Related Commercial Resources

CHAPTER 8. EDUCATIONAL FACILITIES

THIS chapter contains technical, environmental, and design considerations to assist the design engineer in the proper application of heating, ventilation, and air-conditioning systems and equipment for educational facilities.

1. PRESCHOOLS

General Design Considerations

Commercially operated preschools are generally provided with standard architectural layouts based on owner-furnished designs. A typical preschool facility provides programs for preschoolers (typically 3 to 5 years old) for whom learning pre-academic skills is the main objective. These programs focus on preparing students for development in future years. Larger facilities also offer programs for older children, such as kindergarten programs (5 years old). Areas such as lobbies, libraries, and kitchens are also included to support the variety of programs. Given this range of age, special attention for the design of the HVAC systems is required to meet the needs of every age group.

All preschool facilities require quiet and economical systems. The equipment should be easy to operate and maintain, and the design should provide warm floors and no drafts. These facilities have two distinct occupant zones: (1) the floor level, where younger children play, and (2) normal adult height, for the teachers. The teacher also requires a place for a desk; consider treating this area as a separate zone.

Preschool facilities can operate on weekdays from early in the morning to evening (6:00 or 7:00 pm). This schedule can coincide with the normal working hours of the children's parents, plus one hour for drop-off and pick-up. The HVAC systems therefore operate 12 to 14 h per workday, and may be off or on at night and weekends, depending on whether setback is applied.

Supply air outlets should be positioned so that the floor area is maintained at about 24°C without introducing drafts. Both supply and return air outlets should be placed where they will not be blocked by furniture positioned along the walls or within reach of children. Coordination with the architect on location of these outlets is essential. Proper ventilation is crucial for controlling odors and helping prevent the spread of diseases among the children.

Floor-mounted heating equipment, such as electric baseboards heaters, should be avoided because children must be prevented from coming in contact with hot surfaces or electrical devices. However, radiant-floor systems can be used safely and effectively. Other floor-standing devices (e.g., humidifiers, in-room air cleaners) should be avoided.

Table 1 Recommended Temperature and Humidity Design Criteria for Various Spaces in Preschools

Category/Humidity Criteria	Indoor Design Conditions, °C Winter	Indoor Design Conditions, °C Summer
Preschooler classrooms[a]		
30[d] to 60% rh	21.9 to 25.0	23.9 to 25.0
Administrative, offices, lobby, kitchen[b]		
30[d] to 60% rh	21.9 to 25.0	23.9 to 26.1
Storage		
No humidity control	17.8	
Mechanical rooms[c]		
No humidity control	16.1	

Notes:

[a] Calculations based on Tartarini et al. (2020) for students/children wearing typical Western summer and winter clothing, 0.4 and 0.75 clo, respectively, and activity of 1.2 met. Air speed assumed at 0.1 m/s and mean radiant temperature (MRT) assumed equal to air temperature. Temperature range is within acceptable ASHRAE *Standard* 55 range (–0.5 < Predicted mean vote [PMV] < +0.5).

[b] Calculations based on Tartarini et al. (2020) for adults wearing typical Western summer and winter clothing, 0.7 and 1.0 clo, respectively, and activity of 1.0 met. Air speed assumed at 0.1 m/s and mean radiant temperature (MRT) assumed equal to air temperature. Temperature range is within acceptable ASHRAE *Standard* 55 range (–0.5 < PMV < +0.5).

[c] Usually not conditioned.

[d] Considerations such as geographical location, building envelope, and other constraints should be evaluated and discussed with the owner to determine different minimum design relative humidity.

Design Criteria

Table 1 provides a typical range of indoor design conditions for preschools. The text addressing K-12 facilities expands on the data shown in the table; thermal comfort models or data were not found for this age range (3 to 5 years), and the information shown in Table 1 should be used as a guide.

Table 2 provides typical ventilation and exhaust design criteria using the ventilation rate procedure of ASHRAE *Standard* 62.1-2019. Table 3 lists design criteria for acceptable noise in preschool facilities.

Table 2 Minimum Design Criteria for Ventilation and Filtration for Preschools

	Ventilation and Exhaust[a, f, i]				
			Outdoor Air		
Category	**Outdoor Air, L/s per Person**	**Occupant Density[k] per 100 m^2**	**$L/(s \cdot m^2)$**	**L/s per Unit**	**Minimum Filtration Efficiency, MERV[g]**
Preschooler classrooms	5	25	0.9		13[k]
Administrative and office space[b]	5	5	0.3		13[k]
Kitchen[c]			1.5 (exhaust)		[h]
Toilets[d]				35 (exhaust)	NA
Storage[e]	2.5	2	0.3		1 to 4

[j]

Notes:

[a] Based on ASHRAE *Standard 62.1-2019, Table 6.1, default values for ventilation, and Table 6.2 for exhaust rates.*

[b] Based on ASHRAE *Standard* 62.1-2019, Table 6.1, default values for office buildings/ office spaces.

[c] Based on ASHRAE *Standard* 62.1-2019, Table 6.2, for kitchenettes.

[d] Based on ASHRAE *Standard* 62.1-2019, Table 6.2, for private toilets (rate is for toilet room intended to be occupied by one person).

[e] Based on ASHRAE *Standard* 62.1-2019, Table 6.1, for storage rooms.

[f] This table should not be used as the only source for design criteria. Governing local codes, design guidelines, and ASHRAE *Standard 62.1-2019 with current addenda must be consulted. Additional factors such as zone air distribution effectiveness should be applied to determine zone outdoor airflow.*

[g] MERV = minimum efficiency reporting values, based on ASHRAE *Standard* 52.2-2017.

[h] See Chapter 31 for additional information on kitchen ventilation.

[i] Consult local codes for exhaust requirements.

[j] Use default occupancy density when actual occupant density is not known.

[k] NAFA 2012. For new installations it is recommended to take into account filter efficiency losses per ASHRAE *Standard* 52.2-2017, Appendix J, and use MERV-A ratings. This recommendation also applies to existing installations, when possible. See www.ashrae.org/technical-resources/filtration-and-disinfection-faq.

Load Characteristics

Preschool cooling and heating loads depend heavily on ambient conditions, because the rooms typically have exterior exposures (walls, windows, and roofs) and relatively higher needs for ventilation. Although preschool facilities are relatively small, the design engineer must pay special attention to properly calculate the cooling, heating, dehumidification, and humidification loads. Sizing and applying the HVAC equipment is critical for handling the loads and the large amounts of outdoor air from a capacity and occurrence standpoint (peak sensible and latent loads do not always coincide).

Humidity Control

Preschool classrooms require humidity control to provide comfort and prevent health problems. Maintaining relative humidity (rh) levels between 30 and 60% satisfies nearly all people nearly all the time. Note, though, that considerations such as geographical location, weather, building envelope, and other constraints should be carefully evaluated and discussed with the owner to determine minimum relative humidity and comfort expectations, to avoid misunderstandings.

In hot and humid climates, it is recommended that air conditioning and/or dehumidification be operated year-round to prevent growth of mold and mildew. Dehumidification can be improved by adding optional condenser heat/reheat coils, heat pipes, or air-to-air heat exchangers in conjunction with humidity sensors in the conditioned space or return air.

Additional information on humidity control is in the section on K-12 Schools.

Systems and Equipment Selection

HVAC systems for preschools are typically decentralized, using either self-contained or split air-conditioners or heat pumps (typically air- or water-source). When the preschool is part of a larger facility, utilities such as chilled water, hot water, or steam from a central plant can be used. When natural gas is available, the heating system can be a gas-fired furnace, or, when economically justifiable, electric heat can be used.

Table 3 Typical Recommended Design Guidelines for HVAC- Related Background Sound for Preschool Facilities

	Sound Criteria[a, b, c]		
Category	**NC/RC**	**dBa**	**Comments**
Preschooler classrooms	30	35	
Administrative/office areas	40	45	For open-plan office
Service/support areas	35 to 45	40 to 45	
[c]			

Notes:

[a] Based on Chapter 49, Table 1. That table provides additional design guidelines for HVAC-related background sound in rooms.

[b] RC (Room Criterion), from Chapter 8 of the 2021 *ASHRAE Handbook—Fundamentals.*

[c] Approximate overall sound pressure (see Table 1 in Chapter 49).

The type of HVAC equipment selected also depends on the climate and the months of operation. In hot and dry climates, for instance, the primary type of cooling may be evaporative. In colder climates, heating can also be provided by a hot-water hydronic system originating from a boiler plant in conjunction with radiant floor or hot-water coils. For small, decentralized systems without central building control, a zone-level programmable temperature control is recommended (and sometimes required by local code).

Table 4 Applicability of Systems to Typical Areas[d]

	Decentralized Cooling/Heating Systems[c]				Heating Only
Typical Area	**PSZ/SZ Split/VRF[e]**	**PSZ with Energy Recovery and Dehumidification**	**WSHP**	**Geothermal Heat Pump**	**Radiant Floor[b]**
Classrooms	X[a]	X[a]	X	X	X
Administrative areas, lobby	X		X	X	
Kitchen	X		X	X	
Ventilation (outdoor air)	DOAS		DOAS	DOAS	DOAS

SZ = single zone
VRF = variable refrigerant flow
PSZ = packaged single zone
WSHP = water-source heat pump
DOAS = dedicated outdoor air system

Notes:

[a] PSZ for classrooms requires individual thermostatic control.

[b] Typically with cooling system such as PSZ/SZ split.

[c] Heating system for PSZ/SZ split can be gas furnace, hot-water coil, or electric.

[d] See Table 10 for additional systems if preschool is not a stand-alone facility.

[e] Special consideration required for risk associated with refrigerant leaks. ASHRAE *Standards* 15 and 34 should be consulted.

Decentralized systems are dedicated systems serving a single zone, and typically include the following:

- Direct-expansion (DX) split systems and variable refrigerant flow (VRF) systems
- Rooftop packaged air conditioners or heat pumps with or without optional enhanced dehumidification (condenser reheat coil)
- Rooftop packaged air conditioners or heat pumps integrated with an energy recovery module, with optional enhanced dehumidification (condenser reheat coil; see Figure 5). Consult ANSI/ASHRAE/IESNA *Standard* 90.1-2019, section 6.5.6.1, for cases with a high percentage of outdoor air.
- Water-source heat pumps (with cooling tower and supplementary boiler)
- Geothermal heat pumps (ground-coupled, ground-water-source, surface-water-source)
- Packaged dedicated outdoor air systems with DX system for cooling and gas-fired furnace, electric heating, or part of water-source and geothermal heat pump system

Information about decentralized systems can be found in Chapters 5, 18, 49, and 50 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment*. Additional information on geothermal heat pumps can be found in Kavanaugh and Rafferty (1997) and Chapter 35 of this volume. Chapter 6 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment* provides information on radiant heating.

Note that some decentralized systems may need additional acoustical modifications to meet the design criteria in Table 3. Therefore, it is strongly recommended to carefully check the acoustical implications of applying these systems.

Table 5 Typical Spaces in K-12 Schools

	School		
Typical Area	**Elementary (K to 5)[a]**	**Middle (6 to 8)[a]**	**High (9 to 12)[a]**
Classrooms	X	X	X
Science	X	X	X
Computer	X	X	X
Laboratories and science facilities		X	X
Administrative areas	X	X	X
Gymnasium	X	X	X
Libraries	X	X	X
Auditorium			X
Home economics room			X
Cafeteria	X	X	X
Kitchen	X	X	X
Auto repair shop[b]			X
Industrial shop			X
Locker rooms		X	X
Ice rink[b]			X
Natatorium[b]			X
School store[b]			X
Nurse/health suite[c]	X	X	X

Notes:

[a] School grades can vary.

[b] These zones are not typical.

[c] See Nurse/Health Suite section in this chapter for detailed information.

Dedicated Outdoor Air Systems (DOASs). Specialized DOASs should be used to treat outdoor air before it is introduced into classrooms or other areas. DOAS units can bring 100% outdoor air to at least space conditions, which allows the individual space units to handle only the space cooling and heating loads. A detailed description of DOAS is provided in the K-12 Schools section of this chapter. Additional information can be found in Chapters 25 and 51 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment* and Chapter 64 of this volume.

Systems Selection by Application. Table 4 shows the applicability of systems to areas in preschool facilities.

2. K-12 SCHOOLS

General and Design Considerations

K (kindergarten)-12 schools typically include kindergarten, elementary, middle (junior high), and high schools. These facilities are typically one- to three-story buildings.

Elementary schools are generally comprised of 10 to 15 classrooms plus cafeteria, administration, gymnasium, and library areas. Elementary schools are usually used during the school season (late August to June); during summer, they are usually closed or have minimal activity. Current trends include science classrooms and a preschool facility. Typical elementary schools operate between 7:00 am and 4:00 pm.

Middle schools are larger than elementary schools and include additional computer classrooms and locker rooms. A recent trend toward eliminating middle schools (retaining traditional K-8 elementary and 9-12 high schools) (Wright 2003) may require that elementary school designs incorporate some middle school features.

High schools also include a cafeteria and auditorium, and may include a natatorium, ice-skating rink, etc. High schools operate longer hours and are often open during the summer, either as a summer school or to use special facilities such as gymnasiums, natatoriums, etc.

Typical areas found in K-12 schools are shown in Table 5.

K-12 schools require an efficiently controlled atmosphere to ensure a proper learning environment. This involves the selection of HVAC systems, equipment, and controls to provide adequate ventilation and indoor air quality (IAQ), comfort, and a quiet atmosphere. The system must also be easily maintained by the facility's maintenance staff.

The following are general design considerations for each of the areas typically found in K-12 schools:

Classrooms. Classrooms typically range between 80 and 100 m^2, and are typically designed for 20 to 30 students. Each classroom should be, at a minimum, heated and ventilated. Air conditioning should be seriously considered for school districts that have year-round classes in warm, humid climates. In humid climates, seriously consider providing dehumidification during summer, even if the school is unoccupied, to prevent mold and mildew.

Science Classrooms. Science rooms are now being provided for elementary schools. Although the children do not usually perform experiments, odors may be generated if the teacher demonstrates an experiment or if animals are kept in the classroom. Under these conditions, adequate ventilation is essential along with an exhaust fan with a local, timer-based (e.g., 0 to 60 min) on/off switch for occasional removal of excessive odors.

Computer Classrooms. These rooms have a high sensible heat load because of the computer equipment. They may require additional cooling equipment such as small spot-cooling units to offset the additional load. Humidification may also be required. See Chapter 20 for additional information.

Educational Laboratories. Middle and high school laboratories and science facilities may require fume hoods with special exhaust systems. A makeup air system may be required if there are several fume hoods in a room. If there are no fume hoods, a room exhaust system is recommended for odor removal, depending on the type of experiments conducted in the room and whether animals are kept there; when applicable, a local exhaust with on/off switch and a timer can be considered. Associated storage and preparation rooms are generally exhausted continuously to remove odors and vapors emanating from stored materials. The amount of exhaust and location of exhaust grilles may be dictated by local codes or National Fire Protection Association (NFPA) standards. See Chapter 17 for further information. Additional information on laboratories can be found in ANSI/AIHA *Standard* Z9.5-2012 and McIntosh et al. (2001).

Administrative Areas. The office area should be set up for individual control because it is usually occupied during and after school hours. Because offices are also occupied before school starts in the fall, air conditioning for the area should be considered or provisions should be allowed for future upgrades.

Gymnasiums. Gyms may be used after regular school hours for evening classes, meetings, and other functions. The gym may also be used on weekends for group activities. Loads for these occasional uses should be considered when selecting and sizing the systems and equipment. Independent gymnasium HVAC systems with control capability allow for flexibility with smaller part-load conditions. If a wooden floor is installed, humidity control should be considered to avoid costly damage. Cramm (2020) provides information on gym design using packaged HVAC equipment and special considerations for equipment sizing, dehumidification, and system layout.

Libraries. Libraries should be air conditioned to preserve the books and materials stored in them. See Chapters 3 and 24 for additional information.

Table 6 Temperature and Humidity Design Ranges for K-12 Schools

	Indoor Design Conditions		
	Temperature, °C		
Category/Humidity Criteria	**Winter**	**Summer**	**Comments**
Classrooms, laboratories, libraries, auditoriums[a, e]			
30 to 60% rh	21.9 to 25.0	23.9 to 25.0	
Administrative, offices[f]			

30 to 60% rh	21.9 to 25	23.9 to 25.0	
Gymnasiums			
30 to 60% rh	20.3 to 23.3	23.3 to 25.8	For gym with wooden floor, 35 to 50% humidity recommended at all times
Shops			
20 to 60% rh	20.3 to 23.3	23.3 to 25.8	
Cafeteria[b]			
20 to 30% (winter), 50% (summer) rh	21.1 to 23.3	25.8	
Kitchen[b]			
No humidity control	21.1 to 23.3	28.9 to 31.1	
Locker/shower rooms			
No humidity control	26.7		Usually not conditioned
Toilets			
No humidity control	22.2		Usually not conditioned
Storage			
No humidity control	17.8		
Mechanical rooms			
No humidity control	16.1		Usually not conditioned
Corridors			
No humidity control	20.0		Frequently not conditioned
Natatorium[c]			
50 to 60% rh	26.7 to 28.9	26.7 to 28.9	Based on recreational pool
Ice rink[d]			
1.7 to 7.2°C dp (maximum)	10.0 (minimum)	18.3 (maximum)	Minimum 5.5 K temperature difference between dew point and dry bulb to prevent fog and condensation

[g]

Notes:

[a] Calculations based on Tartarini et al. (2020), for students/children wearing typical western summer and winter clothing (0.4 and 0.75 clo, respectively) and activity of 1.2 met. Air speed assumed at 0.1 m/s and mean radiant temperature (MRT) assumed equal to air temperature. Temperature range is within acceptable ASHRAE *Standard 55 range (–0.5 < Predicted mean vote < +0.5).*

[b] Based on Chapter 3.

[c] Based on Chapter 5.

[d] Based on Harriman et al. (2001).

[e] For libraries, keep minimum humidity of –1.1°C dp and maximum of 55% rh.

[f] Calculations based on Tartarini et al. (2020) for adults wearing typical western summer and winter clothing (0.7 and 1.0 clo, respectively) and activity of 1.0 met. Air speed assumed at 19.7 fpm and MRT assumed equal to air temperature. Temperature range is within acceptable ASHRAE *Standard* 55 range (–0.5 < Predicted mean vote < +0.5).

[g] Considerations such as geographical location, building envelope, etc., should be evaluated and discussed with building owner to determine minimum design relative humidity.

Auditoriums. These facilities require a quiet atmosphere as well as heating, ventilation, and, in some cases, air conditioning. Auditoriums are not often used, except for assemblies, practice for programs, and special events. For other considerations, see Chapter 5.

Home Economics Rooms. These rooms usually have a high sensible heat load from appliances such as washing machines, dryers, stoves, ovens, and sewing machines. Different options should be considered for exhaust of stoves and dryers. If local codes allow, residential-style range hoods may be installed over the stoves. A central exhaust system could be applied to the dryers as well as to the stoves. If enough appliances are located within the room, a makeup air system may be required. These areas should be maintained at negative pressure in relation to adjacent classrooms and administrative areas. See Chapter 34 for more information.

Cafeteria and Kitchen. Typical schools require space for preparation and serving of meals. A well-designed school cafeteria includes the following areas: loading/receiving, storage, kitchen, serving area, dining area, dishwashing, office, and staff facilities (lockers, lavatories, and toilets). Chapter 34 provides detailed information on design criteria, load characteristics, and design concepts for these facilities.

Auto Repair Shops. These facilities require outdoor air ventilation to remove odors and fumes and to provide makeup air for exhaust systems. The shop is usually heated and ventilated but not air conditioned. To contain odors and fumes, return air should not be supplied to other spaces, and the shop should be kept at a negative pressure relative to surrounding spaces. Special exhaust systems such as welding exhaust or direct-connected carbon monoxide exhaust systems may be required. See Chapter 33 for more information.

Industrial Shops. These facilities are similar to auto repair shops and have special exhaust requirements for welding, soldering, and paint booths. In addition, a dust collection system is sometimes provided, and the collected air is returned to the space. Industrial shops have a high sensible load from operation of the shop equipment. When calculating loads, the design engineer should consult the teacher about shop operation, and, where possible, diversity factors should be applied. See Chapter 33 for more information.

Locker Rooms. Building codes in the United States require that these facilities be exhausted directly to the outside when they contain toilets and/or showers. They are usually heated and ventilated only. These areas typically require makeup air and exhaust systems that should operate only when required. Where applicable, energy recovery systems can be considered.

Ice Rinks. These facilities require special HVAC and dehumidification systems to keep spectators comfortable, and to prevent roof condensation and fog formation at the surface. Where applicable, energy recovery systems can be considered. See Chapter 5 of this volume, Chapter 44 of the 2022 *ASHRAE Handbook—Refrigeration*, and Harriman et al. (2001) for more on these systems.

Natatoriums. These facilities, like ice rinks, require special humidity control systems. In addition, special construction materials are required. Where applicable, energy recovery systems can be considered. See Chapter 5 and Harriman et al. (2001) for more on these systems.

School Stores. These facilities contain school supplies and paraphernalia and are usually open for short periods. The heating and air-conditioning systems serving these areas should be able to be shut off when the store is closed to save energy.

Nurse/Health Suite. This area accommodates the school nurse and other medical personnel performing services such as

- Assessment and treatment of sick or injured children
- Emergency care
- Health counseling
- Medication administration
- Vision and hearing screening
- Notifying parents about children's health

Design information is provided in the Nurse/Health Suite section later in this chapter.

Design Criteria

A typical HVAC design criteria covers parameters required for thermal comfort, indoor air quality (IAQ), and sound. Thermal comfort parameters (temperature and humidity) are covered by ASHRAE *Standard* 55-2020 and Chapter 9 of the 2021 *ASHRAE Handbook—Fundamentals*. Ventilation and IAQ are covered by ANSI/ASHRAE *Standard* 62.1-2019 and Chapter 16 of the 2021 *ASHRAE Handbook—Fundamentals*. Sound and vibration are discussed in Chapter 49 of this volume and Chapter 8 of the 2021 *ASHRAE Handbook—Fundamentals.*

Thermal comfort is affected by air temperature, humidity, air velocity, and mean radiant temperature (MRT). Although ASHRAE *Standard* 55-2020 scope refers to healthy adults, section E-6 in Appendix E allows applying the standard to classrooms as well. Studies discuss the connection between children's thermal comfort and academic performance, emphasizing lowering space temperature to achieve improved academic results (e.g., Salazar et al. 2018; Wargocki and Wyon 2007, 2013; Wargocki et al. 2019). The range of temperature and humidity shown in Table 6 was established using the *CBE Thermal Comfort Tool* (Tartarini et al. 2020), providing slightly lower temperatures but still within the acceptable ASHRAE *Standard* 55 range (–0.5 < Predicted mean vote < +0.5).

Table 7 Minimum Design Criteria for Ventilation and Filtration for K-12 Schools

Category	Ventilation and Exhaust[a]				Minimum Filtration Efficiency, MERV[c]
	Outdoor Air Rate, L/s per Person	Occupant Density,[i] per 100 m²	Area Outdoor Air Rate L/(s·m²)	Exhaust Rate L/(s·m²)	
Classrooms, Ages 5 to 8	5	25	0.6		13[j]

Ages 9 and over	5	35	0.6		13[j]
Lecture classroom	3.8	65	0.3		13[j]
Art classroom	5	20	0.9	3.5	13[j]
Lecture hall (fixed seats)	3.8	150	0.3		13[j]
Science laboratories[f]	5	25	0.9	5	13[j]
Computer lab	5	25	0.6		13[j]
Media center	5	25	0.6		13[j]
Music/theatre/dance	5	35	0.3		13[j]
Multiuse assembly	3.8	100	0.3		13[j]
Libraries	2.5	10	0.6		13[j]
Auditorium	2.5	150	0.3		10[j]
Administrative/office areas	2.5	5	0.3		13[j]
Gymnasium (playing floors)	10	7	0.9		13[j]
Wood/metal shops	5	20	0.9	2.5	13[j]
Locker rooms				2.5	1 to 4
Cafeteria	3.8	100	0.9		13[j]
Kitchen (cooking)[d, e]	3.8		0.6		NA
Toilets				35 (per unit)	NA
Storage	2.5	2	0.3		1 to 4
Corridors			0.3		13[j]
Natatoriums (pool and deck)			2.4		13[j]
Ice rinks (spectator areas)[h]	3.8	150	0.3		13[j]

[bg]

Notes:

[a] Based on ASHRAE *Standard* 62.1-2019, Tables 6.1 and 6-2. For systems serving multiple zones, apply multiple-zone calculations procedure. See the section on Demand Control Ventilation (DCV) when DCV is considered. Additional factors such as zone air distribution effectiveness should be applied to determine the zone outdoor airflow.

