **operation and maintenance (O&M) management** is necessary to sustain the desired levels of building performance.

Managing O&M includes setting performance goals; developing strategies to achieve them; communicating both the goals and the results to the building managers, operators, and users; providing direction to building operators and maintenance staff; coordinating efforts based on cost and other factors; managing change; and supervising work. Buildings may have several categories of performance goals, including hours of availability, specific functionality, equipment reliability, water use, and **indoor environmental quality (IEQ)**. This chapter presents a general discussion of how buildings may be operated and maintained, as well as strategies, tools, and required documentation for successful O&M management programs.

1. MANAGEMENT

Building O&M activities are performed by people, working with the resources they are provided, to achieve and communicate the objectives and goals set for them. It is the task of O&M managers to set the objectives and goals; provide the resources; document and communicate outcomes; and to hire, organize, and lead those people.

Organization

Per ASHRAE *Guideline* 32-2018, a successful O&M program requires involvement at three levels of the owner’s organization, as shown in [Table 1](#).

Communication

Communication is achieved not only through documents, but also through regular interactions among team members. Program documents should allow each team member to comprehend their individual role, responsibilities, and objectives, as well as how their contributions complement those of others. O&M reports, **building automation system (BAS)** alarms, **automated fault detection and diagnosis (AFDD)** reports, and occupant satisfaction surveys provide technicians and engineers with raw data on which to base actions and recommendations. KPI reports prepared by facilities managers and engineers inform senior managers of performance relative to preset objectives, goals, and targets.

Table 1 Organizational Requirements and Tasks

Level in Organization	Required Resources and Responsibilities	Tasks to Perform
Owner, Executive, Senior Management	MANDATE to operate and maintain infrastructure. FUNDING to hire staff and purchase/upgrade equipment.	Set and communicate strategic objectives and goals for <ul style="list-style-type: none">Safety and reliabilityThermal energy demand intensity, energy use intensity

	RESPONSIBILITY for <ul style="list-style-type: none"> • Safety and reliability of infrastructure • O&M and energy budgets • Occupant satisfaction. 	<ul style="list-style-type: none"> • , O&M cost • Occupant satisfaction Assign resources: <ul style="list-style-type: none"> • Facilities management and engineering professional • O&M technical Review and evaluate results
Facilities Management and Engineering	MANDATE to implement the strategy TECHNICAL PROFESSIONAL knowledge/qualifications BUSINESS PROFESSIONAL knowledge/qualifications LEADERSHIP abilities	Develop and implement tactics <ul style="list-style-type: none"> • Select and implement standards and guidelines • Create • preventive maintenance (PM) program (planned, preventive, and predictive as required) • Plan and record O&M activities • Measure KPIs such as • thermal energy demand intensity (TEDI), energy use intensity (EUI), occupant satisfaction, O&M and energy costs Equip and direct technical staff <ul style="list-style-type: none"> • Create and lead in-house teams • Provide training to in-house staff and record certifications • Procure and manage contracted O&M trades • Provide building automation system (BAS), computerized maintenance management system (CMMS), and reporting tools Report results to owner/executive/senior management
Operators and Technicians	ROLES, RESPONSIBILITIES, and schedules TEAM STRUCTURE for good intergroup coordination Access to facilities DOCUMENTATION TOOLS, including BAS, CMMS, meters, and report forms	Practical field duties Operators <ul style="list-style-type: none"> • Monitor status and report deficiencies • Respond to deficiency reports and raise work requests • Orient technicians executing maintenance Technicians <ul style="list-style-type: none"> • Routine belt/filter/lube/inspect PMs • Corrective maintenance resulting from PMs and from operator reports

Opportunities for interaction among team members can be both formal and informal, and involve staff from each level of the organization. O&M, facilities management, and engineering staff should participate in regular team meetings to review operator and maintenance reports, BAS alarms, AFDD reports, and occupant satisfaction surveys, and they should use these reports to plan corrective maintenance, adjust PM schedules, or develop plans for capital upgrades. Facilities managers and senior managers should meet to review KPIs; and use those KPIs to adjust funding or staffing to achieve goals. Engineers, facility managers, and senior managers should schedule regular opportunities to walk through their buildings with O&M technical staff and meet with occupants. This will give them an opportunity to see and experience conditions first-hand.

Building tenants can be engaged through creative means like energy performance dashboards in building lobbies. For example, at a particular building in Seattle, Washington, the owners commissioned artwork in which brass flowers “bloom” when energy performance is positive, and “wilt” when energy performance is poor. Whether creative or more prosaic, energy dashboards can motivate occupants to feel ownership and do their part to improve building performance.

Benchmarking

Benchmarking is comparing the performance of one building to that of other buildings with certain similarities such as size, function, age, or geographic location. It is good for the O&M management team to study similar facilities to gain new perspectives and learn about other management and strategies. Establishing goals and performance targets for one building can be greatly influenced by understanding what other similar buildings have been able to achieve. Additionally, there is also a growing interest in sharing benchmarking results with building users. Performance disclosure requirements have begun to appear in some municipal codes and in real estate transaction documentation requisites.

Triennially, the U.S. Energy Information Administration conducts the *Commercial Building Energy Consumption Survey (CBECS)*. The results of this survey include national averages for metrics, particularly building size-based energy use intensities (EUIs) that can be used for benchmarking energy performance. ASHRAE *Standard* 100-2018 specifically

includes guidance for both site and source EUIs for energy performance targets based on building size, function, and climate zone. Other organizations that publish data that may be used for benchmarking and targeting are the Building Owners and Management Association ([BOMA.org](https://www.boma.org)) and the U.S. Green Building Council ([USGBC.org](https://www.usgbc.org)). For further information on energy use intensities and benchmarking, see [Chapter 37](#).

In addition to benchmarking the building's operating performance against that of other similar buildings, its current performance can also be compared to its theoretical as-designed performance using the ASHRAE Building Energy Quotient (Building EQ) Tool (www.ashrae.org/technical-resources/building-eq). By combining both as-operated and as-designed ratings, this online tool can provide a measure of performance drift.

Performance comparisons should be made regularly, and results should be shared with the entire facility management team. These actions can be performed at a low cost (or expense, if outsourced) and if done correctly can bring a significant value by informing future management actions.

Plan, Do, Check, Act (PDCA)

A useful concept in operation & maintenance is to improve O&M activities using the Deming Institute's **Plan, Do, Check, Act (PDCA)** cycle (deming.org/explore/pdsa/). In this way, a new idea can be tested on a small scale, and if the results are appealing, the facilities management (FM) team can cautiously scale up. According to Deming, we "plan a change or a test, aimed at improvement"; we "carry it out (preferably on a small scale)"; [and] check or "study the results. What did we learn?" and then Act to "adopt the change or abandon it, or run through the cycle again, possibly under different environmental conditions."

