8. Air Distribution Systems

Revised April 2008

8.1 Overview

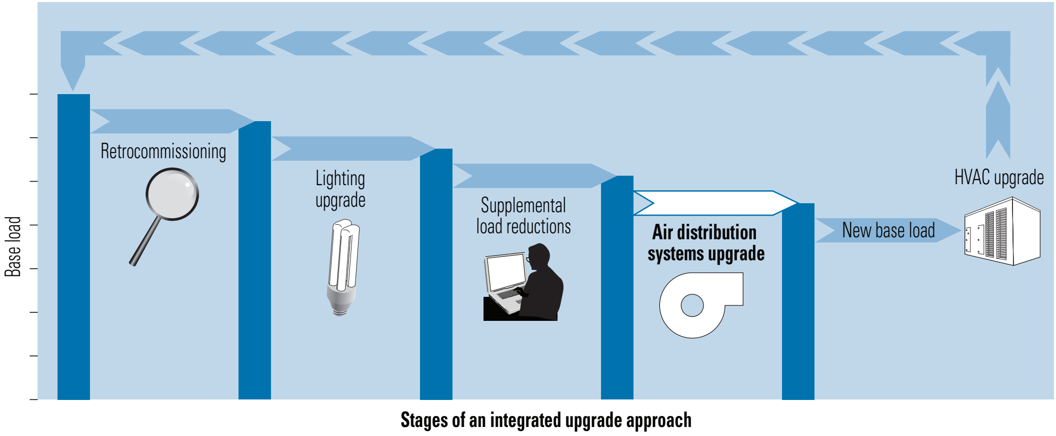
Air distribution systems bring conditioned (heated and cooled) air to people occupying a building, and therefore directly affect occupant comfort. Over the last several decades, significant improvements have been made to the design of air distribution systems as well as to the way in which these systems are controlled. These improved designs and controls can result in dramatic energy savings, yet many buildings continue to rely on obsolete, inefficient systems for this critical function.

The energy savings achieved in the Retrocommissioning, Lighting, and Supplemental Load Reductions stages (**Figure 8.1**) are likely to have reduced the load on the building's HVAC system, sometimes considerably. But before evaluating the potential to replace the existing heating and/or cooling equipment with smaller and more-efficient equipment, optimize the efficiency of the air distribution system itself. Doing so may well enable even greater savings and a reduction in required heating and cooling equipment capacity.

On average, the fans that move conditioned air through commercial office buildings account for about 7 percent of the total energy consumed by these buildings (**Figure 8.2**), so reductions in fan consumption can result in significant energy savings. A U.S. Environmental Protection Agency (EPA) study found that almost 60 percent of building fan systems were oversized by at least 10 percent, with an average oversizing of 60 percent. "Rightsizing" a fan system, or better matching fan capacity to the requirements of the load, is an excellent way to save energy in air distribution systems. There are also opportunities for energy-saving improvements to the air distribution system in four other categories: adjusting ventilation to conform with code requirements or occupant needs, implementing energy-saving controls, taking advantage of free cooling where possible, and optimizing the efficiency of distribution system components. This chapter will describe the opportunities in each of these areas, but first, it is important to gain an understanding of the types of systems that are commonly encountered and the various components of air distribution systems.

Figure 8.1 The staged approach to building upgrades

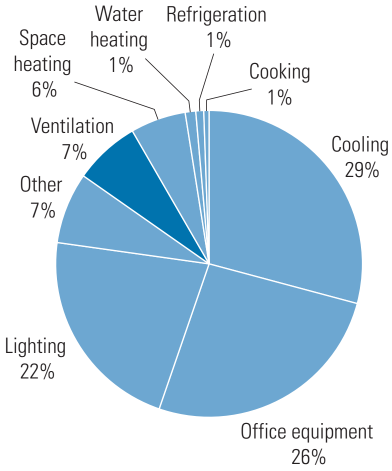
The staged approach to building upgrades accounts for the interactions among all the energy flows in a building. Each stage includes changes that will affect the upgrades performed in subsequent stages, thus setting the overall process up for the greatest energy and cost savings possible. The air distribution systems stage takes advantage of the load reductions achieved in earlier stages.



Courtesy: E SOURCE

Figure 8.2: Typical electricity consumption in commercial office buildings

The power used to circulate conditioned air accounts for approximately 7 percent of commercial office building electricity consumption.



Source: U.S. Department of Energy

8.2 Air-Handling System Types

There are two types of air-handling systems: constant volume (CV) and variable air volume (VAV). In a CV system, a constant amount of air flows through the system whenever it is on. A VAV system changes the amount of airflow in response to changes in the heating and cooling load. VAV systems offer substantial energy savings and are becoming more widespread.

Constant-Volume Systems

Constant-volume systems are the simplest type of air distribution system and are installed in a large percentage of existing commercial buildings. In a CV system, when the supply fan is on, a constant amount of air flows through; there is no modulation of the fan power, no discharge dampering at the fan, and no dampering at the terminal ends of the duct runs. In its simplest configuration, a CV system serves a single space (also called a zone). A thermostat is located in the zone that senses space temperature and sends signals to the air-handling unit to provide heating or cooling based on the thermostat setting.

Reheat systems. In larger buildings, CV systems serve multiple zones with varying heating or cooling requirements. For example, a perimeter office with a vast expanse of south-facing glass may require cooling in the middle of December when the rest of the building requires heating. Constant-volume systems that serve multiple zones are typically designed with some way to vary the temperature of air delivered to each zone. To meet differing cooling loads with a CV system, *terminal reheat* or *zone reheat* is frequently added: an electric resistance element, hot water coil, or other heat source that reheats the cooled air just before it enters the room. The system is sized to provide cooling to the zone with the peak load, and all zones with less cooling load have their air reheated as it enters the zone. In humid climates, reheat systems not only provide terminal control but also strip moisture out of the supply airstream by allowing deep cooling of the primary air.

Reheat systems are as inefficient as they sound: energy is used first to cool and then to reheat the air. The thermostat in a CV-supplied zone only controls the amount of reheat applied to that zone's air. If reheat is not applied, zones will be overcooled, possibly to uncomfortable levels. CV systems without temperature reset (thermostatic control of the supply-air temperature) are now prohibited by many energy codes.

Constant-volume, variable-temperature (CVVT) systems. A CV system that adjusts or resets the temperature of the supply air is a CVVT system. As cooling loads decrease, chilled water flow is reduced (or "reset" in control system parlance) to create warmer supply air. This reset can be controlled by monitoring either the outside air temperature (outside-air reset) or the cooling needs of the warmest zone (warmest-zone reset). Although outside-air reset has simpler controls and thus may be more reliable, it bases its strategy on the frequently incorrect assumption that cooling load varies linearly with the temperature of the outside air. Solar gain through the windows and internal heat gain from people, lights, and equipment all impact the cooling load independently of the outside temperature. Warmest-zone reset, which directly monitors the indoor air temperature of interest, is more accurate: the supply-air temperature is set just low enough to cool the zone with the highest cooling load.

Because CVVT systems respond to changes in cooling load by reducing the load on the chiller, they use less cooling energy than simple CV systems do. In reheat systems, less energy is used to reheat the air because the supply air is already warmer due to the temperature reset. However, the system only responds to the peak load in each zone; large load differences among zones can still cause substantial overcooling or reheating. This is why reduction of building-skin loads with shading or window films is important: it can reduce that peak load, raise the supply-air temperature, and enable all other zones served by that air handler to use warmer supply air, use less chiller energy, and require less reheat energy. Also, for hot water reheat systems, the temperature of the hot water can be reduced based on the outside air temperature or a "coldest-zone reset" to further reduce the energy waste associated with mixing heated and cooled air.

Dual-duct systems. Often found in buildings constructed during the 1960s and 1970s, dual-duct systems are a relatively effective means of maintaining comfort, yet an extremely inefficient method of conditioning air. Dual-duct systems consist of two independent systems, one warm and one cool, that circulate air through all sections of the building via a parallel sets of ducts. Hot and cold air are mixed in local mixing boxes (also called zone dampers or, sometimes, "pair of pants" dampers) in each zone and then fed into that area. Depending on the temperature needs of the zone, the mixture of hot and cold air is adjusted until the desired temperature is reached. Unfortunately, with a dual-duct system, a volume of air that is typically much larger than the actual volume required by the building must be cooled, heated, and circulated.

In addition, the dampers in dual-duct mixing boxes frequently leak, even when they are supposed to be fully closed. During cooling operation, warm duct leakage increases the energy necessary to condition the space. The leakage is a function of construction quality and of the static pressure in the duct. Leakage ratios vary from about 3 percent to about 20 percent, with 5 percent often used as an estimate for well-built systems.

Multizone systems. Multizone systems are similar to dual-duct systems in that two streams of air, hot and cold, are mixed to produce a desired temperature. But whereas dual-duct systems mix the air in individual boxes located at each area or room, multizone systems mix air with dampers near the fans. This conditioned air is then fed to each zone so that each zone receives air at a different temperature based on its load.

