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 personnel and technical requirements. They must also meet system availability and energy use requirements, enhance management and operator skills, and increase communication among the stakeholders of cost-effective operation and maintenance, such as owners, maintenance planners, maintenance technicians, contractors, and occupants.

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 and maintenance 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 must 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 retain the design function 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

System operation defines the parameters under which the building or systems operator can adjust components of the system to satisfy occupant comfort or process requirements, and the strategy for optimum energy use and minimum maintenance.

The **maintenance program** defines maintenance in terms of time 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 or failure.

Failure response classifies maintenance department resources expended or reserved to handle interruptions in the operation or function of a system or equipment covered by the maintenance program. This classification includes two response types—repair and service.

Repair is to make good, or to restore to good or sound condition with the following constraints: (1) operation must be fully restored without embellishment, and (2) failure must trigger the response.

Service effects non-repair maintenance. It is usually based on manufacturers' recommended procedures.

Planned maintenance classifies maintenance department resources invested in prudently 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.

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.

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, provided the action is optional and unrelated.

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.

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.

RESULTS-ORIENTED MAINTENANCE MANAGEMENT

Results-oriented maintenance management provides maintenance with the required reliability and availability at the lowest cost. Implementing this strategy involves identifying actions that, when taken, will reduce the probability of failure most cost-effectively. 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 then useful to compare maintenance costs to the total costs of facility ownership. The major expenditure 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.

The preparation of this chapter is assigned to TC 1.7, Operation and Maintenance Management.

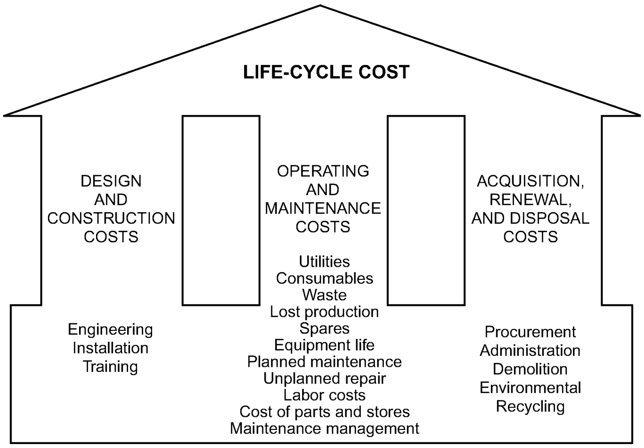

Fig. 1 Three Pillars of Typical Life-Cycle Cost with Cost Elements

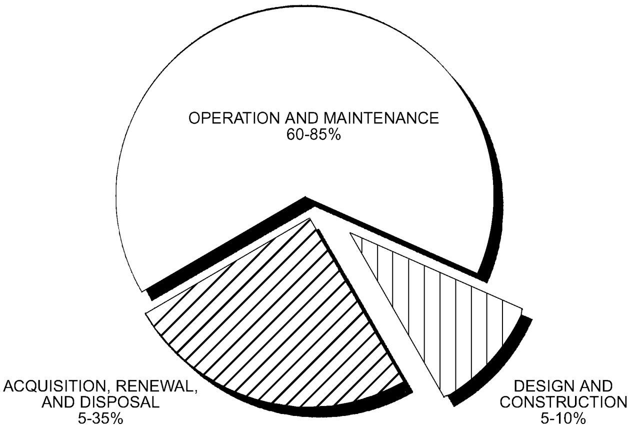

Fig. 2 Life-Cycle Cost Elements: 30 Year Period for Federal Facilities

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. As shown in Figure 2, over a nominal 30 year term, operation and maintenance (O&M) comprise the largest segment of facility ownership cost. Results-oriented maintenance management attempts to minimize operation and maintenance costs through proactive efforts in all three categories.

Prudent facility ownership should invest appropriately in acquisition and design and construction to minimize 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, yielding higher operating costs. In addition, maintenance management should consider an optimum mix of maintenance techniques to minimize maintenance costs. Facility design and maintenance approach decisions should consider their long-term effect on maintenance and operations costs for maximum financial benefit.

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:

- **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.
- **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.
- **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 in which maintenance actions can be performed.
- **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.
- **Availability** is the amount of time that machinery or equipment will be 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.
- **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.
- **Deliverability** is the total amount of production shipped out the door per unit of time. High deliverability is clearly supported by high levels of the other concepts.

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 will ultimately lead to improved results, or profitability.

Results-oriented maintenance management is effective at integrating proactive maintenance effectiveness and efficiency into the

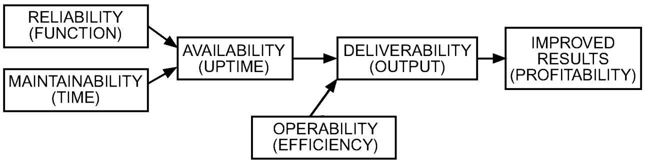

Fig. 3 General Interrelationship of Concepts

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 will probably increase significantly. Appropriate levels of maintainability seldom occur by chance. It requires 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.

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:

- The **operation and maintenance document directory** should provide easy access and be well organized and clearly identified.
- **Emergency information** should be immediately available during emergencies and 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. Building description
    - C. 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
    - 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, usually 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 (system) availability, reliability, maintainability, and performance] and life-cycle costs.

Three common types of maintenance programs are (1) run-to-failure, (2) preventive (or time-based) maintenance, and (3) predictive (or condition-based) maintenance. In **run-to-failure**, no money is spent on maintenance until equipment or systems break down. **Preventive maintenance** is maintenance that is scheduled, either by run time or by the calendar. **Predictive maintenance** is based on equipment monitoring and the use of condition and performance indices to maximize repair intervals. Within each group, the level of effort can vary from cursory to detailed. 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.