Building Life Cycle

It is common for design, construction, commissioning, and operation of a building to be outsourced and performed by separate entities. However, the lengthiest stage of building's life cycle is its operation, so a prudent owner will plan ahead and engage the operations team at the earliest stages of the project, whether it is for new construction or an upgrade. [Figure 1](#) shows that some O&M decisions and tasks begin long before handover of the building from the constructor to the operator. Key among them is the creation of the Asset Registry and PM plan. Note how the figure shows management of the asset registry as well as PM and **corrective maintenance (CM)** data as ongoing tasks from project initiation through the end of life. A **building information model (BIM)** that captures key component data and incorporates it into the construction drawings, which are maintained on-site and updated when changes are made, can be vital to these tasks.

Technical tenant management pertains to the information and activities that the O&M team requires to be followed by the tenant in order to ensure that rented space installations and fit-outs are aligned with the overall building strategy. In other words, the O&M team should be prepared to provide documented baseline requirements to the tenant and the tenant's design and execution team to follow. If the tenant team wants to do something outside of the rules, the O&M team should be advised so it can decide whether the desired change is feasible.



Figure 1. Sample O&M Tasks Over Life of Building

Deliverables include all of the tangible or intangible equipment and information that must be submitted to the O&M team from pre-construction to the commissioning stages. They include but are not limited to drawings, data sheets, vendor lists, design specifications, **installation and operation manuals (IOM)**, and various test results including those for factory performance tests, and site acceptance tests, as well as special verifications and tests that form commissioning activities.

Life-cycle climate performance (LCCP) includes all the measurements to calculate the global impact of the HVAC&R equipment. This work is done initially to baseline the ramifications of the equipment and consumables on environment. It is repeated at regular intervals to detect performance slippage.

Change Management

long before turnover from the constructor, the facilities management team must be prepared to plan, implement, and document evolving building needs. Decisions made in design and construction can make change management easier. For example, zone isolation valves and capped tees can be installed in piping systems to facilitate future changes to space function or size; spare bays can be left in motor control centers and breaker boxes to accommodate future additions; and equipment can be grouped in service rooms and shafts so that space remains for future development.

Following turnover, **change management** begins. a change management process includes the definition of who can request a change and who can approve one. Requests may come from the owner/executive, tenants, user groups, operators, and maintainers. Approval of the change should come from the owner/executive, and where applicable, from the facilities manager, engineer or other technical expert. Whatever the request and approval process, it should be transparent and documented with a written, formal change management policy that specifies what sorts of changes may be made by tenants within the building's original design basis. For example, can tenants connect or disconnect kitchen equipment from existing services in a leased restaurant space or must the O&M team be called in to perform or coordinate this work? Might an update to the design basis be required if, a building were to be equipped with natural gas service where none previously existed? To guard against degradation, the change management policy should contain language to ensure tenant-implemented changes maintain or exceed the specifications of the original equipment.

To facilitate planning and documentation of changes, it is good practice to either employ an in-house engineer, or to have a standing contract with an engineering firm that can maintain the building's basis of design documents and drawings, and update them when needed. Such an engineer may also be the building's **ongoing commissioning authority (OCxA)**, as discussed in the next section. A building management organization may also wish to have one or more standing agreements with prequalified contractors, who can execute small-to-medium scale changes through single-source task orders, or a streamlined bidding process.

2. COMMISSIONING AND OPERATION

Commissioning goes beyond equipment check/test/start procedures or the testing and balancing of distribution systems. It is a formal process for integrating all project requirements throughout all the phases of building development. Commissioning verifies and documents that the facility and its systems are planned, designed, constructed and/or installed, tested, operated, and able to be maintained in order to meet the owner's project requirements. It includes the development and documentation of the **owner's project requirements (OPR)**, the required function of the facility and how its success will be determined, and regular reviews to ensure the OPRs are continuously met over the life of the building. [Chapter 44](#) provides an overview of commissioning for HVAC systems. ASHRAE *Standard 202* and *Guideline 0* offer guidance and define the standard of care that should be taken in delivering a commissioning project with all the major systems typical of a complete facility.

Existing buildings may need to be periodically commissioned as equipment performance naturally drifts from design or building function changes. Research has shown that many buildings have the potential to reduce energy consumption by 10 to 40% by application of commissioning to building operation (Landsberg et al. 2009). Both recommissioning systems that were previously commissioned, and retrocommissioning systems that have not previously undergone commissioning, largely follow the same process as the commissioning of a new facility. However, there are some key differences. For example, in commissioning, the OPR is provided to the **commissioning authority (CxA)** as part of the design documents that establish acceptable performance levels. However, in retro- or recommissioning, the commissioning authority must develop and define the **current facility requirements (CFR)** in conjunction with the building owner and occupants. Guidance for facility retrocommissioning and recommissioning is provided in ASHRAE *Guideline 0.2*.

Both recommissioning and retrocommissioning have a high potential to reset system performance to near original levels. However, it is better to avoid drift from initial performance where possible. To better ensure that building systems remain optimal throughout the facility service life, a policy of **ongoing commissioning (OCx)** should be considered. Ongoing commissioning, a process which significantly overlaps with operation, is a continuation of the commissioning process throughout the service life of the building. With ongoing commissioning, the CFR documents are immediately updated as they change. Ongoing commissioning is cyclical and activities are repeated at intervals appropriate for the facility, its use, and its management team. Guidance for ongoing commissioning is also provided in ASHRAE *Guideline 0.2*.

Guiding Principles for Optimal Performance

In general, there are three guiding principles to optimize facility operation: (1) only turn systems on when needed, (2) only turn systems on to the extent needed, and (3) turn systems off when no longer needed. Note that each principle ends with the word *needed*. Because it is often challenging to understand need, it is worth adding a fourth principle to this list: (4) ensure that occupants are satisfied with the results. These principles can be applied to all building systems that consume energy, including those for occupant conveyance and service water. [Table 2](#) provides examples of the guiding principles in practical applications. Often these principles are instituted with the aid of existing control algorithms, though sometimes additional equipment is required.

ASHRAE *Guideline* 36 provides more comprehensive guidance on operating facilities in a manner that improves building performance. It includes a list of detailed standardized sequences of operation specific to HVAC systems, which can be used to reduce energy consumption, improve fault detection, and improve IEQ.

