CHAPTER 1

HVAC SYSTEM ANALYSIS AND SELECTION

AN HVAC system maintains desired environmental conditions in a space. In almost every application, many options are available to the design engineer to satisfy a client's building program and design intent. In the analysis, selection, and combination of these options, the design engineer should consider the criteria defined here, as well as project-specific parameters to achieve the functional requirements associated with the project design intent. The design engineer should consider sustainability as it pertains to responsible energy and environmental design, as well as constructability of the design.

HVAC systems are categorized by the method used to produce, deliver, and control heating, ventilating, and air conditioning in the conditioned area. This chapter addresses procedures for selecting the appropriate system for a given application while taking into account pertinent issues associated with designing, building, commissioning, operating, and maintaining the system. It also describes and defines the design concepts and characteristics of basic HVAC systems. Chapters 2 to 5 describe specific systems and their attributes, based on their heating and cooling medium and commonly used variations, constructability, commissioning, operation, and maintenance.

This chapter is intended as a guide for the design engineer, builder, facility manager, and student needing to know or reference the analysis and selection process that leads to recommending the optimum system for the job. The approach applies to HVAC conversion, building system upgrades, system retrofits, building renovations and expansion, and new construction for any building: small, medium, large, below grade, at grade, low-rise, and high-rise. This system analysis and selection process (Figure 1) helps determine the optimum system(s) for any building. Regardless of facility type, analysis examines objective, subjective, short-term, and long-term goals.

SELECTING A SYSTEM

The design engineer is responsible for considering various systems and recommending one or two systems that will meet the project goals and perform as desired. It is imperative that the design engineer and owner collaborate to identify and prioritize criteria associated with the design goal. In addition, if the project has preconstruction services, the designer and operator should consult with the construction manager to take advantage of the constructability and consider value-engineered options. Occupant comfort, process heating, and cooling or ventilation criteria may be considered, including the following:

- Temperature
- Humidity
- Air motion
- Air purity or quality

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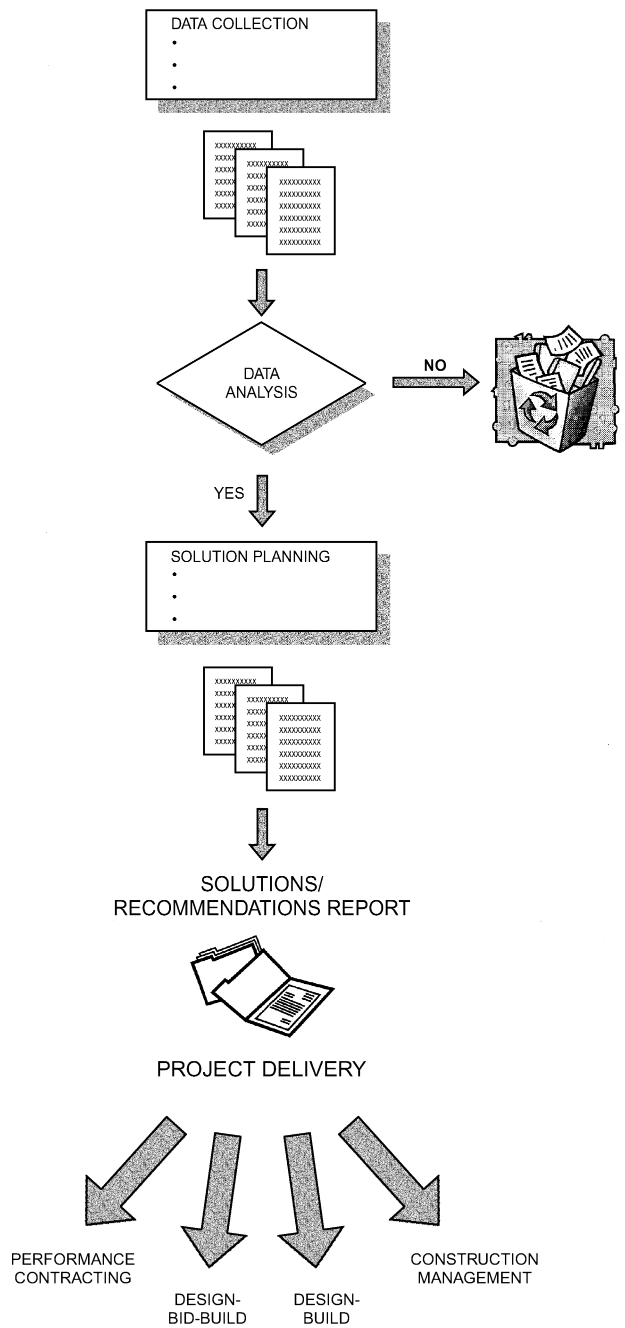

Fig. 1 Process Flow Diagram
(Courtesy RDK Engineers)

- Air changes per hour
- Air and/or water velocity requirements
- Local climate
- Space pressure requirements
- Capacity requirements, from a load calculation analysis
- Redundancy
- Spatial requirements
- Security concerns
- First cost
- Operating cost, including energy and power costs
- Maintenance cost
- Reliability
- Flexibility
- Life-cycle analysis
- Sustainability of design
- Acoustics and vibration
- Mold and mildew prevention

Because these factors are interrelated, the owner, design engineer, and operator must consider how these criteria affect each other. The relative importance of factors such as these varies with different owners, and often changes from one project to another for the same owner. For example, typical owner concerns include first cost compared to operating cost, extent and frequency of maintenance and whether that maintenance requires entering the occupied space, expected frequency of system failure, effect of failure, and time required to correct the failure. Each concern has a different priority, depending on the owner's goals.

