CHAPTER 38

OPERATION AND MAINTENANCE MANAGEMENT

ALTHOUGH facilities maintenance was once the responsibility of trained technical personnel, increasingly sophisticated systems and equipment require overall management programs to handle organization, staffing, planning, and control. These programs should meet present and future occupant, facility personnel, and technical requirements. They should also meet system availability, energy use, and environmental requirements; enhance management and operator skills; and increase communication among stakeholders (e.g., owners, maintenance planners, maintenance technicians, contractors, occupants) of cost-effective operation and maintenance.

Good maintenance management planning includes proper cost analysis and a process to ensure that occupant comfort, energy planning, and safety and security systems are optimal for all facilities. Appropriate technical expertise, whether in-house or contracted, is also important. This chapter addresses the following issues:

- Cost-effectiveness
- Management approaches according to criticality of buildings or systems
- Documentation and record keeping
- Condition monitoring and maintenance
- Operation and maintenance responsibilities of designers, contractors, manufacturers/suppliers, and owners

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 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. Existing systems may need to be reconfigured and recommissioned to accommodate changes. (See Chapter 42 for additional information on commissioning.)

TERMINOLOGY

Condition-based maintenance uses manual and automated inspection and monitoring to establish the current condition of equipment. It also uses condition and performance indices to optimize repair intervals.

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.

Durability is the average expected service life of a system or facility. Table 3 in Chapter 36 lists median years of service life of various equipment. 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.

Failure is the inability of a system or equipment to perform its intended function at an acceptable level.

Fault detection and diagnosis is a systematic procedure to compare measured and expected system performance and determine the cause of discrepancies.

The **maintenance program** defines maintenance in terms of scope, procedures, frequency, and resource allocation. It documents objectives, establishes evaluation criteria, and commits the maintenance department to basic areas of performance, such as prompt response to mechanical failure and attention to planned functions that protect capital investment and minimize downtime and failures.

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

Predictive maintenance is a function of corrective maintenance. Statistically supported objective judgment is implied. Nondestructive testing, chemical analysis, vibration and noise monitoring, and routine visual inspection and logging are classified under this function, provided that the item tested or inspected is part of the planned maintenance program.

Preventive maintenance classifies resources allotted to ensure proper operation of a system or equipment under the maintenance program. Durability, reliability, efficiency, and safety are the principal objectives.

To **repair** is to restore to good condition with the following constraints: (1) operation is fully restored without embellishment, and (2) failure triggers the response.

Results-oriented maintenance provides the required reliability and availability at the lowest cost by identifying and implementing actions that reduce the probability of failure.

Run to failure is a strategy applied when the cost of maintenance or repair may exceed the cost of replacement or losses in the event of failure. Only minimum maintenance such as cleaning or filter change is performed. The equipment may or may not be monitored for proper operation, depending on the consequences of failure. For example, a window air conditioner may be run although it is vibrating and making noise, then replaced rather than repaired.

System effectiveness is a system's ability to perform its intended function.

System operation defines (1) the parameters that the building or systems operator can adjust to satisfy occupant comfort or process

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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.

requirements and (2) the strategy for optimum energy use and minimum 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.

RESULTS-ORIENTED MAINTENANCE MANAGEMENT

Results-oriented maintenance management provides maintenance with the required reliability and availability at the lowest cost. This strategy involves identifying and implementing actions that cost-effectively reduce the probability of failure. In general, investments are made in maintenance to promote longevity of mission-critical assets to help the organization succeed over the long term.

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 are (1) design and construction, (2) operations and maintenance, and (3) acquisition, renewal, and disposal.

Representative life-cycle costs can be distributed as shown in Figure 1. Over the expected life of a typical facility, owners need to apportion funds to cover these basic segments.

It is important to compare the relative significance of these categories over an expected life cycle. Studies of the federal sector (Christian and Pandeya 1997) illustrate the relative amounts of financial resources (in some cases, as much as 85% of total life-cycle costs) required to sustain each phase of facility ownership. The results of these studies are shown in Figure 2. Over a nominal 30 yr term, operation and maintenance (O&M) comprise the largest segment of facility ownership cost. The intent of results-oriented maintenance management is to minimize operation and maintenance costs through proactive efforts in all three segments.