There are several advantages to the multizone design. These systems require less ductwork and dampering, and therefore occupy less space, than a dual-duct system. Furthermore, the location of the mixing dampers facilitates their inspection and repair. Also, these systems tend to be quieter because the noise and vibration associated with air passing over the mixing dampers is not directly above the conditioned space. On the other hand, the disadvantages of multizone systems are the wasted energy to supply simultaneous heating and cooling and the high capital cost for the multizone dampering unit. In addition, the placement of the mixing dampers directly downstream of the main supply fan means that the air velocity will be high as it passes through them, creating significant pressure loss. The supply fan must compensate for this pressure loss to ensure adequate airflow to each zone. Finally, the dampers on the hot and cold supply streams may leak, requiring additional energy to achieve the desired temperature setpoint.

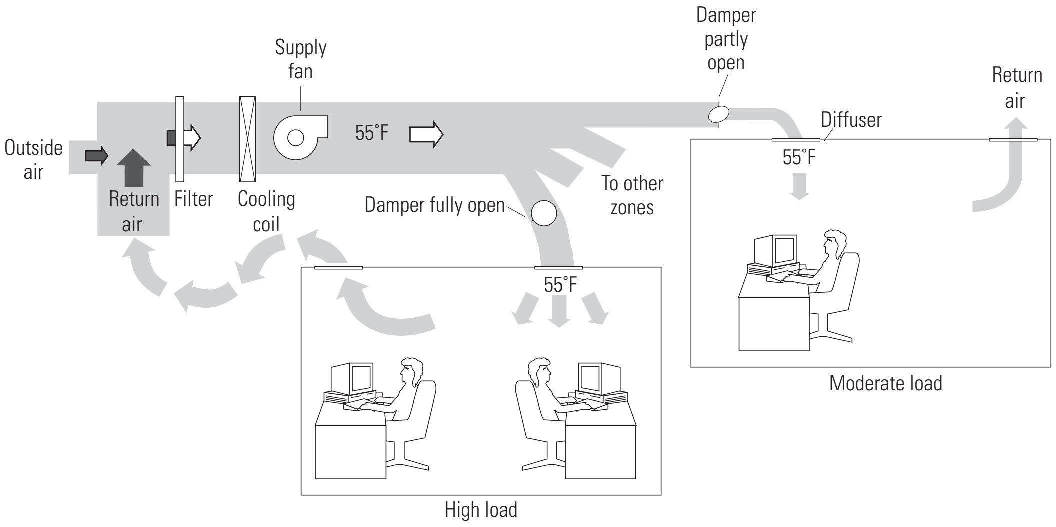
Variable Air Volume Systems

Currently available air distribution components, controls, and design strategies offer much more efficient designs than those installed and operating in many existing buildings. Today's VAV systems can handle changing load requirements by varying the amount of heated or cooled air circulated to the conditioned space in response to varying heating or cooling loads. This reduces fan power requirements, which saves energy and costs.

VAV systems work either by opening or closing dampers or by modulating the airflow through mixing boxes powered by VAV fans as loads in various zones of the building change (**Figure 8.3**). If, for example, more cooling in an area is required, the damper to that area is opened wider, increasing the flow of cold air until the desired temperature is reached. As the damper opens, static pressure in the duct drops, signaling the fan to increase air delivery. Conversely in this same example, if an area is too cool, the damper is slowly closed, reducing the flow of cold air. Used in combination with variable-speed drives (VSDs), this reduction in flow results in a reduction in the fan power needed, saving energy. Converting an existing constant-volume system to a VAV system is a popular option for many building owners, because it allows the system to turn itself down in response to changing demand.

Figure 8.3: Variable air volume system

In a VAV system, dampers control the flow of chilled air to respond to changes in cooling load.



Note: F = Fahrenheit.

Courtesy: E SOURCE

A proper conversion to a VAV system includes changing constant-volume dampers to operate in variable-volume fashion, which typically reduces fan horsepower requirements by 40 to 60 percent. Conversion from constant to variable volume can be complicated in certain circumstances due to nonmechanical factors such as:

- If the existing zone dampers are located in difficult-to-access spaces;
- If the space has a hard ceiling (typically with undersized metal access panels used to reach the mixing dampers for service);
- If the spaces to be converted have a “concealed spline” ceiling tile system (where nearly the entire ceiling must be disassembled to get at one particular spot because all of the ceiling tiles interlock); or
- If asbestos is present in the ceiling space.

It is also possible to convert an existing constant-volume, single-zone system to variable volume without modifying the zone dampers, though careful planning and testing are required for a successful project. In this type of conversion, a VSD is installed to control supply-fan speed. The VSD is controlled by either the return air temperature or the outside air temperature. Typically, to maintain comfort, the airflow reduction range is limited in such systems to 30 to 40 percent of design flow. However, even this modest reduction in airflow can reduce fan power by more than 50 percent. An additional benefit is that, under mild temperature conditions, reheat energy will be reduced along with airflow.

As with constant-volume systems, VAV supply air temperature can be reset (raised) if loads drop enough, thus reducing chiller load as well as fan power. Such a variable-volume, variable-temperature (VVVT) system changes both the temperature and the volume of supply air as needed to achieve maximum load responsiveness while minimizing reheat. A fully loaded VVVT system moves fully chilled air, usually at 55° Fahrenheit (F), at maximum fan capacity with all terminal dampers wide open. As cooling loads drop, the terminal dampers close as necessary and the supply fan slows down. When dampers reach their minimum position, zone reheat is applied (if available). Finally, when all zones are at their minimum stops, the supply air temperature is reset (raised) so that the warmest zone will need no reheat. This has the double effect of reducing the load on the chiller and decreasing the reheat energy throughout the system. The trade-off between resetting supply-air temperature and lowering supply-air volume can be optimized for a given system, perhaps reversing the order of volume reduction and temperature reset. Due to the complexity of the control system, a high degree of expertise is required to successfully commission VVVT systems.

8.3 Air-Handling Components

The major components in an air-handling system are its fans, filters, ducts, and dampers. Each component performs a task critical to the proper operation of the system: Fans circulate the air and provide the pressure required to push it through filters, coils, ducts, transitions, fittings, dampers, and diffusers. Filters clean the air, protecting occupant health, inhibiting bacteria and mold growth, and keeping coil surfaces clean. Ducts convey the conditioned air throughout the building, distributing the air to occupants and then returning it to be conditioned and circulated again. Dampers control the flow and mix of returned and outside air through the ducts to the various parts of the building. All of these components must function well both individually and together to ensure efficient system operation and occupant comfort.

Fans

Fans are the heart of a building's air-handling system. Like a heart that pumps blood through a body, they distribute the conditioned (heated or cooled) air throughout the building. There are two main types of fans: centrifugal and axial (**Figure 8.4**).

Centrifugal fans. Centrifugal fans are by far the most prevalent type of fan used in the HVAC industry today. They are usually cheaper than axial fans and simpler in construction, but they generally do not achieve the same efficiency. Centrifugal fans consist of a rotating wheel, or impeller, mounted inside a round housing. The impeller is driven by a motor, which is usually connected via a belt drive.

Axial fans. Axial fans consist of a cylindrical housing with the impeller mounted inside along the axis of the housing. In an axial fan, the impeller consists of blades mounted around a central hub similar to an airplane propeller. As with an airplane, the spinning blades force the air through the fan. Axial fans are typically used for higher-pressure applications (over 5 inches total static pressure) and are more efficient than centrifugal fans.

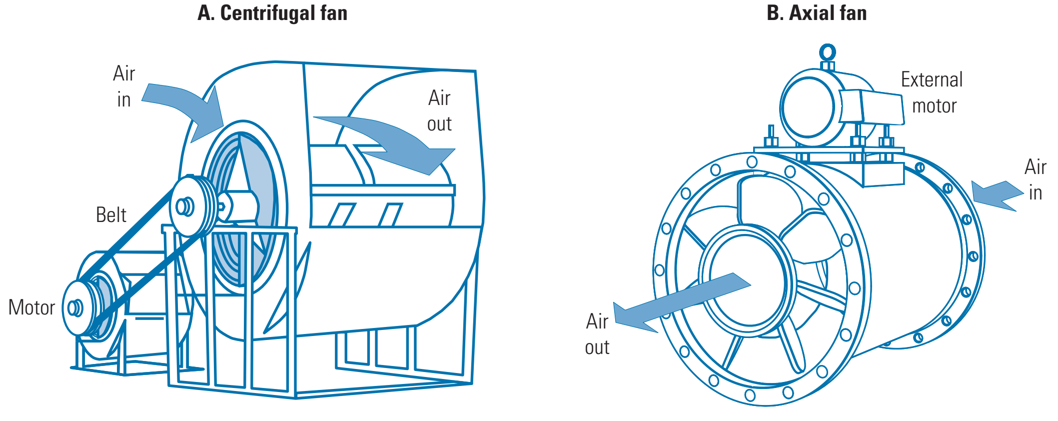
The motor of an axial fan can be mounted externally and connected to the fan by a belt. However, axial fans are often driven by a motor that is directly coupled to the impeller that is mounted within the central hub. As a result, all heat due to motor electrical losses is added to the airstream and must be removed by the cooling system.