[b] This table should not be used as the only source for design criteria. Governing local codes, design guidelines, and ASHRAE *Standard* 62.1-2019 *must* be consulted.

[c] MERV = minimum efficiency reporting values, based on ASHRAE *Standard* 52.2-2017.

[d] See Chapter 34 for additional information on kitchen ventilation.

[e] Consult local codes for kitchen exhaust requirements.

[f] This table should not be used as the only source for laboratory design criteria. Governing local codes and design guidelines such as ANSI/AIHA *Standard* Z9.5-2012 and Chapter 17 of this volume *must* be consulted.

[g] When higher filtration efficiency specified, prefiltration is recommended.

[h] Based on ASHRAE *Standard* 62.1-2019 values for sports and entertainment; for rink playing area, use gymnasium (playing floors) design criteria. Special attention should be given to internal-combustion ice-surfacing equipment for carbon monoxide control. Consult local code for ice rink design.

[i] Use default occupancy density when actual occupant density is not known.

[j] NAFA (2012). For new installations, it is recommended to take into account filter efficiency losses per ASHRAE *Standard* 52.2-2017, Appendix J, and refer to MERV-A ratings. This recommendation also applies to existing installations, when possible. See www.ashrae.org/technical-resources/filtration-and-disinfection-faq for details. Larger, centralized AHUs can be equipped with two-stage filters where the prefilter is MERV 8 and the final filter is MERV-13 or higher (NAFA 2021).

Note that, in addition to thermal comfort criteria, several zones in schools (libraries, gymnasiums, locker rooms, natatoriums, ice rinks, etc.) require additional considerations to account for issues such as mold prevention, condensation, corrosion, etc., as discussed in more detail in the section on Humidity Control. General guidelines for temperature and humidity applicable for K-12 schools are shown in Table 6.

All schools need outdoor air for ventilation. Outdoor air is introduced to occupied areas and then exhausted by fans, through air-to-air energy recovery devices (typically when DOAS systems are used), or exhausted through openings, removing indoor air pollutants generated by occupants and any other building-related sources. ASHRAE *Standard* 62.1 is used as the basis for many building codes. To define the ventilation and exhaust design criteria, consult local applicable ventilation and exhaust standards. Table 7 provides recommendations for ventilation design based on the ventilation rate procedure method of ASHRAE *Standard* 62.1-2019 and filtration criteria for K-12 educational facilities.

Table 8 Typical Recommended Design Guidelines for HVAC-Related Background Sound for K-12 Schools

	Sound Criteria[a, b]		
Category	**NC/RC**	**dBA[c]**	**Comments**
Classrooms	30	35	
Large lecture rooms			
Without speech amplification	25	30	
With speech amplification	30	35	
Science laboratories	35 to 50	40 to 55	See Table 1 of Chapter 49
Libraries	30	35	See Table 1 of Chapter 49
Auditorium	30 to 35	30 to 35	Use as guide only; consult acoustician
Administrative	40	45	For open-office space
Gymnasium	45	50	
Shops	35 to 45	40 to 50	Use as guide only; consult acoustician
Cafeteria	40	45	Based on service/ support for hotels
Kitchen	40	45	Based on service/ support for hotels
Storage	35 to 45	40 to 50	Use as guide only; consult acoustician
Mechanical rooms	35 to 45	40 to 50	Use as guide only; consult acoustician
Corridors	40	45	
Natatoriums	45	50	
Ice rinks	45	50	Based on values for gymnasiums and natatoriums

Notes:

[a] Based on Chapter 49, Table 1. That table provides additional design guidelines for HVAC-related background sound in rooms.

[b] RC (Room Criterion), from Chapter 8 of the 2021 *ASHRAE Handbook—Fundamentals.*

[c] Approximate overall sound pressure (see Table 1 in Chapter 49).

Additional information on IAQ for educational facilities can be found in EPA (2000).

Acceptable noise levels in classrooms are critical for a proper learning environment. High noise levels reduce speech intelligibility and student's learning capability. Although Chapter 49 provides information on design noise criteria, additional sources, such as local codes and ANSI *Standard* S12.60-2010 Part 1, should be consulted for adequate design criteria. Chapter 49 discusses acoustic design techniques, including HVAC noise reduction design and calculations. Commercially available acoustics software can help the designer meet the required noise design criteria.

Table 8 summarizes applicable noise criteria for K-12 schools.

Load Characteristics

Proper cooling, heating, dehumidification, and humidification load calculations and properly sized equipment are critical to both energy efficiency and cost effectiveness. Many computer programs and calculation methodologies, as described in Chapter 18 of the 2021 *ASHRAE Handbook—Fundamentals*, can be used for these tasks. Assumptions and data used for infiltration, lighting, equipment loads, occupancy, etc., are critical for proper load calculations. Although equipment is sized by peak cooling and heating, it is extremely important to analyze the occurrences of the peak sensible and latent cooling loads. In many instances, peak sensible cooling load does not coincide with peak latent cooling load. Ignoring this phenomenon can result in unacceptable indoor humidity. By carefully analyzing and understanding the peak loads and the load profiles, the designer can properly apply and size the most suitable equipment to meet the sensible and the latent cooling loads efficiently. Elementary schools are generally occupied from about 7:00 am to about 3:00 pm; occupation is longer for middle and high schools. Peak cooling loads usually occur at the end of the school day. Peak heating usually occurs early in the day, when classrooms begin to be occupied and outdoor air is introduced into the facility. Although K-12 schools are dominated by perimeter zones (and zones exposed to the roof), careful attention should be given to components of the loads. Typical breakdowns of moisture loads are shown in Table 9.

Table 9 Typical Classroom Summer Latent (Moisture) Loads

Category	Moisture Loads, kg/h	Moisture Loads, %
People	3.3	22.5
Permeance	0.09	0.6
Ventilation	9.2	62.5
Infiltration	2.1	14.4
Doors	0	0
Wet surfaces	0	0
Humid materials	0	0
Domestic loads	0	0

Note: Based on Harriman et al. (2001), Chapter 18, Figure 18.2.

Typically, the dominant cooling loads in classrooms are occupants and ventilation, and ventilation and roof for heating. Given the dominance of ventilation loads, special effort should be made to effectively treat outdoor air before its introduction to the space, as discussed in more detail in the section on Systems and Equipment Selection.

Humidity Control

School buildings host many activities that require special humidity control. Harriman et al. (2001) provide detailed information on the basics of design and equipment selection for proper humidity control for several applications; Chapter 18 of that volume is dedicated to schools.

Classrooms require humidity control to provide comfort and prevent humidity-related problems (e.g., growth of dust mites and fungus, which produce allergens and even toxic by-products). Low humidity, on the other hand, favors longevity of infectious viruses, and therefore their transmission between occupants. Maintaining relative humidity levels between 30 and 60% RH satisfies nearly all people nearly all the time. Chapter 22 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment* discusses the effect of maintaining minimum relative humidity on health and comfort. Issues such as preventing indoor condensation due to operating at elevated relative humidity in colder climates should be checked carefully. It is recommended that the designer discuss comfort expectations with the owner, to avoid misunderstandings.

Libraries require humidity control to provide comfort to the occupants and also to protect books and electronic records. Maintaining dew-point levels between –1 and 15.5°C provides a comfortable environment for the library occupants. However, controlling humidity at this range does not prevent books from absorbing excess moisture. Typically, books take up moisture quickly but lose it slowly. To avoid growth of mold and mildew, a dew point above –1°C and maximum of 55% rh are recommended. As with classrooms, the principal moisture loads for the library are ventilation (the major load) and infiltration.

Gymnasiums with wooden floors require special attention; failure to control humidity in gyms with wooden floors may have costly consequences. The Maple Flooring Manufacturers Association (MFMA 2005) specifies a floor-level humidity between 35 and 50% rh.

Showers and locker rooms require humidity control to prevent corrosion and growth of bacteria and fungus. Therefore, special attention is required to exhaust air quantities and placement of supply and exhaust air registers.

Natatoriums and ice rinks are typically isolated areas with more specialized HVAC equipment specifically designed to address ventilation and humidity control. Chapters 27 and 28 of Harriman et al. (2001) provide detailed information on humidity control for natatoriums and ice rinks, respectively.

Analysis tools such as PsyCalc-Binner (www.linric.com/psycalc/psycalc20help/hlp_binner.htm) can be used to better analyze humidity patterns based on geographic locations.

Room Air Distribution

Air is the primary carrier of heat, moisture, and airborne contaminants in indoor spaces. The distribution of clean supply air and resulting airflow patterns play a crucial role in determining the thermal comfort and health of occupants and the quality of indoor air. Airflow patterns, flow paths of airborne contaminants, and occupants' thermal comfort can depend on several factors, such as

- Number, location, and type of supply diffusers
- Supply airflow rates (air change rates) and associated diffuser throws
- Supply air temperature
- Number, size, and locations of return/exhaust grilles
- Location and strengths of various heat sources in a room

- Arrangement of furniture and other obstructions to airflow
- Location, type, and capacity of in-room air cleaners
- Relative positions of contaminant and heat sources in space

Chapter 20 of this volume details the principles of space air diffusion. In the 2023 *ASHRAE Handbook —HVAC Applications*, Chapter 58 discusses air diffusers, return air grilles, and other air terminals and their effect on occupants' thermal comfort. Ventilation effectiveness is affected by the room air distribution equipment and should be taken in account for proper ventilation rates. ASHRAE *Standard* 62.1 provides typical values for ventilation effectiveness.

To reduce health risks, room air distribution should promote good mixing of space air without increasing transmission risks from person to person. The method of the air distribution to the space should be able to meet various thermal requirements of occupied spaces with varied heat gain conditions. Fully mixed air distribution provides the required thermal comfort, space ventilation, and contaminant removal if the supply diffusers and return air grilles are located properly. Chapter 58 of the 2023 *ASHRAE Handbook —HVAC Applications* discusses fully mixed air distribution in detail, including overhead mixed air supply terminals such as ceiling and sidewall diffusers. It also covers fully stratified air distribution, commonly applied by displacement ventilation (DV) systems, and Example 5 in that chapter demonstrates the application of displacement ventilation for classroom.

Both fully mixed and fully stratified air distribution systems are applicable for most areas found in educational facilities. Zhao et al. (2021) analyzed four types of air diffusers for classroom application: (1) mixing ventilation with sidewall diffuser with adjustable vanes evenly spreading supply air jet onto ceiling area, (2) displacement ventilation with a low-velocity unit, (3) mixing ventilation with a radial ceiling diffuser, and (4) mixing ventilation with a perforated duct diffuser. The study recommended the displacement ventilation and ceiling diffuser as solutions for classrooms in the studied conditions.

Indoor environmental modeling methods such as computational fluid dynamics (CFD) tools and techniques can be applied to properly design the room air distribution. In addition, if CFD analyses are performed properly, designers can better understand complex airflow patterns and the flow path of potential airborne contaminants. This will help in reducing the spread of airborne contaminants and reduce the risk of infection. Chapter 13 of the 2021 *ASHRAE Handbook—Fundamentals* provides information on the principles of CFD. Chapter 59 of the current volume provides additional information and CFD examples.

CFD deals with the simulation and analysis of fluid flow, heat transfer, mass transfer, and other similar transport processes. Laws such as conservation of mass, momentum, and energy, along with numerical methods, are applied to solve the fundamental governing equations of fluid dynamics: (1) continuity, (2) momentum, and (3) energy. The solutions predict and reveal the temporal and spatial variations of the governing variables such as velocity, pressure, temperature, chemical concentrations, etc. in the calculation domain.

Khankari (2021) uses CFD modeling and simulations to demonstrate the importance of properly selected and located supply air diffusers and return air grilles to minimize the spread of airborne contaminants and reduce of the risk of infection without increasing supply airflow rates.

Additional information on the application of CFD for HVAC systems design and analysis can be found in ansight.com/publications/ and ansight.com/presentations/

Systems and Equipment Selection

Selection of HVAC equipment and systems depends on whether the facility is new or existing, and (in the latter case) whether it is to be totally or partially renovated. For minor renovations, existing HVAC systems are often expanded in compliance with current codes and standards with equipment that matches the existing types. For major renovations or new construction, new HVAC systems and equipment should be installed. When applicable, the remaining useful life of existing equipment and distribution systems should be considered.

HVAC systems and equipment energy use and associated life-cycle costs should be evaluated, as well as the program decarbonization targets. Energy analysis may justify new HVAC equipment and systems when an acceptable return on investment can be shown. The engineer must review all the assumptions in the energy analysis with the school administration. Assumptions, especially about hard-to-measure items such as infiltration and part-load factors, can significantly affect the energy use calculated.

Other considerations for existing facilities are (1) whether the central plant is of adequate capacity to handle additional loads from new or renovated facilities; (2) the age and condition of the existing equipment, pipes, and controls; and (3) the capital and operating costs of new equipment. Schools usually have very limited budgets. Any savings in capital expenditures and energy costs may be available for the maintenance and upkeep of the HVAC systems and equipment and for other facility needs.

The type of HVAC equipment selected also depends on the climate and months of operations. In hot, dry climates, for instance, evaporative cooling may be the primary approach. Some school districts may choose not to provide air conditioning. However, in hot, humid climates, it is recommended that air conditioning or dehumidification be operated year-round to prevent growth of mold or mildew.

Chapter 1 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment* provides general guidelines on HVAC systems analysis and selection procedures. Although in many cases system selection is based solely on the lowest first cost, it is suggested that the engineer propose a system with the lowest life-cycle cost (LCC). LCC analysis typically requires hour-by-hour building energy simulation for annual energy cost estimation. Detailed first and maintenance cost estimates of proposed design alternatives, using sources such as R.S. Means (2023a, 2023b), can also be used for the LCC analysis along with software such as BLCC 5.3-21 (FEMP 2021). Refer to Chapters 38 and 59, and the Value Engineering (VE) and Life-Cycle Cost Analysis (LCCA) section of this chapter, for additional information.

System Types. HVAC systems for K-12 schools may be centralized, decentralized, or a combination of both. Centralized systems typically incorporate secondary systems to treat the air and distribute it. The cooling and heating medium is typically water or brine that is cooled and/or heated in a primary system and distributed to the secondary systems. Centralized systems comprise the following systems:

Secondary Systems

- Air handling and distribution (see Chapter 4 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment*)
- In-room terminal systems (see Chapter 5 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment*)
- DOAS with chilled water for cooling and hot water, steam, or electric heat for heating (see Chapter 51 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment*)

Primary Systems

- Central cooling and heating plant (see Chapter 3 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment*)

Typical decentralized systems (dedicated systems serving a single zone, or packaged systems such as packaged variable-air-volume) are

- Water-source heat pumps (WSHPs), also known as water-loop heat pumps (WLHPs)
- Geothermal heat pumps (groundwater heat pumps, ground-coupled heat pumps)
- Hybrid geothermal heat pumps (combination of groundwater heat pumps, ground-coupled heat pumps, and an additional heat rejection device), for cases with limited area for the ground-coupled heat exchanger or where it is economically justified
- Packaged single-zone and variable-volume units
- Light commercial split systems
- Minisplit and variable-refrigerant-flow (VRF) units

Chapters 2, 9, 18, 49, and 50 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment* provide additional information on decentralized HVAC systems. Additional information on geothermal energy can be found in Chapter 35 of this volume.

It is important to note that, to meet the acoustical design criteria in Table 8, designers should avoid locating HVAC equipment in classrooms, and that some centralized and decentralized systems located close to classrooms might need additional sound-attenuating features. Coordination between the HVAC designer, architect, and acoustical consultant is critical for meeting the desired noise criteria. Siebein and Likendey (2004) provide information on the applicability of systems to classrooms with regard to acoustical criteria. Additional information on how HVAC&R manufacturers' acoustical data and application information can be best used can be found in Ebbing and Blazier (1998). Schaffer (1993) provides a practical guide to noise and vibration control for HVAC systems. Commercial acoustics analysis software can also be helpful.

Dedicated Outdoor Air Systems. Although most centralized and decentralized systems are very effective at handling the space sensible cooling and heating loads, they are less effective (or ineffective) at handling ventilation air and the latent loads. As a result, a DOAS should be used. DOAS units (DOAUs) bring 100% outdoor air to at least space conditions, which allows individual space units to handle only the space loads. It is preferable, however, to introduce the outdoor air at a lower humidity ratio than the desired space humidity ratio, to allow the zone HVAC unit to handle only the space sensible cooling load. This approach can be easily implemented in a classroom where a significant amount of outdoor air is required for ventilation. DOAS unit locations should consider peak roof temperatures if the outdoor air intake locations could increase the entering air temperature above the ASHRAE design load temperatures for that climate zone. Intakes can be raised to avoid absorbing radiant heat from the roofs into the incoming airstream.

Example. In a typical classroom with 30 students, the ventilation requirements are 222 L/s. If the outdoor air can be introduced at a humidity ratio of 6.9 g/kg and the space is designed to be maintained at 10 g/kg, the space dehumidification capability of the pre-dehumidified outdoor air is the following:

$$\text{Space dehumidification capability, W} = \text{Latent load factor, W/(L·s)} \times \text{Flow rate, L/s} \times \left(\text{Space humidity ratio} - \text{Supply humidity ratio}\right)$$

Then,

$$\text{Dehumidification capability, W} = 3010 \times 222\left[\frac{(10 - 6.9)}{1000}\right] = 2071\ \text{W} = 2.07\ \text{kW}$$

where 3010 is the air latent factor (see Chapter 18 of the 2013 *ASHRAE Handbook—Fundamentals*), in W/(L · s).

The 2.07 kW of space latent load is equivalent to the latent load of 30 occupants (seated, very light work, 0.045 kW per occupant) and the additional space latent load (e.g., infiltration latent load).

$$\text{Occupant latent load} = 30 \times 0.045 = 1.35\ \text{kW}$$

$$\text{Remainder of total dehumidification capability} = 2.07 - 1.35 = 0.72\ \text{kW}$$

This additional dehumidification capability can help in handling infiltration latent load and others.

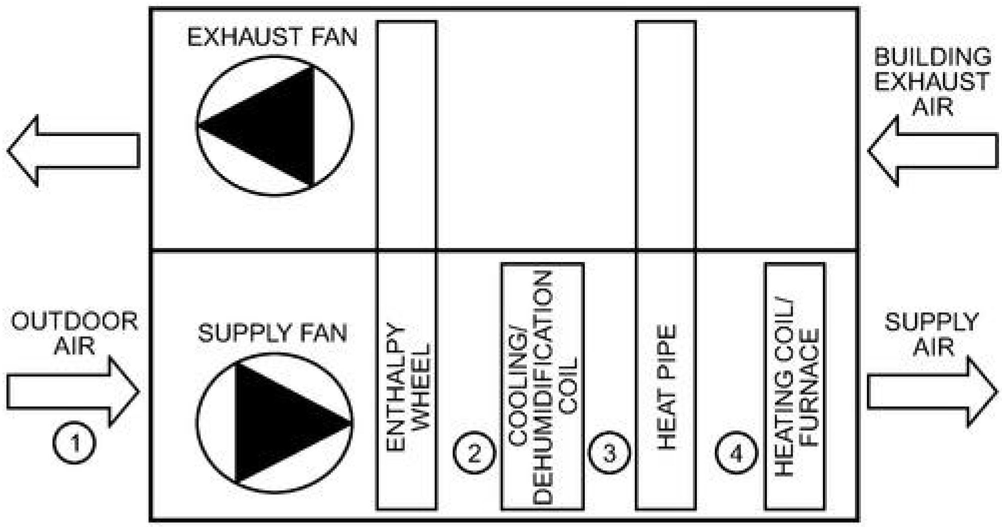

Figure 1. Typical Configuration of DOAS Air-Handling Unit: Enthalpy Wheel with Heat Pipe for Reheat

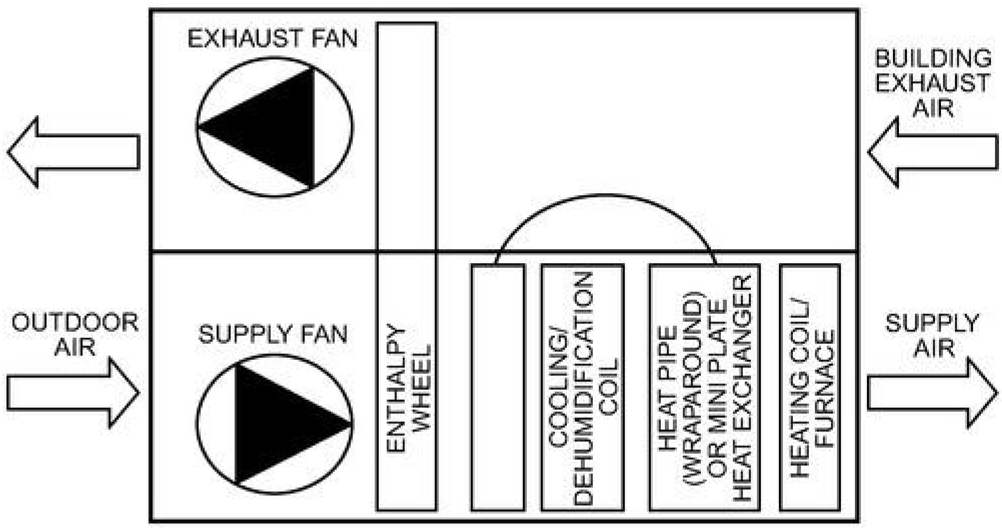

Figure 2. Typical Configuration of DOAS Air-Handling Unit: Enthalpy Wheel with Wraparound Heat Pipe for Reheat

This simple example demonstrates the ability of pre-dehumidified outdoor air to handle the space latent load, resulting in almost full separation of the space latent cooling load treatment from the space sensible cooling load. This approach allows only thermostatic control without losing humidity control in conditioned classrooms.

Typical DOAS units are air-handling units that cool, dehumidify, heat, humidify, and filter the outdoor air before it is introduced to the conditioned space. Typical DOAS units include the following major components:

- Mechanical cooling/dehumidification
  - DX coil
  - Chilled-water coil
- Desiccant-based cooling/dehumidification
  - Desiccant (dehumidification) and direct-expansion (DX) coil (post sensible cooling)
  - Desiccant (dehumidification) and chilled-water coil (post sensible cooling)
- Heating
  - Coils (hot-water, steam, electric, heat pump)
  - Gas-fired furnace
- Humidification
  - Passive (in conjunction with enthalpy wheel heat recovery)
  - Active (steam, electric-to-steam, gas-to-steam)
- Exhaust air recovery: air-to-air heat recovery
  - Rotary (enthalpy wheel, sensible wheel)
  - Fixed (heat pipe, plate heat exchanger, runaround coils)
- Dehumidification enhancements for air-to-air heat recovery
  - Heat pipe based (wraparound coil)
  - Mini plate heat exchanger based

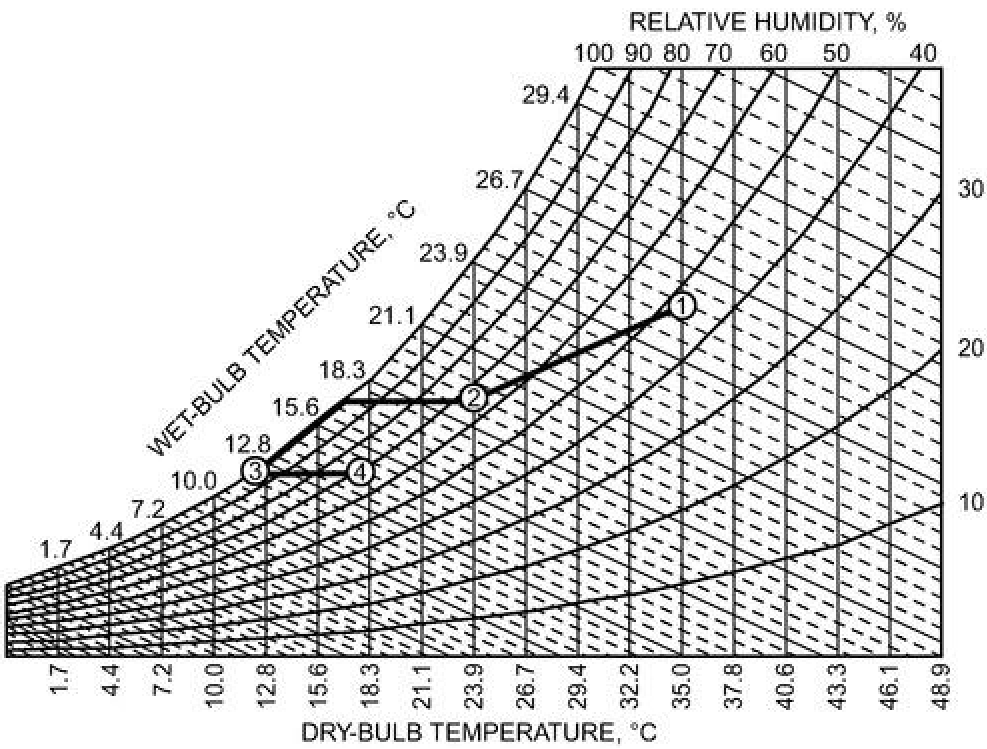

Figure 3. Cooling/Dehumidification Psychrometric Process of Typical DOAS Air-Handling Unit in Figure 1

Which DOAS unit configuration is most cost effective depends on variables such as availability of utilities (chilled water, gas, steam), space constraints, climatic data, utility cost, and budget. DOAS units can be configured easily by using modular components that meet the design criteria. Selection and analysis software of these systems is readily available from DOAS manufacturers, which simplifies configuration and analysis of the most cost-effective system. Typical configurations of DOAS units are shown in Figures 1 and 2. A cooling/dehumidification psychrometrics process of DOAS is shown in Figure 3.