Prudent facility ownership should invest appropriately in acquisition, design, and construction considering future O&M expenses. Low first cost for capital projects or replacement of obsolete equipment must be weighed against the long-term effect of potentially more frequent and/or more time-consuming maintenance and repair, resulting in higher operating costs. In addition, maintenance management should consider an optimum mix of techniques to minimize maintenance costs and mitigate risk of failure. Facility design and maintenance approach decisions should consider their long-term effects on maintenance and operations costs for maximum financial benefit.

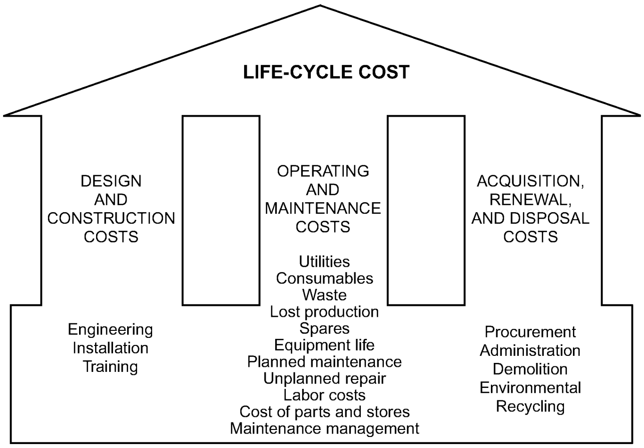

Fig. 1 Three Pillars of Typical Life-Cycle Cost with Cost Elements

Concepts

Identifying the major concepts of results-oriented facility operation and maintenance clarifies how the various elements are interrelated and, when managed effectively, how they contribute to the bottom line. The major concepts include the following:

- **Availability** is the amount of time that machinery or equipment is operable when needed. Often referred to as *uptime*, availability improvements translate to increased production for manufacturing and industrial companies. Availability is often confused with reliability, which can be seen as a component of availability.
- **Capability** is a system's ability 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 cope with the heating load at design winter temperature. Capability must be verified when the system is first commissioned and whenever functional requirements change.
- **Deliverability** is the total amount of production delivered to users per unit of time. High deliverability is clearly supported by high 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 its operating at any other given time until the end of its life. For systems that cannot be repaired during use, dependability is the probability that there will be no failure during use. For systems that can be repaired, dependability is governed by how easily and quickly repairs can be made.
- **Maintainability** is the ease, accuracy, safety, and economy of maintenance. This concept is an important design characteristic. The purpose of maintainability is to improve the effectiveness and efficiency of maintenance.

  For some industries, maintainability is quantitative, corresponding to the probability of performing a maintenance action or repair in 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, in which 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.

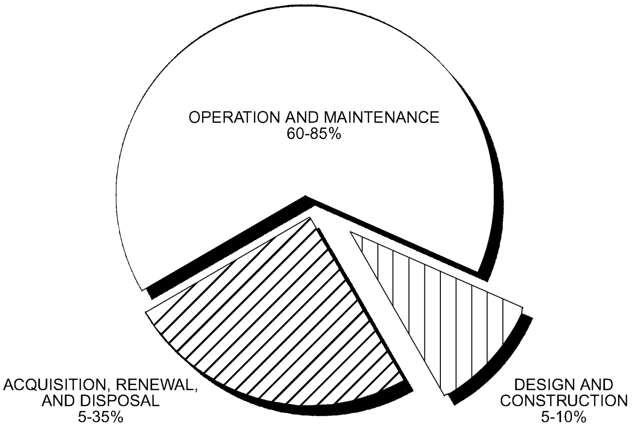

Fig. 2 Life-Cycle Cost Elements: 30-Year Period for Federal Facilities

- **Sustainability** is "providing for the needs of the present without detracting from the ability to fulfill the needs of the future" (ASHRAE 2006). Sustainable maintenance management includes identifying and reducing a building's detrimental environmental effects during its operating lifetime. Sustainability in buildings cannot be achieved simply through sustainable design practices, but also requires sustainable operation and maintenance.
- **System effectiveness** is a system's ability to perform its intended function in terms of performance, availability, and dependability. Ideally, a facility must provide the required level of services satisfactorily and must operate dependably without failure for the given period.