Filters

Air filtration occupies an increasingly important role in the building environment. The high profile of ASHRAE's (the American Society of Heating, Refrigerating, and Air-Conditioning Engineers') indoor air quality standard (Standard 62.1-2007) and recent actions by the Occupational Safety and Health Administration (OSHA) have combined to give air filtration new prominence. Filtration also has a substantial impact on energy efficiency. With static pressure drops of up to 0.072 pounds per square inch (psi), filters can consume an enormous amount of fan power. As with other air-handling components, the key to efficient filtration is to consider the details, especially face velocity (airflow per unit area of filter media).

Figure 8.4: Centrifugal and axial fans

Centrifugal fans (A) are the most common fans used in HVAC applications. They are often cheaper but usually less efficient than axial fans (B).



A. Centrifugal fan

B. Axial fan

Courtesy: E SOURCE

Filters work by capturing particles through gravity or through centrifugal collection, screening, adhesion, impingement, and/or adsorption. The *efficiency* of a filter refers not to energy efficiency, but to how well it removes particles from the airstream. *Pressure drop* is the measure that determines how much fan power is required to move air through the filter, and it varies by the square of the air speed through it. For typical HVAC-duty filters (30 percent ASHRAE dust-spot efficiency) a reasonable target pressure drop is 0.0036 psi. Dirty, thick, or poorly designed filters can have pressure drops as high as 0.072 psi—as much as the entire frictional drag of the duct system. Higher pressure also increases fan noise and vibration, duct leakage, wear and tear on the fan and other mechanical components, and a host of other air-handling ills that add real costs to fan operation. Filter performance and longevity are improved with uniform airflow, which is found upstream of the supply fan rather than downstream. Upstream filter placement also cleans the air before it moves through the cooling coils and the fan, helping to maintain their efficiency as well.

Regular filter maintenance is essential to keeping ductwork and coils clean. Dirt accumulation in ductwork can facilitate the growth of bacteria and mold, particularly if condensation occurs within the ducts. Dirt accumulation on coils impedes heat transfer, reducing system efficiency and increasing HVAC costs. Dirty filters will also reduce airflow, and may therefore reduce occupant comfort.

Visual inspection is not always an adequate way to determine whether filter cleaning or replacement is necessary. A sure-fire way to determine when filter maintenance is necessary is to install a device that measures pressure drop across the filter bank. A signal from such a device can be an input to a building automation system to alert operators when filter maintenance is required.

Commonly found filter types in commercial buildings include dry filters, bag filters, high-efficiency particulate air (HEPA) filters, electrostatic precipitators, and carbon filters.

Dry filters. Dry filters have fine strands of fabric or fiber that intercept smaller particles of about 0.5 to 5.0 micrometers. The pleats in these filters give them greater surface area, but the additional surface also lowers their face velocity. The media is contained in a cardboard frame that is generally thrown away with the fabric when it becomes dirty. These are often used as pre-filters for bag or HEPA filters.

Bag filters. Bag filters use dry media that is arranged in a long stocking shape to extend their surface area or to allow recovery of the collected material. Although commonly used in HVAC systems, bag filters are generally being replaced by rigid dry filters.

HEPA filters. HEPA filters use thin, dry media (such as paper or glass-fiber mats) with very small pores that trap superfine particulates down to 0.01 micrometer in diameter. They are heavily pleated to reduce face velocity but still contribute pressure drops of up to 0.072 psi. HEPA filters are used mostly for the demanding applications of electronics and pharmaceutical production facilities, hospital operating rooms, and facilities that generate radioactive particles. HEPA filters should be coupled with a coarser pre-filter to extend their lifetime.

Electrostatic precipitators. Electrostatic precipitators use a high voltage to ionize particles suspended in the air, then pass the airstream between charged plates that attract and accrete the charged particles. Because there is no physical impediment to the air, these filters have very low pressure drops. However, the power equipment used to create the voltage differences continuously consumes about 20 to 40 watts per 1,000 cubic feet per minute (cfm) of airflow. An efficient fan uses about 140 watts per inch of pressure drop (water gauge) for each 1,000 cfm, so the precipitator energy is about the fan-energy equivalent of 0.004 to 0.007 psi of pressure drop. Electrostatic precipitators are usually used together with low-efficiency dry media filters that capture the largest particles and minimize the need to clean the charged plates.

This dual filter use means that electrostatic precipitator systems typically require more energy consumption and maintenance than a system with conventional filters would. One engineer estimates that electronic filters "double or triple" filter maintenance costs. The effectiveness of electronic air cleaners decreases with heavily dust-laden plates, with high-speed air, and with nonuniform air velocity. The plates that collect the charged particles must periodically be taken out of the duct and washed off, adding a maintenance step more complex than simple filter replacement. However, they do decrease the use of nonrecyclable filter components, and avoid the increasingly difficult problem of filter disposal. For overall HVAC efficiency, electronic filters usually do not make sense unless they can fulfill a specific need, such as local air cleaning in a smoking lounge.

Carbon filters. Carbon filters clean the air of gases and vapors at the chemical or molecular level. The porosity of activated, granulated carbon media is such that large, odor-causing molecules become adsorbed as they seep through the filter. The carbon can adsorb up to half its own weight in gases, which can then be driven off by heating, allowing the carbon to be reused. Carbon filters are not common in typical commercial buildings, unless there is a need to remove persistent sources of odor, such as from local industry.

A common metric for filter performance is the minimum efficiency reporting value (MERV), a rating derived from a test method developed by ASHRAE. The MERV rating indicates a filter's ability to capture particles between 0.3 and 10.0 microns in diameter. A higher MERV value translates to better filtration, so a MERV-13 filter works better than a MERV-8 filter.

Ducts

Like the arteries and veins in the human body, ducts convey the conditioned air from the air-handling unit out through the building and return it back to be conditioned again (or exhausted from the building). They are usually constructed of sheet metal and are insulated.

Ductwork can either be round or rectangular. Rectangular duct material used to be cheaper and more common than round, but the trend these days is to use a spiral version that is fabricated at local manufacturing facilities to the sizes and lengths required for each job. Spiral duct construction is similar to that of a paper drinking straw; a long strip of metal is wrapped around itself in an overlapping, continuous pattern. Spiral ductwork can be fabricated in round or oval cross-section designs. Spiral ducts tend to be less expensive than rectangular and are characterized by lower pressure drop, reduced heat gain or loss (due to the reduced surface area), and reduced weight. Spiral ducts can be manufactured in long lengths, and the spiral-lock seams make the ductwork more rigid. From an architectural standpoint, more new buildings are leaving the ductwork exposed as opposed to concealing it behind a T-bar ceiling, and spiral ductwork has an attractive shape and surface pattern that lends itself to this sort of installation.

Rough-surfaced duct material makes a fan work harder than smooth duct materials do. In engineering terms, the pressure loss of a duct is proportional to the friction factor of its inside skin and to the square of the air speed. The friction factor depends on surface roughness (the average height of protrusions from the surface) and, to a much lesser extent, on duct diameter, air speed, and air density. Smooth sheet metal, usually steel or aluminum, is the best material for ductwork: Rigid fiberglass ductwork suffers nearly 30 percent more pressure drop than sheet metal. The acoustic fiber lining used in many supply ducts (especially just downstream of the fan) has 40 percent more frictional resistance than smooth sheet metal.

Ducts must be properly insulated to prevent excessive energy loss. Duct insulation helps prevent the warming of chilled air and the cooling of heated air as it passes through the ducts. ASHRAE standard 90.1, the energy code governing design of new commercial buildings in many jurisdictions in the U.S., specifies duct insulation with a heat flow resistance level of as much as R-8 in some locations for ducts carrying hot or cold air. This requirement varies by jurisdiction; local energy and/or mechanical codes must be consulted. Proper choice of insulation can also help reduce the transmission of fan and motor noise from the HVAC system to the working spaces inside buildings.

Proper installation of the duct insulation is important as well. Because soft insulation is frequently used, it must be kept from compressing under duct hangers, against the floor or roof structure above, or against the suspended ceiling below. This requires adequate vertical clearance. Some brands of ductwork come complete with an insulation layer.

Dampers

Dampers modulate the flow of air through the ducts to the various parts of the building, reducing or increasing the airflow depending upon conditions. Dampers also regulate the quantity of outside air that is allowed to enter the air-handling unit and mix with return air for ventilation purposes. Dampers can be difficult to maintain and can affect occupant comfort as the space requirements change and as the air-handling system ages.

A typical commercial HVAC system has numerous dampers that alter the flow of outside air, return air, exhaust air, and supply air. An efficient air-handling system minimizes the number of dampers necessary overall and eliminates dampers or uses low-loss dampers at branch takeoffs, reducing the fan power needed to blow air past them but maintaining the capability for minor balancing adjustments. Using variable-speed drives for fan regulation can eliminate the need for fan inlet or discharge dampers.

8.4 Best Opportunities

When considering options for improving the performance of an air distribution system, it is important to remember that the purpose of having an HVAC system in the first place is to regulate the temperature, humidity, freshness, and movement of air in buildings. Accordingly, energy-efficiency retrofit projects should not undermine the system's capability to provide thermal comfort and air quality. The goal of energy retrofit projects should be to improve system efficiency while maintaining or enhancing comfort.