Additional Goals

In addition to the primary goal of providing the desired environment, the design engineer should be aware of and account for other goals the owner may require. These goals may include the following:

- Supporting a process, such as operation of computer equipment
- Promoting a germ-free environment
- Increasing sales
- Increasing net rental income
- Increasing property salability

The owner can only make appropriate value judgments if the design engineer provides complete information on the advantages and disadvantages of each option. Just as the owner does not usually know the relative advantages and disadvantages of different HVAC systems, the design engineer rarely knows all the owner's financial and functional goals. Hence, the owner must be involved in system selection in the conceptual phase of the job. The same can be said for operator participation so that the final design is sustainable.

System Constraints

Once the goal criteria and additional goal options are listed, many constraints must be determined and documented. These constraints may include the following:

- Performance limitations (e.g., temperature, humidity, space pressure)
- Available capacity
- Available space
- Available utility source
- Available infrastructure
- Building architecture

The design engineer should closely coordinate the system constraints with the rest of the design team, as well as the owner, to overcome design obstacles associated with the HVAC systems under consideration for the project.

Constructability Constraints

The design engineer should take into account HVAC system issues before the project reaches the construction document phase. Some of these constraints may significantly affect the success of the design and cannot be overlooked in the design phase. Some issues and concerns associated with constructability are

- Existing conditions
- Maintaining existing building occupancy and operation
- Construction budget
- Construction schedule
- Ability to phase HVAC system installation
- Equipment availability (i.e., delivery lead times)

Few projects allow detailed quantitative evaluation of all alternatives. Common sense, historical data, and subjective experience can be used to narrow choices to one or two potential systems.

Heating and air-conditioning loads often contribute to constraints, narrowing the choice to systems that fit in available space and are compatible with building architecture. Chapters 29 and 30 of the 2005 *ASHRAE Handbook—Fundamentals* describe methods to determine the size and characteristics of heating and air-conditioning loads. By establishing the capacity requirement, equipment size can be determined, and the choice may be narrowed to those systems that work well on projects within a size range.

Loads vary over time based on occupied and unoccupied periods, and changes in weather, type of occupancy, activities, internal loads, and solar exposure. Each space with a different use and/or exposure may require a different control zone to maintain space comfort. Some areas with special requirements (e.g., ventilation requirements) may need individual systems. The extent of zoning, degree of control required in each zone, and space required for individual zones also narrow system choices.

No matter how efficiently a particular system operates or how economical it is to install, it can only be considered if it (1) maintains the desired building space environment within an acceptable tolerance under all conditions and occupant activities and (2) physically fits into, on, or adjacent to the building without being objectionable.

Cooling and humidity control are often the basis of sizing HVAC components and subsystems, but the system may also be determined based on **ventilation** criteria. For example, if large quantities of outside air are required for ventilation or to replace air exhausted from the building, only systems that transport large air volumes need to be considered.

Effective heat delivery to an area may be equally important in selection. A distribution system that offers high efficiency and comfort for cooling may be a poor choice for heating. The cooling, humidity, and/or heat delivery performance compromises may be small for one application in one climate, but may be unacceptable in another that has more stringent requirements.

HVAC systems and associated distribution systems often occupy a significant amount of **space**. Major components may also require special support from the structure. The size and appearance of terminal devices (e.g., grilles, registers, diffusers, fan-coil units, radiant panels) affect architectural design because they are visible in the occupied space.

Construction budget constraints can also influence the choice of HVAC systems. Based on historical data, some systems may not be economically feasible for an owner's building program. In addition, annual maintenance and operating budget (utilities, labor, and materials) should be an integral part of any system analysis and selection process. This is particularly important for building owners who will retain the building for a substantial number of years. Value-engineered solutions can offer (1) cost-driven performance, which may provide for a better solution for lower first cost; (2) a more sustainable solution over the life of the equipment; or (3) best value based on a reasonable return on investment.

Sustainable energy consumption can be compromised and long-term project success can be lost if building operators are not trained to efficiently and effectively operate and maintain the building systems. For projects in which the design engineer used some form of energy software simulation, these data should be passed on to the building owner so that goals and expectations can be measured and benchmarked against actual system performance. HVAC design is not complete without continuous system performance years after the system selection and analysis has been completed and the systems installed and turned over to the building owner.

Narrowing the Choices

The following chapters in this volume present information to help the design engineer narrow the choices of HVAC systems:

- Chapter 2 focuses on a distributed approach to HVAC.
- Chapter 3 provides guidance for large equipment centrally located in or adjacent to a building.
- Chapter 4 addresses all-air systems.
- Chapter 5 covers building piping distribution, including in-room terminal systems.

Each chapter summarizes positive and negative features of various systems. Comparing the criteria, other factors and constraints, and their relative importance usually identifies one or two systems that best satisfy project goals. In making choices, notes should be kept on all systems considered and the reasons for eliminating those that are unacceptable.

Each selection may require combining a primary system with a secondary (or distribution) system. The primary system converts energy from fuel or electricity into a heating and/or cooling medium. The secondary system delivers heating, ventilation, and/or cooling to the occupied space. The systems are independent to a great extent, so several secondary systems may work with a particular primary system. In some cases, however, only one secondary system may be suitable for a particular primary system.