Air-to-air energy recovery is an important element in a DOAS unit. In addition to recovering energy from the exhaust air, a well-designed energy recovery module, such as an enthalpy wheel, can enhance and stabilize operation of the cooling and heating elements in the DOAS unit. As shown in Figure 3, the process of bringing outside air from point 1 to point 2 can be defined as "compressing" the outdoor air conditions to almost return air conditions. Proper location of supply and exhaust fans is suggested to minimize cross contamination between the supply and exhaust airstreams of the DOAS unit. Rotary air-to-air heat exchangers can apply purge sections to further minimize potential carryover. Additional information about DOAS systems can be found in ASHRAE (2017). See ANSI/AHRI *Standard* 920 for additional information.

Given the need for more stringent and complex control schemes for outdoor air preconditioning, DOAS units typically incorporate, direct digital control (DDC) systems, either stand-alone (independent) microprocessor-based controller or with the ability to communicate with and be controlled by the building automation system (BAS) and part of the building management system (BMS). Newer control systems use an integrated control system where the DOAS unit is part of the entire HVAC control system, providing enhanced features such as full coordination with other systems for variables (set points, scheduling, etc.). The control system can be purchased as an option or installed in the field by the controls vendor. Typical supply air conditions for a DOAS air-handling unit are shown in Table 10.

Typical arrangements of DOAS integrated with local cooling and heating systems are shown in Figure 4, where pretreated outdoor air from the DOAU is introduced directly to the space. Another option is the DOAS air terminal unit (ATU) described in Chapter 58; this is a series fan-powered terminal with ventilation air inlet connected to the DOAS unit air distribution, with a sensible cooling coil operating at elevated chilled-water temperature. The latent load is handled by the DOAS, and a heating coil can be added if required. DOAS-ATUs are available with higher-efficiency (MERV-13) filters for enhanced filtration.

Additional information on DOAS systems can be found in Chapter 25 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment*.

Typical DOAS unit control provides the required air flow at the desired temperature and humidity levels, based on building space requirements and operation schedules. Typical control features include

- Outdoor and exhaust airflow control in response to building zones OA requirements (typical for DCV)
- Outdoor and exhaust airflow control in response to building pressure requirements
- Switch from 100% OA (occupied) mode to 100% RA (unoccupied) mode by opening and closing air dampers
- Control of supply air conditions (temperature and humidity)

More advanced control system with integrated DOAS control can offer additional features such as dynamic temperature and dew point for enhanced dehumidification.

Detailed information on DOAS unit control and control modes can be found in Chapter 51 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment*.

Systems with High Percentage of Outdoor Air. Air-handling systems with a high percentage of outdoor air (above 30%) can be found in several areas in educational facilities. To prevent indoor air quality problems and conserve energy, an energy recovery module can be added to pretreat the outdoor air before it is mixed with return air. Figure 5 shows a typical rooftop packaged AC unit with energy recovery module. See Chapter 26 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment* for more information on energy recovery equipment and systems.

The addition of an energy recovery module is dependent on the percentage of outdoor air and the geographic location. See ANSI/ASHRAE/IES *Standard* 90.1-2019, section 6.5.6.1, for the correlation between geographic location and percentage of outdoor air (OA). Checking the exceptions provided in that section is strongly recommended.

Systems Selection by Application. Table 11 shows the applicability of systems to areas in K-12 school facilities.

Displacement Ventilation and Active/Induction Chilled Beams

Displacement Ventilation. The use of displacement ventilation (as opposed to the more traditional mixing ventilation) for classrooms has been extended for enhanced IAQ and thermal comfort. In displacement ventilation, fresh air at colder temperature than the room air is discharged close to the floor level, and warm air is exhausted at or close to the ceiling. After being discharged at a low level, the colder supply air rises as it is heated by heat sources (e.g., people, computers), also allowing effective removal of containments generated in the room.

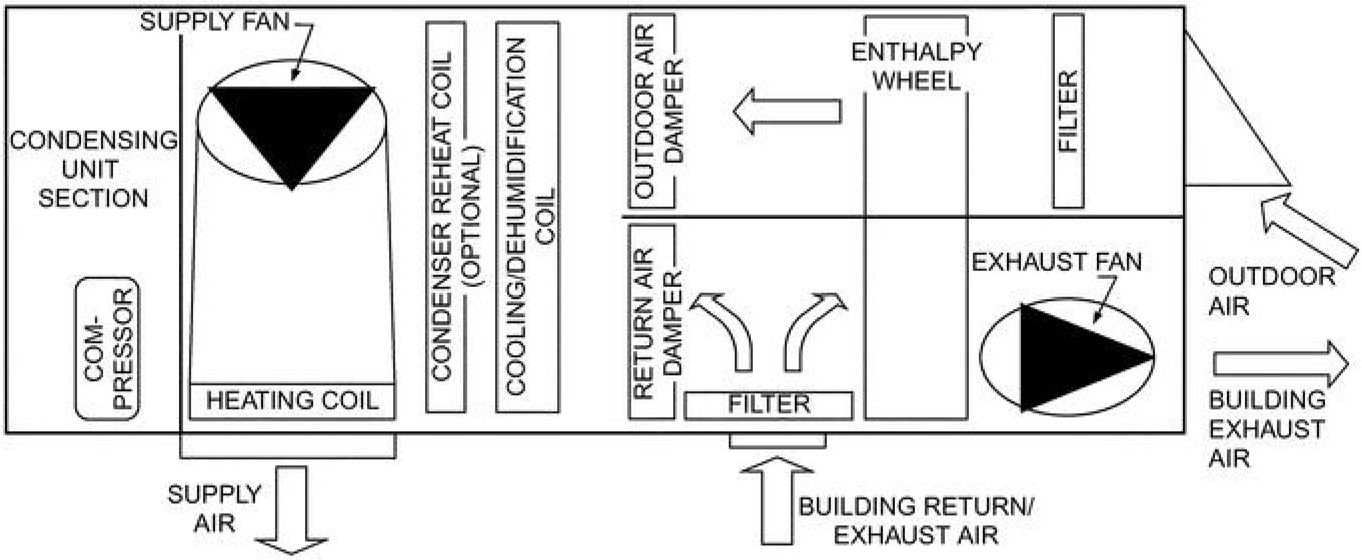

Figure 4. Typical Configuration of Rooftop Packaged Air Conditioners with Energy Recovery Module and Enhanced Dehumidification (Condenser Reheat Coil)

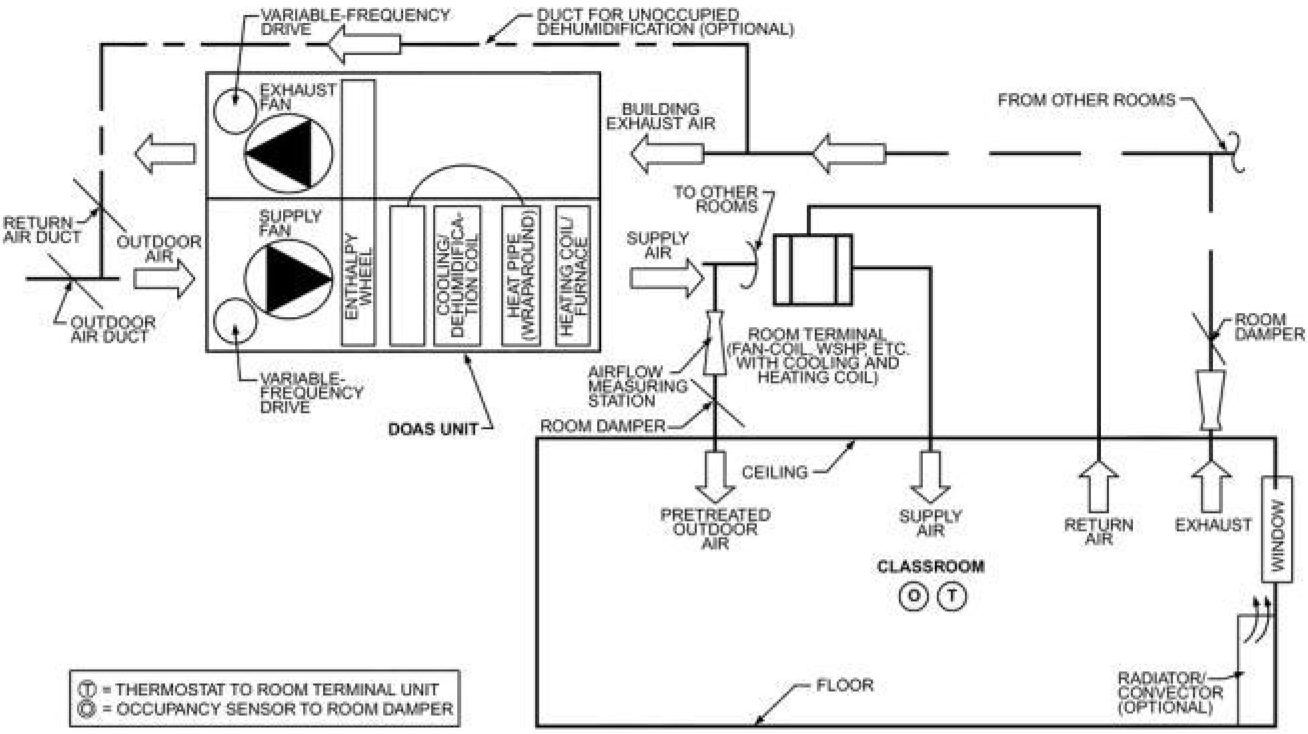

Figure 5. Typical Schematic of DOAS with Local Classroom Cooling/Heating Terminal (*Note*: CO_2 sensor can be added for DCV to control room OA damper)

Guidelines and procedures for designing displacement ventilation systems can be found in California Energy Commission (2006), Chen and Glicksman (2003), Skistad et al. (2002), Chapter 20 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment,* and Chapter 58 of this volume.

Typical displacement ventilation systems for classrooms include the following main subsystems (Figure 6):

- DOAS air-handling unit that can cool and dehumidify outdoor air to 15 to 17°C and 5 to 7 g/kg for summer, and heat air to 18 to 20°C for winter
- Zone fan-powered terminal with sensible cooling capability (located outside the conditioned zone)
- Special displacement ventilation diffusers
- Heating radiators or convectors placed below windows in perimeter zones
- Control systems (thermostats, occupancy, and CO_2 sensors)

In addition to the traditional displacement ventilation system described previously, displacement ventilation with induction can also be considered for classrooms. A displacement ventilation system with induction uses special terminals to provide additional cooling and heating with the displacement ventilation effect. These terminals are not equipped with fans, resulting in lower noise levels as required by more stringent noise criteria.

Table 10 Typical Design Criteria for DOAS Air-Handling Unit

	Supply Air Conditions[a]		
	Temperature, °C	**Humidity Ratio, g/kg**	**Minimum Air Filtration Efficiency, MERV[b]**
Winter	18 to 20	4 to 6	13[c] (supply), 8 (exhaust)
Summer	15[d] to 18	6 to 9	13[c] (supply), 8 (exhaust)

Notes:
MERV = minimum efficiency reporting values

[a] Building location may dictate optimum supply condition in recommended range.

[b] Filter efficiency definition per ASHRAE Standard 52.2-2017.

[c] NAFA 2012. For new installations, it is recommended to take into account filter efficiency losses per ASHRAE *Standard* 52.2-2017, Appendix J, and refer to MERV-A ratings. This recommendation also applies to existing installations, when possible. See www.ashrae.org/technical-resources/filtration-and-disinfection-faq for details.

[d] Refer to ASHRAE *Standard* 90.1-2016, section 6.5.2.6. This standard restricts the supply air temperature to 15°C; when required by the standard, this criterion should be used.

A displacement ventilation system with induction includes the following main subsystems:

- DOAS air-handling unit that can cool and dehumidify outdoor air to 12 to 14°C and 5 to 7 g/kg for summer, and heat air to 18 to 20°C for winter
- Zone displacement ventilation with induction terminal, equipped with two- or four-pipe cooling and heating coil mounted along perimeter walls and windows
- Control systems (thermostats, occupancy, and CO_2 sensors)

Active (Induction) Chilled Beams. The use of active/induction chilled beams for classrooms and other areas in educational facilities has been extended for enhanced IAQ, thermal comfort, and energy conservation. As with displacement ventilation with induction, an active/induction chilled beam terminal includes special small air jets that induce room air to flow through cooling or heating coils, depending on the system (two- or four-pipe). The primary air is outdoor air pretreated in a DOAS unit, as described previously. Figure 7 shows the principle of active/induction chilled-beam terminals. See Chapter 58 for additional information on chilled beams.

Although more room space is required for chilled-beam induction, these systems allow significant size and capacity reductions in air-handling systems, and decouple sensible cooling and heating from ventilation and humidity control. Temperatures of chilled water distributed to the chilled-beam terminals are typically elevated to around 13°C, which can reduce energy consumption; note that this system requires dew-point safeties. Hot water can be provided from a standard hot-water boiler at 66 to 82°C, or lower if condensing boilers applied.

An active/induction chilled-beam system typically includes the following main subsystems:

- DOAS unit that can cool and dehumidify outdoor air to 12 to 14°C and 5 to 7 g/kg for summer, and heat air to 18 to 20°C for winter
- Zone active/induction chilled-beam terminal, equipped with two- or four-pipe cooling and heating
- Control systems (thermostats, occupancy, and CO_2 sensors)

Specialized Equipment. Areas such as natatoriums and ice rinks need specialized equipment to address the unique design requirements and the cooling, dehumidification, and heating characteristics. Natatoriums typically use special units that can introduce large quantities of outdoor air and allow active humidity control (mainly dehumidification). This equipment is similar to DOAS, and typically uses chilled water or a DX system for dehumidification. For systems with air-cooled condensers, condenser heat can be recovered to heat the swimming pool. See Chapter 5 of this volume for more information on natatoriums. Similarly, an ice rink requires special equipment; selection depends heavily on the school's location and seasonal use. Ice rink HVAC and dehumidification equipment can be desiccant-based or self-contained mechanical refrigeration. See Chapter 5 of this volume, Chapter 25 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment*, and Chapter 44 of the 2022 *ASHRAE Handbook—Refrigeration* for more information on ice rinks.

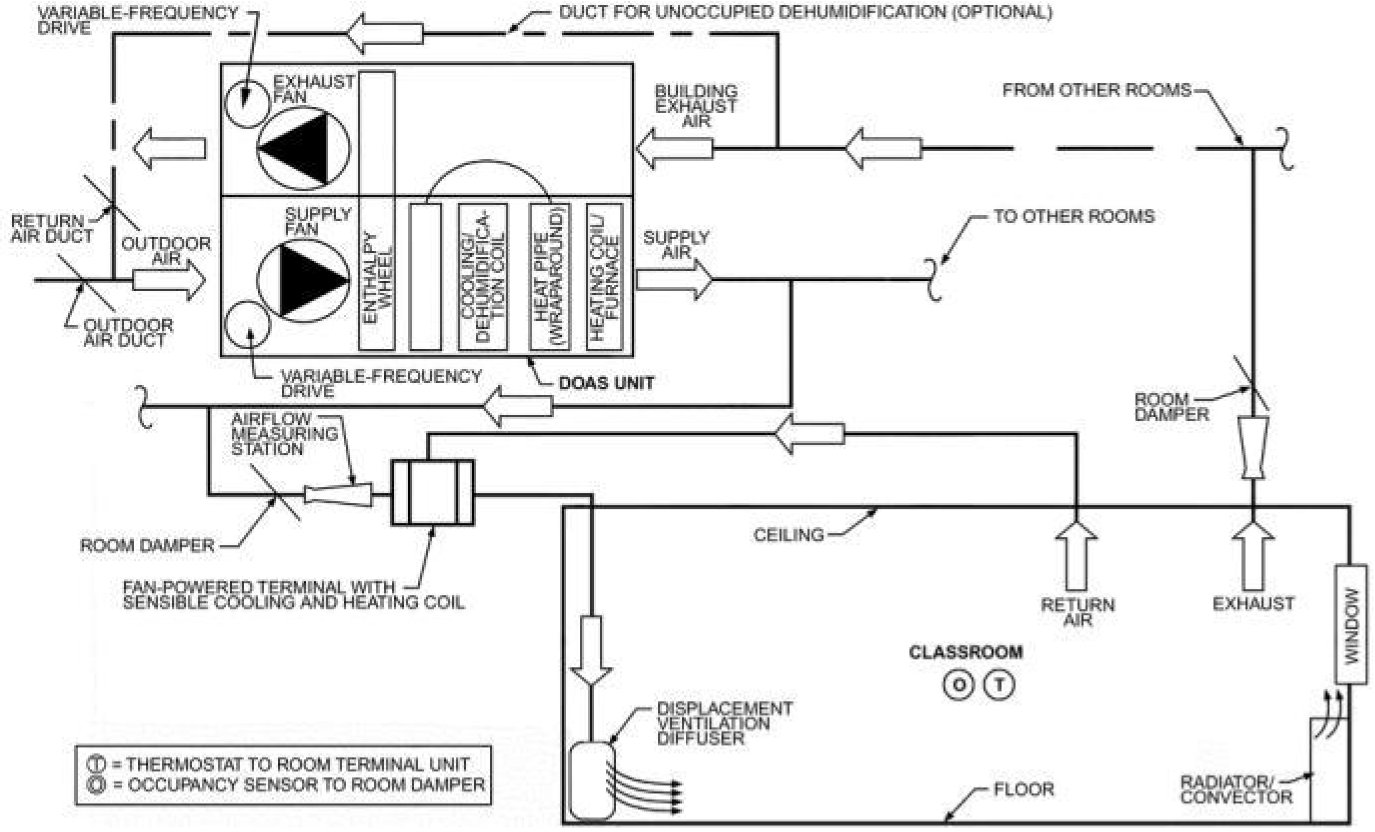

Figure 6. Typical Displacement Ventilation System Layout (*Note*: CO_2 sensor can be added for DCV to control room OA damper)

Table 11 Applicability of Systems to Typical Areas

	Cooling/Heating Systems							Heating Only	
	Centralized			Decentralized					
Typical Area[c]	**SZ[a]**	**VAV[h]/Reheat**	**Fan Coil (Two- and Four-Pipe)**	**PSZ/ SZ[a] Split/VRF[g]**	**PVAV[h]/ Reheat**	**WSHP**	**Geothermal Heat Pump and Hybrid Geothermal Heat Pump**	**Baseboard/ Radiators**	**Unit Heaters**
Classrooms	X	X	X	X	X	X	X	X	
Laboratories and science facilities[b]	X	X	X	X	X	X	X	X	
Administrative areas	X	X	X	X	X	X	X	X	
Gymnasium[e]	X	X		X					X
Libraries	X	X	X	X	X	X	X	X	
Auditorium[e]	X	X		X	X				
Home economics room	X	X	X	X	X	X	X	X	
Cafeteria[e]	X			X					
Kitchen[e]	X			X					X
Auto repair shop									X
Industrial shop									X
Locker rooms								X	X
Ventilation (Outdoor Air)	DOAS	d	DOAS	DOAS[f]	d	DOAS	DOAS	DOAS	DOAS

SZ = single zone
VAV = variable air volume
PSZ = packaged single zone
PVAV = packaged variable air volume
WSHP = water-source heat pump
DOAS = dedicated outdoor air system
VRF = variable refrigerant flow
Notes:

[a] SZ and PSZ/SZ split for classrooms requires individual thermostatic control.

[b] Systems for laboratories must comply with local codes and be in accordance with current practices for laboratories.

[c] Systems and equipment for ice rinks and natatoriums not shown; refer to specialized equipment section.

[d] Special attention should be given for adequate OA supply in VAV applications without DOAS; consult ASHRAE *Standard* 62.1-2019 Section 6.2.5, and ASHRAE *Guideline* 36-2021.

[e] In some cases, these areas can be served by SZ, WSHP, and geothermal HP systems without OA from DOAS. High-volume low-speed (HVLS), large-diameter fans can be considered for this area.

[f] When percentage of outdoor air dictates use of energy recovery in SZ or PSZ unit, OA for DOAS may not be required.

[g] Special consideration is required for risk associated with refrigerant leaks. ASHRAE *Standards* 15 and 34 should be consulted.

[h] For VAV systems, consider using a fan-powered terminal with optional MERV-13 filters for improved filtration.

Chapters 27 and 28 of Harriman et al. (2001) also provide detailed information on humidity control for natatoriums and ice rinks, respectively.

Demand Control Ventilation (DCV). Demand control ventilation can reduce the cost of operating the HVAC systems. To ensure proper IAQ and comply with ASHRAE *Standard* 62.1-2019 and local codes that allow DCV, the designer must carefully follow section 6.2.6 (Dynamic Reset) of the standard. *Standard* 62.1-2019 explicitly allows use of CO_2 levels or occupancy to reset intake airflow in response to space occupancy levels. Pay special attention to the area served by the HVAC system and the system type. Areas such as gymnasiums and auditoriums can benefit from CO_2-based DCV, commonly used in single-zone systems without DOAS, serving one space with varying occupancy. In these cases, DCV control is simple, reliable, and cost-effective. Systems such as multizone VAV with recirculated air without DOAS require special attention to ensure adequate OA supply to multiple zones under varying loads (such as classrooms). This problem complicates the design, operation, and maintenance of DCV control systems and also adds the cost of additional sensors.

A simpler approach for DCV is in systems that use DOAS: the OA supply to each individual space can be controlled independently by occupancy sensors that can reduce the OA to a preset value (and also turn off the lights), or by CO_2 sensors (see Figure 4). DVC set points for CO_2 should be based on the ambient differential of CO_2 (e.g., outdoor ambient CO_2 level + 650 ppm).