Concept Interrelationships

Results-oriented maintenance management concepts are closely related and interdependent. 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. Here, maintainability and reliability are considered independent concepts, both of which contribute to availability. Increased availability, along with operability, can significantly improve profitability. Figure 3 shows these relationships: reliability and maintainability combine to yield availability, which then combines with operability to yield deliverability. Because these concepts are interrelated, improvements in any area (all else being equal) ultimately lead to improved results, or profitability.

Results-oriented maintenance management is effective at integrating proactive maintenance effectiveness and efficiency into the total cost of facility ownership. 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 probably increase significantly. Appropriate levels of maintainability seldom occur by chance. They require up-front planning, setting objectives, disciplined design implementation, and feedback from prior projects. It is vital to identify critical maintainability and production reliability issues and integrate them into facility project designs to achieve long-term facility owning and operating benefits.

Each concept has a sustainability element. For example, good reliability and availability may minimize or eliminate the need for installed spare capacity, thereby reducing the facility's footprint and use of resources. Good operability increases efficiency and reduces energy use. Sustainability is clearly an overriding benefit of effective, results-oriented maintenance management.

DOCUMENTATION

Operation and maintenance documentation should be prepared as outlined in ASHRAE *Guideline* 4. Information should be documented as soon as it becomes available. This supports design and construction activities, systems commissioning, and training of operation and maintenance staff.

A complete operation and maintenance documentation package consists of the following documents:

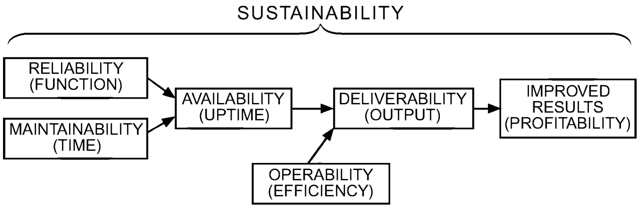

Fig. 3 General Interrelationship of Concepts

- The **operation and maintenance document directory** should provide easy access and be well organized and clearly identified.
- **Emergency information** should be distributed to emergency personnel and be immediately available during emergencies; it 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 manual** should contain the following information:
  - I. Equipment data sheets (specific to installed equipment)
    - A. Operating and nameplate data
    - B. Warranty
  - II. Maintenance program information
    - A. Manufacturer's installation, operation, and maintenance instructions
    - B. Spare parts information
    - C. Preventive maintenance actions
    - D. Schedule of actions
    - E. Action descriptions
    - F. History
- **Test reports** document observed performance during start-up and commissioning and should be compiled throughout the service life of the facility.
- Copies of **construction documents** should be included.

These documents should be available to the entire facilities department.

MAINTENANCE MANAGEMENT

Maintenance management is the planning, implementation, and review of maintenance activities. Myriad levels of maintenance management, ideally determined by cost-effectiveness and by health and safety concerns, can be established. Cost-effectiveness is the balance between system effectiveness (e.g., maintenance levels, equipment and system availability, reliability, maintainability, and performance) and life-cycle costs.

There are three main maintenance strategies. In **run-to-failure**, minimal 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 maintenance** is based on equipment monitoring to establish the current condition of equipment and on condition and performance indices to optimize repair intervals. *Predictive maintenance*, a type of condition-based maintenance, goes one step further, using predictions of future equipment condition to optimize maintenance actions. Within each group, the level of effort can vary from cursory to extensive. Maintenance programs may incorporate features of all these 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.

Proper operation and maintenance are important factors in providing good indoor air quality (IAQ) and ensuring that life safety systems operate as designed.

The success of maintenance management depends on dedicated, trained, and accountable personnel; clearly defined goals and objectives; measurable benefits; management support; and constant examination and reexamination.