Once subjective analysis has identified one or two HVAC systems (sometimes only one choice remains), detailed quantitative evaluations must be made. All systems considered should provide satisfactory performance to meet the owner's essential goals. The design engineer should provide the owner with specific data on each system to make an informed choice. Consult the following chapters to help narrow the choices:

- Chapter 9 of the 2005 *ASHRAE Handbook—Fundamentals* covers physiological principles, comfort, and health.
- Chapter 32 of the 2005 *ASHRAE Handbook—Fundamentals* covers methods for estimating annual energy costs.
- Chapter 35 of the 2007 *ASHRAE Handbook—HVAC Applications* covers methods for energy management.
- Chapter 36 of the 2007 *ASHRAE Handbook—HVAC Applications* covers owning and operating costs.
- Chapter 38 of the 2007 *ASHRAE Handbook—HVAC Applications* covers mechanical maintenance.
- Chapter 47 of the 2007 *ASHRAE Handbook—HVAC Applications* covers sound and vibration control.

Other guidelines to consult are ASHRAE standards; local, state, and federal guidelines; and special agency requirements [e.g., U.S. General Services Administration (GSA), Food and Drug Administration (FDA), Joint Commission on Accreditation of Healthcare Organizations (JCAHO), Leadership in Energy and Environmental Design (LEED™)].

Selection Report

As the last step, the design engineer should prepare a summary report that addresses the following:

- The goal
- Criteria for selection
- Important factors, including advantages and disadvantages
- Other goals
- Security concerns
- Basis of design
- HVAC system analysis and selection matrix
- System narratives
- Budget costs
- Recommendation

A brief outline of each of the final selections should be provided. In addition, HVAC systems deemed inappropriate should be noted as having been considered but not found applicable to meet the owner's primary HVAC goal.

The report should include an HVAC system selection matrix that identifies the one or two suggested HVAC system selections (primary and secondary, when applicable), system constraints, and other constraints. In completing this matrix assessment, the design engineer should have the owner's input to the analysis. This input can also be applied as weighted multipliers, because not all criteria carry the same weighted value.

Many grading methods are available to complete an analytical matrix analysis. Probably the simplest is to rate each item excellent, very good, good, fair, or poor. A numerical rating system such as 0 to 10, with 10 equal to excellent and 0 equal to poor or not applicable, can provide a quantitative result. The HVAC system with the highest numerical value then becomes the recommended HVAC system to accomplish the goal.

The system selection report should include a summary followed by a more detailed account of the HVAC system analysis and system selection. This summary should highlight key points and findings that led to the recommendation(s). The analysis should refer to the system selection matrix (such as in Table 1) and the reasons for scoring.

With each HVAC system considered, the design engineer should note the criteria associated with each selection. Issues such as close temperature and humidity control may eliminate some HVAC systems from consideration. System constraints, noted with each analysis, should continue to eliminate potential HVAC systems. Advantages and disadvantages of each system should be noted with the scoring from the HVAC system selection matrix. This process should reduce HVAC selection to one or two optimum choices to present to the owner. Examples of similar installations for other owners should be included with this report to support the final recommendation. Identifying a third party for an endorsement allows the owner to inquire about the success of other HVAC installations.

HVAC SYSTEMS AND EQUIPMENT

The majority of buildings built, expanded, and /or renovated may be ideally suited for decentralized HVAC systems, with equipment located in, throughout, adjacent to, or on top of the building. The alternative is primary equipment located in a central plant (either inside or outside the building) and distributing air and/or water for HVAC needs from this plant.

Decentralized System Characteristics

Temperature, Humidity, and Space Pressure Requirements. A decentralized system may be able to fulfill any or all of these design parameters.

Capacity Requirements. A decentralized system usually requires each piece of equipment to be sized for zone peak capacity, unless the systems are variable-volume. Depending on equipment type and location, decentralized systems do not benefit as much from equipment sizing diversity as centralized systems do.

Redundancy. A decentralized system may not have the benefit of back-up or standby equipment. This limitation may need review.

Facility Management. A decentralized system can allow the building manager to maximize performance using good business/facility management techniques in operating and maintaining the HVAC equipment and systems.

Spatial Requirements. A decentralized system may or may not require equipment rooms. Because of space restrictions imposed on

Table 1 Sample HVAC System Analysis and Selection Matrix (0 to 10 Score)

Goal: Furnish and install an HVAC system that provides moderate space temperature control with minimum humidity control at an operating budget of 70,000 Btu/h per square foot per year

Categories	System #1	System #2	System #3	Remarks
1. Criteria for Selection: • 78°F space temperature with ±3°F control during occupied cycle, with 40% rh and ±5% rh control during cooling. • 68°F space temperature with ±2°F, with 20% rh and ±5% rh control during heating season. • First cost • Equipment life cycle				
2. Important Factors: • First-class office space stature • Individual tenant utility metering				
3. Other Goals: • Engineered smoke control system • ASHRAE *Standard* 62.1 ventilation rates • Direct digital control building automation				
4. System Constraints: • No equipment on first floor • No equipment on ground adjacent to building				
5. Other Constraints: • No perimeter finned-tube radiation or other type of in-room equipment				
TOTAL SCORE				

Source: RDK Engineers.

the design engineer or architect, equipment may be located on the roof and/or the ground adjacent to the building. Depending on system components, additional space may be required in the building for chillers and boilers. Likewise, a decentralized system may or may not require duct and pipe shafts throughout the building.

First Cost. A decentralized system probably has the best first-cost benefit. This feature can be enhanced by phasing in the purchase of decentralized equipment as needed (i.e., buying equipment as the building is being leased/occupied).

Operating Cost. A decentralized system can save operating cost by strategically starting and stopping multiple pieces of equipment. When comparing energy consumption based on peak energy draw, decentralized equipment may not be as attractive as larger, more energy-efficient centralized equipment.

Maintenance Cost. A decentralized system can save maintenance cost when equipment is conveniently located and equipment size and associated components (e.g., filters) are standardized. When equipment is located outdoors, maintenance may be difficult during bad weather.