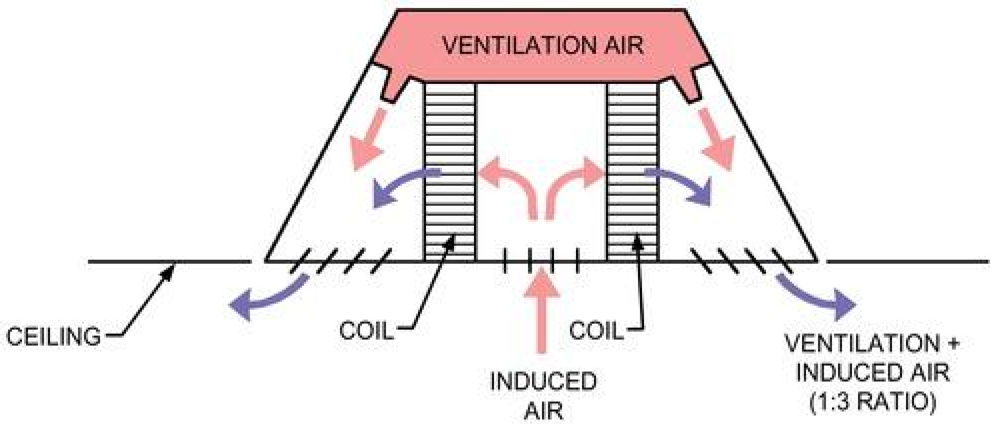

Figure 7. Typical Active/Induction Chilled-Beam Terminal (Rumsey and Weale 2006)

Ultraviolet Germicidal Irradiation (UVGI) Systems. Ultraviolet germicidal irradiation (UVGI) systems can help schools reduce microorganisms before they can infect the students. UV-C (germicidal wavelengths) damages the DNA/RNA of virus, bacteria, and fungi and prevents microorganisms from replicating. UVGI disinfection devices are powerful and proven protection tools for disinfecting air and surfaces from not just SARS-CoV-2, but also from influenza, MRSA, *C. diff*, and other emerging pathogens. It has been used to disinfect spaces for over 100 years.

Bahnfleth (2020) provides background information on UVGI and application information. Su et al. (2017) present a case study of the application of UVGI for classroom. Chapter 17 of the 2020 *ASHRAE Handbook—Fundamentals* discusses ultraviolet lamp systems, and Chapter 62 of this volume details UVGI systems and applications. ASHRAE *Standard* 185.2-2020 also provides information on UV lamps. Additional information can be found in Kowalski (2009).

UVGI systems should be designed based on the following criteria: maximum air velocity, UV-C distance, exposure time, and UV-C dose in microwatt-seconds per square centimetre. Safety interlocks should be provided at all air-handling access doors to protect against UV-C exposure. UVGI systems must not introduce UV-V or UV-A into the space.

Applications for UVGI systems include

- Cafeterias
- Hallways
- Athletic facilities/gymnasiums
- Classrooms
- Administrative areas/buildings
- Nurses' suites

Upper room/upper air UV fixtures are designed to provide targeted airborne pathogen reduction in high-risk areas as shown in Figure 8. They are used in lobbies, classrooms, hallways, cafeterias, libraries, etc., and in areas with either high or low ceilings. Installation can be permanent or temporary. Both fan-assisted and natural-convection models are available, as well as modular ceiling units integrated in a suspended ceiling with internal fans, and UV-C integrated with high-volume, low-speed (HVLS) ceiling fans.

In-AHU and in-duct UV fixtures are installed inside AHUs and ductwork. They can provide disinfection of airborne infectious pathogens, and in-AHU can also disinfect coils and drain pan surfaces (Figure 9). They can be applied to new and existing ventilation systems to disinfect and distribute air. Condensation and carryover of moisture in certain areas (coils, drain pans, humidifiers, filters, etc.) in AHUs can promote the growth of bacteria, mold, and odor and accelerate equipment degradation and failure. Using UVGI eliminates these risks and problems.

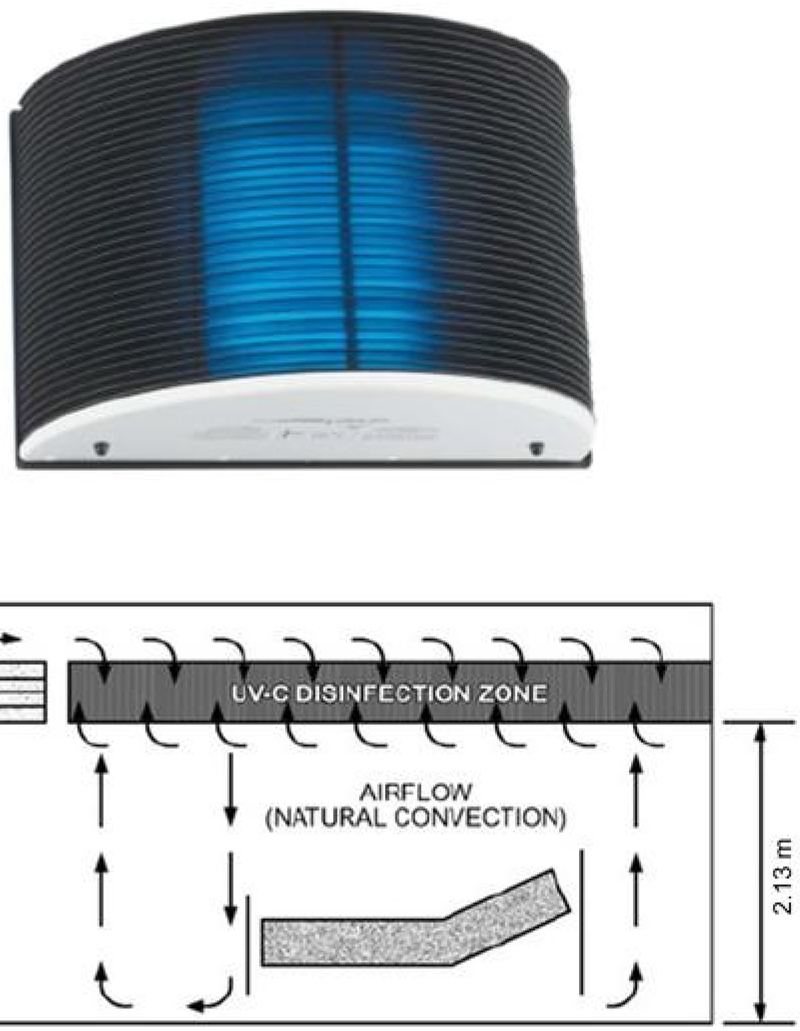

Figure 8. Upper Room Air Disinfection (Bahnfleth 2020)

In-room surface/room disinfection is designed for high-level disinfection of contaminated surfaces that can spread infection. Fixed and portable units can be applied for disinfection of floors, desks, and table surfaces. This approach is suitable for classrooms, cafeterias, or other areas where contaminated surfaces can spread sickness; it is also useful for disinfecting are as, such as keyboards, monitors, lab and cafeteria equipment.

Figure 9. In-AHU Air and Surface Disinfection (Bahnfleth 2020)

Carefully consider safety and potential hazards (see Chapter 62).

In-Room Air Cleaners

These units can be considered when HVAC equipment and system design do not meet ASHRAE recommendations for ventilation and filtration and when removal of contaminants near a source is needed, or higher-risk activities occur.

An in-room air cleaner is installed in occupied space, rather than in the HVAC system. They are also known as portable, stand-alone, purifiers, plug-in, or room air cleaners.They come in several types and sizes:

- Miniature desktop units
- Portable units designed to be operated on the floor or tabletop
- Larger fixed units that can be permanently installed on ceilings, walls, or floors

In some cases, larger fixed units use ducts for air distribution across larger spaces.

In-room air cleaners may contain one or more technologies designed to remove or inactivate air contaminants. Media filters, including high-efficiency particulate air (HEPA) filters, can remove particles, including those containing viruses and other microorganisms. UV-C kills or inactivates viruses and microorganisms to make them noninfectious but does not remove them from the air. Technologies such as ionizers or UV-PCO (photocatalytic oxidation) claim to remove or destroy multiple types of contaminants, but may convert them to other compounds that might be harmful. These technologies are designated by the U.S. Centers for Disease Control (CDC) as emerging technologies without an established body of evidence reflecting proven efficacy under as-used conditions. For more information, refer to the *Filtration & Disinfection Guide* from the ASHRAE Epidemic Task Force (www.ashrae.org/technical-resources/filtration-disinfection) and Chapter 66 in this volume.

Many devices are rated by the Association of Home Appliance Manufacturers (AHAM). The rate of particle removal from air is called the **clean air delivery rate (CADR)**, typically in units of cubic meters per hour (m^3/h), where

$$\text{CADR} \approx \text{Airflow rate} \times \text{Removal efficiency}$$

To reach a desired air exchange rate in air changes per hour (ACH), use the following:

$$\text{ACH} = \text{CADR}\ (\text{m}^3/\text{h})/\text{Room volume}\ (\text{m}^3)$$

To size and select an in-room air cleaner, the following information is needed:

- **Contaminant(s)** to be controlled.
- **Space size**: length, width, and ceiling height.
- **Space layout**: space arrangement, power access, potential safety issues.
- **Noise criteria**: acceptable noise level (e.g., 40 dBA); noise rating at a specific fan speed reported for device (if known).

- **Air distribution**: how air is distributed in the space, whether air cleaner(s) can be placed with air intakes unobstructed by furniture, and whether outlets can move air as far as possible before being deflected or drawn into a return or exhaust grille. Optimally, in-room air cleaners should have fixed locations.
- **Existing HVAC system**: total supply air and return air.
- **Ventilation (outdoor air)**: how much comes in through HVAC system or windows, If unknown, assume none.
- **Filtration**: existing filters information and efficiency (MERV).
- **Amount of clean air needed (CADR)**: what flow rate of clean air is needed? Is there a target for the clean-air equivalent number of air changes per hour needed between ventilation and filtration combined (e.g., 3, 6, or 12 ACH equivalent)?

In-Room Air Cleaner Sizing Example. A typical educational space has the following specifications:

Space size: 14 × 6 m room (84 m^2) with 2.74 m ceilings and volume of 230 m^3
Existing HVAC system

- Total supply airflow rate = 1700 m^3/h
- Return airflow = 1360 m^3/h
- Outdoor Air = 340 m^3/h
- Filter Efficiency = MERV 8 (~35% efficient for 1-6 μm particles)

Required total ACH = 6

Noise criterion = 40 dBA

Using ASHRAE's free (I-P only) Equivalent Outdoor Air Calculator tool (tinyurl.com/equivOAcalc), a CADR in-room air cleaner capable of 340 m^3/h is needed (Figure 10).

Name of Space / AHU / Building	Units	Classroom with MERV 8
Area	Sq Ft	900
Average Ceiling Height	Ft	9
Volume	Cu Ft	8100
Total Supply Air	CFM	1000
Total Outdoor Air	CFM	200
Supply Air ACH	ACH	7.41
Outdoor Air ACH	ACH	1.48
Central AHU Filter MERV Rating	MERV	8
UVC Single Pass Inactivation	%	0.00%
In Room Fan HEPA Filter	CADR	200
Number of In Room Fan HEPA Filters	Qty	1
Effective Air Changes Based on Technology		
ACH_OA	ACH	1.48
ACH_MERV filter in AHU	ACH	3.29
ACH_e,c	ACH	0.00
ACH_air cleaner	ACH	1.48
Sub-Total Effective ACH	ACH	6.26
Total Effective ACH_e		6.26
Time Required to achieve Target Air Changes	Target Air Changes	6
Minutes	Min	57.54
Hours	Hours	0.96

Figure 10. In-Room Air Cleaner Sizing Example

In-Room Air Cleaner Selection.

For **airflow**, specify that the unit's CADR be equal to or higher than needed (340 m^3/h in the preceding example) at the fan speed and associated noise level that is acceptable in the space. Some manufacturers note that the best performance for capturing small viral particles is at the lower fan speed.

A HEPA air cleaner or MERV of 13 or more is recommended for **filtration** of particles or inactivates viruses

When adding **accessories**, be careful not to get add technology that may cause problems or costs more to maintain.

Units may have high-speed and lower-speed options. Consider specifying one to run at a lower speed some or most of the time to control **noise/sound levels**. The noise level recommendations should be per noise recommendations in this chapter. If more than one unit is specified, take in account the noise generated by multiple units (in dB or dBA). Bluyssen et al. 2021 noted that in-room air cleaners can cause noise issues. Therefore applying properly defined noise data from the in-room air cleaner manufacturer to meet the space noise criterion is critical for implementation of this equipment. Chapter 49 covers acoustical design techniques and HVAC noise reduction design techniques and calculation procedures. Commercially available acoustics software can assist the designer with meeting the required noise design criteria.

Also, be sure to address **location and air distribution**. Unit(s) should be in the space without air inlets or outlets being blocked or causing gusts of air that may re-entrain dust from surfaces or cause discomfort.

Although the clean air delivery rate (CADR) is the main variable in sizing and selecting in-room air cleaners, performance can depend on its location in the room and whether the clean air reaches the occupants' **breathing zone**; this is the most critical space in a room where the sources and receptors of infectious aerosols reside. The location of portable air cleaners relative to other room supply air diffusers and return air grilles, or the location of supply air diffusers and return air grilles for permanent ducted units, in relation to other supply air diffusers and return air grilles can impact airflow patterns in the breathing zone. Special attention is needed for optimal location of portable air cleaners and supply air diffusers and return air grilles.

Multiple units may be necessary. If a higher CADR is needed or a single unit leads to noise issues, two or more air cleaner units will be needed to give higher airflow, flexibility (CADRs are additive), and acceptable noise level.

There are no U.S. federal certifications or standards for rating how well an air cleaner removes pollutants from indoor air (except for *Military Standard* 282, used only to rate particle reduction by high-efficiency filters). However, ASHRAE *Standard* 52.2 and ANSI/AHAM *Standard* AC-1-1988 can be used for rating particle removal by in-duct or portable air cleaners. These can be used for comparisons among different devices. No guidelines or standards are available for assessing the comparative ability of air cleaners to remove gaseous pollutants or radon and its progeny, and research is currently inadequate to draw firm conclusions regarding the relative effectiveness of air-cleaning devices in removing such pollutants.

As shown in the in-room air cleaner sizing example, the designer should consider combining several air-cleaning technologies to produce the desired MERV-13 equivalent level of air cleaning. For example, if a MERV-11 filter is used with UV-C, the UV-C device should provide at least 60% inactivation efficiency in conjunction with the filter to equal the efficiency of a MERV-13 filter (for 1 to 3 mm particles). Another way to look at air cleaning and disinfection is to calculate the equivalent amount of outdoor air in air changes per hour that is necessary to achieve the same reduction of airborne viral particles as would be achieved with a MERV-13 filter. This calculation can be done with a combination of air cleaning options. The ASHRAE Equivalent Outdoor Air Calculator tool (tinyurl.com/equivOAcalc) can help with this method.

Additional resources on in-room cleaners and combining air cleaning options include the following web sites:

- www.epa.gov/indoor-air-quality-iaq/what-guidelines-are-available-compare-air-cleaners-1
- ahamverifide.org/ahams-air-filtration-standards/
- www.rehva.eu/fileadmin/content/documents/Downloadable_documents/REHVA_COVID-19_Recommendation_Criteria_for_room_air_cleaners_for_particulate_matter.pdf
- www.epa.gov/indoor-air-quality-iaq/air-cleaners-and-air-filters-home
- www.aham.org/AHAM/News/Latest_News/New_Air_Cleaner_Standard_Measures_Virus_Removal.aspx
- www.ashrae.org/file%20library/about/position%20documents/filtration-and-air-cleaning-pd-feb.2.2021.pdf

Indoor air quality monitoring is used to improve the respiratory health of students and staff by reducing air pollutants and asthma triggers such as viruses, allergens, mold, dust, etc. IAQ monitoring involves continuously collecting data on the particles, gases, and chemicals present in the monitored space, including

- Carbon dioxide (CO_2)
- Particulate matter at PM_{10} (i.e., <10 μm diameter)
- Particulate matter at $PM_{2.5}$ (i.e., <2.5 μm diameter)
- Particulate matter at $PM_{1.0}$ (i.e., <1 μm diameter) in certain cases
- Volatile organic compounds (VOCs)

Figure 11. Space IAQ Dashboard Example (courtesy of Senseware)

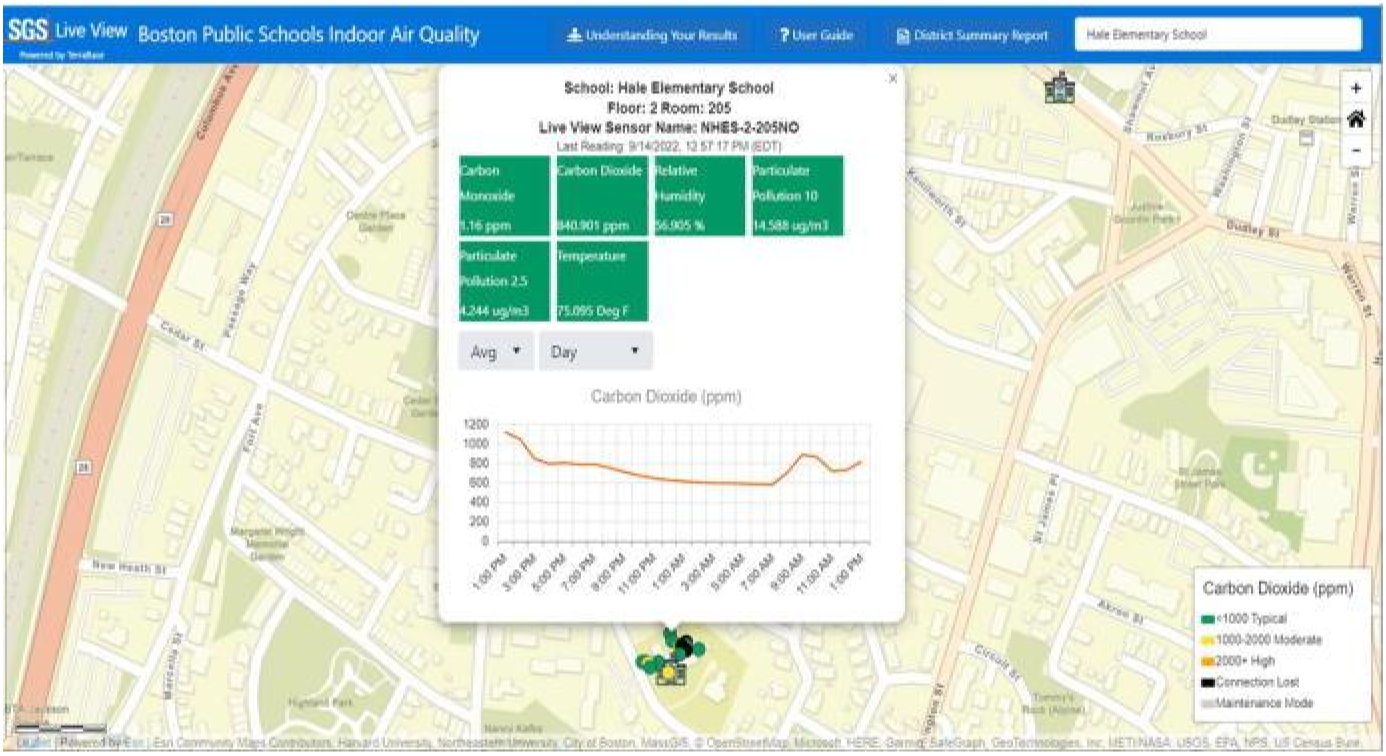

Figure 12. School District-Level IAQ Dashboard Example (bostonschoolsiaq.terrabase.com)

Chapter 10 of the 2021 *ASHRAE Handbook—Fundamentals* discusses the health effects of VOCs and specifically refers to the TVOC concentrations as an indicator of the ability of the combined VOC exposure to produce adverse health effects. Therefore, VOC monitoring should be carefully applied. Although there is no recommended range for $PM_{1.0}$, tracking this particulate size can provide additional information about the space filtration system operation.

The following pollutants can optionally be tracked and monitored:

- Carbon monoxide (CO)
- Formaldehyde (HCHO)
- Hydrogen sulfide (H_2S)
- Nitrogen dioxide (NO_2)
- Ozone (O_3)
- Sulfur dioxide (SO_2)

Additional factors such as temperature and humidity (which in most cases monitored by the HVAC control systems) are important air quality parameters. Other indoor environmental quality (IEQ) data such as noise and lighting can also be monitored.

The intent of IAQ monitoring is to identify trends, spot problem areas, and adjust and alert accordingly. As indicated, IAQ monitoring can help reduce airborne disease risk, identify areas that inhibit occupant wellbeing, and detect anomalies such as mold growth. Another important reason for monitoring additional parameters in schools (beyond CO_2) is **overcleaning**. Although CO_2 monitors are an adequate first IAQ monitoring step, they cannot detect and alert for overcleaning, which results in extremely high VOC levels. When school facility personnel want to gain additional insights into the impact of COVID-19 mitigation efforts, adding a VOC sensor to the CO_2 sensor in an augmented IAQ monitoring device allows greater understanding of levels of airborne contaminants.

IAQ monitoring can be

- **Continuous (24/7)** or real-time indoor air quality monitoring, using IAQ sensors that collect continuously IAQ variables (e.g., CO_2, $PM_{2.5}$)
- **One-time IAQ testing,** typically by an IAQ professional service using probes and other instrumentation for a single point in time.

A typical IAQ monitoring process includes the following:

- Installation of **hardware** such as sensors, detectors, etc., to track and monitor indoor air pollutants and parameters
- Installation and application of **software** packages and **dashboards** to track and analyze data and alert users
- Development and implementation of **procedures** and **processes** to solve and mitigate IAQ issues discovered by the monitoring systems

An example of an IAQ dashboard serving a single space is shown in Figure 11. Figure 12 shows an example of live IAQ monitoring in a school district.

UL *Standard* 2906 provides guidance on sensor selection, placement, reporting considerations, and sensor maintenance for ongoing assessment of IAQ in buildings. Other sources on IAQ data and monitoring include the following:

- WELL®
  - standard.wellcertified.com/air/air-quality-standards
  - v2.wellcertified.com/en/v2.2/air
  - v2.wellcertified.com/en/v2.2/air/feature/1
  - v2.wellcertified.com/en/v2.2/air/feature/5
  - v2.wellcertified.com/en/v2.2/air/feature/8
  - standard.wellcertified.com/air/air-quality-standards
- USGBC – LEED
  - www.usgbc.org/resources/leed-v4-building-design-and-construction-current-version
  - *LEED v4: Reference Guide for Building Design and Construction*
- RESET[R]: www.reset.build/standard/air
- WHO
  - apps.who.int/iris/handle/10665/260127
  - Guidelines for Indoor Air Quality—Selected Pollutants

Outdoor Air Quality Monitoring. Although ASHRAE *Standard* 62.1-2019, sections 4,6.1.4 and Appendix D, provides guidance and information on outdoor air treatment, special attention should be paid where natural ventilation and operable windows are used. Outdoor air quality monitoring can be achieved via local monitoring devices or by cloud-based services.

The following air pollutants, which are made up of both particles and gases, can be harmful in high concentrations:

- Ground-level ozone (O_3)
- Sulfur dioxide (SO_2)
- Carbon monoxide (CO)
- Nitrogen dioxide (NO_2)
- Fine and coarse particulate matter (PM_{10} and $PM_{2.5}$)

Individual air pollutants can be made up of primary pollutants (air pollutants directly emitted) and secondary pollutants (not directly emitted but formed when other pollutants react in the atmosphere). Chapter 11 of the 2021 *ASHRAE Handbook—Fundamentals* provides information on outdoor air contaminants.

Common methods of measuring outdoor air quality include

- Governmental monitoring stations: most reliable, set up in specific locations and measuring specific pollutants, but not real-time monitoring.

- Satellites: instruments observe air quality around the world, and the data is used by air quality managers and researchers.
- Local low-cost sensors: monitoring of specific pollutants without the ability to conduct in-depth air quality data analysis or advanced QA; accuracy of these low-cost air quality sensors can be questionable. These sensors also need regular calibration.

Figures 13, 14, and 15 show examples of real-time outdoor air quality data.

In the United States, outdoor air quality is reported according to the U.S. Environmental Protection Agency (EPA)'s **American Standard Air Quality Index (AQI)**. This measure runs from 0 to 500; the higher the AQI value, the greater the level of air pollution and the greater the health concern. The level of AQI is based on the five major air pollutants presented previously, which are regulated by the U.S. Clean Air Act. Each of these pollutants has a national air quality standard set by EPA to protect public health.