Table 2 Examples of General Operating Principles in Practice

Guiding Principle	Building System		
	HVAC	Lighting	Domestic Hot Water
Turn systems on only when needed	Heat and cool spaces no more than needed to maintain set points. Start morning warm-up/cool-down as late as possible while meeting IEQ set points upon occupancy.	Turn lighting on only when spaces are occupied.	Lower storage temperatures when building is unoccupied for extended periods.
Turn systems on only to extent needed and augment system output with available free sources	Use economizers to offset need for mechanical cooling. Ventilate spaces based on demand. Reset chilled- and heating-water temperatures based on outdoor air conditions. Use set-point setback and setups during unoccupied hours.	Use multilevel general lighting and task lighting. Coordinate lighting power with available daylighting	Use lowest storage temperature such that delivery temperature to farthest faucet matches design temperature. Use recovered heat to preheat hot water.
Turn systems off when no longer needed	When spaces are unoccupied for extended periods, reset cooling set points to maximal values and reset heating and ventilation set points to minimal values. As early as possible, allow system to coast to unoccupied set points, while maintaining IEQ set points during occupancy.	Turn lighting off when spaces are unoccupied.	Lower storage temperatures when building is unoccupied for extended periods.
Ensure that occupants are satisfied	Survey occupant satisfaction with temperature, humidity, odor, noise, and hours of operation. Trend key points in the BAS, looking for points in “operator” mode, and indicators that occupants are using electric heaters. Walk the building talking to occupants. Look for signs of discontent like sweaters on chair backs, heaters under desks, and personal desktop thermometers.	Survey occupant satisfaction with lighting level, color, and angle. Walk the building at different times of day, talking to occupants. Look for signs of discontent like broken blinds, papers taped to windows, and desk lamps.	Survey occupant satisfaction with water temperature and flow. Trend water temperature in the BAS, looking for points in operator and/or temperature swings. Tour a locker room at shift change and talk to occupants. Use a shower, a toilet, and a sink. Look for signs of discontent like broken lockers, benches, and taps.

Automated Fault Detection and Diagnosis (AFDD)

Manual patrols of the facility are a key strategy to detect faults and alert maintenance staff to the presence of some issues that require attention (e.g., burned-out lamps), but there may be a lag between a fault’s occurrence and its detection. Depending on the equipment and its criticality, this lag could significantly impact building performance. Additionally, there are some faults (e.g., outdoor air dampers failed open) that are not easily discovered by patrol and may not be alarmed in the BAS, so advancements in building automation have given rise to AFDD. This software can keep operations and maintenance staff better apprised of the conditions of HVAC&R equipment and systems, and can help manage both equipment-level and system-level maintenance. With AFDD, system performance indicators are automatically monitored, measured, and compared to expected values. The expected values may be input into the

AFDD software manually, or they may be extracted from **building information modeling (BIM)**, a computer-based tool increasingly used during building design and construction. Discrepancies are identified and analyzed for root causes using algorithms based on engineering principles and empirical data, and a list of recommended corrective actions is automatically generated. For example, the outdoor air damper fault mentioned above could be identified by an AFDD algorithm noticing excessive high or low temperature in the mixed air stream.

The value of AFDD has been validated in part by studies that document a wide variety of detected operating faults common in HVAC equipment (Breuker and Braun 1998; Breuker et al. 2000; Comstock et al. 2002; House et al. 2001, 2003; Jacobs et al. 2003; Katipamula et al. 1999; Proctor 2004; Rossi 2004; Seem et al. 1999). AFDD’s main value is its ability to identify unwanted operating conditions that are not easily discoverable by cursory observation. This is particularly true for equipment in locations without easy access (e.g., on roofs, above ceilings, in walls) that are inspected infrequently. More examples of detected faults include frequent cycling of pump or fan **variable frequency drives (VFDs)** through their ranges; pump or fan VFDs operating for extended periods at the top of their ranges; economizers in packaged air conditioners and heat pumps not operating properly; low or high (depending on the season) refrigerant charges; condenser and filter fouling; faulty sensors and controls; and simultaneous heating and cooling. For a detailed explanation of AFDD, see [Chapter 63](#).

Operator Logs

Operator logs can be a rich source of information on equipment and system performance. Their review should be thought of as an extension of operator patrols; the frequency of those reviews should be such that any necessary adjustments can be made within a reasonable time to optimize building performance, costs, and occupant satisfaction, and to minimize equipment damage. [Table 3](#) shows an example operator log excerpt.

Table 3 Sample Operator Log Excerpt

Date	Location	Item	As-found	As-Left	Recommended Follow-up	HVAC System Specialist Disposition
03/01/2022	B330	S-1	Outdoor Air Damper actuator appears seized	Not modulating OA.	Check damper for obstruction/ice. Check actuator motor operation	HVAC mechanic sent to check. Actuator needs replacement and vanes need lube. Work scheduled.
03/01/2022	B466	S-3	Unit is labeled "S-3" in the field, but "J-1" in the BAS	Hung tag on unit noting discrepancy	Change label in BAS	Label on graphics screen changed to match field
03/02/2022	B500	S-1	AFDD report – supply fan VFD cycling	NA	Engage engineering support	Checked supply air system. Tweaked VAV box control loops and supply fan discharge air pressure set-point.

Source: After Dillenbeck and Sheppard (2017).

Dillenbeck and Sheppard (2018) suggest conducting short daily meetings, where operators, facility managers and engineers review BAS alarms, along with the operator’s log from the previous day’s shifts. If available, AFDD reports and trend logs may be reviewed at the same meetings. In a typical log entry, the operator reports the location, item, issue and most importantly, recommended action. Within two working days, the HVAC System Specialist writes a disposition to the line item. The log is reviewed and discussed at the daily meetings.

In reviewing logs, pay attention to parameters deviating from allowable tolerances, and to opportunities for system optimization. Regardless of the nature of the poor performance or opportunity for improvement, a thorough analysis should be conducted to ensure that the situation is well understood. Only then should changes be devised and implemented. There are a variety of analysis methods that may be used to pinpoint sources of poor performance, or evaluate opportunities for improvement. In selecting an analysis method, care must be taken that the rigor of the analysis be commensurate with the scale and scope of the problem or opportunity.

Table 4 Maintenance Strategies

	Maintenance Strategy		
	Run-to-Failure	Preventive	Predictive
Principal objective	Minimize maintenance tasks and expenses	Maintain safety, reliability, and efficiency	Maintain safety, reliability, and efficiency with minimal downtime
	Best option for temporary buildings, low-cost components, and applications where unpredictable downtime is acceptable	Best option for lower-cost components of high-value assets and applications where routine downtime is acceptable	Best option for higher-cost components of high-value assets and applications where downtime should be minimized

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Key advantages	Minimal need for permanent staff and training Little planning and tracking of repairs	Safe and predictable work for lower-trained maintenance staff Basic planning and tracking of maintenance Maintains system performance and IEQ at design levels Achieves design-basis asset life	Safest and most interesting work for higher-trained O&M staff Lowest downtime Provides opportunities to optimize system performance and IEQ Maximizes asset life
Key disadvantages	Call-outs for emergency response can impact staff safety and morale Unreliable system performance can impact building occupant morale Most unpredictable downtime Shortest asset life Reduced system performance and safety as original equipment degrades or is improvised	Higher materials and labor costs than predictive maintenance if applied to higher-cost tasks and parts Highest planned equipment downtime as compared to run-to-failure or predictive maintenance	Requires highly skilled and paid operations and engineering staff to gather and interpret data Most sophisticated planning and tracking of systems monitoring records, inspection reports, and maintenance Requires expensive monitoring and diagnostic equipment, which must be maintained

3. MAINTENANCE

Maintenance tasks can include inspection, adjustment/calibration, lubrication, cleaning, nondestructive testing, and repair or replacement of components. All these tasks are designed to minimize the risk of failure and to preserve the performance of building assets, thus enabling them to meet owner and occupant requirements for thermal comfort, IEQ, energy efficiency, and costs. Some maintenance tasks are designed to reveal indications of future performance. These **condition indicators** can be evaluated by observation, as with fan belt wear; or by measurement, as with compressor amperage draw. As soon as condition indicators suggest unacceptable future performance, remedial actions should be expedited to avoid failures or excessive repair costs.