Reliability. A decentralized system usually has reliable equipment, although the estimated equipment service life may be less than that of centralized equipment. Decentralized system equipment may require maintenance in the occupied space, however.

Flexibility. A decentralized system may be very flexible because it may be placed in numerous locations.

Level of Control. Decentralized systems often use direct refrigerant expansion (DX) for cooling, and on/off or staged heat. This step control results in greater variation in space temperature and humidity, where close control is not desired or necessary. As a caution, oversizing DX or stepped cooling can allow high indoor humidity levels and mold or mildew problems.

Sound and Vibration. Decentralized systems often locate noisy machinery close to building occupants, although equipment noise may be less than that produced by large central systems.

Constructability. Decentralized systems frequently consist of multiple and similar-in-size equipment that makes standardization a construction feature, as well as purchasing units in large quantities.

Centralized System Characteristics

Temperature, Humidity, and Space Pressure Requirements. A central system may be able to fulfill any or all of these design parameters.

Capacity Requirements. A central system usually allows the design engineer to consider HVAC diversity factors that reduce installed equipment capacity. As a result, this offers some attractive first-cost and operating-cost benefits.

Redundancy. A central system can accommodate standby equipment that decentralized configurations may have trouble accommodating.

Facility Management. A central system usually allows the building manager to maximize performance using good business/facility management techniques in operating and maintaining the HVAC equipment and systems.

Spatial Requirements. The equipment room for a central system is normally located outside the conditioned area: in a basement, penthouse, service area, or adjacent to or remote from the building. A disadvantage with this approach may be the additional cost to furnish and install secondary equipment for the air and/or water distribution. A second consideration is the access and physical constraints throughout the building to furnish and install this secondary distribution network of ducts and/or pipes and for equipment replacement.

First Cost. Even with HVAC diversity, a central system may not be less costly than decentralized HVAC systems. Historically, central system equipment has a longer equipment service life to compensate for this shortcoming. Thus, a life-cycle cost analysis is very important when evaluating central versus decentralized systems.

Operating Cost. A central system usually has the advantage of larger, more energy-efficient primary equipment compared to decentralized system equipment. In addition, with multiple pieces of HVAC equipment, a central system allows strategic planning and management of the HVAC systems through staging equipment based on HVAC demands.

Maintenance Cost. The equipment room for a central system provides the benefit of maintaining HVAC equipment away from occupants in an appropriate service work environment. Access to occupant workspace is not required, thus eliminating disruption to the space environment, product, or process. Because of the typically larger capacity of central equipment, there are usually fewer pieces of HVAC equipment to service.

Reliability. Centralized system equipment generally has a longer service life.

Flexibility. Flexibility can be a benefit when selecting equipment that provides an alternative or back-up source of HVAC.

Level of Control. Centralized systems generally use chilled water for cooling, and steam or hydronic heat. This usually allows for close control of space temperature and humidity where desired or necessary.

Sound and Vibration. Centralized systems often locate noisy machinery sufficiently remote from building occupants or noise-sensitive processes.

Constructability. Centralized systems usually require more coordinated installation than decentralized systems. However, consolidation of the primary equipment in a central location also has benefits.

Among the largest centralized systems are HVAC plants serving groups of large buildings. These plants improve diversity and generally operate more efficiently, with lower maintenance costs, than individual central plants. Economic considerations of larger centralized systems require extensive analysis. The utility analysis may consider multiple fuels and may also include gas and steam turbine-driven equipment. Multiple types of primary equipment using multiple fuels and types of HVAC-generating equipment (e.g., centrifugal and absorption chillers) may be combined in one plant. Chapters 12 to 14 provide design details for central plants.

Primary Equipment

The type of decentralized and centralized equipment selected for buildings depends on a well-organized HVAC analysis and selection report. The choice of primary equipment and components depends on factors presented in the selection report (see the section on Selecting a System). Primary HVAC equipment includes refrigeration equipment; heating equipment; and air, water, and steam delivery equipment.

Many HVAC designs recover internal heat from lights, people, and equipment to reduce the size of the heating plant. In buildings with core areas that require cooling while perimeter areas require heating, one of several heat reclaim systems can heat the perimeter to save energy. Sustainable design is also important when considering recovery and reuse of materials and energy. Chapter 8 describes heat pumps and some heat recovery arrangements, Chapter 36 describes solar energy equipment, and Chapter 25 introduces air-to-air energy recovery. In the 2007 *ASHRAE Handbook—HVAC Applications*, Chapter 35 covers energy management and Chapter 40 covers building energy monitoring. Chapter 17 of the 2005 *ASHRAE Handbook—Fundamentals* provides information on sustainable design.

The search for energy savings has extended to **cogeneration** or **total energy [combined heat and power (CHP)]** systems, in which on-site power generation is added to the HVAC project. The economic viability of this function is determined by the difference between gas and electric rates and by the ratio of electric to heating demands for the project. In these systems, waste heat from generators can be transferred to the HVAC equipment (e.g., to drive turbines of centrifugal compressors, serve an absorption chiller, etc.). Chapter 7 covers cogeneration or total energy systems. Alternative fuel sources, such as waste heat boilers, are now being included in fuel evaluation and selection for HVAC applications.

Thermal storage is another cost-saving concept, which provides the possibility of off-peak generation of chilled water or ice. Thermal storage can also be used for storing hot water for heating. Many electric utilities impose severe charges for peak summer power use or offer incentives for off-peak use. Storage capacity installed to level the summer load may also be available for use in winter, thus making heat reclaim a viable option. Chapter 34 of the 2007 *ASHRAE Handbook—HVAC Applications* has more information on thermal storage.