HVAC&R maintenance and utility costs represent a significant portion of a facility's operating 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 economical, operation and maintenance requires staff with the right combination of technical and managerial skills. Technical skills include not only operation and maintenance mechanics, but also the engineering skills of the physical plant engineer. Managerial skills include managing the facility in life-cycle terms and on a day-to-day basis. Management on this level may administer contracts with tenants, service contracts, and labor unions. Specialized contractual maintenance companies require yet another level of management.

Physical plant engineers require a variety of skills to coordinate the equipment selected by the designer, the operating and maintenance personnel, and the 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.

LEVELS OF EFFORT

The criticality and complexity of the system to be operated and maintained must be considered. Building types range from houses to commercial offices, institutional buildings, processing plants, refrigerated storage facilities, and mission-critical facilities. All installed systems, no matter how simple, should have a commissioning plan; this gives the building or system owner and operators a means of operating the system in the most economical manner, minimizing energy consumption and maintenance costs while meeting user requirements.

Basic Systems

Many systems have simple operating procedures such as changing 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.

Most building managers call onsite maintenance staff to change filters, belts, and motors. However, cleaning condenser and evaporator coils and assessing refrigeration and control systems require a more specialized technician. In most small facilities, maintenance contractors provide this service. The frequency of maintenance depends in part on hours of system use and type of operation in the facility.

Smaller facilities may also have 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 are used.

Dirty evaporator and condenser coils and filters require additional energy to operate because of higher head pressures and inefficient heat transfer. The system must also operate longer to satisfy space conditions. Although these items are variable and difficult to quantify, proper unit and system maintenance improves system operation and equipment life cycles, 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 documentation that accompanies commissioning, the 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 be implemented sequentially to reduce the failure response required. Over time, maintenance programs can be adjusted for the particular characteristics of the system. Computerized maintenance programs 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). The maintenance program should be tailored to each specific facility. 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, should the staff not have adequate technical expertise.

Complex Systems

Some buildings, 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 large enough 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.

To facilitate proper commissioning, management should be involved with the design process and construction of the facility. Because facilities are long-term investments, any first-cost compromises must consider both life-cycle cost and the ability to satisfy occupant comfort while maintaining reasonable energy budgets.

Logged information can be used with proper database management systems as predictive maintenance to reduce failure response requirements. These systems may be used to indicate weaknesses in the systems so that management can make appropriate decisions or system changes. Like small and medium-sized systems, large systems may require an outside contractor or manufacturer's 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. The 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 of 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.

CONDITION-BASED MAINTENANCE

Condition-based maintenance involves carrying out maintenance only on the basis of the condition(s) 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 may be monitored on an on/off basis where comparison can be made against some fixed known values (e.g., tabulated values of acceptable vibration). Generally more useful in engineering building systems is trending over a period of time: either measuring the 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 main fan is drawing 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 filter can withstand when fully loaded with dust (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 dust loading is slow. Also, monitoring it via 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 will alert building management before the 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 the system users. As the filter blocks, 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.

RESPONSIBILITIES

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 redundancy and component isolation requirements. System design must include proper operation and maintenance information, flowcharts, and instrumentation requirements. The installing contractor must turn over the newly installed system to the owner in an organized and comprehensive manner.

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 effect on durability and loss prevention (Loveley 1973).

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 may become available that would affect the operation and/or maintenance program. When this occurs, the switch from the existing to the 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 and 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.

REFERENCES

ASHRAE. 1996. Guideline for the HVAC commissioning process. *Guideline* 1-1996.

ASHRAE. 1993. Preparation of operating and maintenance documentation for building systems. *Guideline* 4-1993.

Christian, J. and A. Pandeya. 1997. Cost predictions of facilities. *Journal of Management in Engineering* 13(1):52-61.

Loveley, J.D. 1973. Durability, reliability, and serviceability. *ASHRAE Journal* 15(1):67.

Stum, K. 2000. Compilation and evaluation of information sources for HVAC&R system operations and maintenance procedures. ASHRAE *Research Project* RP-1025.

BIBLIOGRAPHY

Blanchard, B.S., D. Verma, and E.L. Peterson. 1995. *Maintainability: A key to effective serviceability and maintenance management*. John Wiley & Sons, New York.

Criswell, J.W. 1989. *Planned maintenance for productivity and energy conservation*, 3rd ed. Prentice Hall, Englewood Cliffs, NJ.

Fuchs, S.J. 1992. *Complete building equipment maintenance desk book*. Prentice Hall, Englewood Cliffs, NJ.

Lawson, C.N. 1989. Commissioning—Construction phase. *ASHRAE Transactions* 95(l):887-894.

Mobely, R.K. 1989. *An introduction to predictive maintenance.* Van Nostrand Reinhold, New York.

NCMS. 1999. *Reliability and maintainability guideline for manufacturing machinery and equipment*, 2nd ed. National Center for Manufacturing Sciences, Ann Arbor, MI.

National Academy of Sciences. 1998. *Stewardship of federal facilities: A proactive strategy for managing the nation's public assets.* National Academy, Washington, D.C.

Petrocelly, K.L. 1988. *Physical plant operations handbook*. Prentice Hall, Englewood Cliffs, NJ.

Trueman, C.S. 1989. Commissioning: An owner's approach for effective operations. *ASHRAE Transactions* 95(1):895-899.