Maintenance Strategies

Maintenance activities can be planned or unplanned, active or reactive; but in general, there are three basic maintenance strategies that define when maintenance activities are performed ([Table 4](#)).

In **run-to-failure maintenance**, minimal or no resources are invested until equipment or systems break down. Once breakdown occurs, the equipment is repaired or replaced. This strategy is most often used when the cost of maintenance or repair exceeds the cost of an item’s replacement, and unexpected downtime is acceptable. The equipment may or may not be monitored for proper operation, depending on the consequences of a loss of beneficial use. If run-to-failure maintenance is unplanned, then replacements are treated reactively with levels of urgency that depend on the criticality of the equipment and the system it supports. If planned, then spare parts, components, or equipment are kept on hand to replace failed units to minimize downtime.

Preventive maintenance is planned and scheduled, either by equipment run time or by calendar. In this strategy, maintenance tasks are performed at frequencies recommended by the manufacturer, industry standard, or as adapted to field conditions. The time between repetitions of a maintenance task is the **task frequency**. Tasks may be performed once per shift, daily, weekly, monthly, quarterly, semiannually, annually, or at other frequencies. For example, ASHRAE Standard 180 recommends that variable-speed drives on air handlers be checked for proper operation every six months. Task frequencies are typically derived from manufacturers’ recommendations, which are based on failure mode effect analyses, average time between failures, and other reliability data. However, these frequencies can (and should) be adjusted to suit actual field conditions. For example, if acceptable condition indicators are found on three successive inspections of heat exchanger tubes, the frequency of tube inspections can be reduced. Similarly, if unacceptable conditions are found in two successive inspections, the frequency should be increased; in this case, depending on the criticality of the component, a systematic root cause analysis may be undertaken to identify the cause of unacceptable performance.

This proactive strategy is typically used for essential building equipment such as pumps, air handlers, boilers, ductwork, elevators, and transformers. One of the disadvantages of preventive maintenance is that it can lead to excessive routine downtime and maintenance costs, because tasks are performed on schedule regardless of whether they are required. Thus, predictive maintenance strategies, which optimize task frequencies, continue to grow in popularity.

Predictive maintenance uses measurements of the condition and/or performance quality of equipment and systems to guide maintenance activities. Current conditions and performance can be compared to benchmarks determined by industry standards or facility historical performance. Rates and types of component wear and/or performance degradation are used to predict when failure is likely to occur. Corrective maintenance can be planned and scheduled to take place just in time before failure or loss of beneficial use. By basing maintenance actions on analysis of actual field data, both excessive and insufficient maintenance frequencies can be avoided, thereby minimizing

downtime and maximizing maintenance personnel productivity and plant reliability. The emergence of BAS has reduced the cost of the monitoring and data-analysis required for predictive maintenance. In the past, a filter change program might have run on a calendar because, given travel and labor charges, the cost of a maintenance call to change filters was essentially equal to the cost of a maintenance call to read the pressure gauge across a filter bank. With BAS, a maintenance call can be initiated by an operator reading a screen at a remote location; in the most sophisticated and integrated of systems, a pressure drop reading beyond set-point can trigger a facility's **computerized maintenance management system (CMMS)** to initiate a maintenance call automatically. The trade-off for this high-performance functionality is the cost to purchase and maintain the BAS, and its software integration to the CMMS.

Subcategories of predictive maintenance go by various names (e.g., condition-based maintenance, reliability-centered maintenance, benefit-based maintenance). Each subcategory focuses on a particular performance index to determine when and what maintenance should be performed. All forms of predictive maintenance, however, rely on nondestructive testing and observation to obtain the data on which future performance is predicted. Future failure predictions can be based on nearly any indicator of performance degradation that changes gradually over time. Typical nondestructive diagnostics include tools and techniques such as (1) thermal infrared imaging; (2) electrical current analysis; (3) vibration analysis; (4) chemical analysis of lubricants and heat transfer media; (5) measurement of pressure and temperature differentials in fluid flows; (6) ultrasonic and eddy-current testing of pipe and vessel walls; (7) dye penetrant testing to identify cracks; and (8) visual inspections of all types.

Condition and performance measurements can be completed either continuously or periodically. Some periodic measurements are performed manually by operators on routine patrols or while performing other tasks. For example, the condition of water or glycol in hydronic loops can be checked by sampling fluids while cleaning strainer baskets and changing filters. Visually checking fan belts for wear, and using ultrasonic microphones to detect leaks in steam or compressed air systems, can be easily incorporated into regular patrols.

Choosing the Best Combination of Maintenance Strategies

The ideal maintenance program preserves the required asset reliability and availability at the lowest cost by identifying and implementing actions that reduce the probability of failure to an acceptable level. It is unlikely that a single strategy will satisfy the safety, availability, reliability, performance, and economic criteria for all assets in a facility. Thus, optimal maintenance programs generally incorporate all three basic strategies selectively. For example, a program might use a run-to-failure replacement strategy for lighting, windows, and door weatherstripping; a preventive strategy for roughing filter changes, strainer cleaning, and residential water heater replacement; and a predictive strategy for chillers and boilers. Each strategy has advantages, disadvantages, and cost implications that should be considered when defining a maintenance program. [Table 4](#) provides a simple characterization of the strategies.

When developing a maintenance program, the needs of each asset class or system should be considered separately. For each asset, an economic analysis weighing the costs and benefits of the three basic strategies should be performed. Because maintenance takes place over the life of an asset, the economic analysis will need to determine the net present values of costs and benefits. For details on performing net present value calculations, see [Chapter 38](#).

The economic evaluation may include many factors; however, those that are essential to strategy selection include

- Safety issues related to asset failure
- Owner and occupant requirements for availability and performance of the asset
- Cost to purchase the asset
- Life-cycle labor costs for maintenance associated with the asset
- Cost to replace the asset
- Cost of downtime resulting from asset failure
- Cost of required staff training to maintain the asset
- Cost of required instrumentation and diagnostic tools to maintain the asset

Other factors may include benefits, such as productivity improvements attributable to the enhanced occupant comfort provided by improved indoor environmental conditions, and concerns such as environmental impacts. Qualitative benefits such as these do not have simple monetary values and will need to be assigned monetary worth. To reduce subjectivity, it is recommended that formulas be developed for valuing non-monetary benefits. Once the costs and benefits have been determined and summed, they can be compared to determine which of the three strategies has the greatest benefit, or the least cost. This information can then be used to more objectively select the optimal maintenance strategy for each asset, asset class, or system.