With ice storage, colder supply air can be provided than that available from a conventional chilled-water system. This colder air allows use of smaller fans and ducts, which reduces first cost and (in some locations) operating cost. These life-cycle savings can offset the first cost for storage provisions and the energy cost required to make ice. Similarly, thermal storage of hot water can be used for heating.

Refrigeration Equipment

Chapters 2 and 3 of this volume summarize the primary types of refrigeration equipment for HVAC systems.

When chilled water is supplied from a central plant, as on university campuses and in downtown areas of large cities, the utility service provider should be contacted during system analysis and selection to determine availability, cost, and the specific requirements of the service.

Heating Equipment

Steam boilers and heating-water boilers are the primary means of heating a space using a centralized system, as well as some decentralized systems. These boilers may be (1) used both for comfort and process heating; (2) manufactured to produce high or low pressure; and (3) fired with coal, oil, electricity, gas, and sometimes waste material. Low-pressure boilers are rated for a working pressure of either 15 or 30 psig for steam, and 160 psig for water, with a temperature limit of 250°F. Packaged boilers, with all components and controls assembled at the factory as a unit, are available. Electrode or resistance electric boilers that generate either steam or hot water are also available. Chapter 31 has further information on boilers, and Chapter 26 details air-heating coils.

Where steam or hot water is supplied from a central plant, as on university campuses and in downtown areas of large cities, the utility service entering the building must conform to the utility's standards. The utility provider should be contacted during project system analysis and selection to determine availability, cost, and specific requirements of the service.

When primary heating equipment is selected, the fuels considered must ensure maximum efficiency. Chapter 30 discusses design, selection, and operation of the burners for different types of primary heating equipment. Chapter 18 of the 2005 *ASHRAE Handbook—Fundamentals* describes types of fuel, fuel properties, and proper combustion factors.

Air Delivery Equipment

Primary air delivery equipment for HVAC systems is classified as packaged, manufactured and custom-manufactured, or field-fabricated (built-up). Most air delivery equipment for large systems uses centrifugal or axial fans; however, plug or plenum fans are often used. Centrifugal fans are frequently used in packaged and manufactured HVAC equipment. Axial fans are more often part of a custom unit or a field-fabricated unit. Both types of fans can be used as industrial process and high-pressure blowers. Chapter 20 describes fans, and Chapters 18 and 19 provide information about air delivery components.

SPACE REQUIREMENTS

In the initial phase of building design, the design engineer seldom has sufficient information to render the optimum HVAC design for the project, and its space requirements are often based on percentage of total area or other experiential rule of thumb. The final design is usually a compromise between what the engineer recommends and what the architect can accommodate. At other times, the building owner, who may prefer a centralized or decentralized system, may dictate final design and space requirements. This section discusses some of these requirements.

Equipment Rooms

Total mechanical and electrical space requirements range between 4 and 9% of gross building area, with most buildings in the 6 to 9% range. These ranges include space for HVAC, electrical, plumbing, and fire protection equipment and may also include vertical shaft space for mechanical and electrical distribution through the building.

Most equipment rooms should be centrally located to (1) minimize long duct, pipe, and conduit runs and sizes; (2) simplify shaft layouts; and (3) centralize maintenance and operation. With shorter duct and pipe runs, a central location could also reduce pump and fan motor power requirements, which reduces building operating costs. But, for many reasons, not all mechanical and electrical equipment rooms can always be centrally located in the building. In any case, equipment should be kept together whenever possible to minimize space requirements, centralize maintenance and operation, and simplify the electrical system.

Equipment rooms generally require clear ceiling height ranging from 10 to 18 ft, depending on equipment sizes and the complexity of air and/or water distribution.

The main electrical transformer and switchgear rooms should be located as close to the incoming electrical service as practical. If there is an emergency generator, it should be located considering (1) proximity to emergency electrical loads and sources of combustion and cooling air and fuel, (2) ease of properly venting exhaust gases to the outdoors, and (3) provisions for noise control.

Primary Equipment Rooms. The heating equipment room houses the boiler(s) and possibly a boiler feed unit (for steam boilers), chemical treatment equipment, pumps, heat exchangers, pressure-reducing equipment, air compressors, and miscellaneous equipment. The refrigeration equipment room houses the chiller(s) and possibly chilled-water and condenser water pumps, heat exchangers, air-conditioning equipment, air compressors, and miscellaneous equipment. Design of these rooms needs to consider (1) equipment size and weight, (2) installation and replacement, (3) applicable regulations relative to combustion air and ventilation air, and (4) noise and vibration transmission to adjacent spaces. ASHRAE *Standard* 15 should be consulted for refrigeration equipment room safety requirements.

Some air-conditioned buildings require a cooling tower or other type of heat rejection equipment. If the cooling tower or water-cooled condenser is located at ground level, it should be at least 100 ft away from the building to (1) reduce tower noise in the building, (2) keep discharge air and moisture carryover from fogging the building's windows and discoloring the building facade, and (3) keep discharge air and moisture carryover from contaminating outside air being introduced into the building. Cooling towers should be kept a similar distance from parking lots to avoid staining car finishes with atomized water treatment chemicals. Chapters 38 and 39 have further information on this equipment.

It is often economical to locate the heating and/or refrigeration plant in the building, on an intermediate floor, in a roof penthouse, or on the roof. Electrical service and structural costs are higher, but these may be offset by reduced costs for piping, pumps and pumping energy, and chimney requirements for fuel-fired boilers. Also, initial cost of equipment in a tall building may be less for equipment located on a higher floor because some operating pressures may be lower with boilers located in a roof penthouse.