KNOWLEDGE AND SKILLS

To be effective and efficient, operation and maintenance programs require staff with the right combination of technical and managerial skills. Technical skills range from hands-on correct application of methods and procedures to the analytical problem-solving expertise of the physical plant engineer.

Physical plant engineers require a variety of skills to effectively operate HVAC systems selected by the designer, implement the maintenance program, manage operating 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 overseeing the stewardship of the facility in life-cycle terms and on a day-to-day basis. Management at this level may develop maintenance strategy; determine program goals and objectives; and administer contracts with tenants, service providers, and labor unions. Specialized contractual maintenance companies require the manager to have a basis understanding of the specialty to define the required work and to determine whether the requirement has been met.

LEVELS OF EFFORT

The criticality and complexity of the system to be operated and maintained must be considered when developing the maintenance strategy. Building complexity and criticality range from residential, commercial, institutional, and industrial, to mission-critical facilities (e.g., cleanrooms, operating rooms). The maintenance strategy and resultant maintenance program must account for system complexity and criticality so that the desired uptime results are achieved.

The foundation of an effective maintenance program is obtaining good baseline data, which commissioning can provide. All installed systems, no matter how simple, should have a commissioning plan; this gives the building or system owner and users a means of operating the system in the most economical manner, minimizing energy consumption and maintenance costs while meeting user requirements. The following sections provide example levels of effort for maintaining three expected types of systems.

Basic Systems

Basic systems may include mechanical equipment such as a rooftop unit with an air handler, refrigeration compressor, and condensing system in a single package. Many of these systems have simple operating procedures, such as switching a single-zone thermostat from heating to cooling to control temperature for building occupants. Maintenance procedures for this type of system are usually limited to those recommended by most manufacturers or lessons learned through operating experience with the system.

In most situations, an onsite maintenance staff changes filters, belts, and motors, and lubricates bearings. However, tasks such as cleaning condenser and evaporator coils and assessing refrigeration and control systems may require a more specialized technician. This also applies to heating components such as gas or oil burners and electric elements. Tasks that may have previously been done by the onsite maintenance staff may now require certification and special equipment [e.g., U.S. Environmental Protection Agency (EPA) certification of technicians and recovery units for refrigeration handling]. In most small facilities, maintenance contractors provide this service. The frequency of maintenance depends in part on system run time and type of operation in the facility.

Smaller facilities may also have more complex control systems, especially when zoning is critical for a variety of load conditions. Whenever the operator cannot service and repair the systems or components installed, the owner should ensure that qualified contractors and technicians perform the work.

Dirty evaporator and condenser coils and filters require additional energy to operate, because inefficient heat transfer creates higher compressor discharge pressures, so more energy is required for a given load. The system must also operate longer to satisfy space conditions. Although these items are variable and difficult to quantify, proper maintenance improves system operation and equipment life, regardless of system size.

Medium-Complexity Systems

The next level of systems uses several pieces of mechanical equipment acting together through a control system to provide a variety of comfort zones.

Commissioning and training are increasingly important with these types of systems to ensure optimum comfort at minimal energy cost. Without detailed commissioning documentation, operation staff cannot effectively consider factors such as energy budgets when addressing building occupants' comfort complaints.

To manage maintenance in medium-sized facilities, programs must be developed for maintenance personnel. Maintenance programs should define which equipment is included, what tasks are to be done, and when the tasks are to be performed. The goal of the maintenance program is to reduce the risk and impact of equipment failure. Over time, maintenance programs can be adjusted for the system's particular characteristics. Computerized maintenance management systems (CMMS) can help management track program progress and report results.

Medium-sized systems can have many levels of specialization and separation of operation and maintenance functions. Operation and maintenance (O&M) personnel may be employed by the building owner or user. These personnel should have the general technical knowledge to operate and maintain these systems in accordance with operational and performance goals determined by management. It is beneficial for O&M staff to have experience or knowledge about commissioning in case they did not participate in the original facility commissioning process.

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. The maintenance program may evolve based on experience, introduction of new technology, or expiration of equipment warranty requirements. It may be necessary to contract out certain maintenance program functions for complex equipment, if staff do not have adequate technical expertise.