4. O&M OBJECTIVES, GOALS, AND KEY PERFORMANCE INDICATORS

Goal setting begins with the end in mind, and bridges the gap between the desired outcome and the point of origin. **Objectives** are broad outcomes, and **goals** are the intermediate steps toward those objectives. For example, an organization's senior management might establish an objective of being recognized for sustainability. To support this objective, goals might include reducing water consumption by 2% annually, reducing energy waste by 15% by the end of the year, or achieving an energy utilization index (EUI) of 155,000 Btu/ft² · yr in two years. The quantifiable measures used to evaluate progress toward the goals are their **key performance indicators (KPIs)**. To be meaningful, goals should be linked to KPIs.

McCluney (2017) identified eleven types of KPIs: quantitative, qualitative, leading, lagging, input, process, output, practical, directional, actionable, and financial. This list could be arranged into headings and subheadings, or into a matrix, to produce **lagging financial indicators** or **leading process indicators**. Li et al. (2019) made the point that many well-recognized building industry KPIs are either whole-building related (EUI, TEDI) or component-specific (EER/SEER for packaged DX equipment, HSPF for air source heat pump, COP for chillers). Li et al. asserted the need for individual and subsystem-level KPIs, and suggested that they be integrated into the US Department of Energy's (DOE) **Building Performance Database (BPD)** and into ASHRAE's own building, and energy performance *Standards* 90.1 and 189.1.

Example KPIs applicable to O&M management are presented in [Table 5](#). Some items in [Table 5](#) merit further discussion. First, many of the indicators are lagging and cannot be viewed or analyzed until after the system performs and data is collected. So, the facility manager is only equipped to be reactive. Few of the indicators are leading whereby they can be observed in advance of the system performing, in which case the facility manager is equipped to be proactive. Organizations wishing to be proactive must incorporate leading indicators in their KPIs. One strategy would be to measure the percentage of equipment with assigned tag numbers and preventive maintenance tasks active in a CMMS. A building with a high percentage of system tags and active PMs is likely using some model of planned, predictive maintenance. This should lead to more optimal equipment performance and longer equipment life. The same may be said of energy meters and reporting of metrics. Existence of such equipment and reporting indicates a desire and will to improve performance, so performance-enhancing action is more likely to follow.

However, some lagging indicators are of great value. A particularly long-view lagging indicator is capacity utilization of heating and cooling equipment. For various reasons, it is common for buildings to have oversized heating and cooling systems; despite that, at the end of a system's life, facility managers often decide to replace those oversized systems like-for-like. However, a facility manager, equipped with the records of 25 years of 60% chiller utilization on design days has a firm basis for advising an owner and instructing an engineer to replace the oversized plant with smaller, less expensive equipment. Frank et al. (2017) discuss the limitations of modeling in the construction of a building with very tight energy targets. Energy use in the client's previous building provided the benchmark for energy use in the new building. Verifying that the tight energy targets had been achieved was only possible because of the client's monitoring and collection of appropriate data.

Table 5 Key Performance Indicators

Performance Indicator	Objective
Percentage of equipment with assigned tag numbers, and PMs active in a CMMS.	High-performance O&M program/Mature capability to perform preventive maintenance
Top ten repeated equipment failures	Identify systems and components for attention
Numbers of work requests entered, completed, closed, canceled etc.	High-performance O&M program/Healthy maintenance workflow
Mean time between failures	Long intervals are desirable. Watch for intervals beginning to shrink
Mean time to repair	Keep as short as possible
Scores on surveys of occupant satisfaction with IEQ.	Satisfied occupants/Given zone's occupants satisfied
Change in survey scores of occupant satisfaction with IEQ.	Satisfied occupants/Upward trends toward high satisfaction
Presence of unit heaters, sweaters and desk-top thermometers in workspaces	Satisfied occupants/No need for adaptive behaviors
Energy use intensity (EUI).	Energy efficiency/Total building energy use per year, divided by gross floor area, is minimized
Thermal energy demand intensity (TEDI).	Energy efficiency/Space and ventilation heating output, divided by modeled floor area, is minimized
Percentage of buildings equipped with energy metering, and up-to-date reports of calculated values for EUI and TEDI	Energy efficiency/Mature capability to measure and report efficiency
Facility condition index	Facilities in good health/Calculated value of repair needs, divided by current replacement value of the facility, is minimized
Percentage of time a room's IEQ meets set-point.	Satisfied occupants/Stable IEQ

Percentage of fan or pump run-time above 80%	High-performance O&M program, and energy efficiency/Equipment modulates to reduce maintenance needs and conserve energy
Capacity utilization of heating and cooling equipment	High-performance O&M program; Identify over or under-sized equipment Provides opportunity to right-size at end-of-life replacement
Water consumption	Identify normal water use/alarm excessive water use which could indicate upset condition/incentivize reduction

When establishing O&M objectives, goals, and KPIs, consideration must also be given to available financial and human resources, the age of equipment and systems, and capital projects planned for the near future. The objectives, goals, and KPIs selected for a critical-care hospital or hazard-classed biological research facility should be different, both in scope and in scale, from those selected for a shopping mall or multiresidential housing complex. Regardless of the type of facility and equipment, KPIs that can and will be monitored by the available staff with the available resources should be selected. The term **sustainability** has come to mean providing for the needs of the present while not compromising the ability of future generations to meet their own needs. However, when applied to building O&M, its historical definition (able to be maintained at a certain level) continues to be useful. ASHRAE *Guideline 32* suggests using the term to indicate that "sustainable" O&M maintenance practices are those which keep building systems operating at their intended levels of performance. This includes establishing and monitoring KPIs that are sustainable.

5. DOCUMENTATION

"Having access to accurate, structured, and timely information about an asset is critical for effective whole-life asset management and is as important as the functionality and performance of the physical inventory itself."—buildingSMART International (2021)

The National Institute of Science and Technology (NIST) study *Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry* (O'Connor et al. 2004) shows that all stakeholders in the capital facilities industry (designers, contractors, product suppliers, and owners) waste a huge amount of money looking for, validating, and/or recreating facility information that should be readily available. The total cost of these activities within the capital facilities industries was conservatively estimated at \$15.8 billion in 2002, with two-thirds of that cost occurring during the facilities operations and maintenance phase.

As far back as the 1950s, internationally accepted standards have been developed to organize the information associated with construction and affiliated industries. The Construction Specifications Institute (CSI) maintains *MasterFormat*, *Omniclass*, and *UniFormat*, which are used throughout North America. Several other countries with similar classification standards, including the U.K. (*Uniclass*) from the Construction Industry Project Information Committee (CPIC), and Norway and Netherlands in concert with the Nordic chapter of buildingSMART International, formerly the International Alliance for Interoperability (IAI); and the Japan Construction Information Center (JACIC), which develops the Japanese Construction Classification System (JCCS).