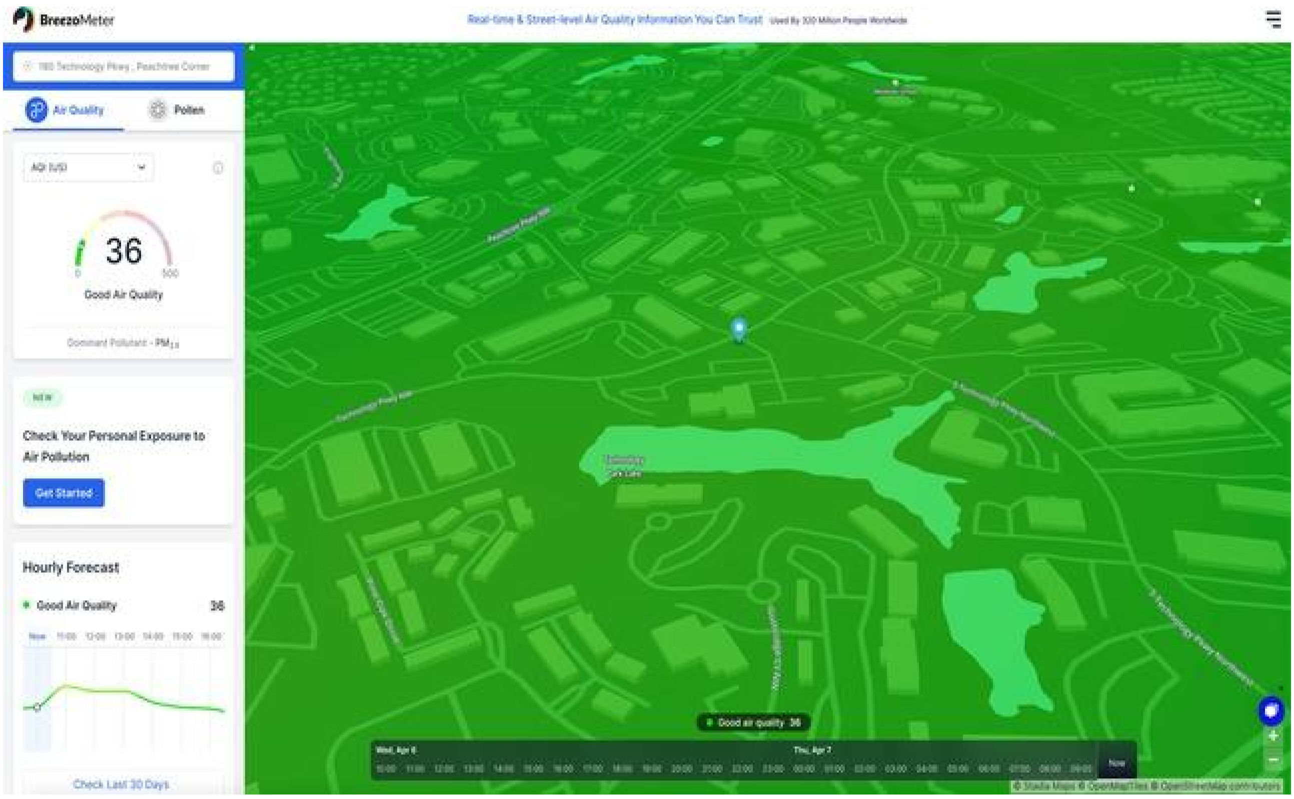

Figure 13. Real-Time Outdoor Air Quality Data Example: Map (courtesy of Breezometer [www.breezometer.com/air-quality-map/air-quality/united-states/peachtree-corners])

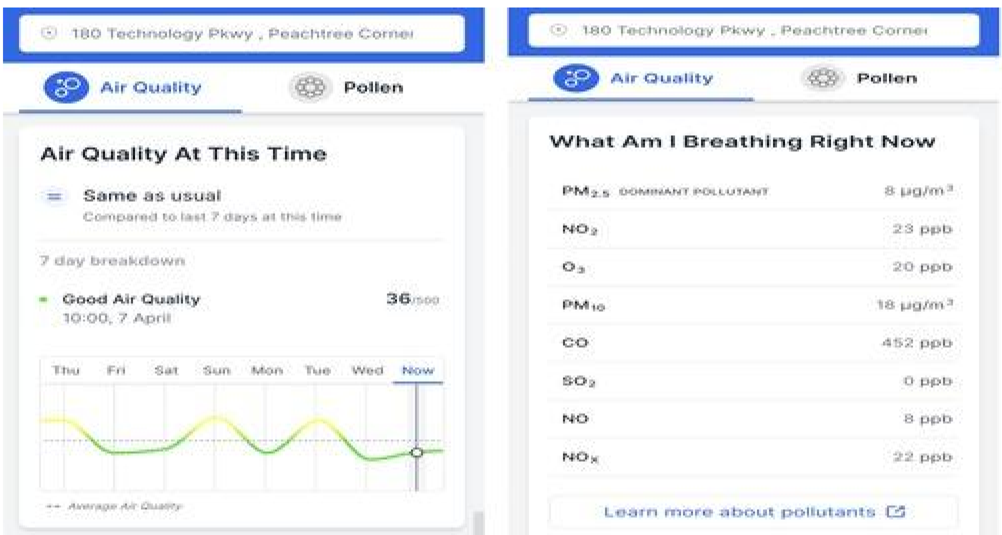

Figure 14. Real-Time Outdoor Air Quality Data Example (courtesy of Breezometer [www.breezometer.com/air-quality-map/air-quality/united-states/peachtree-corners])

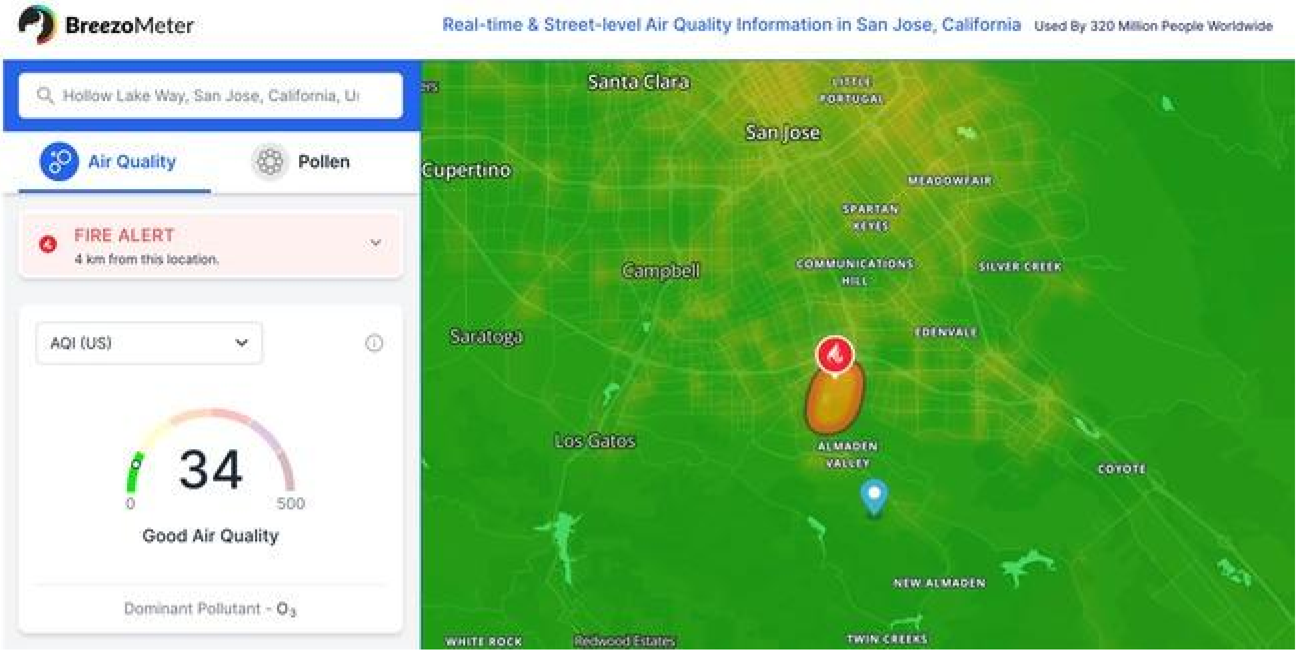

Figure 15. Real-Time Outdoor Air Quality Data Example: Outdoor Fire Alert (courtesy of Breezometer)

The AQI is divided into six categories, each of which corresponds to a different level of health concern and has a specific color. Note that there other countries use different index standards and scales: for example, IQA in France and DAQI in the UK.

Pollen, dust, and smoke from wildfires, which contain chemicals, gases, and fine particles, can also harm health. Breathing these fine particles can affect lung function and worsen asthma and other existing heart and lung conditions.

Sources of additional information include

- www.airnow.gov/aqi/aqi-basics/
- www.airnow.gov/aqi/aqi-basics/using-air-quality-index/
- www.airnow.gov/sites/default/files/2020-05/aqi-technical-assistance-document-sept2018.pdf
- apps.who.int/iris/handle/10665/345329

Nurse / Health Suite

The nurse/health suite accommodates the school nurse and other medical personnel and the services they perform. Typically, these facilities are located close to the main offices; the size normally depends on the total population of the school.

Typical guidelines for medical suites in elementary, middle, and high schools vary and often are based on the school district's space programming guidelines and number of students. These facilities can include

- Waiting area
- Nurse office
- Treatment room
- Isolation room(s)
- Rest/infirmary area
- Bathroom/toilet room(s)
- Storage area

In some cases, additional areas (e.g., examination room, health assistant room, file room) can be found.

HVAC systems for the nurse/health suite should be dedicated to that space and able to provide additional outdoor air, exhaust, and air pressure control in certain areas of the suite.

Table 12 Typical Recommended Temperature and Humidity Ranges for K-12 Nurse/Health Suite

Category/Humidity Criteria	Indoor Design Conditions	
	Temperature, °C	
	Winter	Summer
Nurse/Health Suite[a]		
30 to 60% RH[b]	21.1 to 23.9	21.1 to 23.9

Notes:

[a] Based on ASHRAE *Standard* 170-2021, Table 8.2, General Outpatient spaces, Urgent Care areas

[b] ASHRAE *Standard* 170-2021, Table 8.2, does not specify minimum relative humidity. Watch interior spaces to confirm no condensation is occurring, which would allow mold and moisture issues. Considerations such as geographical location, building envelope and other constraints should be evaluated and discussed with the owner to determine different minimum design relative humidity

Table 13 Typical Recommended IAQ Parameter Ranges for K-12 Nurse/Health Suite

IAQ Parameter	Indoor Air Quality (IAQ) Parameters Ranges		
	Recommended Range	Note	Reference
Carbon dioxide (CO_2), PPM	700 to 1000	For operation in recirculation/minimum OA mode.	
Particulate matter $PM_{2.5}$, µg/m^3	35 (max.), Less than 12 recommended	Per EPA for primary and secondary standards, 24 h standards with 98th percentile forms	
Particulate matter PM_{10}, µg/m^3	150 (max.)	Per EPA for PM_{10}, 24 h standards with one expected exceedance forms	www.epa.gov/pm-pollution/national-ambient-air-quality-standards-naaqs-pm

The COVID-19 pandemic has highlighted the probability of an infected, contagious person entering a nurse's suite; in preparation for future potential infectious aerosols, nurse's stations should be designed and built to accommodate these threats. Modernized HVAC systems designed and installed for the nurse suite should apply principles of an airborne isolation room applied for certain areas in hospitals. Note that an airborne infection isolation room compliant with ASHRAE *Standard* 170-2021 can be expensive to construct and operate, and may not be justified by a risk assessment. However there are pragmatic levels of containment can be achieved at a reasonable cost.

Design Criteria. The nurse/health suite can be considered as an outpatient health care facility for parameters required for thermal comfort, IAQ, sound, and health considerations. Consult local codes and standards and ASHRAE *Standard* 170-2021 to address these parameters. For design guidelines for HVAC-related background sound in rooms, see Chapter 49 of this volume and Chapter 8 of the 2021 *ASHRAE Handbook—Fundamentals*.

Typical design criteria and recommendations for temperature, humidity, ventilation, filtration, IAQ, and noise are shown in Tables 12, 13, 14, and 15.

Although, there is no current recommended range for $PM_{1.0}$, an additional $PM_{1.0}$ sensor will enable school technical personnel to monitor the sub-micron particle filtration efficiency of installed MERV-13 (or 15) filters. Use of a VOC sensor should be carefully investigated and coordinated (if applied), as well as regularly calibrated and maintained. Chapter 10 of the 2021 *ASHRAE Handbook—Fundamentals* discusses the health effects of VOCs, including using TVOC concentrations as an indicator of the ability of the combined VOC exposure to produce adverse health effects. As indicated in that chapter, the approach of tracking TVOC is no longer supported because the irritant potential and toxicity of individual VOCs vary widely and measured values depend on the sampling and methods used to quantify the TVOC levels.

Table 14 Minimum and Recommended ACH based Design Criteria for Ventilation and Filtration for K-12 Schools Nurse/Health Suite

Category	Ventilation and Exhaust				Minimum Filtration Efficiency, MERV[h]
	Minimum Outdoor Air (ACH)	Minimum Total Air (ACH)	Recommended[k] (100% OA with Energy Recovery and with Recirculation/Minimum OA Capability)		
			Recommended Outdoor Air (ACH)	Recommended Total Air (ACH)	
Waiting area[a, k]	2	10 (all exhausted)	2 to 10	10 (all exhausted)	13 h
Nurse office[b, k]	2	6	2 to 6	6	13 h
Treatment room[c, k]	2	6	2 to 6	6	13 h

Rest/infirmary room[d,k]	2	6	2 to 6	6	13 h
Isolation room[e,k]	2	12 (all exhausted)	2 to 12	12 (all exhausted)	13 h
Bathroom/toilet room[f]	NR	4 (all exhausted)	NR	4	

[i,j]

Notes:

[a] Based on 2019 California Mechanical Code table 4-A Waiting Area Primary Care Clinic, July 1, 2021, Supplement

[b] Based on ASHRAE *Standard 170-2021, Table 8-2, Urgent Care Treatment for minimum outdoor air, and 2019 California Mechanical Code Table 4-A Treatment room, July 1, 2021, Supplement*

[c] Based on ASHRAE *Standard 170-2021, Table 8-2, Urgent Care Treatment for minimum outdoor air, and 2019 California Mechanical Code Table 4-A Treatment room, July 1, 2021, Supplement*

[d] Based on ASHRAE *Standard 170-2021, Table 8-2 Urgent Care Treatment for minimum outdoor air, and 2019 California Mechanical Code Table 4-A Treatment room, July 1, 2021, Supplement*

[e] Based on ASHRAE *Standard 170-2021, Tables 7-1 (inpatient) and 8-1 (specialized outpatient) Spaces for Airborne Infection Isolation (AII) Room.*

[f] Based on ASHRAE *Standard* 170-2021, Table 8-2 Toilet Room

[h] MERV = minimum efficiency reporting values, based on ASHRAE *Standard 52.2-2017. It is recommended to take in account filter efficiency losses per ASHRAE Standard 52.2-2017, Appendix J and refer to MERV-A ratings, which will result in higher MERV value.*

[I] This table should not be used as the only source for design criteria. Governing local codes, design guidelines, etc

[j] Lower minimum MERV is suggested by ASHRAE *Standard* 170-2021, given the recommended improved IAQ. MERV-13 is shown as minimum recommended filter efficiency

[k] Recommended values are above the required minimum requirements to address optional enhanced IAQ.

Table 15 Typical Recommended Design Guidelines for HVAC-Related Background Sound for K-12 Schools Nurse/Health Suite

	Sound Criteria[a, b, c]	
Category	**NC/RC**	**dBa**
Nurse/health suite	35	40

Notes:

[a] Based on Chapter 49, Table 1. That table provides additional design guidelines for HVAC-related background sound in rooms.

[b] RC (Room Criterion), from Chapter 8 of the 2021 *ASHRAE Handbook—Fundamentals.*

[c] Approximate overall sound pressure (see Table 1 in Chapter 49).

Nurse/health suites need outdoor air for ventilation. Outdoor air is introduced to the occupied areas and then exhausted by fans, used for energy recovery, or exhausted through openings, removing indoor air pollutants generated by occupants and any other building-related sources. ASHRAE *Standard* 170-2021 can be used to define the ventilation and exhaust design criteria, along with codes such as the 2019 *International Mechanical Code®*. Consult applicable local ventilation and exhaust standards to ensure compliance.

Table 14 provides recommendations for ventilation design and filtration based on ASHRAE *Standard* 170-2021, section 8 (General Outpatient Spaces) and 2019 *California Mechanical Code* (July 1, 2021, Supplement). Note that ASHRAE *Standard* 62.1-2019, Table 6.1, also provides ventilation requirements that are identical to ASHRAE *Standard* 170-2021, section 8, but it is based on people outdoor air rate and area outdoor air rate. Both ASHRAE *Standards* 170-2021 and 62.1-2019 are minimum standards that provide control of environmental comfort, asepsis, and odor

Noise levels in the nurse suite are based on typical noise levels for hospitals and clinics, as shown in Table 1 of Chapter 49. Note that, since there is no specific requirement for each area found in the nurse/health suite, the criterion for procedure room was selected as representative of all the areas in this suite. Table 15 summarizes applicable noise criteria for K-12 schools' nurse/health suite.

The HVAC system for the nurse/health suite will be selected based on that for the school as a whole. An independent system serving the suite is preferable. The system can be part of a decentralized system serving the school or served by a central chilled- and hot-water system for heating and cooling. Although the minimum design requirements for ventilation and air circulation rate are based on ASHRAE *Standard* 170-2021 and the 2019 *California Mechanical Code*, Table 4-A, supplement July 1, 2021, it is recommended to consider a 100% outdoor air system that can also operate as a recirculation unit and minimum outdoor air.

Figure 16 depict a conceptual design of a nurse/health suite serving a school with 500 to 600 students. The total area of the suite is around 84 m^2 and includes three cots (one cot per 200 students) and one isolation room. The

HVAC system is based on 100% OA DOAU, providing four, six, ten, and twelve air changes per hour, as shown in Figure 17. The DOAU is equipped with a counterflow air-to-air energy recovery heat exchanger (no cross contamination) and can supply highly filtered air (MERV-13), cooling, heating, dehumidification, and humidification. Special attention should be given to properly locating supply diffusers, return (preferably low return), and exhaust grilles.

To minimize any potential infection, three areas (isolation room, waiting area, and toilet) are equipped with ceiling-mounted/upper-air UV-C.; in the waiting room. this equipment has an internal fan. In addition to the standard temperature and humidity control devices, the system can be equipped with IAQ sensor to track and control variables such as CO_2, $PM_{2.5}$, PM_{10}, and ACH. Figures 17 and 18 depict the air change rate and pressure relations of each space and the control and monitoring devices, respectively.

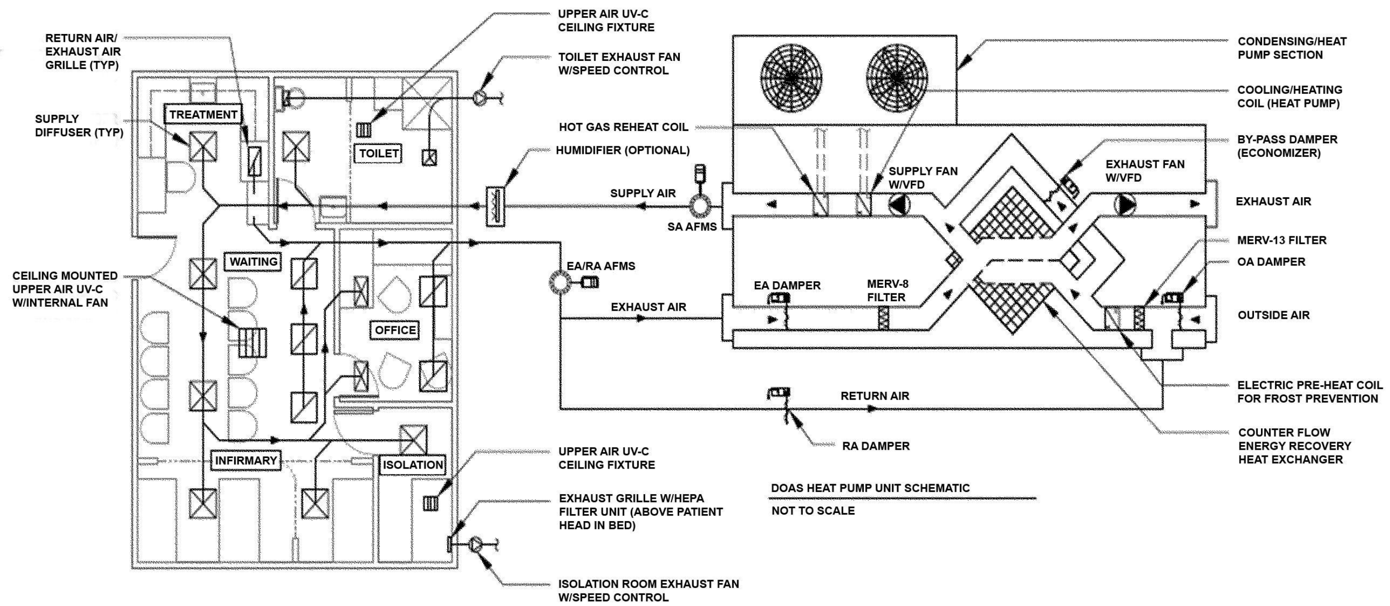

Figure 16. Conceptual Design of Nurse/Health Suite (84 m^2 suite, 500 to 600 students, with one cot per 200 students and one isolation room)

The nurse/health suite HVAC system should be constant volume (CV) and operate at the following main modes:

- **Occupied Mode: 100% OA.** This is the typical mode, with the highest level of protection. Both fans of the DOAS are on. The energy recovery system is fully used, and temperature and humidity controlled to maintain desired levels. Cooling, heating, dehumidification (through cooling and hot-gas reheat and other applicable systems such as HW and electric SCR), and humidification (with optional humidifier) are used. Airflow is controlled and tracked by airflow measuring stations to maintain the desired supply air, total space ACH, and exhaust air for energy recovery. Local (toilet and isolation room) exhaust fans are set to the proper exhaust airflow option to keep the flow measuring station on; isolation room exhaust stays constant, and variable-frequency drive (VFD) fans are adjusted as needed to maintain that constant airflow speed. Additional protection can come from UVGI units. CO_2 will be the lowest and close to ambient (outdoor) CO_2 levels. and IAQ sensors for PM $_{2.5}$ and PM $_{10}$ are tracked to confirm filtration effectiveness.

- **Occupied Mode: Recirculation/Minimum OA.** This mode provides the lowest level of protection and should be used when applicable. Only the supply fan of the DOAU is on. The energy recovery system is bypassed, the OA damper moves to minimum OA position and OA airflow is measured to confirm the desired minimum OA flow rate. The return air damper is open, the exhaust air damper is closed, and the temperature and humidity are controlled to maintain their desired levels. Cooling, heating, dehumidification (through cooling and hot-gas reheat), and humidification (with optional humidifier) are used. Airflow is tracked by airflow measuring stations to maintain the desired supply air, total space ACH, and return air. Local (toilet and isolation room) exhaust fans are set to the proper air exhaust airflow. UVGI units can be used for extra protection. CO_2 is maintained around 700 to 1000 PPM. IAQ sensors for PM $_{2.5}$ and PM $_{10}$ are tracked to confirm filtration effectiveness.

- **Unoccupied Mode.** This mode is used during unoccupied hours. The energy recovery system is bypassed, the OA damper moves to 0% (closed), the return air damper opens, and the exhaust air damper closes. Temperature and humidity will be controlled to maintain the desired levels for setback/setup. The DOAU supply fan cycles on demand. Cooling, heating, dehumidification (through cooling and hot-gas reheat) and humidification (with optional humidifier) are used. Local (toilet and isolation room) exhaust fans are off. Confirm that any infectious waste is removed at the end of the day and not stored in these spaces while the system is off.