Complex Systems

Systems containing more than several pieces of mechanical equipment, including those with central plants, are considered to be complex. Some of these facilities, including those with central plants, require management to hire, direct, and oversee two staffs: one of operation personnel, and the other of maintenance personnel.

The operations budget should be appropriate to support computerized maintenance programs, which detail proper timing of system maintenance procedures so that all systems operate at maximum efficiency while maintaining occupant comfort. Annual and life-cycle cost planning are essential to ensure the most cost-effective operation and maintenance of these systems.

If the building is being commissioned, O&M management should be involved with the predesign, design, and construction phases of the facility. Because facilities are long-term investments, any first-cost compromises must consider both life-cycle cost and ability to satisfy occupant comfort while maintaining reasonable energy budgets.

Logged operating information can be used with proper database management systems as a predictive maintenance tool by monitoring the rate of condition and performance degradation before the equipment actually fails. This tool may be used to indicate equipment needing attention so that management can make appropriate decisions or changes. Like basic and medium-complexity systems, complex systems may require an outsourced contractor or manufacturer's technical support for specific equipment.

CONDITION MONITORING AND ASSESSMENT

An important aspect of operation and maintenance engineering systems is assessing equipment condition. For complex systems, it may be necessary to monitor several conditions (e.g., temperature, vibration, and load) so that the overall condition can be assessed.

One of the most effective condition-monitoring practices is the routine operating plant inspection conducted by the technician during regularly scheduled plant tours. A technician's knowledge, experience, and familiarity with the plant are invaluable tools in plant diagnostics. Plant familiarity, however, is lost with frequent technician staff changes.

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

Other condition-monitoring 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/cleaning frequency, and (5) measuring temperature differences for correct control valve response or chiller operation.

In some cases, multiple parameters are required. For example, to determine the degree of contamination of an air filter bank on a variable-air-volume (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.

Timely detection of equipment faults can reduce energy consumption and operating costs. Surveys and site measurements have documented a wide variety of operating faults in common HVAC equipment.

FAULT FREQUENCY AND COSTS

Air Conditioners

Breuker and Braun (1998) and Breuker et al. (2000) compiled fault data for air conditioners from a database of more than 6,000 "no air-conditioning" fault cases between 1989 and 1995. Frequencies of fault occurrence and repair costs were estimated from a statistically representative sample of the data and are presented in Table 1.

Table 1 Normalized Frequency of Occurrence and Repair Costs for Air Conditioners

	% of Total	
Cause	**Frequency[a]**	**Cost[b]**
Controls error	21	10
Electrical problem	20	7
Refrigerant leak	12	5
Condenser	7	9
Air handling	7	5
Evaporator	6	6
Compressor	5	24
Cooling water loop	4	4
New installation	—	10
Other	18	20

[a] In-service equipment only [b] New and in-service equipment

Table 2 Normalized Frequency of Occurrence and Repair Costs for Chillers

	% of Total*					
	Centrifugal Compressor		**Screw Compressor**			
			Water-Cooled		**Air-Cooled**	
Cause	**Frequency**	**Cost**	**Frequency**	**Cost**	**Frequency**	**Cost**
Control box/ starter	33	18	30	23	39	22
System-level fault	23	21	28	28	27	27
Condenser	17	8	5	4	10	12
Compressor	11	46	5	29	6	23
Lubrication	7	5	15	7	—	—
Piping	7	2	16	8	10	4
Evaporator	2	1	2	1	8	12

*Normalized costs may not sum to 100 because of rounding.