Since the late 1990s, buildingSMART International has been developing and maintaining **The Industry Foundation Classes (IFC)**, as an open international standard for **Building Information Model (BIM)** data that are exchanged and shared among software applications. The IFC BIM standard includes a wide range of building system elements that can be used for planning, designing, constructing, and operating a facility. Major CADD software vendors now offer building design software tools that code each object in a design per the IFC, facilitating data exchange from early design through construction and ultimately into the operation and maintenance phase.

In 2003, the **U.S. General Services Administration (GSA)**, through its **Public Buildings Service (PBS)**, established the **National 3D-4D-BIM Program**. This program has evolved into a collaboration between the Public Buildings Information Technology Services (PB-ITS) and PBS, through its governance board. The program supports BIM uses across all PBS business lines, stating

In the future, BIM will empower design and construction professionals to work collaboratively throughout the project delivery process, focusing their energy on higher order functions such as creativity and problem solving, while computers do the tedious tasks of counting and checking.

But for real property owners and managers such as PBS, BIM holds great promise beyond improving productivity in the design and construction process. Ultimately, this technology has the potential to enable the seamless transfer of knowledge from facility planning through design, construction, facility management and operation, and recapitalization or disposal. While all parties involved in design and construction stand to gain from the adoption of BIM, it is the owners who will potentially benefit the most, through the use of the facility model and its embedded knowledge throughout the 30 to 50 year facility lifecycle.

To support the adoption of BIM, ASHRAE has sponsored two research projects: RP-1609, *Defining the Capabilities, Needs and Current Limitations of Building Information Modeling (BIM) in Operations and Maintenance for HVAC&R* (Hitchcock et al. 2015); and RP-1801, *Standardizing and Utilizing ASHRAE Online BIM Data Exchange Protocols*

(Hitchcock et al. 2020). These research projects produced detailed use case documentation for asset management, including specification of HVAC&R equipment data property sets targeting O&M activities in both human readable spreadsheet format and **Extensible Markup Language (XML) schema definition (XSD)** format. These allow data based on the 1801 XSD to be transformed to other data formats using readily available XML technologies and methodologies. Project deliverables included a user guide with illustrative videos for implementing the adoption of the 1801 work process use case in professional practice.

O&M Documents

Information on the facilities, systems, and equipment is essential for appropriate and informed operation and maintenance. It also aids in staff training; troubleshooting; updating program elements such as schedules and operating strategies; updating maintenance approaches; budgeting; assessing and communicating performance; and managing facility upgrade and retrofit projects. ASHRAE *Guidelines* 0 and 4 and *Standard* 105 and 180 provide detailed guidance on preparing accurate, relevant operation and maintenance documentation that is easy to use and update. Additionally, ASHRAE *Standard* 90.1 includes documentation requirements for specific systems, such as building envelope, lighting, power, HVAC, service hot water, conveyance, and others. The design and commissioning team should ensure that a comprehensive systems manual (as outlined in these guidelines and standards) is provided to the owner. In this volume, [Chapters 41](#) and [60](#) also address BIM and the role it plays in building documentation.

For new construction, the design team should establish operation and maintenance documentation requirements as part of the owner's 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 tasks. The requirements for operation and maintenance programs developed for existing facilities are the same, but the O&M staff may play a larger role in developing the documents.

For projects involving new equipment, it is critical that all information required to operate and maintain the systems and equipment be compiled before turnover to the owner's staff. Moreover, it is essential that the information be made available to the entire facilities department so that everyone responsible and accountable for operating and/or maintaining equipment has sufficient information to successfully perform their role. Whether operation and maintenance documentation is being assembled by the design team or by the facilities team, it is a good practice to compile the information into a series of interrelated manuals as it becomes available. In addition to being used by the facilities team to operate and maintain the building, this information can be used to support design and construction activities, commissioning, initial training of O&M staff, and facility start-up.

A complete operation and maintenance library includes a document directory, an emergency information and procedures manual, a facility operating manual with operating procedures and as-built construction documents for all major systems, and a facility maintenance manual with detailed maintenance procedures and commissioning test reports for all major systems and equipment. Recommended contents for each manual are provided in [Table 6](#).

The O&M library will serve the facility for the building's lifespan. It contains documents and manuals that evolve and grow. During the life of the building, staff will turn over any number of times. An **operation and maintenance document directory** lists and identifies the location of all the information and documents held by the facilities team. A directory that is well organized and current facilitates quick reference by both existing and new technicians and operators.

Additionally, regardless of building type, function, or size, it is imperative that **emergency information** be directly distributed to emergency response personnel. Including this critical information in the operation and maintenance library ensures that it is immediately available when needed by nontechnical persons (e.g., security and medical responders), as well as by technical persons (e.g., building operators, utility personnel, firefighters).

Table 6 Recommended Tables of Contents for Manuals Forming O&M Documentation Library

Operating Manual	Safety Manual	Maintenance Manual
General information <ul style="list-style-type: none"> - Building function - Building description with as-built construction documents - Energy budget - Operating standards with sequences of operation, set points, and acceptable ranges of values - Operating logs - Communication requirements: (1) performance, progress, and status reporting to management, and (2) advising occupants of seasonal changes and other alterations Technical information <ul style="list-style-type: none"> - System descriptions, including as-built drawings 	Communication protocols <ul style="list-style-type: none"> Objectives Key performance indicators (KPIs) Regulations Responsibilities and accountabilities Building and building maintenance related hazards Training requirements for emergency topics, type, and frequency Required safety measures <ul style="list-style-type: none"> - Safe work practices - Engineering controls - Administrative controls 	Equipment inventory <ul style="list-style-type: none"> - Equipment description, function, and associated system - Data sheets (approved submittals) with operating and nameplate data - Purchase date and warranty information - Equipment location Maintenance program and procedure information <ul style="list-style-type: none"> - Maintenance plan with KPIs - Manufacturer installation, operation, and maintenance (IOM) instructions - Spare parts information (may be in the IOMs)

- | | | |
|---|---|--|
| <ul style="list-style-type: none"> • - Seasonal start-up and shut-down procedures • - Operating routines and procedures • - Emergency procedures • - Other special procedures (e.g., operation during extreme weather) • - Basic troubleshooting | <ul style="list-style-type: none"> • - PPE | <ul style="list-style-type: none"> • - Corrective and planned maintenance task lists with frequencies, as applicable • - Health and safety plan (HASP) • - Required personal protective equipment (PPE) • - Emergency procedures • - Reports for air and water distribution systems testing, adjusting, and balancing (TAB); systems commissioning; factory tests; etc. • - Repair histories |
| <p>Required testing</p> <ul style="list-style-type: none"> • - List of systems requiring testing, along with required test frequencies and procedures (e.g., fire protection system, boilers and pressure vessels, etc.) • - Log of test dates and results • - Contact information for contractors providing third-party testing | <p>What to do in the event of an emergency, including the following, as applicable</p> <ul style="list-style-type: none"> • - • - Fire • - Security breach • - Flood • - Gas leak • - Power outage • - Plumbing overflow • - Elevator entrapment • - HVAC • - Refrigerant release • - Chemical spill | |
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Documentation Methods