Regulations applicable to both gas and fuel oil systems must be followed. Gas fuel may be more desirable than fuel oil because of the physical constraints on the required fuel oil storage tank, as well as specific environmental and safety concerns related to oil leaks. In addition, the cost of an oil leak detection and prevention system may be substantial. Oil pumping presents added design and operating problems, depending on location of the oil tank relative to the oil burner.

Energy recovery systems can reduce the size of the heating and/or refrigeration plant. Well-insulated buildings and electric and gas utility rate structures may encourage the design engineer to consider energy conservation concepts such as limiting demand, ambient cooling, and thermal storage.

Fan Rooms

Fan rooms house HVAC air delivery equipment and may include other miscellaneous equipment. The room must have space for removing the fan(s), shaft(s), coils, and filters. Installation, replacement, and maintenance of this equipment should be considered when locating and arranging the room.

Fan rooms in a basement that has an airway for intake of outside air present a potential problem. Low air intakes are a security concern, because harmful substances could easily be introduced (see the section on Security). Placement of the air intake louver(s) is also a concern because debris and snow may fill the area, resulting in safety, health, and fan performance concerns. Parking areas close to the building's outside air intake may compromise ventilation air quality.

Fan rooms on the second floor and above have easier access for outside and exhaust air. Depending on the fan room location, equipment replacement may be easier. The number of fan rooms required depends largely on the total floor area and whether the HVAC system is centralized or decentralized. Buildings with large floor areas may have multiple decentralized fan rooms on each or alternate floors. High-rise buildings may opt for decentralized fan rooms for each floor, or for more centralized service with one fan room serving the lower 10 to 20 floors, one serving the middle floors of the building, and one at the roof serving the top floors.

Life safety is a very important factor in HVAC fan room location. Chapter 52 of the 2007 *ASHRAE Handbook—HVAC Applications* discusses fire and smoke management. State and local codes have additional fire and smoke detection and damper criteria.

Horizontal Distribution

Many decentralized systems and central systems rely on horizontal distribution. To accommodate this need, the design engineer needs to take into account the duct and/or pipe distribution criteria for installation in a ceiling space or below a raised floor space. Water systems usually require the least amount of ceiling or raised floor depth, whereas air distribution systems have the largest demand for horizontal distribution height. Steam systems need to accommodate pitch of steam pipe, end of main drip, and condensate return pipe pitch. Another consideration in the horizontal space cavity is accommodating the structural members, light fixtures, rain leaders, cable trays, etc., that can fill up this space.

Vertical Shafts

Buildings over three stories high usually require vertical shafts to consolidate mechanical, electrical, and telecommunication distribution through the facility.

Vertical shafts in the building provide space for air distribution ducts and for pipes. Air distribution includes HVAC supply air, return air, and exhaust air ductwork. If a shaft is used as a return air plenum, close coordination with the architect is necessary to ensure that the shaft is airtight. If the shaft is used to convey outside air to decentralized systems, close coordination with the architect is also necessary to ensure that the shaft is constructed to meet mechanical code requirements and to accommodate the anticipated internal pressure. Pipe distribution includes heating water, chilled water, condenser water, and steam supply and condensate return. Other distribution systems found in vertical shafts or located vertically in the building include electric conduits/closets, telephone cabling/closets, uninterruptible power supply (UPS), plumbing, fire protection piping, pneumatic tubes, and conveyers.

Vertical shafts should not be adjacent to stairs, electrical closets, and elevators unless at least two sides are available to allow access to ducts, pipes, and conduits that enter and exit the shaft while allowing maximum headroom at the ceiling. In general, duct shafts with an aspect ratio of 2:1 to 4:1 are easier to develop than large square shafts. The rectangular shape also facilitates transition from the equipment in the fan rooms to the shafts.

In multistory buildings, a central vertical distribution system with minimal horizontal branch ducts is desirable. This arrangement (1) is usually less costly; (2) is easier to balance; (3) creates less conflict with pipes, beams, and lights; and (4) enables the architect to design lower floor-to-floor heights. These advantages also apply to vertical water and steam pipe distribution systems.

The number of shafts is a function of building size and shape. In larger buildings, it is usually more economical in cost and space to have several small shafts rather than one large shaft. Separate HVAC supply, return, and exhaust air duct shafts may be desired to reduce the number of duct crossovers. The same applies for steam supply and condensate return pipe shafts because the pipe must be pitched in the direction of flow.

When future expansion is a consideration, a pre-agreed percentage of additional shaft space should be included. The need for access doors into shafts and gratings at various locations throughout the height of the shaft should also be considered.

Rooftop Equipment

For buildings three stories or less, system analysis and selection frequently locates HVAC equipment on the roof or another outside location, where the equipment is exposed to the weather. Decentralized equipment and systems are more advantageous than centralized HVAC for smaller buildings, particularly those with multiple tenants with different HVAC needs. Selection of rooftop equipment is usually driven by first cost versus operating cost and/or maximum service life of the equipment.

Equipment Access

Properly designed mechanical and electrical equipment rooms must allow for moving large, heavy equipment in, out, and through the building. Equipment replacement and maintenance can be very costly if access is not planned properly. Access to rooftop equipment should be by means of a ship's ladder and not by a vertical ladder. Use caution when accessing equipment on sloped roofs.

Because systems vary greatly, it is difficult to estimate space requirements for refrigeration and boiler rooms without making block layouts of the system selected. Block layouts allow the design engineer to develop the most efficient arrangement of the equipment with adequate access and serviceability. Block layouts can also be used in preliminary discussions with the owner and architect. Only then can the design engineer verify the estimates and provide a workable and economical design.