Although there are different ways to address air-handling system efficiency opportunities, one effective approach is to start at the conditioned space and work back to the air-handling unit. Looking at the opportunities in this order enables building operators to take advantage of downstream savings when addressing upstream opportunities. For example, repairing corroded zone mixing dampers that are stuck in the full-cooling position in a dual-duct system will provide better comfort to the occupants while also reducing the amount of cool air that the air-handling unit must provide. Fixing the zone dampers may unearth upstream opportunities to take advantage of the reduced cooling load with system control reset strategies or the installation of rightsized equipment.

Optimize Zone-Level Performance

The zone-level equipment consists of zone mixing dampers (such as dual-duct mixing dampers or VAV mixing boxes), reheat coils (hot water or electric), and the thermostats that control this equipment in response to user preferences. As facilities age, zone-level equipment often falls out of calibration or into disrepair, impairing its ability to provide comfort and undermining overall system performance. Fixing zone-level problems can lead to more comfortable occupants as well as upstream energy savings.

Some of the most common opportunities to consider at the zone level are:

- *Recalibrate thermostats.* In systems with pneumatic controls, the thermostats periodically require recalibration (typically, every 6 to 12 months) in order to regulate space temperature more accurately. Though thermostat calibration should be checked if a comfort complaint exists, it is preferable to evaluate the thermostats on a regular basis as a proactive maintenance measure.
- *Inspect dampers.* For systems with zone dampers, periodically inspect the damper, linkage, and actuator for proper operation. In older buildings where maintenance has not been rigorous, it is likely that some of the zone dampers are frozen in position, rendering them ineffective at regulating comfort. Because evaluating and repairing nonfunctional zone dampers can be time-consuming and costly (especially in large buildings that may have hundreds or even thousands of zones), consider allocating a portion of the annual maintenance budget for this purpose to address a certain quantity or percentage of zones. For example, in a 100,000-square-foot, 10-story office building with 150 VAV zones, the maintenance budget might include time and money to evaluate 50 VAV zones per year.
- *Prevent overcooling.* In zone-level reheat systems, performance should be evaluated to keep cooling levels as low as possible. For hot water reheat systems, verify operation of the hot water reheat valve to ensure that it opens and closes in response to control system commands. Check the coil itself to confirm that water is flowing through when it is supposed to and that the coil is not clogged. Confirm the sequence of operation to make sure the reheat coil only operates when it is supposed to. For a single-duct VAV system, the reheat coil typically operates after the VAV damper has reached its minimum airflow position while the zone is calling for heat. If the reheat system is electric, verify proper operation of the coil in response to system commands. Verify the capacity of the electric coil by measuring its input power with an amp probe or true RMS (root-mean-square) power meter. Compare the calculated value with the nameplate value. If the calculated value is much lower than the nameplate value, the coil may have burned-out elements and may require replacement.
- *Disable reheat systems in summer months.* For CV reheat systems, consider whether the zone-level reheat systems can be disabled during the summer. Some facilities with electric reheat systems have successfully shut off the reheat coils at the breaker during the cooling season, leading to significant energy savings. In conjunction with this change, it may be necessary to adjust the supply-air temperature to avoid overcooling certain spaces, and it may be necessary to leave the reheat coil breakers active in certain spaces (such as interior zones) in order to maintain comfort.
- *Regulate static pressure.* Dual-duct systems typically include static balancing dampers for the hot and cold ducts (also called hot and cold “decks”). The purpose of static balancing dampers is to regulate the static pressure in the hot and cold decks in response to zone demands. Over time, these systems (consisting of a static pressure sensor, damper, actuator, and linkage) can fall into disrepair. Failure of the static balancing dampers can cause significant energy waste and discomfort. For example, if the static balancing damper for the cold deck is stuck in a nearly closed position, none of the zones will have an adequate source of cold air, leading to overheating.

Convert CV Systems to VAV

Retrofits involving conversion from CV to VAV are perhaps the most widely employed energy-saving retrofit to commercial HVAC systems, because typical airflow requirements for VAV systems are only about 60 percent that of CV systems. VAV systems also cool only the air volume required to meet demand, rather than meeting demand by simultaneously heating and cooling large volumes of air. **Table 8.1** presents cost and savings data from several large VAV retrofits.

To determine whether the existing system is VAV or CV, review the original design drawings for the HVAC system. If there is a schedule of VAV terminals in the equipment list that includes a minimum and maximum airflow (cfm) for each zone, it is a VAV system.

The conversion of an older constant-volume reheat, multizone, or dual-duct system to a modern, energy-efficient variable air volume system is a task to be undertaken with serious consideration and expert analysis. Unless the facility's management possesses expertise in the

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Table 8.1: Installation cost and energy savings from variable air volume retrofits

The cost and savings of VAV retrofits vary widely, though most retrofits cost between $1 and $4 per square foot.

	AT&T Bell Laboratories, Indian Hills Complex, Naperville, IL	Lamonts Apparel Inc. (Factoria Square), Bellevue, WA	One Bellevue Center, Bellevue, WA	Fanny Allen Hospital, Colchester, VT	General American Life Insurance Co., St. Louis, MO	St. Louis Children's Hospital, St. Louis, MO	100 Market Building,[a] Portland, OR
Building size (ft^2)	1,200,000	50,000	344,715	114,000	450,000	560,000	120,000
Nominal fanpower (hp)	3,300	40	400	85	750	1,470	150
Peak flow (cfm)	600,000	44,000	n/a	58,800	n/a	n/a	132,000
Project cost							
VAV retrofit cost ($)	3,500,000	33,620	965,104	810,838	1,013,000	405,000	575,000
Utility rebate ($)	0	26,167	814,793	552,666	0	0	0
Net cost ($)	3,500,000	7,453	150,311	258,172	1,013,000	405,000	575,000
Cost per square foot ($\$/ft^2$)	2.90	0.67	2.80	7.10	2.30	0.70	4.80
Cost per nominal fan hp ($/hp)	1,060	840	2,412	9,539	1,350	275	3,833
Cost per peak cfm ($/cfm)	5.80	0.80	n/a	13.80	n/a	n/a	4.40
Project savings							
Fan energy savings (kWh/year)	15,000,000	97,456	2,052,391	1,336,592	7,146,974	2,416,160	2,000,000
Fan power savings (kW peak)	900	n/a	234	255	n/a	n/a	200
Energy savings ($/year)	1,200,000	9,211	79,111	129,086	248,000	138,000	80,000
Payback with rebate (years)	2.9	0.8	1.9	2.0	4.1	2.9	7.2
Payback without rebate (years)	2.9	3.6	12.2	6.3	4.1	2.9	7.2

Note: cfm = cubic feet per minute; ft^2 = square foot; hp = horsepower; kWh = kilowatt-hour; n/a = not available; VAV = variable air volume.

a: In this project, TRAV control logic by Microgrid/Hartman was utilized to control the VAV systems. The cost for this project includes fees for design, project management, contractor management, and commissioning.

Courtesy: E SOURCE

conversion of CV systems, this would require the services of an engineering firm or an HVAC controls contractor. In some cases, the local energy utility may be able to provide technical assistance and incentives to help evaluate and implement the project.

The three factors that affect the feasibility of implementing a VAV retrofit are the implementation cost, the annual energy cost savings, and the building owner's minimum attractive rate of return. Surprisingly, in the case of VAV retrofit projects, the most volatile term in the cost-effectiveness equation is the implementation cost, because of the number of factors that influence the effort required to complete the retrofit. The difference between high and low energy cost savings, even when estimated using the simplest of methods, will not typically vary by more than a factor of two. On the other hand, the implementation cost can vary by a factor of ten or more depending on the characteristics of the HVAC system to be converted and the installation conditions. In certain circumstances, it will not be cost-effective to convert to a VAV system. The following factors provide an indication of whether a specific conversion project is likely to be straightforward (and therefore relatively low cost) or to present challenges that will make it more expensive.

Building-level factors

- Consider what type of access the contractor will have to the zone dampers. For example, will the contractor have to work in cramped or inaccessible spaces to access a multizone system? Check the equipment accessibility of dual-duct systems where the zone dampers are located out in the conditioned space: Is the ceiling a T-bar system that facilitates access for equipment installed above the ceiling, or is it a "hard-lid" system that makes it more challenging to access the dampers?
- If the building includes asbestos-containing materials, they may either have to be removed or contained during the retrofit process, which can add significantly to project cost.

System-level factors

- In an existing CV system, check the age and condition of the existing zone dampers and actuators. If they are in good condition, it will make the conversion easier than if the contractor also has to repair components along the way. It would not make sense to make costly changes to a system that has maintenance issues that would prevent it from functioning properly.
- For a dual-duct or multizone system, see whether the existing hot and cold dampers are controlled by one or two actuators. Converting these systems to VAV usually requires two actuators so that the hot and cold air supply can be regulated independently. Having two actuators already installed usually leads to a simpler, less expensive conversion. It is possible to add a second actuator if there is only one, but it will add cost and complexity to the project.
- If the existing system is in poor condition, a major portion of the total project cost for a VAV conversion can be attributed to system maintenance and replacement as opposed to an energy retrofit project. The energy savings are a benefit of such a conversion, but the focus ought to be how to make the HVAC system meet the occupants' thermal comfort requirements.