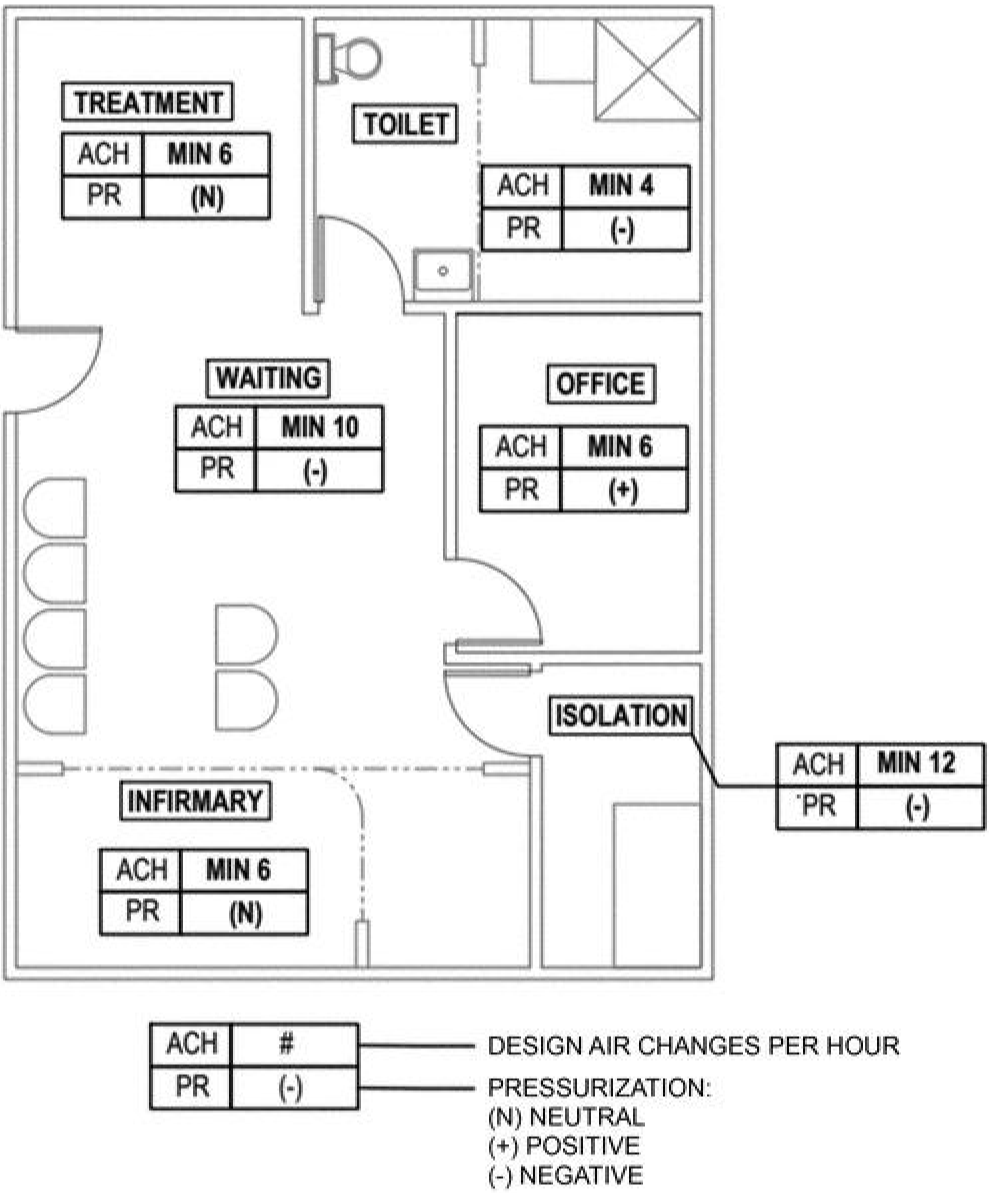

Figure 17. Pressurization Plan of Example Nurse/Health Suite

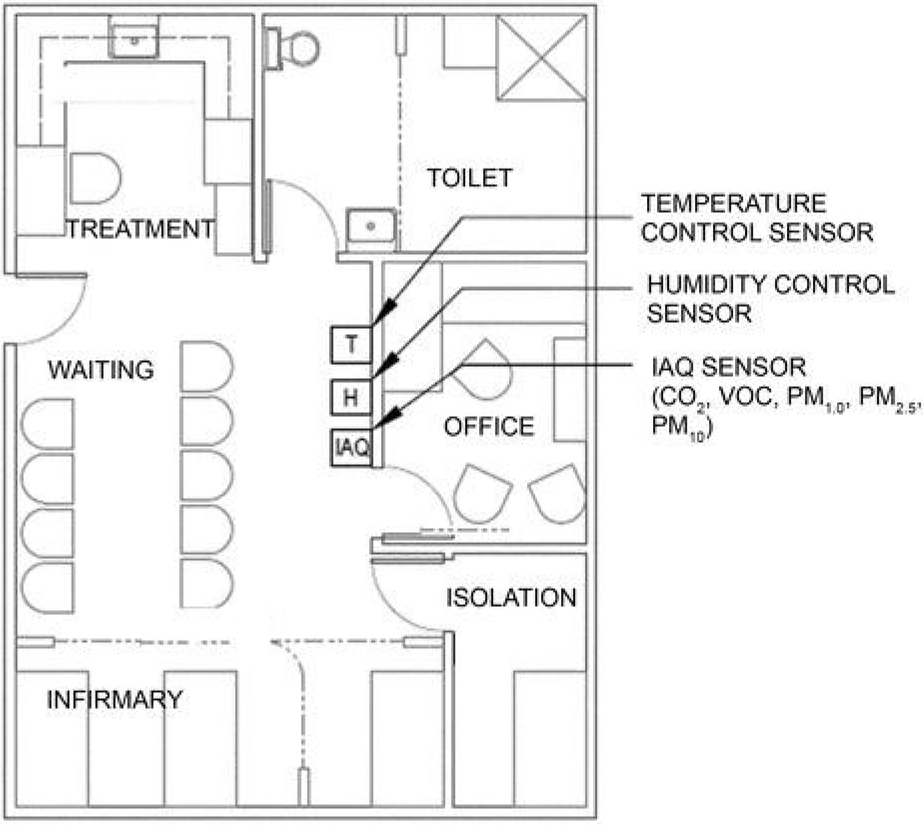

Figure 18. Example of Nurse/Health Suite Temperature, Humidity, and IAQ Sensor Placement

Note that the preceding description is general and, depending on project requirements, more project specific sequences can be developed.

3. COLLEGES AND UNIVERSITIES

General and Design Considerations

College and university facilities can be comprised of a campus, cluster of buildings, or a single isolated building. Some colleges and universities have satellite campuses scattered throughout a city or a state. The design criterion for each building is established by the requirements of its users. The following are major facilities commonly found on college and university campuses.

Libraries/Learning Centers. Libraries and learning centers are central to the purpose of modern college and university. A library can be a collection of printed and electronic material and/or a place where individuals or groups of students gather for study or other academic activities. A typical library includes the following areas:

- Collection/stacks
- Library staff and services
- Main reading room
- Specialty areas (special collections, music and audiovisual resources, computer areas, etc.)
- Support areas

Temperature and humidity control is needed for maintaining the printed materials and the collections. Proper air distribution can be challenging because of different ceiling heights, stacks, mezzanines, etc. Reading rooms require air supply without draft, and special collections or rare books areas need a dedicated air-handling system. Noise is also critical in libraries; an acoustic consultant must review or be part of the mechanical design. See Chapter 24 for specifics on HVAC design for libraries.

Academic Buildings and Professional Schools. These buildings accommodate classrooms, which are the core of the university teaching and learning experience. There are two main categories of classrooms, with several subcategories (Neumann 2003):

Flat-floor classrooms are typically rectangular, basic, and easily reconfigurable for different teaching needs. In most cases, the number of students is relatively low. Sometimes, a larger flat-floor room can be subdivided to smaller rooms by folding or sliding partitions.

Sloped-floor classrooms are used when the class size exceeds that at which all students can see each other clearly in a flat-floor classroom. Sloped-floor classrooms typically have more than 40 students. Those with a capacity of 250 students or more are generally referred as auditoriums, which require theater design consideration.

Academic buildings also have faculty offices and auxiliary areas to support teaching activities. Professional schools are typically allocated to a specific academic discipline. Each of these schools has specific needs, depending on the academic requirements. The HVAC design and systems for classrooms and other administrative areas are similar to classrooms in high schools (see Table 11).

Science Teaching and Research Facilities. College and university science facilities accommodate highly specialized areas for teaching and research in several disciplines (e.g., chemistry, biology, physics). Teaching facilities are designed mainly for group instruction, typically with one or more instructors and 12 to 32 students; an average-sized teaching lab can accommodate 24 students. The laboratory should be designed to support a range of activities for various courses: for example, a chemistry lab should be able to handle introductory chemistry, organic chemistry, etc.

Research facilities can be part of a science teaching building or grouped in a stand-alone research facility. Research facilities are customized and designed for graduate and postgraduate students, typically under the direction and supervision of several principal investigators (PIs). Unlike teaching labs, which are designed for large group instruction, research labs should be designed to accommodate the activities of individuals or small groups. Given potentially hazardous activities in teaching and research labs, the most critical factor in designing systems for labs is safety; this concern has major implications on the design of HVAC and mechanical systems.

Teaching and research labs may contain fume hoods, machinery, lasers, vivariums, areas with controlled environments, and departmental offices. The HVAC systems and controls must be able to accommodate diverse functions of the facility, which may have 24 h, year-round operation, and yet be easy to service and quick to repair. Variable-air-volume (VAV) systems can be used. Proper control systems should be applied to introduce and extract the required quantities of supply and exhaust air. Maintaining the required space pressure differential to adjacent spaces and the minimum airflow under all circumstances is extremely critical for safe laboratory operation. Energy can be saved by recovering energy from exhaust air and tempering outdoor makeup air. Pay special attention to containment in the exhaust air stream. Examine potential carryover of air from exhaust to supply, and interaction with the energy recovery device adsorbent for cases with total (sensible and latent) energy recovery. In general, air exhausted from fume hoods should not be used for energy recovery. Where heat recovery from fume hoods exhaust is considered, careful coordination with the site health and safety (H&S) officer is required. Other energy-saving systems used for laboratory buildings include (1) active chilled beams (Rumsey and Weale 2006), (2) ice storage, (3) heat reclaim chillers to produce hot water for domestic use or for booster coils in the summer, and (4) cooling tower free cooling.

The design engineer should discuss expected contaminants and concentrations with the owner to determine construction materials for fume hoods and fume exhaust systems. Close coordination with H&S personnel is vital for safe laboratory building operation. Back-up or standby systems for emergency use should be considered, such as alarms on critical systems. Maintenance staff should be thoroughly trained in upkeep and repair of all systems, components, and controls. For design criteria and other design information on laboratories and vivariums, see Chapter 17, ANSI/AIHA *Standard* Z9.5-2012, DiBerardinis et al. (2013), and McIntosh et al. (2001). Additional information on energy conservation in labs can be found on the Laboratory Benchmarking Tool (LBT) web site (lbt.i2sl.org).

Some research facilities include vivariums (animal facilities). These spaces are commonly associated with laboratories, but usually have their own separate areas. Additional areas that can found in vivariums are necropsy rooms, surgery suites, and other specialty areas. Animal facilities need close temperature control and require a significant amount of outdoor ventilation to control odors and prevent the spread of diseases among the animals. Animal facilities are discussed in Chapters 17 and 25, and by the National Research Council (NRC 1996).

Housing

Student Housing. Housing is an integral part of student's academic and social life. Student housing of the past had few amenities, and for years the emphasis was on economy and reduced construction cost. Today, more housing administrators are changing this philosophy by providing an enhanced, rich on-campus residential life. Student and staff housing facilities include the following:

- Dormitories (residence halls)
- Suites
- Apartments and studios
- Couples housing

Dormitories (residence halls) are typically for freshman students. Student living units are generally single- or double-occupancy rooms that open directly to a corridor. The building can be a high rise or low rise, depending on the setting or the location of the campus. Typically, there are two students per room, with one single-occupancy room reserved for the resident assistant. On the ground floor are public facilities, which may include a living room, reception desk, kitchen/lounge, and cafeteria. Dorm rooms often do not have individual kitchens or bathrooms; communal bathrooms usually serve one floor.

Suites are typically occupied by older undergraduate students. The suite plan typically connects four to six double-occupancy sleeping room rooms with a shared bathroom and living room.

Apartments and **studios** are often occupied by upper-division and graduate students, and are basically suites with kitchens and private bathrooms. Apartments and studios are the most desirable housing and are the most expensive because of their additional plumbing and electrical systems.

Couples housing generally consists of one-, two-, or three-bedroom apartments in separated complexes. A couples housing facility may have a section for married couples, who often have young children whose safety and security needs must be considered. These facilities may have outdoor play areas and child care facilities.

Faculty Housing. Faculty members typically find housing outside the campus, but the high cost of local living has convinced many universities that offering on-campus housing will attract the best candidates to their academic institution. This type of housing is similar to typical residential housing and can include duplexes, apartments, townhouses, and single-family homes.

Air conditioning in campus housing for students and faculty should be quiet, easily adjustable, and draft free. Systems that require little space and have low total owning and operating costs should be selected.

Pay special attention to the ventilation requirements by applying applicable local codes and ASHRAE standards. Note that both ASHRAE *Standards* 62.1-2022 and 62.2-2022 cover areas in college and university housing facilities and thus should be consulted. Table 16 lists design criteria for housing facilities.

Typically, decentralized systems with DOAS or air-to-air energy recovery should be used for these applications:

- Water-source heat pumps (WSHPs), also known as water-loop heat pumps (WLHPs)
- Geothermal heat pumps (groundwater heat pumps, ground-coupled heat pumps)
- Hybrid geothermal heat pumps (combination of groundwater heat pumps, ground-coupled heat pumps, and an additional heat rejection device), where there is limited area for the ground-coupled heat exchanger or where it is economically justified
- Light commercial split systems
- Minisplit and variable-refrigerant-flow (VRF) units
- Fan-coil units

When dormitories are closed during winter breaks, the heating system must supply sufficient heat to prevent freeze-up. If the dormitory contains non-dwelling areas, such as administrative offices or eating facilities, these facilities should be designed as a separate zone or with a separate system for flexibility, economy, and odor control. Solar energy can be considered for domestic hot water (DHW).

Athletics and Recreational Facilities

College and university sports facilities ranging from large arenas for ice hockey, basketball, and other spectator sports, to small gymnasiums and fitness centers. College sports activities are heavily influenced by intercollegiate sports, which are governed by extensive standards and regulations of the National Collegiate Athletic Association (NCAA). A university's participation in intercollegiate sports is well known to be an important revenue source and is often critical in prospective students' decision-making processes. Typical sports facilities that can be found in universities campuses are

- Collegiate arenas (indoor sport arenas dedicated to a particular sport, or multipurpose)
- Gymnasiums (for activities such as physical education)
- Field houses (for outdoor activities to be played indoors during bad weather)
- Natatoriums
- Recreation centers (multipurpose activity courts, fitness/weight room)

Chapter 5 of this volume covers design practices for several of these facilities. For ice rinks and arenas, consult Chapter 44 of the 2022 *ASHRAE Handbook—Refrigeration* and Chapter 27 of Harriman et al. (2001) (which covers natatoriums, as well).

Social and Support Facilities

Social and support facilities and campus centers include common areas designed to improve and expand student services: for example, auditoriums, lounges, lobbies, dining and food services, offices and administration, libraries, cafés and snack bars, classrooms, meeting rooms, bookstores and other retail areas, banks, printing shops, etc. Given this variety of applications, the reader should refer to Chapters 2, 3, 5, 24, and 34 of this volume and other application-specific sources for the design of HVAC&R systems for these areas.

Cultural Centers

Universities and colleges with cultural facilities and academic programs such as music, theater, dance, and visual arts enhance the cultural and artistic lives of students. The two main cultural facilities are performing arts and visual arts centers. Several areas are common for both these areas are

- **Public support areas,** which include lobby, student common, café, gift shop, box office, coat room, and restroom facilities
- **Administration/faculty areas,** including offices, administration areas, and conference rooms
- **Back of the house,** such as loading docks, shipping and receiving, maintenance and building operation, mechanical rooms, and control rooms
- **Performing arts,** with unique spaces such as
    - **Performance spaces,** including seating areas, stage, orchestra pit, dimmer room, audio rack room, and lighting and sound control
    - **Backstage/performer support,** such as the green room, dressing rooms, wardrobe, laundry, and storage
    - **Theater, music, and dance instruction areas,** which include rehearsal rooms, dance studios, instrumental rehearsal rooms, listening labs, and music and instrument storage
- **Museums,** which include art galleries, workrooms, art storage, and conservation areas
- **Fine arts instruction rooms,** comprising design, drawing, painting, print making studios, photographic darkrooms, and library
- **General arts instruction,** such as lecture halls, classrooms, seminar rooms, and computer labs

Table 16 Housing Rooms Design Criteria[a]

	Inside Design Conditions							
	Winter		Summer					
Category	Temperature	Relative Humidity[b]	Temperature	Relative Humidity	Minimum Ventilation Rate	Exhaust	Filter Efficiency[e]	Noise, RC (N);QAI < 5 dB Level[f]
Dorm, suite rooms	21 to 23°C	30 to 35%	23 to 26°C	50 to 60%	c	c, d	8 to 13 MERV	30
Apartments and studio rooms	21 to 23°C	30 to 35%	23 to 26°C	50 to 60%	c	c, d	8 to 13 MERV	30
Couple and faculty housing	21 to 23°C	30 to 35%	23 to 26°C	50 to 60%	c	c, d	8 to 13 MERV	30

NR = not required.

[a] This table should not be used as the only source for design criteria. The data contained here can be determined from ASHRAE handbooks, standards, and governing local codes.

[b] Evaluate considerations such as geographical location, building envelope, and other constraints and discuss with building owner to determine minimum design relative humidity.

[c] Per ASHRAE *Standards 62.1-2022 and 62.2-2022.*

[d] Air exhaust from bathroom, toilet, and kitchen areas.

[e] Per ASHRAE *Standard* 52.2-2017. MERV-13 is recommended.

[f] Based on Chapter 49.

Cultural centers encompass a large number of specialty areas, and careful attention required when designing, constructing, and maintaining the HVAC&R systems. See Chapters 2, 3, 5, and 24 for details.

Central Utility Plants

Universities and college campuses typically have large central utility plants or smaller mechanical rooms serving an individual building or cluster of buildings. The central utility plants can supply chilled water, steam, and electrical power or only steam or chilled water. In these cases, chilled water, steam, or hot water is generated at a building level or in one smaller utility plant serving a cluster of buildings. The setup depends heavily on site constraints, including geographic location. The central utility plant comprises chillers, boilers, steam specialties, primary and secondary pumps, cooling towers, heat exchangers, combined heat and power (CHP) prime movers, and CHP auxiliary equipment, electrical power transformers, switchgears, control systems, etc. In the 2020 *ASHRAE Handbook—HVAC Systems and Equipment*, see Chapter 3 for design of central heating and cooling plants, Chapter 7 for CHP, Chapter 11 for steam systems, and Chapter 12 for district heating and cooling.

In addition to accommodating the mechanical and electrical equipment, central utility plants also house engineering, operation, and maintenance personnel. Central plants are not conditioned but generally are heated and ventilated; storage areas, shops, and other support areas are heated, ventilated, or cooled, depending on the use. Offices, administration areas, and control rooms are typically fully conditioned.

Where economically justifiable, chilled water and steam can be purchased from an independent operator.

Central plant optimization tools have been gaining momentum for large campuses, allowing optimal operation of central utility plants containing on-site power generation, chiller plants, heating plants, and storage systems. The section on Selected Topics on Energy and Design provides information on these systems.

4. SUSTAINABILITY, ENERGY EFFICIENCY, AND INDOOR AIR QUALITY

Over recent years the educational community has increasingly embraced the principles of sustainable design, energy efficiency, and indoor environmental quality. Beginning as a means to educate the students in conserving earth resources, this approach also provides benefits such as enhanced IAQ and lower operating costs. Note that any energy efficiency upgrades and measures should not compromise occupant health; balancing IAQ and comfort against energy efficiency and cost is critical.

There are several definitions of sustainability, green buildings, and high-performance buildings. In the context of this chapter, these terms refer to a building that minimizes the use of energy, water, and other natural resources and provides a healthy and productive indoor environment (e.g., IAQ, lighting, noise). The HVAC&R designer plays a major role in supporting the design team in designing, demonstrating, and verifying these goals, particularly in the areas of energy efficiency and indoor environmental quality. Because energy efficiency and IAQ are areas of expertise of the HVAC&R designer, this section covers these topics in more detail.

Several tools and mechanisms are available to assist the HVAC&R designer in designing sustainable educational facilities; common tools include the following:

Advanced Energy Design Guide (AEDG) for K-12 Schools

The *Advanced Energy Design Guide for K-12 Schools* (ASHRAE 2008) was developed to help designers of K-12 facilities achieve energy savings of at least 30% compared to ANSI/ASHRAE/IESNA *Standard* 90.1-1999.

An updated version of the *Advanced Energy Design Guide for K-12 Schools* (ASHRAE 2011) is also available to help designers of K-12 facilities achieve energy savings of at least 50% compared to ANSI/ASHRAE/IESNA *Standard* 90.1-2004. Most recently, *Advanced Energy Design Guide for K-12 School Buildings—Achieving Zero Energy* (ASHRAE 2018) is available to help designers to achieve net zero energy.

These guides provide recommendations for energy-efficient design based on geographic location, covering issues such as envelope, lighting, HVAC, and service water heating (SWH), and can be found online through the ASHRAE Bookstore.

ANSI/ASHRAE/ICC/USGBC/IES *Standard* 189.1-2020

This standard provides minimum requirements for the siting, design, construction, and plan for operation of high-performance green buildings to

- Balance environmental responsibility, resource efficiency, occupant comfort and well-being, and community sensitivity
- Support the goal of development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

This standard provides minimum criteria that apply to the following elements of building projects:

- New buildings and their systems

- New portions of buildings and their systems
- New systems and equipment in existing buildings

The standard addresses site sustainability, water use efficiency, energy efficiency, indoor environmental quality (IEQ), and the building's impact on the atmosphere, materials, and resources.

Leadership in Energy and Environmental Design (LEED®)

Many schools are seeking LEED certification from the U.S. Green Building Council (USGBC). The LEED for Schools (USGBC 2009a) rating system is unique to the design and construction of K-12 schools.

The system awards credits in seven categories:

1. Sustainable sites (SS)
2. Water efficiency (WE)
3. Energy and atmosphere (EA)
4. Materials and resources (MR)
5. Indoor environmental quality (IEQ)
6. Innovation and design process (ID)
7. Regional priority (RP)

Categories 1 to 5 include prerequisites, which are mandatory for certification, and credits. The last two categories are credits only.

Typically, the HVAC&R designer is heavily involved in the (1) energy and atmosphere and (2) indoor environmental quality categories. In the EA category, the HVAC&R designer, along with the architect, electrical engineers, and plumbing engineers, demonstrates compliance with prerequisite EA 2 by using the following procedures:

- Option 1: Whole-building energy simulation, by demonstrating 10% improvement (for new construction) or a 5% improvement in the proposed building performance rating for major renovations to existing buildings over ANSI/ASHRAE/IESNA *Standard* 90.1-2007, appendix G. Projects registered after April 7, 2016, are subject to the four-point mandatory minimum, and must demonstrate an 18% improvement in the proposed building performance rating for new building or 14% improvement in the proposed building performance for major renovation to existing buildings compared to the baseline building performance rating.

- Option 2: Prescriptive compliance path, for less than 18 600 m^2, using *Advanced Energy Design Guide for K-12 Schools* (ASHRAE 2008). With this option, the project needs to comply with all the prescriptive measured identified in ASHRAE (2008) and also comply with all applicable criteria as established in the guide for the climate zone in which the building is located. Projects outside the United States may use ASHRAE/ASHRAE/IESNA *Standard* 90.1-2007, Appendices B and D, to determine the appropriate climate zone. This option is not available for projects registered after April 7, 2016, to meet the four-point mandatory minimum.

- Option 3: Prescriptive compliance path: *Advanced Buildings™ Core Performance™ Guide*, developed by the New Buildings Institute (2007). This option is applicable for buildings less than 9300 m^2.

Additional EA credits can be obtained by demonstrating additional energy cost savings compared to the ANSI/ASHRAE/IESNA *Standard* 90.1-2007's Appendix G and from other sections of the EA group, such as on-site renewable energy, enhanced commissioning, measurement and verification, and green power. In addition, the HVAC&R designer is involved in issues of indoor environmental quality; these issues are typically associated with minimum and enhanced ventilation, acoustics, thermal comfort, controls, daylighting, mold prevention, etc.

Details and additional information on new construction and major renovations of K-12 facilities or previous editions of LEED for schools can be found on the USGBC web site at new.usgbc.org/leed.