AIR DISTRIBUTION

Ductwork should deliver conditioned air to an area as directly, quietly, and economically as possible. Structural features of the building generally require some compromise and often limit the depth of space available for ducts. Chapter 9 discusses air distribution design for small heating and cooling systems. Chapter 33 of the 2005 *ASHRAE Handbook—Fundamentals* discusses space air distribution and duct design.

The design engineer must coordinate duct layout with the structure as well as other mechanical, electrical, and communication systems. In commercial projects, the design engineer is usually encouraged to reduce floor-to-floor dimensions. The resultant decrease in available interstitial space for ducts is a major design challenge. In institutional and information technology buildings, higher floor-to-floor heights are required because of the sophisticated, complex mechanical, electrical, and communication distribution systems.

Exhaust systems, especially those serving fumes exhaust, dust and/or particle collection, and other process exhaust, require special design considerations. Capture velocity, duct material, and pertinent duct fittings and fabrication are a few of the design parameters necessary for this type of distribution system to function properly, efficiently, and per applicable codes. Refer to Chapters 29 and 30 of the 2007 *ASHRAE Handbook—HVAC Applications* for additional information.

Air Terminal Units

In some instances, such as in low-velocity, all-air systems, air may enter from the supply air ductwork directly into the conditioned space through a grille, register, or diffuser. In medium- and high-velocity air systems, an intermediate device normally controls air volume, reduces duct pressure, or both. Various types of air terminal units are available, including (1) a fan-powered terminal unit, which uses an integral fan to mix ceiling plenum air and primary air from the central or decentralized fan system rather than depending on induction (mixed air is delivered to low-pressure ductwork and then to the space); (2) a variable-air-volume (VAV) terminal unit, which varies the amount of air delivered to the space (this air may be delivered to low-pressure ductwork and then to the space, or the terminal may contain an integral air diffuser); or (3) other in-room terminal type (see Chapter 5). Chapter 19 has more information about air terminal units.

Duct Insulation

In new construction and renovation upgrade projects, HVAC supply air ducts should be insulated in accordance with energy code requirements. ASHRAE *Standard* 90.1 and Chapter 26 of the 2005 *ASHRAE Handbook—Fundamentals* have more information about insulation and calculation methods.

Ceiling and Floor Plenums

Frequently, the space between the suspended ceiling and the floor slab above it is used as a return air plenum to reduce distribution ductwork. Check regulations before using this approach in new construction or a renovation because most codes prohibit combustible material in a ceiling return air plenum. Ceiling plenums and raised floors can also be used for supply air displacement systems to minimize horizontal distribution, along with other features discussed in Chapter 4.

Some ceiling plenum applications with lay-in panels do not work well where the stack effect of a high-rise building or high-rise elevators creates a negative pressure. If the plenum leaks to the low-pressure area, tiles may lift and drop out when the outside door is opened and closed.

Return air temperature in a return air plenum directly below a roof deck is usually higher by 3 to 5°F during the air-conditioning season than in a ducted return. This can be an advantage to the occupied space below because heat gain to the space is reduced. Conversely, return air plenums directly below a roof deck have lower return air temperatures during the heating season than a ducted return and may require supplemental heat in the plenum.

Raised floors using an air distribution system are popular for computer rooms and cleanrooms, and are now being used in other HVAC applications. Underfloor air displacement (UFAD) systems in office buildings use the raised floor as a supply air plenum, which could reduce overall first cost of construction and ongoing improvement costs for occupants. This UFAD system improves air circulation to the occupied area of the space. See Chapter 17 of the 2007 *ASHRAE Handbook—HVAC Applications* and Chapter 33 of the 2005 *ASHRAE Handbook—Fundamentals* for more information on displacement ventilation and underfloor air distribution.

PIPE DISTRIBUTION

Piping should deliver refrigerant, heating water, chilled water, condenser water, fuel oil, gas, steam, and condensate drainage and return to and from HVAC equipment as directly, quietly, and economically as possible. Structural features of the building generally require mechanical and electrical coordination to accommodate P-traps, pipe pitch-draining of low points in the system, and venting of high points. When assessing application of pipe distribution to air distribution, the floor-to-floor height requirement can influence the pipe system: it requires less ceiling space to install pipe. An alternative to horizontal piping is vertical pipe distribution, which may further reduce floor-to-floor height criteria. Chapter 36 of the 2005 *ASHRAE Handbook—Fundamentals* addresses pipe distribution and design.

Pipe Systems

HVAC piping systems can be divided into two parts: (1) piping in the central plant equipment room and (2) piping required to deliver refrigerant, heating water, chilled water, condenser water, fuel oil, gas, steam, and condensate drainage and return to and from decentralized HVAC and process equipment throughout the building. Chapters 10 to 14 discuss piping for various heating and cooling systems. Chapters 1 to 4 and 33 of the 2006 *ASHRAE Handbook—Refrigeration* discuss refrigerant piping practices.

Pipe Insulation

In new construction and renovation projects, certain HVAC piping may or may not be insulated depending on code requirements. ASHRAE *Standard* 90.1 and Chapter 26 of the 2005 *ASHRAE Handbook—Fundamentals* have information on insulation and calculation methods.

SECURITY

Since September 11, 2001, much attention has been given to protecting buildings' HVAC systems against terrorist attacks. The first consideration should be risk assessment of the particular facility, which may be based on usage, size, population, and/or significance. Risk assessment is a subjective judgment by the building owner of whether the building is at low, medium, or high risk. An example of low-risk buildings may be suburban office buildings or shopping malls. Medium-risk buildings may be hospitals, educational institutions, or major office buildings. High-risk buildings may include major government buildings. The level of protection designed into these buildings may include enhanced particulate filtration, gaseous-phase filtration, and various controlled schemes to allow purging of the facility.