When soliciting bids from contractors, it can be helpful to look for nearby buildings that are similar in age and design to the building in question and determine whether VAV conversion has been implemented. Often, several similar buildings that used the same design and construction team would have been built in a city during the same era. As a result, the energy retrofit solutions that worked (or did not work) at one building might be applied to another. And a contractor who has already converted similar HVAC systems in previous projects will likely be able to provide a more competitive price than ones who will need to figure it out as they go.

Once the conversion is complete, have the new system commissioned by an independent contractor as part of the retrofit project to ensure that everything operates according to plan.

Rightsize Fans

If HVAC fans are oversized, replacing them with ones that are correctly sized—"rightsizing" them—can be cost-effective. Rightsizing can be implemented separately or in combination with the installation of premium-efficiency motors and VSDs. In general, rightsizing with a premium-efficiency motor, energy-efficient belts, and a VSD is the best alternative. A rightsized system saves energy costs, but there are other advantages as well:

- *Lower first costs.* Because the capacity required from the fan system is reduced, the system can be more accurately tailored to the new airflow requirements. By installing smaller, more energy-efficient equipment that meets these requirements, first costs are also reduced.
- *Comfort.* If the fan system supplies too much air to occupants, energy is wasted and comfort can be compromised. Too much air can result in disturbing drafts, increased humidity, and noise.
- *Longer equipment life.* Prolonged operation at very low speed of an oversized motor with a VSD can reduce the useful life of the motor and associated equipment. Properly sized equipment will be more suited to operation at reduced capacities.

As a first step, the opportunity for rightsizing an air distribution system can usually be determined by building maintenance staff. Once an opportunity has been identified, however, it is usually necessary to hire an HVAC engineer to verify it, to conduct a more detailed analysis, and to make recommendations for optimizing the system.

The approach to assessing the potential for rightsizing varies depending upon whether the existing system is constant or variable volume. Either way, though, it is critical that the proper amount of outside air is maintained to ensure occupant health and comfort. Consult local building codes for information about required outside-air quantities.

Diagnosing oversized fans in VAV systems. Although VAV systems are more energy efficient than CV systems, the potential for rightsizing may still exist. Building maintenance staff may be able to determine whether the VAV fans are oversized by using one of three methods: measuring fan-system static pressure, measuring the fan-motor current draw (amperage), or checking the fan-control vanes and dampers.

The first method is to measure the static pressure of the main supply fan system. It is best to get a baseline measurement on a hot, humid day. Make sure that all fan vanes and dampers and all VAV boxes are fully open. Compare the static pressure reading with the static pressure setpoint. If the reading is less than the setpoint and building occupants are comfortable, the setpoint can be adjusted to the lower static pressure.

Static pressure measurements must be taken at the same location in the distribution system as the pressure sensor that regulates system operation, usually about two-thirds of the way down the main supply duct. If such a measurement is not possible or practical, the desired setpoint can be found by gradually reducing the fan speed each day until the pressure is as low as possible but occupant space is still comfortable. This change will significantly reduce fan power requirements. Be sure to survey occupants periodically to assess comfort. It may also be necessary to restore the old setpoint on extremely hot days. In those cases, consider having the control system programmed to automatically reset the static pressure setpoint (for more on pressure reset, see the Modify Controls section).

Next, measure the fan-motor power draw using a true RMS power meter. For a VAV system, make this measurement when the cooling system is operating under a peak load (for example, on a hot, humid day). Next, read the full-load power rating off the motor's nameplate or from the operating manual. Compare these two numbers. If the measured power is less than 75 percent of the motor's rating, the motor is oversized.

Comparisons of measured to rated current can be misleading because a motor's power factor drops when it is lightly loaded. Therefore, measuring only current does not provide an accurate estimate of motor loading. Better accuracy will be achieved by using an RMS power meter that measures voltage and current simultaneously and displays true power. Also, when comparing measured input power to nameplate power, keep in mind that 1 kilowatt = 0.746 horsepower (hp). Power meters typically display results in kilowatts, but motor nameplates in the U.S. are labeled in horsepower.

Last, check the position of the fan control vanes or dampers when the cooling system is operating under a peak load. If the vanes or dampers are closed more than 20 percent, the fan may be oversized.

Diagnosing oversized fans in CV systems. If it is not economically feasible to retrofit to a VAV system, rightsizing a CV system is generally a profitable choice. However, building maintenance staff is typically limited to just one method of determining the potential for rightsizing: measuring fan-system static pressure.

Measure the main supply fan system static pressure on a hot, humid day. Make sure that all fan vanes and dampers are fully open. If the measured static pressure is greater than the design pressure (found in building mechanical drawings), the fan is probably supplying too much air and is a good candidate for rightsizing.

Three ways to rightsize. If analysis indicates that a supply fan is oversized, considerable energy can be saved by rightsizing the fan in one of three ways:

- *Larger pulleys.* Replacing an existing belt-driven pulley with a larger one will reduce its speed, and since fan power is proportional to the cube of speed, even small speed reductions can reduce energy costs appreciably. The new pulley should operate the fan at a reduced speed that still matches peak load requirements.
- *Static pressure adjustment (VAV systems only).* Reducing static pressure in a VAV system reduces the fan horsepower consumption. By gradually reducing the static pressure setpoint to a level low enough to keep occupants comfortable, fan speed will be reduced, thereby reducing energy consumption.
- *Smaller, premium-efficiency motors.* Once the fan flow rate has been properly adjusted, the existing motor will probably be larger than necessary. Replace the existing, oversized motor with a smaller, premium-efficiency motor that matches the load. For example, rightsizing a 75-hp standard-efficiency motor to a 50-hp premium-efficiency motor could reduce motor energy consumption by about 33 percent. Some premium-efficiency motors operate at slightly higher speeds than the motors they replace. Because a fan's power consumption increases in proportion to the cube of its speed, it is important to compare the nameplate speed of the existing motor with its premium-efficiency replacement. See the Pick Premium-Efficiency Motors section.

Estimating potential savings. The expected benefits of rightsizing can be estimated using a commercially available fan analysis software program. The U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy has collected information about several such packages (www.eere.energy.gov/buildings/tools_directory/subjects.cfm/pagename=subjects/pagename_menu=materials_components/pagename_submenu=hvac_systems). This software generally requires information about the existing fan system such as:

- Operating schedule
- Type of flow control
- Duty cycle
- Motor horsepower and efficiency
- Peak flow rate
- Peak cooling coil load

Install Variable-Speed Drives

Variable-speed drives are an efficient and economical retrofit option that should be considered for all VAV systems. VSDs allow the motor speed to vary depending on actual operating conditions, rather than operating continuously at full speed. Varying a fan's speed allows it to match changing load requirements more closely, and because fan power draw is proportional to the cube of its speed, reducing speed can save a lot of energy. For example, reducing a fan's speed by 20 percent can reduce its energy requirements by nearly 50 percent (**Figure 8.5**). Installing a VSD on the fan motor allows the fan to automatically match this reduced capacity, slowing down in response to reduced demand, thereby saving energy.

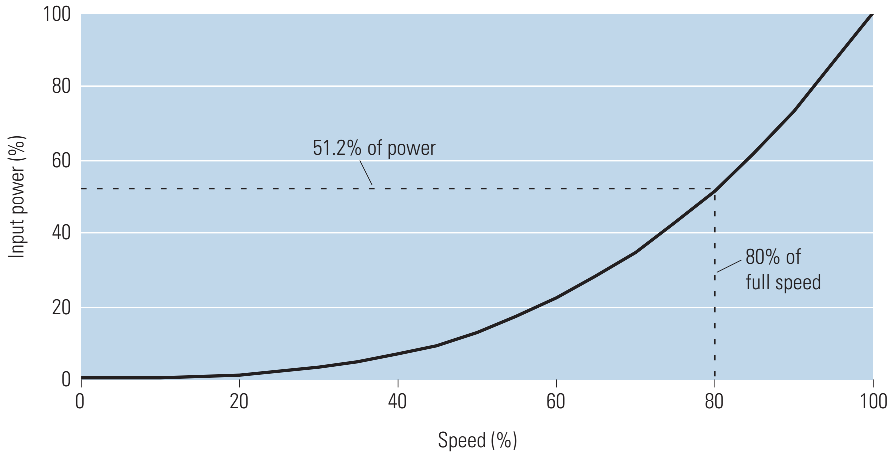
CASE STUDY: Big Savings from a VAV System Retrofit

A retrofit to the 12-story City Hall in Phoenix, Arizona, demonstrates the savings achievable by matching fan power to cooling and heating load. The building originally had a constant-volume, dual-duct system with cold deck temperature reset, supplied by four 60-hp supply-air fans and two 50-hp return-air fans. Pre-retrofit, the fan energy consumption was over 2.2 million kilowatt-hours per year. Analysis of the building's loads showed that the fans were considerably oversized, moving a constant 220,000 cubic feet per minute when the peak load actually called for only 130,000 cfm. On this basis, two of the supply fans and both return fans were disconnected, resulting in an immediate savings of over 50 percent. A bypass duct was installed around each of the disabled return fans, eliminating substantial friction losses.