Other studies also identify significant maintenance problems. A California Energy Commission project (Jacobs et al. 2003) studied 215 rooftop units in 75 buildings and found that 63% of the economizers were malfunctioning, 46% had incorrect refrigerant charge, and 39% had low airflow. Additionally, there were numerous controls-related problems. Diagnostic test results from over 55,000 air-conditioning units (Proctor 2004) showed that over 95% of residential units failed the test because of duct leakage; airflow restriction; deficient insulation, refrigerant charge, or evaporator airflow; oversized units; or noncondensables in the refrigerant. Charge was incorrect in 62% of the residential units and 60% of the commercial units, and recommended charging methods were not used 74% of the time. Evaporator airflow was low in 63% of commercial units. Rossi (2004) analyzed data collected by technicians servicing 1468 cooling stages in residential and commercial unitary equipment. Fifty-eight percent of the stages required tune-ups and 10% required major maintenance to remove refrigerant-line restrictions or replace compressors. Of the units requiring tune-up, 63% needed refrigerant charge, 22% had dirty evaporator coils, 10% had dirty condenser coils, 4% were overcharged, and 1% had evaporator fans running too fast.

Chillers

Four manufacturers provided 170 service records for centrifugal chillers, 228 service records for water-cooled screw chillers, and 111 service records for air-cooled screw chillers (Comstock et al. 2002). Results are shown in Table 2. The most common faults were (1) in the control box and starter, and (2) refrigerant leakage, a system-level fault. Infrequent compressor-motor burnouts are the most expensive.

Screw chillers show fewer problems with bearing failure than chillers with centrifugal compressors, but have more problems with piping systems. Repair costs for motor burnout in air-cooled screw compressors are lower than for other compressor types. Refrigerant leakage was slightly more common for air-cooled than for water-cooled chillers, but the relative repair costs were lower; smaller air-cooled screw chillers use less refrigerant, and thus have lower refrigerant replacement costs.

Air-Handling Systems

Faults in air-handling units (AHUs) have been reported from limited field tests of methods to automatically detect and diagnose these faults (House et al. 2003). House et al. (2001) tested a rule-based fault detection and diagnosis (FDD) method in five AHUs in a single building over 15 weeks. Faults were found in 52% of the occupied hours; faults included excessive mode switching, failure to maintain supply air temperature at set point, excessive ventilation during heating mode, and prolonged manual override of automatic controls. Observed control problems were known to building operators and resulted in replacement of numerous damper motors.

Katipamula et al.'s (1999) method detects AHU outdoor air problems, such as too little outdoor air, which is a potential air quality problem; too much outdoor air, resulting in excessive heating or cooling; inappropriate operation of the economizer; and control problems such as mechanical cooling when the AHU is supplying 100% outdoor air and should satisfy the cooling load, bias in the outdoor air temperature sensor, or a stuck outdoor air damper. The system, which is based on rules developed from engineering models of air-handler performance and is implemented as a decision tree, was evaluated in 32 AHUs in seven test buildings and found problems in nearly all of the AHUs. Problems found included faulty sensors, mislocated sensors, stuck dampers, operation during unscheduled times, excess ventilation, and inadequate ventilation (Katipamula et al. 2003).

A set of performance indices was developed to detect zone temperature and airflow errors and excessive control action in VAV terminal boxes (Seem et al. 1999). Significant flow errors were found in two of 24 dual-duct VAV boxes in a field test; one box had a defective motor capacitor, and the other had an incorrectly installed damper actuator.

CONDITION-BASED MAINTENANCE

Condition-based maintenance involves carrying out maintenance only on the basis of the conditions monitored and the interpretation of those conditions. This should result in performing maintenance work only when necessary; therefore, plant reliability will be optimized, and personnel productivity will improve.

Many repairs are a direct result of maintenance-induced failures occurring during scheduled maintenance. Condition-based maintenance prevents unnecessary, repetitive work. There can, however, be added costs involved in supplementary training and instrumentation.

Conditions are monitored on an on/off basis and comparisons are made versus known values (e.g., tabulated values of acceptable vibration). Generally more useful in analysis of building systems is trending over a period of time: either measuring conditions at a regular interval so that a gradual deterioration can be tracked and remedial work planned in advance or, where deterioration can be rapid, continual monitoring.

In the case of air filters in a VAV system, assuming the fan draws air through the filter and is controlled to a fixed static pressure, the filter change criterion is a function of the maximum differential pressure the fully loaded filter can withstand without bursting and the energy consumption of the fan. It may be more economical to change the filter before the maximum pressure is reached if the rate of loading is slow. Monitoring with the energy management system rather than changing on a fixed time interval means that if something occurs to rapidly accelerate dust loading (e.g., nearby construction work), the system alerts building management before filters are overloaded and could potentially burst.