There are two basic methods for collecting and archiving operation and maintenance documents: (1) hard-copy paper documents and (2) soft-copy, electronic documents maintained in a computer database or building information model. The chosen method should be aligned with maintenance program complexity and scope, as well as the accessibility needs of facility management and the skill level of maintenance staff. Both methods allow staff to enter, archive, update, and evaluate information on building systems and assets efficiently and effectively. However, with advances in communications technology and the prevalence of computers and other smart devices, many staff members find it easier to maintain, access, and update documents electronically and, at times, remotely. Nevertheless, in general, operators of small, single, and simple buildings still tend to rely on paper documents whereas operators of large, complex buildings and facilities are more inclined to use computer-based documentation methods. Regardless of which method is used, it is important that O&M staff be provided adequate time to regularly collect and document the required performance 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 software tool to

- Plan, schedule, and track maintenance activities
- Store maintenance histories and asset inventory information
- Communicate building operation and maintenance information
- Generate reports to quantify maintenance productivity.

It can be 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 in a CMMS are specified by the facility management team, depending on the facility's needs and the management team's goals. Typical CMMS modules include provisions for requesting, generating, and tracking the progress of work orders; inventory control; maintenance planning; equipment histories; maintenance contracts; and key performance indicator (KPI) tracking, analyzing, and reporting.

Although a CMMS is not required to manage maintenance activities, they are becoming more commonly used (Sapp 2016). When implementing a CMMS in a new or existing facility or upgrading an existing CMMS, the requirements of the tool, as well as communication protocols and interfaces, must be carefully planned. 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 CMMS 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 should be used. Providing these tools was an objective of ASHRAE research projects RP-1609 and RP-1801 (Hitchcock et al. 2015, 2020). Project deliverables are available online from the ASHRAE Data Portal (data.ashrae.org). Selecting the right software does not guarantee that a CMMS will improve maintenance productivity, so it is important to evaluate, document, and align facility management processes with how the CMMS will be used. When implementing or upgrading a CMMS, adequate time should be allocated to design new processes and develop a set of system requirements, using a participatory approach that includes all stakeholders (Berger 2009).

6. STAFFING

In addition to maintaining building assets in acceptable working order, it is important for maintenance staff to be able to provide good customer service. This means responding effectively to service requests and complaints from building occupants. The level of customer service provided, and how that service is perceived, are determinants of both success and continued support for the maintenance organization. Thus, determining quantity and necessary skills of staff is critical. Questions that every operation and maintenance department must answer include

- How many persons are needed to operate the facility? How many are needed to maintain the facility?
- What skills must the operations and maintenance teams possess?
- Should the facility operation and/or the facility maintenance be self-performed or contracted with a service provider?

One of the first steps in estimating staff size requirements is to translate the maintenance plan into a series of tasks and then to estimate the time necessary to perform each task, considering the number and frequency of all tasks, as well as when they can or need to be completed. The size of the staff should be such that work loads are appropriate and that personnel can perform their assigned maintenance tasks and duties both safely and within acceptable time limits. References, such as APPA (2011), provide standard labor units for maintenance tasks to help develop projections of time requirements.

Facility operating hours also affect staff sizing. For example, hospital maintenance staff need to be on site around the clock to ensure building systems and other critical systems are functioning properly and to address any operational issues that may arise. Other considerations for staff sizing include available funding, staff sourcing, labor agreement provisions, vacations, sick days, when maintenance is likely to be required, and business imperatives.

Table 7 Common Roles Within Operations and Maintenance Department

Role or Job Function	Key Responsibilities:
Shift operator	Provide patrols and respond to emergent issues, including BAS alarms Document condition indicators as required Document conditions and issues requiring resolution or further attention Attend each day's roundup meeting
Equipment or system engineer/professional	Triage reports from operators Determine skills, tools, etc. required to resolve outstanding issues Prioritize work Ensure that corrective work is not dropped, waylaid, or misinterpreted Work with site trades Manage service contracts Manage special system requirements (such as water treatment) for performance and safety
BAS and controls programmers and technicians	Diagnose and resolve issues with the BAS instruments, electronic components, and computer code
Planner/scheduler	Review operator and system reports Issue work requests Plan and schedule work Review and update task descriptions
Project leader	Work with stakeholders to develop project scopes Maintain a prioritized list of proposed projects Develop and execute capital funded projects Assist in bidding work and securing contractors Work with the contractors to execute the work
Project comptroller	Track operating, maintenance, and capital project costs Prepare regular reports for business management
Facility manager, head of section, or department head	Oversee the department Provide guidance and direction to the department staff Manage operating and capital budgets

Communicate facility and departmental needs and performance to senior management

As with other organizational departments, the maintenance department should be staffed by people with a variety of talents. The nature of the job tasks dictates the required levels of skill staff members must possess to perform the work. For example, facilities with large central heating plants may require stationary operating engineers, and industrial facilities with large centrifugal chillers requiring a compressor teardown to inspect bearings every five years require a different level of skilled maintenance than facilities served by residential-style furnaces or small packaged rooftop units. Factors to consider when defining needed skill sets include the complexity and criticality of the equipment and systems to be maintained, the rigor of the maintenance program, the actual maintenance tasks that must be performed, and whether any special skills or certifications are required to perform them.

In addition to tradespeople and regardless of facility size, equipment type, or system complexity, there are certain roles that every operation and maintenance department needs to fulfill. In large organizations, the roles may be discrete; in small organizations, individual staff members may need to take on multiple responsibilities. Exact titles vary depending on the preference of the defining organization, but the essential functions, adapted from Dillenbeck and Sheppard (2018), include operators, engineers, planners, project leaders and department heads. [Table 7](#) provides a summary of each role.

7. TRAINING

ASHRAE research project RP-771 (Johnson 1997) examined buildings in the eastern United States and Canada from 1993 to 1997 and found “a significant reduction of maintenance costs in each of the case studies against a rising training investment over the same period. Lower energy consumption was also experienced. . . .” Operation and maintenance management staff must have technical, engineering, and managerial skills. Managerial skills include managing budgets and providing direction, guidance, correction, and coaching to the personnel who operate and maintain the facility. Engineering and facility management responsibilities may include developing operation and maintenance strategies; determining program goals and objectives; and administering contracts with tenants, service providers, and labor unions. Even when specialized contract maintenance companies provide certain services, the facility manager needs to be skilled in these areas to be a smart consumer of services.