The remaining two fans were converted to variable air volume by installing variable-speed drives controlled by static pressure sensors in the ducts. The interior zone dual-duct boxes were converted to VAV boxes by sealing off the connection from the hot deck and connecting a new pneumatic actuator to the cold deck damper that was operated by a zone thermostat. The new system registered average savings of 70 percent compared to constant-volume operation, with a maximum demand reduction of 78 percent. Complaints of discomfort also decreased. Based on a conservative estimate of 50 percent average annual VAV savings, the $90,000 project saved 1.7 million kWh, worth over $135,000 per year, resulting in a payback of about eight months.

Figure 8.5: Fan power input versus speed

The load on a fan motor increases as the cube of its speed. Therefore, using a variable-speed drive (VSD) to reduce speed to 80 percent of full speed reduces power consumption to just $(0.8)^3$, or 51.2 percent of its original load level. The VSD itself does consume some power, so careful assessment is necessary for any application where average fan speed will exceed 90 percent of full speed.



Courtesy: E SOURCE

A VSD is not a motor; it is an electronic device that varies the speed of a motor by changing the frequency of the electrical power between 0 and 60 Hertz. The EPA study "Variable Air Volume Systems Maximize Energy Efficiency and Profits" showed that VSDs can greatly reduce the energy used by the same fan operating under similar airflow volumes and static pressure conditions. Overall, the study indicated that VSDs provided an average energy savings of 52 percent.

VSDs make economic sense when installed on motors that operate many hours per year at fluctuating loads, and especially on larger motors. **Table 8.2** presents representative installed costs for VSDs of various sizes.

Modify Controls

Modifying the way the distribution system operates, not just the system itself or its components, can also save energy.

Optimized scheduling. An optimum start-and-stop procedure is a common-sense control philosophy that can result in significant energy savings. Normally, a system is set to automatically turn itself on and off based upon the expected occupant working hours. For example, a building's cooling system might come on at 6:00 a.m. and shut off at 7:00 p.m. Adjusting these times for varying seasons will reduce energy costs. In the spring and fall seasons, when cooling is required but the peak temperatures are typically lower than the summer peak temperatures, the system can be set to come on later in the morning and shut off earlier in the day. Of course, the system can also be shut down if the building is unoccupied.

Supply-air temperature reset. Most cooling coils are designed to deliver 53° to 55°F air to satisfy cooling requirements on the hottest day of the year. During periods of milder weather, this temperature can be automatically reset upward to improve system efficiency by reducing wasteful reheating of already cooled air. Supply-air temperature reset can be accomplished in a few different ways.

Table 8.2: Installed costs of VSDs for various size motors

Installed costs for variable-speed drives range from approximately $2,500 for a 5-horsepower (hp) drive to $16,000 for a 100-hp drive. Note that the price per horsepower declines dramatically as power capacity increases.

Motor hp	Installed cost ($)	Price per hp ($)
5.0	2,475	495
7.5	2,950	393
10.0	2,950	295
15.0	3,675	245
20.0	4,900	245
25.0	5,875	235
30.0	6,825	228
40.0	9,275	232
50.0	10,400	208
60.0	11,800	197
75.0	15,200	203
100.0	15,800	158

Courtesy: E SOURCE; data from R.S. Means Electrical Cost Data, 2007 edition

The most common reset strategy is to implement a simple proportional reset based on the outside air temperature; on a hot day, the supply-air temperature (SAT) is set to its design (or original) value, and when the weather is cooler, the SAT is increased. This is usually specified in a table that lists two outside temperatures and the corresponding SAT. For example, at 95°F outside temperature, the SAT is set to 53°F; at 65°F outside temperature the SAT is set at 68°F. The SAT is then reset proportionally between these two points. With a proportional reset system, building operating staff will often provide better comfort if they "tune" the reset parameters based on observed performance. Some buildings will require a colder SAT on mild days due to higher internal loads (people, lights, office equipment) or due to higher solar gain through windows. Conversely, buildings with efficient lighting systems and high-performance glazing may achieve good comfort with a warmer SAT at the same outside conditions.

For HVAC systems that include digital controls at the zone level, it is also possible to reset the SAT based on the "worst-case zone" approach. Under this scenario, the SAT setpoint is reset so that the zone with the greatest cooling requirement has its zone damper fully opened to provide 100 percent flow. All other zones, which have lower cooling requirements, will automatically adjust the VAV damper to maintain comfort.

For VAV systems, particularly those with VSDs installed, it is important to consider the impact of SAT reset on fan power; if the SAT is reset too high, then the energy saved due to reduced reheat will be overshadowed by increased fan power requirements.

Pressure reset. Pressure reset is a method that can yield additional energy savings in systems that have VSDs installed. Pressure and flow are related. Reducing the pressure supplied by fans also reduces the flow supplied, which in turn reduces the power required. By reducing the duct pressure by 30 percent when less air is required, almost instantaneous fan energy savings of more than 50 percent can be achieved above and beyond the application of a VSD. The desired setpoint can be found by gradually reducing the fan speed each day until the pressure is as low as possible but occupant space is still comfortable. It is possible to have two or more pressure settings; for example, one for daytime and one for evening or one for summer and one for winter. With HVAC systems that include digital zone controls, it is also possible to implement a static pressure reset based on the worst-case zone approach described above for supply-air temperature reset. The strategy is the same: The static pressure setpoint is reset so that the zone damper in the worst-case zone is fully open. Keep in mind that, if both temperature and pressure resets are to be implemented simultaneously, some thought must be given to how these savings measures will interact.

CASE STUDY: Air Distribution System Upgrade Saves Energy, Boosts Comfort

The building known as 600 B Street is a 24-story, 334,000-square-foot, Class A commercial office facility located in San Diego. The 25-year-old high-rise facility had unreliable cooling equipment, high operating and maintenance costs, and substantial numbers of tenant complaints.

Prior to the energy-efficiency implementation, the fan systems could not provide adequate comfort on hot, humid days. The variable air volume dampers would open fully in an attempt to satisfy the space-conditioning requirements. But as the chiller plant and air-handling systems reached their capacity limits, the supply-air temperature would climb too high and the system static pressure would be too low, blowing large quantities of air that was too warm and humid to provide the required cooling effect. As a result of these problems with static pressure control, the system was drafty on hot days and noisy on cold days. Variable-speed drives were installed on the supply fans to gain energy savings and quiet the system during low-load operation, reducing tenant complaints.

To allow faster resetting of the HVAC system variables and to maximize the potential for savings, 25 percent of the VAV terminal controllers in the building were switched from pneumatic control to digital (electronic) zone-terminal control and the information from the zones was used to reset the static pressure setpoint for the air-handling units and the supply-air temperature setpoint. Ideally, all of the VAV terminal controllers would have been replaced, but the cost of doing so would have been high. The digital system is configured to reset static pressure and supply-air temperature continually based on the loads being served.

After a two-year period of measurement and verification, it was determined that fan energy was reduced by 73 percent. The 800,000 kilowatt-hours per year in electrical savings equates to about $120,000 per year in energy cost savings, resulting in a very cost-effective retrofit. Including the incentives offered by the local utility, the energy retrofit project (which included chiller plant measures in addition to the modifications to the air system) paid for itself within about three months. The indoor air quality has also improved dramatically, resulting in an 85 percent drop in tenant complaints.

As a result of the project's documented level of energy efficiency and its positive effect on occupant thermal comfort, the project was honored by ASHRAE for both the San Diego Chapter and the Western Region.

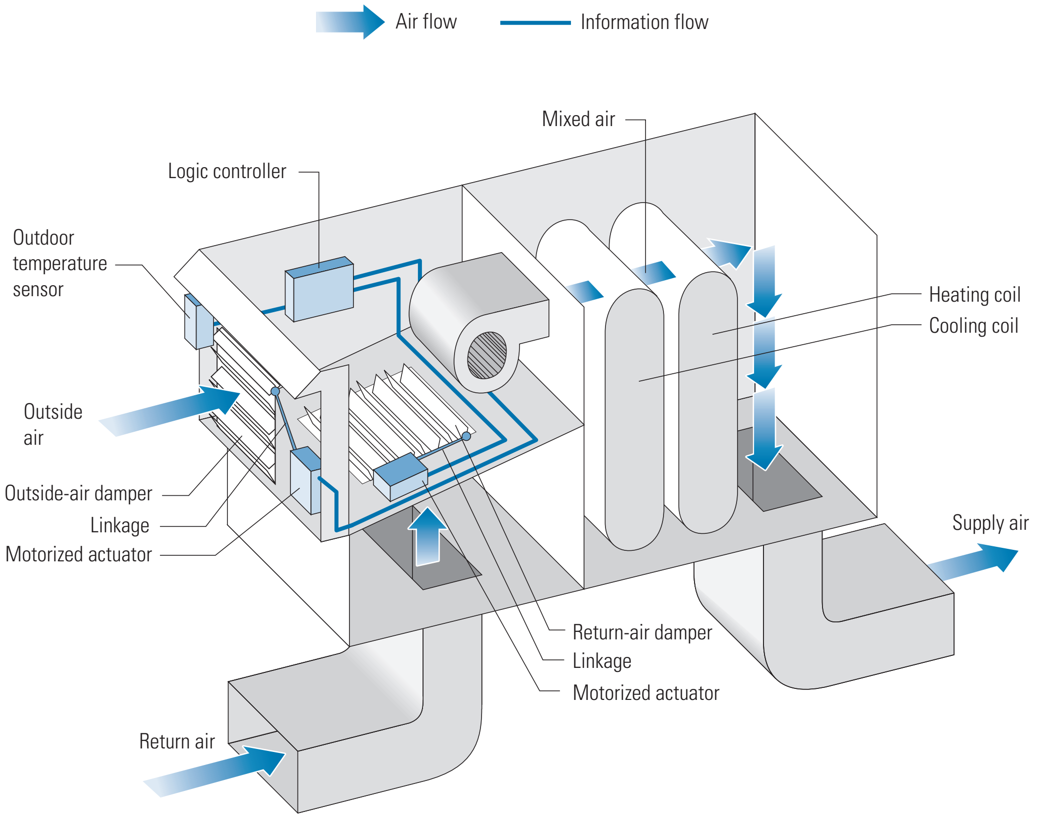
Economizer cooling. Air-side economizers consist of a collection of dampers, sensors, actuators, and logic devices on the supply-air side of the air-handling system (**Figure 8.6**). The outside-air damper is controlled so that when the outside air temperature is below a predefined setpoint, the outside-air damper opens, allowing more air to be drawn into the building. On hot days, the economizer damper closes to its lowest setting, which is the minimum amount of fresh air required by the local building code.