In a constant-volume system (again, assuming the main fan is drawing air through the filter), the change criterion is a function of the maximum differential pressure the filter can withstand and the drop in flow rate that can be tolerated by system users. As the filter becomes dirty, energy consumption decreases and filter efficiency improves. A fixed time interval for filter bank changing/cleaning is not optimum. Changing on the basis of a monitored condition should optimize filter life and minimize labor cost for building cleaning and this aspect of plant maintenance.

BENEFITS OF DETECTING AND DIAGNOSING EQUIPMENT FAULTS

An HVAC&R system tune-up pilot program in Wisconsin evaluated energy and demand savings at nine sites, including retail and grocery stores, restaurants, and an office building (Karmar and Valerie 1995). Energy savings of up to 15% were achieved in most buildings. A two-year study of rooftop heating and cooling equipment by the Electric Power Research Institute (Krill 1997) found significant changes in unit performance caused by low refrigerant charge (the most common problem), filter maintenance, or coil cleaning, and concluded that the cost of annual maintenance would likely exceed utility savings.

Rossi's (2004) fault survey of unitary equipment used measurements by service technicians to compute four performance indices, from which unit efficiency was estimated and savings potential calculated. Fifty percent of the equipment was estimated to have a savings potential of at least $170/year, and 33% had a potential of at least $225/year.

Automated detection and diagnosis of faults may reduce service costs as well as operating costs. Li and Braun (2004a) developed an economic evaluation procedure to estimate savings from 20 monitored field sites. The sites included small retail, play areas for fast-food restaurants, and modular classrooms, in coastal and inland California climates. Hardware and software costs for their FDD system were estimated at $250 to $600 for individual units, and $700 to $1500 for a site with four units. Payback periods were less than one year, with savings in operating costs and an estimated 70% reduction in service costs.

The automated FDD system used by Li and Braun predicts the values of six measured system temperatures as a function of load and environmental conditions: evaporator, superheat, condenser, liquid-line subcooling, and hot-gas temperatures in the refrigerant loop and air-side differences across the evaporator and condenser (Rossi and Braun 1997, modified by Li and Braun 2004b). Differences between measurement and prediction were used to detect and classify compressor-valve leakage; condenser fouling; evaporator fouling; liquid-line restriction; noncondensable gas; and refrigerant leakage, undercharge, and overcharge. In another system now in widespread use, service technicians provide equipment specifications and operating conditions, including evaporator inlet and outlet air temperatures and refrigerant temperatures and pressures, and receive an on-the-spot analysis of refrigerant charge and evaporator airflow relative to manufacturer's specifications (Downey and Proctor 2002).

RESPONSIBILITIES

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 items such as access, redundancy, and component isolation requirements.

System design must include operation (e.g., temperature, humidity, cleanliness, air change rate, relative pressure), flow diagrams, instrumentation, and control sequences. 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 balance, fume hood certification).

An effective director should be able to organize, staff, train, plan, and control the operation and maintenance of a facility with the cooperation of senior management and all departments. A manager's responsibilities include administering the operation and maintenance budget and protecting the life-cycle objectives. Before selecting a least-cost alternative, a manager should determine its effects on durability and loss prevention (Loveley 1973).

CONVERSION TO NEW TECHNOLOGY

Operation and maintenance programs are based on the technology available at the time of their preparation. The programs should be adhered to throughout the required service life of the facility or system. During the service life, new technology (e.g., automated detection and diagnosis of operating faults) may become available that would affect the operation and/or maintenance program. Conversion from existing to new technology must be assessed in life-cycle terms. The existing technology must be assessed for the degree of loss from shorter return on investment. The new technology must be assessed for (1) all initial, operation, and maintenance costs; (2) the correlation between its service life and the remaining service life of the facility; and (3) the cost of conversion, including revenue losses from associated downtime.

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