Requirements for Knowledge, Skills and Competencies

To determine the knowledge, skills, and competencies (KSCs) required of O&M staff, and the training best suited to develop those KSCs, ASHRAE research report RP-1650 (Mukhopadhyay et al. 2020) reviewed literature, and surveyed facility managers. The KSCs were grouped under the headings of

1. I. System configuration
2. II. Variables for building performance
3. III. Methods and procedures
4. IV. Installation, repair, and replacement
5. V. Programming
6. VI. Controls and interoperability

Instructional goals for different O&M staff were determined according to the requirements of their jobs to create, analyze, evaluate, understand, or apply a given KSC. For example, professional engineers reporting KPIs must understand and evaluate information, then apply skills to create reports; pipe-fitters must understand modifications to be made, then apply skills to implement a change; operating engineers must understand and evaluate information from the BAS and field instruments, then apply skills to adjust equipment. Among the most significant observations of the report was that modern high-performance buildings are characterized by continuously modulating equipment, controlled by sophisticated automation systems. Adjusting a single variable on a chilled-water pump’s variable frequency drive can cascade through the building’s chilled-water system, impacting occupant satisfaction, and the building’s EUI. Therefore, “(t)he inclusion of the above mentioned KSCs in the requirements of O&M personnel prompts a fundamental shift in the approach to O&M from ‘component-based’ to ‘systems thinking’” (Mukhopadhyay et al. 2020).

Listed in roughly declining order of rigor, RP-1650 considered five categories of training programs for their effectiveness in developing systems-level KSCs: two- and four-year colleges; technical certifications; continuing education programs; vendors’ courses; and industry training programs/seminars. Each was acknowledged to have its place, but the report concluded firmly that the training offered by diploma- or degree-granting colleges (typically pursued before entering the workforce) was the best for instilling the systems awareness required to operate and maintain modern high-performance buildings.

Mukhopadhyay et al. (2020) cited the curriculum of one two-year college's building automation diploma, which included: math and physics in the context of building systems; mechanical and electrical installation, and maintenance skills; building automation and controls hardware and programming; HVAC, electrical and BAS systems diagnostics; theory of building performance and energy management; and communication and teamwork.

Other training options include industry certifications typically pursued by those already in the workforce. One such certification cited in RP-1650 is the Building Operator Certification (BOC). Originally developed in the late 1990s, this program has expanded and several agencies throughout the United States offer training using its curriculum. Achieving this certification requires the student to complete a series of short courses and pass certification tests. ASHRAE also offers certifications in several specializations.

Continuing education programs and short courses can be offered by an employer to their staff for skills upgrading. These may not offer certifications, but are useful to keep staff apprised of industry state-of-the art. They include courses offered through the ASHRAE Learning Institute and other noncommercial entities. Most equipment vendors offer courses specific to their technology. Offered on-site or at a vendor's location, they can be important opportunities for staff to learn details specific to high-cost, or high-priority equipment in an owner's facility, and should be offered to staff required to operate or service such equipment.

Lastly, there are industry training programs offered by for-profit training companies to develop specific KSCs.

Plan and Program

The O&M management training plan and program should be established in the predesign phase of a construction project and be incorporated into the project commissioning plan and construction documents. However, the training plan can be a stand-alone document and can be initiated at any time in the life of the facility. The plan should identify the knowledge and skills necessary for everyone with a stake in the facility. This includes the owner, facility managers, building operators, and occupants. However, all stakeholders will not require the same degree or amount of training. Facility managers and operators require in-depth systems and equipment training, whereas the training requirements for occupants will simply provide a general awareness of how occupant behavior can impact facility performance. The plan will necessarily evolve over time. It should always be reviewed annually and define

- The knowledge, skills, and competencies expected to meet the key responsibilities of each job (refer to [Table 7](#) for key responsibilities for some technical jobs)
- Who needs to be trained, what current knowledge and skill levels are, and the budget and other resources allocated for training
- The training schedule and how it fits into the larger project
- The duration of initial training and requirements for refresher courses and/or continuous education
- Specifications for trainers as well as training materials, delivery methods, and archives of reference materials
- Specifications for documentation, verification, and records of training efforts and accomplishments

For construction projects, training should incorporate the owner's project requirements; for existing facilities, it should integrate the current facility requirements. Training for the facility management team should cover all the building systems and equipment, including mechanical, electrical, plumbing, controls, conveyance, and any special or unique systems (e.g., those for laboratories and cleanrooms) in the facility. As appropriate to specific job duties, training should cover the OPR and/or current facility requirements, as well as routine operation and maintenance. It should also include simple and major repairs, overhauls, failure modes, system interactions, and emergency operations and procedures. ASHRAE *Guideline* 1.3-2018 provides additional guidance for development and implementation of training programs that support acceptable building performance.

8. SELF-PERFORMANCE VERSUS CONTRACT

For many enterprises with large building, facilities maintenance organizations are not part of the core business, and economic considerations become an important factor in determining whether maintenance will be self-performed or provided by a contractor. For self-performance, another factor to consider is the cost of training for development and training for various credentials. Wage structures, the available labor pool, staff skills, and ability to perform specialized tasks are among the other factors considered when deciding to self-perform or contract facility O&M.

Often, owners of one (or even several) small buildings cannot justify the expense of employing in-house maintenance personnel. Thus, they may decide to contract out all operations and 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 as well as industry standards and guidelines such as ASHRAE *Standards* 180 and 100 and ASHRAE *Guidelines* 4 and 36. The contract should specify periodic operational checks of equipment operating schedules, set points, and indoor air

quality, and there should also be provisions to protect key building owner intellectual property and ensure it is available for continued use beyond the service provider's contract. Such intellectual property includes

- Equipment tagging database and equipment tags installed in the field
- Preventive maintenance task list and schedule for each piece of equipment
- Operator's log books and electronic logs
- Records of inspections and preventive and corrective maintenance performed
- End-of-life and capital upgrade plans
- BAS and other programmable system hardware and software, including all passwords and access permissions

When the owner employs in-house operations and maintenance staff, responsibilities should include operation checks and maintenance duties (as needed and within staff capabilities), in addition to responding to occupant complaints and overseeing corrective actions. At minimum, it is reasonable to expect the changing of filters, belts, and motors; lubrication of bearings; and similar routine maintenance. In many buildings, particularly larger ones or campuses, in-house maintenance staff may include specialized expertise, reducing the need to retain contractors. However, whenever the operator cannot service and repair the systems or components installed, the owner should ensure that qualified contractors and technicians perform the work. Additionally, when there are regulatory or certification requirements to perform specialized work, the owner's in-house staff must either possess the certification, or the work must be contracted out to someone who does possess the required certification.

Commonly, a mix of the two approaches is used: routine performance checks and inspection tasks are self-performed, and repairs to major equipment are contracted to factory-authorized service providers. This approach can reduce expenses associated with the tools and training necessary for infrequently needed maintenance activities.

Often, with the mixed approach, cost-plus service agreements (in which the service provider is paid for all allowed expenses, plus a fee for profit) are used because they make it easy to begin work when only a partial scope of required work is known, especially in cases where costs can unexpectedly increase, such as with emergency repairs. 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.

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