All economizers are not created equal. The simplest and most common type is the basic dry-bulb economizer that controls the outside-air damper based on a specified temperature setpoint. An enhancement to this approach is an enthalpy (or total energy content) economizer, which accounts for both the temperature and the humidity of the outside air and can improve the energy savings associated with the economizer by not cooling with outside air under high-humidity conditions. One of the most advanced economizer control strategies available today is a differential enthalpy system, in which two enthalpy sensors are installed (one for the outside air and the other for the return air). Under the differential control strategy, the system preferentially uses whichever air source (outside or return) has lower enthalpy when there is a need for cooling.

When the outside temperature and humidity are mild, economizers save energy by cooling buildings with outside air rather than using refrigeration equipment to cool recirculated air. A properly operating economizer can cut energy costs by as much as 10 percent of a building's

Figure 8.6: The components of an economizer

When the air outside is cooler than the return air and sufficiently dry, economizers cool buildings by bringing in outside air, thereby reducing the load on the compressor.



Courtesy: E SOURCE

total energy consumption (up to 20 percent in mild, coastal climates), depending mostly on local climate and internal cooling loads.

Economizer commissioning and maintenance are vital to proper operation and energy savings. A large number of newly installed economizers do not work properly, and their problems increase as they age. To make matters worse, malfunctioning economizers often waste much more energy than they were intended to save. If an economizer breaks down when its damper is wide open, peak loads can shoot up as cooling or heating systems try to compensate for the excess air entering the building. A computer simulation of an office building in arid Phoenix, Arizona, shows that a damper permanently stuck in the wide-open position could add as much as 80 percent to that building's summer peak load, assuming the building had enough cooling capacity to meet the much higher load resulting from cooling excessive outside air.

Demand-controlled ventilation. Many building codes in the United States base their ventilation requirements on a standard written by ASHRAE that requires that commercial buildings bring in a specified minimum amount of fresh air to ensure adequate indoor air quality. To adhere to this standard, the choice made in most buildings is to ventilate at the fixed minimum rate per person based on the building type and the assumed occupancy, which is usually the building's design occupancy. But because the number of people occupying the space at any given time can vary widely, the ASHRAE standard offers another way to ventilate based on actual occupancy numbers. This is called demand-controlled ventilation (DCV).

Because the average amount of carbon dioxide (CO_2) exhaled by a person in a fixed time period at a given activity level is well known, the concentration of CO_2 in the air inside a building is a good indicator of the number of people in a space and the rate at which the air in the space is being diluted with outside air. The more occupants a building has at any given time, the higher the level of CO_2 in the air. The ASHRAE standard allows building operators to use DCV to bring in and condition only the air necessary for the actual occupancy. In a DCV system, sensors monitor the CO_2 levels inside and send a signal to the HVAC controls, which regulate the amount of outside ventilation air that is drawn into the building. Though ASHRAE does not set a maximum allowable CO_2 concentration, the most recent version of the standard recommends that the indoor CO_2 level be no more than 700 parts per million (ppm) above the outside level, which is typically about 350 ppm.

CASE STUDY: Power Exhausts Cut Cooling Costs

The majority of conventional air-handling units are able to provide 100 percent outside air. However, at one 200,000-square-foot office building in a Boston suburb, it was noticed that air-conditioning compressors in the rooftop units operated on all sunny days, even when outside air temperature was as low as 35° Fahrenheit. The reason was that solar-heated interior air had no way to escape from the building, so even with outside air dampers wide open, the rooftop units could not provide enough outside air to cool the building without the aid of mechanical refrigeration.

The solution was to install power exhausts in the rooftop units that exhausted all indoor air when the building was in economizer cooling mode. Roughly 1,000 hours per year were found to have proper conditions for free cooling. After the installation of the power exhausts, cooling compressors only operated when the outside air temperature was above 55°F. The installation cost $75,000 and paid for itself in under four years.

DCV systems save energy by reducing the need to heat or cool outside air. The only system change is the ratio of recirculated air to outside air; fan power is usually unaffected. DCV systems can save from $0.05 to $1.00 per square foot, depending on the occupancy schedule and climate (see sidebar).

The overall cost for implementing DCV has dropped substantially in recent years, opening up new opportunities for savings and spurring changes in some building codes. Also, several HVAC equipment manufacturers now offer DCV-ready rooftop units and variable air volume (VAV) boxes. This equipment is shipped with terminals for the CO_2 sensor wires and controls that are preprogrammed to implement a DCV strategy. By limiting installation costs to the cost of mounting the sensor and running wires to the rooftop unit or VAV box (wireless models are also available), DCV-ready HVAC equipment substantially reduces the cost of implementing DCV.

Facilities that would likely reap energy savings with the use of DCV tend to have long operating hours, widely varying and largely unpredictable occupancy levels, and at least moderate annual heating or cooling loads. A large number of facilities meet this description, including grocery stores, supermarkets, big-box stores, theaters and other performance spaces, lecture halls, places of worship, sports arenas, restaurants and bars of all types, and department stores. In fact, the majority of commercial facilities that are not now using DCV are at least potential targets for the technology.

Care must be applied when planning a DCV retrofit to ensure that adequate air quality is maintained. Of paramount concern are the location and quantity of CO_2 sensors. Although it might be tempting to install a single CO_2 sensor in the return-air duct for the entire building, this could lead to situations where the average CO_2 level is acceptable but the level in specific, highly occupied spaces (such as a packed conference room) is too high. For this reason, it is typically more effective to install CO_2 sensors in each high-occupant-density or high-diversity space and use them to command the minimum position of the VAV box.

Many energy codes that permit DCV also have required minimum ventilation and airflow rates (such as 0.15 cfm per square foot). Be sure to confirm local requirements before committing to a project.

A study conducted in 2003 at Purdue University shows favorable paybacks for DCV in a variety of buildings. The study investigated four types of buildings—a restaurant, a retail store, a

RESOURCES: Demand-Controlled Ventilation Design Tools

Several free tools are available to evaluate potential energy savings from demand-controlled ventilation:

- Carrier provides the Hourly Analysis Program (www.commercial.carrier.com/commercial/hvac/general/1,,CLI1_DIV12_ETI496,00.html?SMSESSION=NO).
- Honeywell has the Savings Estimator (http://customer.honeywell.com/Business/Cultures/en-US/Products/Applications+and+Downloads/Economizer+Logic+Module+(W7212)+Simulator+and+Demand+Control+Ventilation+Savings-Estimator.htm).
- AirTest offers a spreadsheet-based demand-controlled ventilation savings analyzer (https://www.airtesttechnologies.com/support/software/index.html).

school, and an office—in each of two cities in California and three cities outside the state. Total energy savings ranged from 6.4 to over 50 percent, and payback periods ranged from 0.25 to 6.8 years, though paybacks were well under two years for most of the modeled facilities.

Keep in mind that CO_2 concentration rates do not indicate the levels of other potential air contaminants contained within the space. If a facility contains significant nonhuman sources of contaminants (such as materials or products containing volatile organic compounds), additional ventilation may be required to provide acceptable indoor air quality. This makes warehouses, kitchens, dry cleaners, and many types of industrial facilities poor candidates for DCV. Consult local building codes for proper ventilation rates.

Pick Premium-Efficiency Motors

All new motors installed in HVAC applications have been required to meet minimum federal energy-efficiency standards since October 1997. The motors that drive older HVAC systems are likely to be inefficient by today's standards, and even newer systems that meet the current federal motor efficiency standards can be made more efficient. Motors that perform to the National Electrical Manufacturers Association's NEMA Premium (NP) specification (see **Table 8.3**) can yield highly cost-effective energy savings in HVAC applications because these applications tend to have long running hours.