For existing schools, the LEED rating system for existing buildings can be applied (see USGBC web site).

ENERGY STAR for K-12 Facilities

Similarly to appliances, a building or manufacturing plant can earn the ENERGY STAR label. An ENERGY STAR-qualified facility meets strict energy performance standards set by the U.S. EPA and uses less energy, is less expensive to operate, and causes fewer greenhouse gas emissions than its peers. To qualify, a building must score in the top 25% based on the EPA's National Energy Performance Rating System, which considers energy use among other, similar types of facilities (including K-12 educational facilities) on a scale of 1 to 100. This rating system accounts for differences in operating conditions, regional weather data, and other important considerations.

To determine eligibility for the ENERGY STAR label, as well as LEED-EB certification, the EPA's free online tool, Portfolio Manager, can be used (www.energystar.gov/benchmark). If the school facility scores 75 or higher (of a maximum of 100) using Portfolio Manager, a professional engineer will verify and approve the analysis. Detailed procedures for earning the ENERGY STAR labels can be found at www.energystar.gov, including case studies, useful information for educational facilities, and a list of professional engineers who provide free verification services. A database of ENERGY STAR labeled K -12 schools can be found online as well.

Collaborative for High Performance Schools (CHPS)

CHPS (www.chps.net) is leading a national movement to improve student performance and the entire educational experience by building the best possible schools. CHPS provides useful information for designing and maintaining high-performance schools. The following is a list of best practices and information available from CHPS:

- Planning for high-performance schools
- Design for high-performance schools
- Maintenance and operations of high-performance schools
- Commissioning of high-performance schools
- High-performance relocatable classrooms

CHPS developed criteria for new construction and major renovations (chps.net/chps-criteria). CHPS has criteria available for every state; if a local adaptation has not been adopted in certain area, the national version (US-CHPS v2.0 [2020]) can be used (chps.net/us-chps-online).

The following sections included in the CHPS criteria:.

- Integration and innovation
- Indoor environmental quality
- Energy
- Water
- Site
- Materials and waste
- Operations

International Institute for Sustainable Laboratories (I^2SL)

I^2SL facilitates a network of technical capabilities to address the needs of facility designers, engineers, owners, and facility managers of laboratory and similar high-performance facilities normally found in higher education. Examples of help include

- Providing infrastructure assessments
- Offering technical assistance
- Sharing new technologies through customized training and workshops
- Assisting with project charettes
- Developing case studies and best practices
- Supporting the next generation of sustainable design professionals

Table 17 Examples of Domestic and International Rating Systems

Rating System	Country
BRE Environmental Assessment Method (BREEAM)	U.K.

Comprehensive Assessment System for Building Environmental Efficiency (CASBEE)	Japan
Germany Sustainable Building Certificate (DGNB)	Germany
Green Building Evaluation Standard (Three-Star System)	China
Green Globes System	United States, Canada
Green Star	Australia
Hong Kong Building Environmental Assessment Method (HK-BEAM)	China (Hong Kong only)
National Green Building Standard	United States

Additional information can be found at lbt.i2sl.org.

EnergySmart Schools

The EnergySmart Schools (U.S. DOE 2009) program provides energy efficiency information on planning, financing, design build and operation and maintenance of schools at www.energy.gov/sites/prod/files/2013/11/f5/ess_o-and-m-guide.pdf.

Other Domestic and International Rating Systems

Additional domestic and international systems are shown in Table 17.

Underwriters' Laboratories (UL) Verified Healthy Building Program

The UL's Verified Healthy Building program (www.ul.com/services/verified-healthy-buildings) verifies that a building's indoor spaces provide a healthy environment for occupants in up to five categories:

- Indoor air quality
- Water quality
- Building hygiene
- Lighting
- Acoustic

There are three tiered levels offered.

In **Tier 1: Verified Healthy Building for Indoor Air**, building spaces are evaluated against rigorous methodologies for IAQ and policies and plans are devised for continual improvement of IAQ. HVAC system inspections verify preventative maintenance and focus on ventilation, filtration, and hygiene to help ensure excellent IAQ into the future.

Tier 2: Verified Healthy Building for Indoor Air and Water addresses topics covered by Tier 1 as well as assessing building water quality (both for human consumption and for prevention of waterborne pathogens).

Tier 3: Verified Healthy Building for Indoor Environment: Air, Water, Hygiene, Light and Acoustics, includes Tier 1 and 2 topics and further addresses building hygiene, lighting and acoustics.

UL aligns their program criteria with industry-recognized third-party organizations such as the EPA, NIOSH, WHO, CDC, ASHRAE and LEEDv4.1.

International WELL Building Institute's (IWBI) WELL Building Standard (WELL)

IWBI's WELL Building Standard is a performance-based system for measuring, certifying, and monitoring features of the building environment. The *WELL Building Standard*™ v.2 is used to deliver enhanced human health and well-being; its categories include

- Air
- Water
- Nourishment
- Light
- Movement

- Thermal comfort
- Sound
- Materials
- Mind
- Community
- Innovation

Each category includes mandatory preconditions for certification and optimizations items. The rating is based on the number of points achieved for certifications at bronze, silver, gold, or platinum levels.

Detailed information about WELL can be found at v2.wellcertified.com/en/wellv2/overview

RESET®

The RESET® standard (www.reset.build/standard) is a sensor-based and performance-driven data standard and certification program for the built environment. It creates a structure for data quality, continuous monitoring, and benchmarking, using technology to assess performance of buildings and interior spaces in operation.

The standard consists of five (5) stand-alone standards:

- Materials
- Air
- Water
- Energy
- Circularity

They are modular and can be implemented separately or together depending on the needs of the project.

The RESET® *Air Standard* (www.reset.build/standard/air) is a data standard for air quality monitoring, prioritizing ongoing results and long-term occupant health with a focus on the operational phase. Indoor air quality data must be continuously gathered through air quality monitors that measure the following parameters:

- Particulate matter (PM2.5)
- Total volatile organic compounds (TVOC)
- Carbon dioxide (CO_2)
- Temperature
- Relative humidity

5. ENERGY CONSERVATION CONSIDERATIONS

Energy standards such as ANSI/ASHRAE/IESNA *Standard* 90.1-2019 and local energy codes should be followed for minimum energy conservation criteria. Because the HVAC&R designer deals mostly with the mechanical systems, Table 18 presents a list of selected energy conservation measures. Note that additional measures such as modifications to lighting, motors/drives, building envelope, and electrical services should be considered for energy reduction. Energy procurement or supply-side opportunities should also be investigated for energy cost reduction.

Table 18 Selected Potential Energy Conservation Measures

Category	Description
HVAC air side	DDC systems upgrade Variable-speed drives on fan motors Conversion from constant volume (CV) to variable air volume (VAV), where applicable Air-side economizer Temperature set point adjustments

	Exhaust fume hood controls modifications Reheat minimization DOAS and air-to-air energy recovery Destratification fans Airflow reduction and air-side retrocommissioning in laboratories Active chilled beams (classrooms, laboratories, etc.) Natural ventilation (where applicable) Evaporative cooling (where applicable)
Chiller plants	Chiller plant operation optimization (hydronic system) Chiller(s) replacement Chiller energy source switching Heat recovery (from CHP) driven chiller Cooling tower repair, optimization, replacement Cooling tower water treatment optimization Cooling tower fans conversion to variable speed Water-side free cooling Conversion of DX system to chilled water Offline chiller isolation Chilled/condenser water temperature reset Thermal storage
Boiler plants	Boiler optimization/replacement Burner optimization/replacements Oxygen and excess air trim controls Conversion of linkage-based burner control to parallel positioning (servo motors) Dual-fuel switching/capability Boiler heat recovery (stack economizer) Condensing boilers Boiler temperature reset Offline boiler isolation Automatic blowdown control Blowdown heat recovery Condensate systems upgrade and optimization Feed water delivery improvements Water treatment optimization
Steam and chilled-water distribution	Steam distribution pressure control Steam trap repair/replacement/program Insulation repairs/upgrade Piping balancing Variable-speed pumping Primary/secondary piping Conversion from constant flow to variable flow
Energy management and control systems	LAN systems/network interfacing Equipment sequencing Conversion to DDC system Space temperature setback and setup Demand control ventilation (DCV) Chiller plant efficiency monitoring (see ASHRAE *Guideline* 22-2008) Boiler plant efficiency monitoring (steam flow and gas flow) Duty cycling Chiller plant control optimization Boilers sequencing optimization Load shedding Remote communications Equipment performance and energy use monitoring Preventive/predictive maintenance Automated/web-based fault detection and diagnostics (FDD) Airflow and water flow measurements Energy metering and submetering Emissions and/or CO_2 tracking Use of information systems and building analytics

Central plant supply side and renewable energy	Combined heat and power (CHP) Solar energy (thermal) Photovoltaic applications Wind energy Geothermal energy and hybrid geothermal systems
Domestic hot water	Condensing water heaters Demand (tankless or instantaneous) water heaters Heat pump water heaters Solar domestic water heater and pool water heating

Source: Adapted from Petchers (2002).

6. ENERGY MEASUREMENT AND VERIFICATION (M&V)

Energy measurement and verification (M&V) is the process of measuring and verifying both energy and cost savings resulting from implementation of an energy conservation measure. An energy conservation measure is defined as the installation or modification of energy-using equipment, or systems, for the purpose of reducing energy use and/or costs.

M&V should be used to demonstrate savings in utility resources (e.g., energy, water) delivered through any type of savings project or program. This typically includes

- Building owners and managers
- Facility managers, plant and process engineers
- Energy service companies (ESCO) and other energy services professionals, such as energy auditors and energy management consultants, who provide advice or deliver energy savings through an energy performance (EPC), or other contracting arrangements

Energy M&V essentially compares energy use before and after an energy retrofit, taking into account and adjusting for non-retrofit changes (e.g., weather, occupancy schedules) that affect energy use. These variables must be removed to objectively calculate the energy savings from the energy conservation measure. Chapter 42 provides additional information on M&V.

The following is a short overview of M&V methodologies from the two major authorities. Other sources for M&V include DOE (2015) and EVO (2018).

ASHRAE *Guideline* 14-2014

ASHRAE *Guideline* 14-2014 is a reference for calculating energy and demand savings associated with performance contracts. In addition, it sets forth instrumentation and data management guidelines and describes methods for accounting for uncertainty associated with models and measurements; for compliance, the overall uncertainty of savings estimates must be below prescribed thresholds. It does not discuss other issues related to performance contracting.

Guideline 14 describes three M&V procedures. The three approaches are closely related to and support the options provided in the *International Performance Measurement and Verification Protocol* (IPMVP) (EVO 2018):

- **Whole-building approach.** This approach uses a main meter to measure energy flow to the whole building, a group of buildings, or separate sections of a building. Energy flow is usually electric, gas, oil, and thermal. One or more of the systems served by the meter may have energy conservation measures (ECMs) applied. This approach may involve using monthly utility bill data, or data gathered more frequently from a main meter.
- **Retrofit isolation approach.** This approach uses meters to isolate energy use and/or demand of ECM-controlled subsystems (e.g., lighting, chiller, boiler) from that of the rest of the facility. These measurements may be made once before and once after the retrofit, periodically, or continuously. Savings derived from isolated and metered systems may be used as a basis for determining savings in similar but unmetered systems in the same facility, if they are subjected to similar operating conditions throughout the baseline and post-retrofit periods.
- **Whole-building calibrated simulation approach.** This approach involves using a computer simulation tool to create a model of the facility's energy use and demand. The model, which is typically of pre-retrofit conditions, is calibrated or checked against actual measured energy use and demand data, and possibly other operating data. The calibrated model is then used to predict energy use and demand under post-retrofit conditions. Savings are derived by comparing modeled results under the two sets of conditions, or by comparing modeled and actual metered results.

International Performance Measurement and Verification Protocol (IPMVP; 2007)

The IPMVP groups M&V methodologies into four general categories (Table 19).

Table 19 IPMVP M&V Options

M&V Option	Performance[a] and Usage[b] Factors	Savings Calculation
Option A: Retrofit isolation with key parameter measurement	Based on combination of measured and estimated factors when variations in factors are not expected. Measurements are spot or short-term and taken at component or system level, in both baseline and postinstallation cases. Measurements should include key performance parameter(s) that define ECM's energy use. Estimated factors are supported by historical or manufacturer's data. Savings determined by engineering calculations of baseline and postinstallation energy use based on measured and estimated values.	Direct measurements and estimated values, engineering calculations and/or component or system models often developed through regression analysis. Adjustments to models are not typically required.
Option B: Retrofit isolation with all-parameter measurement	Based on periodic or continuous measurements of energy use taken at the component or system level when variations in factors are expected. Energy or proxies of energy use are measured continuously. Periodic spot or short-term measurements may suffice when variations in factors are not expected. Savings determined from analysis of baseline and reporting period energy use or proxies of energy use.	Direct measurements, engineering calculations, and/or component or system models often developed through regression analysis. Adjustments to models may be required.
Option C: Utility data analysis (whole facility)	Based on long-term, continuous, whole-building utility meter, facility level, or submeter energy (or water) data. Savings determined from analysis of baseline and reporting-period energy data. Typically, regression analysis is conducted to correlate with and adjust energy use to independent variables such as weather, but simple comparisons may also be used.	Based on regression analysis of utility meter data to account for factors that drive energy use. Adjustments to models are typically required.
Option D: Calibrated computer simulation (retrofit isolation or whole facility)	Computer simulation software is used to model energy performance of a whole facility (or subfacility). Models must be calibrated with actual hourly or monthly billing data from the facility. Implementation of simulation modeling requires engineering expertise. Inputs to the model include facility characteristics; performance specifications of new and existing equipment or systems; engineering estimates, spot-, short-term, or long-term measurements of system components; and long-term whole-building utility meter data. After the model has been calibrated, savings are determined by comparing a simulation of the baseline with either a simulation of the performance period or actual utility data.	Based on computer simulation model (e.g., eQUEST) calibrated with whole-building, end-use metered data, or both. Adjustments to models are required.

Source: FEMP (2008).

[a] Performance factors indicate equipment or system performance characteristics, such as kW for a chiller or watts/fixture for lighting.

[b] Operating factors indicate equipment or system operating characteristics such as annual cooling ton-hours for chillers or operating hours for lighting.

The options are generic M&V approaches for energy and water saving projects. As in ASHRAE *Guideline* 14, the IPMVP M&V approaches are divided into two general types: retrofit isolation and whole facility. Retrofit isolation methods look only at the affected equipment or system independent of the rest of the facility; whole-facility methods consider the total energy use and deemphasize specific equipment performance.

7. SELECTED TOPICS IN ENERGY AND DESIGN

Energy Efficiency, Integrated Project Delivery (IPD), and Building Design

An integrated project delivery (IPD) process is vital for the design of high-performance educational facilities. Chapter 60 covers the concept of integrated building design (IBD) and IPD in detail, and additional information can be found on the Northwest Energy Efficiency Alliance's BetterBricks web site (www.betterbricks.com/solutions/integrated-design).

Unlike sequential project delivery (SPD), in which the elements of the built solution are defined and developed in a systematic and sequential manner, the integrated project delivery (IPD) encourages holistic collaboration of the project team during all phases of the project, resulting in cost-effective and environmentally friendly design. IPD is accomplished by responding to the project objectives, typically established by the owner before team selection. A typical process includes the following phases:

1. Project justification
2. Project initiation
3. Concept development
4. Design
5. Construction preparation
6. Construction
7. Owner acceptance
8. Use, operation, and maintenance

Detailed information on each phase can be found in Chapter 60.

In high-performance buildings, the objectives are typically related to site sustainability, water efficiency, energy and atmosphere, materials and resources, and indoor environmental quality. These objectives are in fact the main components of several rating systems. As indicated previously, the HVAC&R designer is heavily involved in meeting energy efficiency objectives. Energy use objectives are typically the following:

- Meeting minimum prescriptive compliance (mainly local energy codes, ANSI/ASHRAE/IESNA *Standard* 90.1, etc.)
- Improving energy performance by an owner-defined percentage beyond the applicable code benchmark
- Demonstrating minimum energy performance (or prerequisite) and enhanced energy efficiency (for credit points) for sustainable design rating (e.g., USGBC; LEED®; energy and atmosphere using ANSI/ASHRAE/IESNA *Standard* 90.1, Appendix G)
- Providing a facility/building site energy density (e.g., energy utilization index [EUI]) less than an owner-defined target (e.g., EPA, ENERGY STAR’s Portfolio Manager)
- Providing a facility/building source energy density less than an owner-defined target
- Deriving an owner-defined percentage of facility source energy from renewable energy

Building Energy Modeling

Building energy modeling has been an important tools in the process of IPD and sustainable design. Building energy modeling uses sophisticated methods and tools to estimate the energy consumption and behavior of buildings and building systems. To better clarify the concept of energy modeling, the difference between HVAC sizing and selection programs and energy modeling tools will be described.

Design, sizing selection, and equipment sizing tools are typically used for design and sizing of HVAC&R systems normally at the design point. Examples include the following:

- Cooling/heating loads calculations tools
- Ductwork design
- Piping design
- Acoustics
- Equipment selection programs for air-handling units, packaged rooftop units, fans, chillers, pumps, diffusers, etc.

These tools are used to specify cooling and heating capacities, airflow, water flow, equipment size, etc., at a design point as defined and agreed by the client.

Energy modeling (or building modeling and simulation) is used to model the building’s thermal behavior and the performance of building energy systems. Unlike design tools, which are used for one design point or for sizing, the building energy simulation analyzes the building and its systems up to 8760 times (or hour-by-hour, or in some cases in smaller time intervals).

A building energy simulation tool is a computer program consisting of mathematical models of building elements and HVAC&R equipment. To run a building energy simulation, the user must define the building elements, equipment variables, energy cost, and so on. After these variables are defined, the simulation engine solves mathematical models of the building elements, equipment, etc., typically through a sequential process, 8760 times (one for every hour). Results include annual energy consumption, annual energy cost, hourly profiles of cooling loads, and hourly energy consumption. Chapter 19 of the 2021 *ASHRAE Handbook—Fundamentals* provides detailed information on energy modeling techniques.

Typically, energy modeling tools (or building energy simulation programs) have to meet minimum requirements to be accepted by rating authorities such as the USGBC and local building codes. The following is a typical minimum modeling capabilities for building energy simulation program:

- 8760 h per year
- Hourly variations in occupancy, lighting power, miscellaneous equipment power, thermostat set points, and HVAC system operation are defined separately for each day of the week and holidays
- Thermal mass effects
- Ten or more thermal zones
- Part-load performance curves for mechanical equipment
- Capacity and efficiency correction curves for mechanical heating and cooling equipment
- Air-side economizers with integrated control
- Capable of performing design load calculations to determine required HVAC equipment capacities and air and water flow rates in accordance with generally accepted engineering standards and handbooks (e.g., *ASHRAE Handbook—Fundamentals*)
- Testing according to ASHRAE *Standard* 140

Energy modeling is typically used for the following applications:

- As a decision support tool to analyze several design alternatives and select the optimal solution for a given set of criteria for energy systems in new construction and retrofit projects.
- To provide vital information to the engineer about the building behavior and systems performance during the design stage
- To demonstrate compliance with energy standards such as ASHRAE *Standard* 90.1, section 11 (energy cost budget method)
- To support LEED certification in the energy and atmosphere (EA) section
- To model existing buildings and systems and analyze proposed energy conservation measures (ECMs) by performing calibrated simulation
- To demonstrate energy cost savings as part of measurements and verification (M&V) protocol by using calibrated simulation procedures

Energy modeling is used intensively in LEED for Schools (USGBC 2009a), energy and atmosphere (EA), prerequisite 2 (minimum energy performance), and for EA credit 1 (optimize energy performance). An energy simulation program meeting the preceding requirements and those of ASHRAE *Standard* 90.1, Appendix G, is used to perform whole-building energy simulation to demonstrate energy cost savings. The number of credits awarded is in correlation to the energy cost reduction. ASHRAE *Standard* 90.1-2016 added another simulation-based compliance path based on Appendix G (Performance Rating Method).

Energy Benchmarking and Benchmarking Tools

Energy benchmarking is an important element of energy use evaluation and tracking, comparing a building's normalized energy consumption to that of other similar buildings. The most common normalization factor is gross floor area. Energy benchmarking is less accurate than other energy analysis methods, but can provide a good overall picture of relative energy use.

Relative energy use is commonly expressed by an energy utilization index (EUI), which is the energy use per unit area per year. Typically EUI is defined in terms of MJ/m^2 per year. In some cases, the user is interested in energy cost benchmarking, which is known as the cost utilization index (CUI), with units of \$/m^2 per year. It is important to differentiate between *site* EUI and *source* EUI. Building energy use can be reported as the actual energy used on site (i.e., site EUI), or as energy used at the energy source (i.e., source EUI). About two-thirds of the primary energy that goes into an electric power plant is lost in the process as waste heat.

One of the most important sources of energy benchmarking data is the U.S. DOE Energy Information Administration's (DOE/EIA) Commercial Building Energy Consumption Survey (CBECS). Table 2 of Chapter 37 shows an example of EUI calculated based on DOE/EIA 2003 CBECS. As shown in that table, the mean site EUI for high schools is 765 MJ/yr per square meter.

The following is a list of common energy benchmarking tools:

- U.S. EPA ENERGY STAR Portfolio Manager (www.energystar.gov/benchmark)
- Laboratory Benchmarking Tool (LBT), the successor to Labs21's benchmarking tool (lbt.i2sl.org)

An example of laboratory energy benchmarking(in I-P units) is shown in Figure 19.

Comprehensive information on energy benchmarking and available benchmarking tools can be found in Glazer (2006) and Chapter 37.

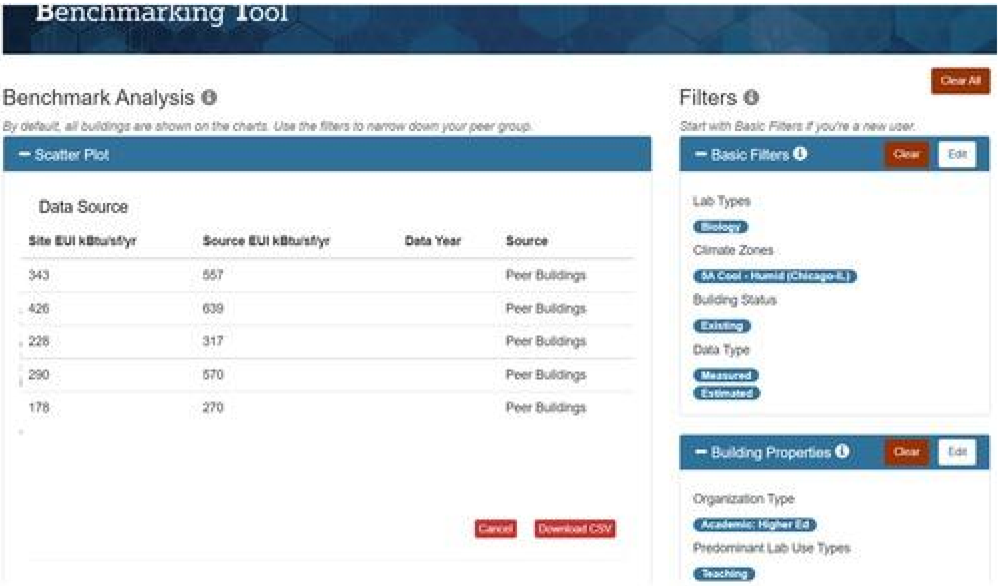

Figure 19. Example of Laboratory Building Energy Benchmarking (Laboratory Benchmarking Tool [LBT])

Combined Heat and Power in Educational Facilities

Combined heat and power (CHP) plants and building cooling, heating, and power (BCHP) can be considered for large facilities when economically justifiable. Chapter 7 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment* and other sources such as Meckler and Hyman (2010), Orlando (1996), Petchers (2002), and ASHRAE's *Combined Heat and Power Design Guide* (2015) provide information on CHP systems. Additional Internet-based sources for CHP include the following:

- U.S. EPA Combined Heat and Power (CHP) Partnership, at www.epa.gov/chp/
- U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, at www.energy.gov/eere/

A market analysis report by Ryan (2004) clearly suggests that secondary schools (9-12) are more suitable for BCHP than primary schools, because secondary schools

- Are more likely to operate 12 months a year
- Are more likely to contain an indoor swimming pool facility
- Are more likely to operate into the evenings and weekends, allowing longer period of BCHP operation
- Typically contain gymnasiums with shower facilities

The EPA's Combined Heat and Power (CHP) Partnership web site can be consulted for procedures of conducting feasibility studies and evaluations for CHP integration.