Enhanced particulate filtration for air-handling systems to the level of MERV 14 to 16 filters not only tends to reduce circulation of dangerous substances (e.g., anthrax), but also provides better indoor air quality (IAQ). Gaseous-phase filtration can remove harmful substances such as sarin and other gaseous threats. Low-risk buildings may only include proper location of outdoor air intakes and separate systems for mailrooms and other vulnerable spaces. Medium-risk buildings should consider adding enhanced particulate filtration, and high-risk buildings might also add gaseous filtration. The extent to which the HVAC system designer should use these measures depends on the perceived level of risk.

In any building, consideration should be given to protecting outside air intakes against insertion of dangerous materials by locating the intakes on the roof or substantially above grade level. Separate systems for mailrooms, loading docks, and other similar spaces should be considered so that any dangerous material received cannot be spread throughout the building from these vulnerable spaces. Emergency ventilation systems for these types of spaces should be designed so that upon detection of suspicious material, these spaces can be quickly purged.

A more extensive discussion of this topic can be found in ASHRAE's *Guideline* 29.

AUTOMATIC CONTROLS AND BUILDING MANAGEMENT SYSTEM

Basic HVAC system controls are available in electric, pneumatic, or electronic versions. Depending on the application, the design engineer may recommend a simple and basic system strategy as a cost-effective solution to an owner's heating, ventilation, and cooling needs. Chapter 46 of the 2007 *ASHRAE Handbook—HVAC Applications* and Chapter 15 of the 2005 *ASHRAE Handbook—Fundamentals* discuss automatic control in more detail.

The next level of HVAC system management is direct digital control (DDC), with either pneumatic or electric control damper and valve actuators. This automatic control enhancement may include energy monitoring and energy management software. Controls may also be accessible by the building manager using a modem to a remote computer at an off-site location. Building size has little to no effect on modern computerized controls: programmable controls can be furnished on the smallest HVAC equipment for the smallest projects. Chapter 41 of the 2007 *ASHRAE Handbook—HVAC Applications* covers building operating dynamics.

Automatic controls can be prepackaged and prewired on the HVAC equipment. In system analysis and selection, the design engineer needs to include the merits of purchasing prepackaged versus traditional building automation systems. Current HVAC controls and their capabilities need to be compatible with other new and existing automatic controls. Chapter 39 of the 2007 *ASHRAE Handbook—HVAC Applications* discusses computer applications, and ASHRAE *Standard* 135 discusses interfacing building automation systems.

Using computers and proper software, the design engineer and building manager can provide complete facility management. A comprehensive building management system may include HVAC system control, energy management, operation and maintenance management, medical gas system monitoring, fire alarm system, security system, lighting control, and other reporting and trending software. This system may also be integrated and accessible from the owner's computer network and the Internet.

The building management system is an important factor in choosing the optimum HVAC system. It can be as simple as a time clock to start and stop equipment, or as sophisticated as a computerized building automation system serving a decentralized HVAC system, multiple building systems, central plant system, and/or a large campus. With a focus on energy management, the building management system can be an important business tool in achieving sustainable facility management that begins with using the system selection matrix.

Security should be an integral part of system design and building management. Hazardous materials and contaminated air can be introduced into the building through ventilation systems. When recommending the optimum HVAC system for the project, security should not be overlooked, no matter what the application.

Planning in the design phase the early compilation of record documents (e.g., computer-aided drawing and electronic word files, checklists, digital photos taken during construction) is also integral to successful building management and maintenance.

MAINTENANCE MANAGEMENT SYSTEM

Whereas building management systems focus on operation of HVAC, electrical, plumbing, and other systems, maintenance management systems focus on maintaining assets, which include mechanical and electrical systems along with the building structure. A rule of thumb is that 20% of the cost of the building is in the first cost, with the other 80% being operation, maintenance, and rejuvenation of the building and building systems over the life cycle.

When considering the optimum HVAC selection and recommendation at the start of a project, a maintenance management system should be considered for HVAC systems with an estimated long useful service life.

Another maintenance management business tool is a **computerized maintenance management software (CMMS)** system. The CMMS system can include an equipment database, parts and material inventory, project management software, labor records, etc., pertinent to sustainable management of the building over its life. CMMS also can integrate computer-aided drawing (CAD), digital photography and audio/video systems, equipment run-time monitoring and trending, and other proactive facility management systems.

In scoring the HVAC system selection matrix selection, consideration should also be given to the potential for interface of the building management system with the maintenance management system.

BUILDING SYSTEM COMMISSIONING

When compiling data to complete the HVAC system selection matrix to analytically determine the optimum HVAC system for the project, a design engineer should begin to produce the design intent document/basis of design that identifies the project goals. This process is the beginning of building system commissioning and should be an integral part of the job documentation. As design progresses and the contract documents take shape, the commissioning process will continue to be built into what will eventually be the final commissioning report approximately one year after the construction phase has been completed and the warranty phase comes to an end. For more information, see Chapter 42 in the 2007 *ASHRAE Handbook—HVAC Applications* or ASHRAE *Guideline* 1.

Building commissioning contributes to successful sustainable HVAC design by incorporating the system training requirements necessary for building management staff to efficiently take ownership and operate and maintain the HVAC systems over the installation's useful service life.

In addition to building system commissioning, air and water balancing is required to achieve peak building system performance. Review in the design phase of a project should consider both, and both commissioning and balancing should continue through the construction and warranty phases. Based on the systems selected, commissioning and balancing can cost from $0.50 to $2.00 or more per square foot.

With building certification programs (e.g., LEED™), commissioning is a prerequisite because of the importance of ensuring that high-performance energy and environmental designs are long-term successes.

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