Table 8.3: Premium versus standard efficiencies of totally enclosed, fan-cooled motors

NEMA Premium motors often exceed the efficiencies of standard-efficiency motors by 1.5 to 2 percent. Although that may not seem like much, given their very long running hours in HVAC applications, it is often quite easy to justify the higher cost of premium-efficiency motors based on energy savings alone, particularly if the local utility offers a rebate.

	Efficiency (%)					
	3,600 rpm		1,800 rpm		1,200 rpm	
Motor horsepower	Standard	NEMA Premium	Standard	NEMA Premium	Standard	NEMA Premium
1.0	75.5	77.0	82.5	85.5	80.0	82.5
1.5	82.5	84.0	84.0	86.5	85.5	87.5
2.0	84.0	85.5	84.0	86.5	86.5	88.5
3.0	85.5	86.5	87.5	89.5	87.5	89.5
5.0	87.5	88.5	87.5	89.5	87.5	89.5
7.5	88.5	89.5	89.5	91.7	89.5	91.0
10.0	89.5	90.2	89.5	91.7	89.5	91.0
15.0	90.2	91.0	91.0	92.4	90.2	91.7
20.0	90.2	91.0	91.0	93.0	90.2	91.7
25.0	91.0	91.7	92.4	93.6	91.7	93.0
30.0	91.0	91.7	92.4	93.6	91.7	93.0
40.0	91.7	92.4	93.0	94.1	93.0	94.1
50.0	92.4	93.0	93.0	94.5	93.0	94.1
60.0	93.0	93.6	93.6	95.0	93.6	94.5
75.0	93.0	93.6	94.1	95.4	93.6	94.5
100.0	93.6	94.1	94.5	95.4	94.1	95.0

Courtesy: E SOURCE; data from NEMA and U.S. Department of Energy

After completing the building upgrade stages described earlier in this manual, building heating and cooling loads are likely to have been reduced, allowing for the installation of smaller motors that better match the reduced power requirements. Although NP motors also often come with a price premium, the cost of a smaller, premium-efficiency motor will often be less than that of a standard-efficiency motor of the same size as the existing motor, making the premium-efficiency motor an easy choice. Also, many utilities offer rebates on the purchase of NP motors that are designed to cover all or a portion of the price premium.

The DOE offers a free software application called MotorMaster that is an excellent tool for evaluating the economics of alternative motor choices. The software comes with a frequently updated database of commercially available motors and allows the user to compare the initial and lifecycle cost implications of replacing an existing motor with a standard- or premium-efficiency motor. MotorMaster can be downloaded from www1.eere.energy.gov/industry/bestpractices/software.html#mm.

Here are a few additional issues to consider when evaluating HVAC motors.

Motor speed. Some premium-efficiency motors operate at higher speeds. All induction motors have a synchronous speed (the speed at which the magnetic field within the motor is rotating) and a full-load speed (the speed at which the motor shaft rotates when the motor is providing full-load torque or power). A motor's full-load speed will always be less than its synchronous speed by a few percent. The difference between synchronous and full-load speed is called slip.

The exact amount of slip a motor has depends on its design, construction, and loading. Be aware that premium-efficiency motors tend to have lower slip, which means that their full-load speed tends to be higher than that of less-efficient models. As noted earlier, the power a fan requires to move air varies by the cube of its speed, so power draw and energy consumption are very sensitive to motor speed. In air-circulation systems that are not controlled by a VSD, it is therefore conceivable that replacing an existing motor with a NP motor could actually result in greater energy consumption, even though the new motor operates at higher efficiency. Therefore, when selecting a premium-efficiency motor, it is important to compare its rated full-load speed to that of the motor it will replace. If necessary, the fan's speed can be reduced by increasing the diameter of its pulley.

Voltage balance. Three-phase induction motors (that is, motors that draw power from three phase conductors) are designed, specified, and rated by their manufacturers on the assumption that exactly the same voltage will be fed to each phase and that equal current will therefore flow through the coils connected to each phase, generating a uniform magnetic field from each pole pair. When this voltage is not balanced, however, significant harm can come to the motor, including reduced performance, increased heat, shortened life, and dramatically reduced efficiency. Phase unbalance dramatically increases the heat generated within a motor. That increase then feeds upon itself, because hotter windings have higher resistance, pushing up losses further. Just a 3.5 percent unbalance can increase total motor losses by 20 to 25 percent, which is equivalent to bringing the efficiency of a 90 percent efficient motor down to 87.5 to 88 percent.

Unbalance is defined by NEMA as 100 times the maximum deviation from the average of the voltages on the three phases, divided by that average voltage. For example, if the phase voltages measured at a motor's terminals are 465, 470, and 473 volts, the average voltage is 469.3 and the maximum deviation is 4.3 volts. The unbalance, then, is 4.3/469.3 = 0.9 percent. A well-balanced system should have voltage unbalance of less than 1 percent. If voltage unbalance is greater than 1 percent, evaluate the loading on each phase. The unbalanced phase may be carrying significantly more or less load than the others, in which case rebalancing the loads across the phases will also rebalance phase voltages.

Shaft alignment. In typical fan-system configurations, the motor and the fan each have shafts that are connected with a belt or belts and two pulleys. If the pulley faces are not square with each other, then the belt and shafts are not in alignment. Improperly aligned shafts can not only result in poor efficiency and higher operating costs, but also can lead to premature failure and increased maintenance costs. Whenever a motor is replaced or rewound, be sure to pay close attention to the shaft alignment.

Use Energy-Efficient Belt Drives

Belts are often used to transfer power from the motor to the fan system being driven. Standard V-belt drives can be found in the majority of belt applications. They are the lowest-cost option of the belt family. The trade-off, as usual, is reduced energy efficiency. New V-belts typically achieve efficiencies in the 90 to 95 percent range. A worn belt, however, can considerably reduce the efficiency by slippage caused by slackening and worn grip surfaces. Cogged V-belts are similar to standard V-belts, except that the normally flat underside has longitudinal grooves in it, allowing better grip and less slip than standard V-belts. They typically offer a 2 to 5 percent efficiency bonus.

Less commonly found synchronous belts combine toothed belts with grooved sprockets. The belts are called "synchronous" because both sprockets rotate in exact synchrony, eliminating losses from slippage and creep and significantly reducing maintenance because the nonstretch belt does not need retensioning. These belts transmit power by engaging teeth rather than tension-induced friction, so they operate much more efficiently than V-belts, achieving efficiencies in the range of 97 percent to 99 percent.

A potential downside to synchronous belts is that by reducing slippage, they will actually increase the speed of the fan, which will result in more airflow, but it will also require more power from the motor. For example, reducing belt slip on a constant-volume centrifugal fan by 3 percent will result in a corresponding 3 percent increase in rotational speed for the fan wheel and an increase in the volume of air that is delivered. Because such a fan has a cubic relationship between airflow and horsepower, however, the horsepower required to drive the fan will increase by $(1.03)^3$, or 1.093—a 9.3 percent increase from the previous requirements. So the building owner who wants energy savings may instead be getting increased airflow and increased energy use (and possibly an overheated fan motor) if the proper precautions are not taken. Retrofits from V-belts to synchronous belts should be coordinated with the replacement of standard-efficiency motors with properly sized premium-efficiency motors. Doing both retrofits together reduces total labor costs and offers an opportunity to correct for any changes in speed from the new motor or belts at zero marginal cost. Additionally, when selecting synchronous belts it is important to follow manufacturer guidelines for sizing and tensioning the belts to ensure quiet, trouble-free operation.

V-belts should be a standard replacement part in every building's maintenance program, requiring replacement every few months. Energy-efficient synchronous belts can easily be incorporated into a standard maintenance program, and the savings generated greatly outweigh the slight increase in cost per belt.

Consider a Testing, Adjusting, and Balancing Contractor

The modifications outlined above are likely to alter the operating characteristics of a building's HVAC system. Normally, the engineer or contractor who performed the work will be responsible for what is called the testing, adjusting, and balancing (TAB) of the modified or new system. TAB involves measuring and analyzing the various flows of air, chilled water, hot water, steam, etc., and ensuring that distribution of heating and cooling throughout the building meets the required specifications as outlined in the contract documents. Independent TAB contractors serve as an unbiased third party to ensure accuracy of the TAB measurements and are worth retaining if further oversight is desired. To find a qualified TAB firm, look for a firm that is certified by a recognized national professional society such as the Associated Air Balance Council. In addition, confirm that the TAB firm has experience with balancing systems in the type of facility in question (such as office, university building, or laboratory). Finally, ask for references.

8.5 Summary

This chapter illustrates the many options that are available to optimize constant-volume and variable air volume air distribution systems. Some of the strategies to remember are:

- Address zone-level opportunities first.
- Consider converting a CV system to VAV.
- Rightsize fan system to match actual loads.
- Install VSDs where practical.
- Consider improved controls to optimize scheduling and to implement temperature or pressure reset, economizer cooling, and demand-controlled ventilation.
- Install rightsized, premium-efficiency motors where possible.
- Install energy-efficient belts.

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