Maor and Reddy (2008) describe a procedure to optimally size the prime mover and thermally operated chiller for a large school by combining a building energy simulation program and a CHP optimization tool.

A database of CHP installations is available at doe.icfwebservices.com/chpdb/.

CHP is more common for large colleges and universities than for primary or secondary schools, given their larger scale and ability to use waste heat efficiently. Because many large colleges and universities are equipped with large district cooling and heating facilities, the integration of CHP can be very cost effective.

The type of prime mover depends heavily on the electrical and thermal loads, ability to use the waste heat efficiently, and utility rates. Typically, schools are good candidates for gas-fired reciprocating engine prime movers or microturbine-based systems. Large universities can use reciprocating engine prime movers or gas-fired combustion turbines. Table 1 in Chapter 7 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment* provides information on the applicability of CHP.

Renewable Energy

The U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) (U.S. DOE 2014; www.energy.gov/eere) discusses several renewable energy (RE) options for schools, including solar, wind, and biomass.

Renewable energy utilization can add credits for USGBC LEED for Schools (USGBC 2009a), energy and atmosphere (credit 2) by awarding credits depending on the percentage of renewable energy used.

Given the increased number and popularity of solar systems in educational facilities, only these systems will be discussed in this chapter. Geothermal energy is also considered renewable; these systems are discussed earlier in this chapter and in Chapter 35.

Solar: Photovoltaic. Photovoltaic (PV) technology is the direct conversion of sunlight to electricity using semiconductor devices called solar cells. Photovoltaics are almost maintenance-free and seem to have a long lifespan. Their longevity, lack of pollution, simplicity, and minimal resource requirements make this technology highly sustainable, and, along with the proper financing mechanisms (as explained later), these systems can be economically justifiable.

Educational facilities are excellent candidate for PV technology due to the following reasons:

- Availability of large roof area or (in some cases) areas suitable for PV canopies
- Hours and seasons of operation
- Educational as a showcase of renewable energy technologies

The most common PV cell technology in use today is crystalline silicon, which uses silicon wafers wired together and attached to a module substrate. Crystalline silicon cells may be monocrystalline or polycrystalline, with the monocrystalline cells typically having a higher efficiency and correspondingly higher cost. Thin-film PV technologies, such as amorphous silicon and cadmium-telluride, are based on depositing chemicals directly onto a substrate (e.g., glass or flexible stainless steel). The cost of producing crystalline silicon PV modules has dropped dramatically in recent years, and as a result, crystalline silicon technology currently accounts for over 90% of PV module production worldwide.

PV modules produce direct current (DC), not the alternating current (AC) used to power most building equipment. Thus, an inverter is required to transform the DC power to grid-quality AC power. The simplest type of PV installation is a grid-connected system that operates when the utility grid is operating and shuts down in the event of a utility grid outage. Adding storage batteries to the system increases cost but can also add functionality, such as the ability to operate the PV/storage during a grid outage to provide back-up power, or the ability to deploy energy storage to reduce peak customer demand at a facility. Design and installation of PV systems require careful evaluation and engineering expertise to accommodate issues such as availability of spaces, installation type (roof, parking canopy, or ground mount), site constraints, etc., which impact the cost and the economics of the installation.

The ability to transfer excess electricity generated by a photo-voltaic system back into the utility grid can be advantageous for schools. Most utilities are required to buy excess site-generated electricity back from the customer. In many states, public utility commissions or state legislatures have mandated net metering: utilities pay and charge equal rates regardless of which way the electricity flows. School districts in these states will find PV more economically attractive. A good source of information on rebates and incentives for solar systems and other renewable technologies is the Database of State Incentives for Renewables & Efficiency (DSIRE [NCSU 2018], www.dsireusa.org), which is a comprehensive source of information on state, local, utility, and federal incentives and policies that promote renewable energy and energy efficiency.

PV systems should be integrated during the early stages of the design. In existing facilities, a licensed contractor can be employed for a turnkey project, which should include sizing, analysis, economic analysis, design documents, specifications, permits, documentation for incentives, etc. The DSIRE database also provides state requirements for licensed solar contractors.

RETScreen® (Renewable Energy and Energy-Efficient Technologies) is a free decision support tool at www.retscreen.net, developed to assist in evaluation of energy production and savings, costs, emission reductions, financial viability, and risk for various types of renewable energy technologies (RETScreen 2021). The program is available in 35 languages.

In addition, several commercial tools are available for analysis of PV systems.

Financing PV projects in the educational sector can be more complex because of tax exemptions and questions of how to most efficiently allocate public funds and leverage incentives; detailed information can be found in Bolinger (2009) and Cory et al. (2008). The primary mechanism that has emerged to finance public-sector PV projects is a third-party ownership model. This model allows the public sector take advantage of all the federal tax and other incentives without large up-front outlay of capital. The public sector does not own the solar PV, but only hosts it in its property. The cost of the electrical power generated is then secured at a fixed rate, which is lower than the retail price for 15 to 25 years.

Figures 20, 21, and 22 show examples of educational facilities' PV projects.

Figure 20. Example of PV Installation at Ohlone College, Newark Center, Newark, CA: 450 kW, 3530 m^2 (Esberg 2010)

Figure 21. Example of PV Installation at Twenhofel Middle School, Independence, KY: 22 kW (Seibert 2010)

Solar: Thermal. Educational facilities can be good candidates for active thermal solar heating systems. In most cases, a solar hot-water system can reduce the energy required for service hot water and pool heating. Solar heating design and installation information can be found in ASHRAE (1988, 1991). Chapter 37 of the 2020 *ASHRAE Handbook—*

HVAC Systems and Equipment and Krieth and Goswami (2007) are good sources of information for design and installation of active solar systems. Online sources include the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy's site at www.energy.gov/eere.

Figure 22. PV Installation at Discovery Elementary, Net Zero Energy School, Arlington, VA: 500 kW (Beaufait 2018)

Value Engineering (VE) and Life-Cycle Cost Analysis (LCCA)

The use of value engineering (VE) and life-cycle cost analysis (LCCA) is growing in all types of construction and as part of the integrated project delivery (IPD) concept. In some cases, public facilities such as schools are required to use these procedures. Both VE and LCCA are logical, structured, systematic processes used with decision support tools to achieve overall cost reduction, but there are some distinctions between them (Anderson et al. 2004).

In value engineering, the project team examines the proposed design components in relation to the project objectives and requirements. The intent is to provide essential functions while exploring cost savings opportunities by modifying or eliminating nonessential design elements. Examples are using alternative systems or substituting equipment.

Life-cycle cost analysis is used to evaluate design alternatives (or alternative systems, equipment substitutions, etc., as part of VE) that meet the facility's design criteria with reduced cost or increased value over the life of the facility or system.

The combination of VE and LCCA is suitable for schools, because they are often government funded and intended for longer lifespans than commercial facilities. Unfortunately, VE and LCCA often are not included in the early design stages, resulting in a last-minute effort to reduce cost and stay within the budget. This leads to compromising on issues such as energy efficiency and overall value of the facility. Therefore, VE and LCCA should be deployed in the early stages of the project. VE and LCCA programs for large schools can add 0.1 to 0.5% in initial cost, but can save 5 to 10% of initial costs and 0.5 to 10% of operation and maintenance costs (Dell'Isola 1997).

LCCA is recommended for economic evaluation as part of any school construction. Chapters 38 and 60 discuss LCCA in detail. Other methodologies such as simple payback should be avoided because of inaccuracies and the need to take in account the time value of money. LCCA is more accurate: it captures all the major initial costs associated with each item, the costs occurring during the life of the system, and the value of money for the entire life of the system.

Chapter 38 provides details, tools, and examples of LCCA (see Table 7 in that chapter). Anderson et al. (2004) provides detailed information on all the aspects of design, construction management, cost control, and other resources for building and renovating schools.

The School as a Learning Tool for Energy Conservation and Sustainability

Schools are excellent for enhancing students' interest in energy efficiency and sustainable design from a young age. USGBC (2009a)'s LEED® for Schools awards one point for integrating high-performance features in the school curriculum (ID section, credit 3). Sources for this integration include the following:

- National Energy Education Development (NEED) project (www.need.org)
- National Energy Foundation educational resources (nef1.org/)
- Energy Information Administration's Energy Kids web site (www.eia.gov/kids/index.cfm)

In addition, real-time feedback on how systems such as photovoltaic electrical generation, geothermal heat pumps, and water conservation save energy and operating costs is recommended. Seibert (2010) shows these features, as shown in Figure 23.

Figures 24, 25, and 26 show examples of net-zero school Building dashboard systems designed to motivate student engagement and environmental stewardship. These examples won a 2018 ASHRAE Technology award (Beaufait 2018).

Figure 23. Integration of Sustainability Features for Educational Purposes, Twenhofel Middle School, Independence, KY (Seibert 2010)

Figure 24. Integration of Sustainability Features for Educational Purposes, Discovery Elementary School, Arlington, VA (www.vmdo.com/architecture-blog/building-dashboard-systems-inspire-student-engagement-and-environmental-stewardship)

Energy Dashboards and Energy Management Information Systems (EMIS)

Energy dashboards and energy management information systems (EMIS) provide information such as energy consumption, energy cost, EUI, CO_2 levels, or Energy Star rating. In some cases, the energy dashboard is part of an enterprise that incorporates features such as fault detection and diagnostics (FDD) tools, tracking of energy conservation projects, information-sharing tools, and other analytical features to enhance energy conservation. Educational facilities are good candidates for this system: for example, a school district can monitor and track the energy consumption of every school in the district in nearly real time. Figure 27 shows an example EMIS.

Figure 25. Integration of Sustainability Features for Educational Purposes, Discovery Elementary School, Arlington, VA: Energy Dashboard (158.59.255.83)

Figure 26. Integration of Sustainability Features for Educational Purposes, Discovery Elementary School, Arlington, VA: Classroom (158.59.255.83)

Figure 28 shows an example of higher education energy dashboard for a campus-scale facility with multiple buildings, where each individual building can be tracked, as shown in Figures 28 and 29.

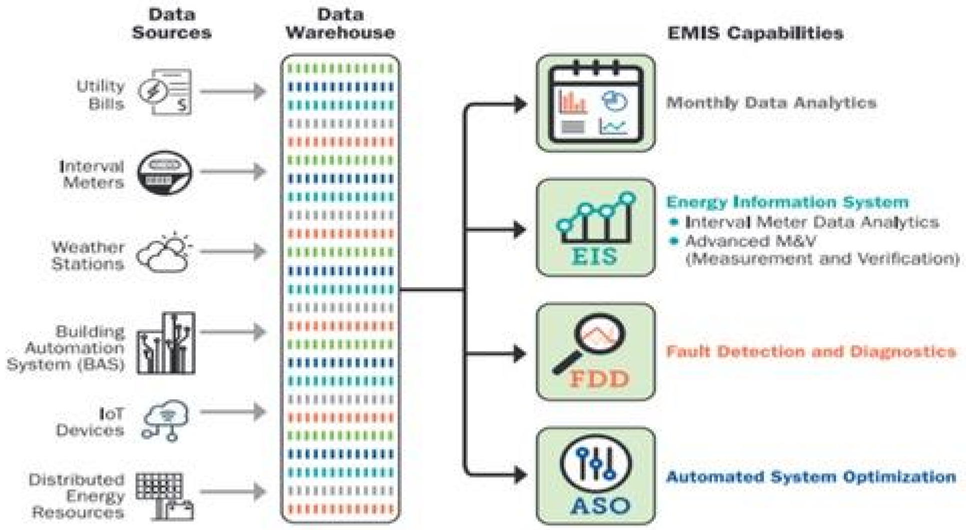

Figure 27. Typical Energy Management and Information System (EMIS) Layout (Kramer et al. 2020)

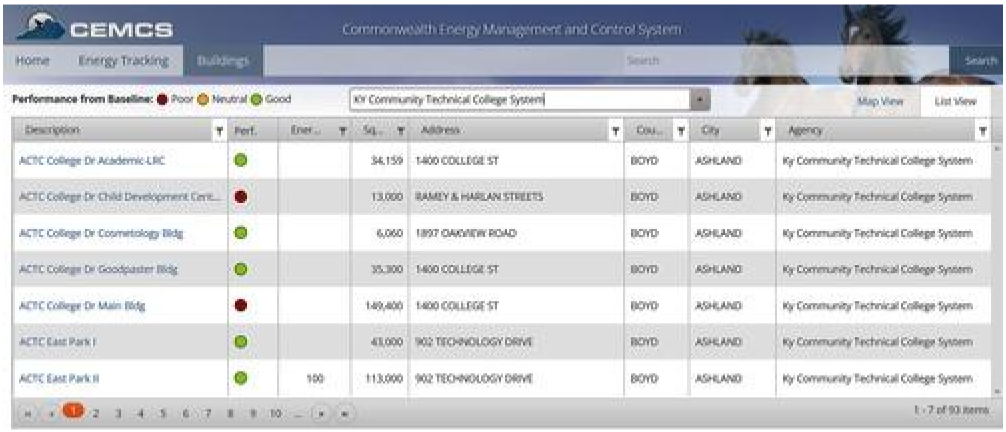

Figure 28. Energy Dashboard, Kentucky Community Technical College (www.kyenergydashboard.ky.gov/Buildings)

Examples of EMIS with extra features such as IAQ monitoring, asset management, and tenant billing are shown in Figures 30, 31, and 32. Figure 33 shows an example of EMIS used to analyze the impact of energy efficiency on infectious disease risk.

Figure 29. Energy Dashboard for Kentucky Community Technical College: ACTC East Park II Building

Remember, however, that regardless of its sophistication, an energy dashboard or EMIS will not save energy without action by site personnel (e.g., adjusting schedules or set points, fixing equipment malfunction).

Figure 30. Example of Comprehensive EMIS Features (courtesy of Johnson Controls)

Figure 31. Example of EMIS Energy Analytics (courtesy of Johnson Controls)

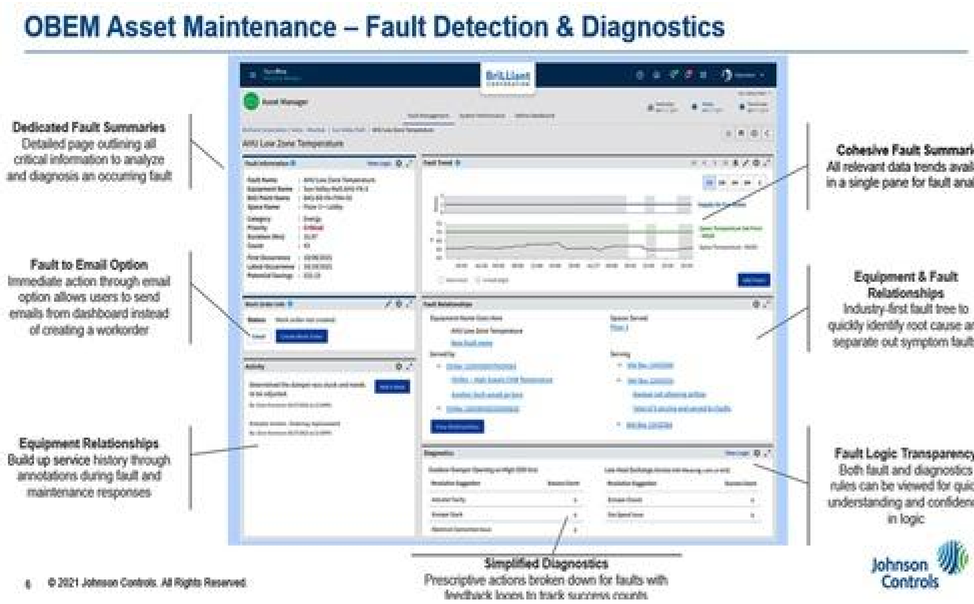

Figure 32. Example of Fault Detection and Diagnostics Screen (courtesy of Johnson Controls)

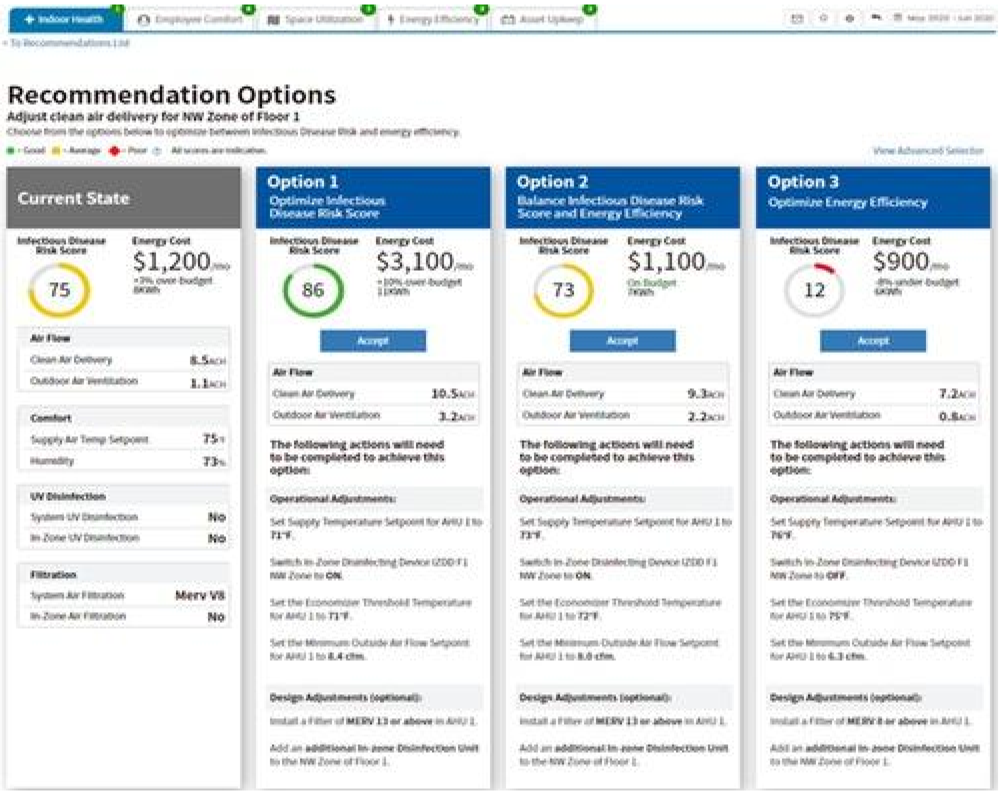

Figure 33. Example of Using EMIS to Optimize Energy Efficiency and Infectious Disease Risk (courtesy of Johnson Controls)

Central Plant Optimization for Higher Education Facilities

Higher education facilities where numerous individual buildings are combined in a campus setting often use large central plants to provide cooling, heating, and/or power. These applications are ideal for central plant optimization, to improve operations and lower operating costs. Given the complexity of such large central plants, which use multiple types of equipment, an optimization solution can help to ensure efficient operation.

Common components in large central plants include the following:

Central Cooling Plants

- Multiple **chillers** of different types (e.g., electric cooling only, electric heat pump or heat recovery, thermally operated [steam and hot-water absorption or gas-fired absorption], steam-driven electric chillers). Each type has unique characteristics with respect to operating, efficiency at full- and part-load conditions, and controls (e.g., variable-speed drive, slide valves, inlet guide vanes).
- Multiple **cooling towers** of various types, different efficiencies, a wide range of operation (in range and approach), and different fan controls (e.g., variable speed, staging of cells, fan motor stages).
- **Cold storage** (chilled water or ice).
- **Water-side economizer.**
- Multiple chilled- and condenser-water **pumps** of different sizes.
- Different **chilled-water distribution** arrangements such as primary/secondary (e.g., constant-flow primary and variable-flow secondary), variable-flow primary, etc.
- Different **condenser water distribution** arrangements such as headered layout, dedicated pump for each chiller, etc.

Central Heating Plants

- Multiple **steam boilers** with different fuel types (e.g., gas powered, dual fuel).
- Multiple **hot-water boilers** with different fuel types (e.g., gas powered, dual fuel).
- **Heat pump chillers.**
- **Hot-water storage.**

- **Waste heat heat exchangers.**
- **Hot-water pumps.**
- **Hot-water distribution systems.**

On-Site Power Generation and Storage

- **Power generating prime movers** (e.g., reciprocating engines, gas turbines, micro turbines, steam turbines, fuel cells).
- **Battery storage.**
- **Solar photovoltaics.**

In addition to having to properly operate and maintain various equipment, the operation of central plants is further complicated by variables such as

- **Weather.** Changes in ambient conditions affect campus cooling, heating, and electrical loads that must be met by the central plant. Ambient conditions also affect the operation and efficiency of the plant equipment (e.g., impact of wet-bulb temperature on cooling tower operation).
- **Load profiles.** The cooling, heating, and electrical loads of the campus, on an hourly or sub-hourly basis, determine what central plant equipment needs to operate and at what capacities and combinations. Campus load profiles are typically an aggregation of a large number of buildings, each with different individual load patterns (e.g., classrooms, lecture halls, laboratories, dormitories, dining facilities, recreational facilities, office/administration).
- **Utility rates.** Utility rate structures (for electricity, fossil fuels, and water) can vary significantly depending on the application and location. To minimize operating cost, knowledge of the rate structures is critical (e.g., time-of-use charges, demand ratchets, real time pricing).

Central plant optimization solutions typically attempt to minimize the plant's energy consumption by altering variables and making decisions related to the following:

- Chilled-water temperature set points
- Condenser-water temperature set points
- Chilled-water differential pressure set points
- Staging of chillers, water-side economizers, and cold storage systems
- Sequencing and speed control of chilled-water and condenser pumps
- Sequencing of cooling towers and cooling tower fan speed control
- Hot-water temperature set points
- Boiler, heat recovery heat exchangers, hot-water storage staging
- Heat pump and heat recovery chillers/heater
- Staging of on-site electrical power prime mover generators (e.g., reciprocating engines, gas turbine) and electrical storage

Given this complexity, and with so many decisions to make, a single control sequence or manual operation without the aid of more sophisticated tools cannot maximize operating efficiency or minimize operating cost of all plant equipment, under all weather conditions, load conditions, and utility rate structure scenarios. In addition, at any given moment in time, there may be multiple ways to meet a cooling, heating, and electrical load by the different types of plant equipment. For example, in a large central plant, the current cooling load could be met by an electric centrifugal chiller, heat pump chiller, water-side economizer, thermally operated chillers, or cold water storage tank. Similarly, for cases that have on-site power generation equipment, electrical power can be generated at the site, purchased from the local utility, or discharged from electrical storage; furthermore, waste heat from the power generation can be used to provide heat or heat for thermally operated chillers, and the optimal approach at any moment may not be intuitively obvious.

Chapter 43 provides information on optimization theory, methods, and procedures for central plants. Typical central plant optimization involves determining the control sequence and parameters (i.e., set points) that minimize total operating costs or total energy consumption. In Chapter 43, two broad classifications of optimization procedures are discussed: static optimization and dynamic optimization. **Static optimization** addresses the problem of optimizing the operation of a system at a given instant by operating each component of the system at conditions that achieve an optimal result. Typically, energy cost minimization involves using an objective function that is the sum of the operating costs of each component (e.g., chillers, pumps, cooling towers, boilers) with respect to all discrete and continuous controls and subject to both equality and inequality constraints (imposed by the physical realities of the system).

Dynamic optimization addresses control of the system over time. Therefore, it must account for the possibility that future conditions (e.g., weather, loads, utility prices) may impact the optimal control decisions in a given moment. In addition, present control decisions may impact operating conditions and optimal control decisions in the future. Methods such as model-predictive control (MPC) have been established to implement dynamic optimization of building systems. Figure 34 shows an example of a dynamic central plant optimization framework suitable for the operation of a higher education campus.

Central plant optimization solutions are typically integrated with site controls so that optimal operation of the plant occurs automatically. Some systems may also be able to run in an advisory mode, wherein the system provides recommendations to facilities personnel on how to optimize plant operating but does not directly control. Another common feature is real-time tracking of the plant's current operating conditions and efficiency, as shown in Figure 3516.

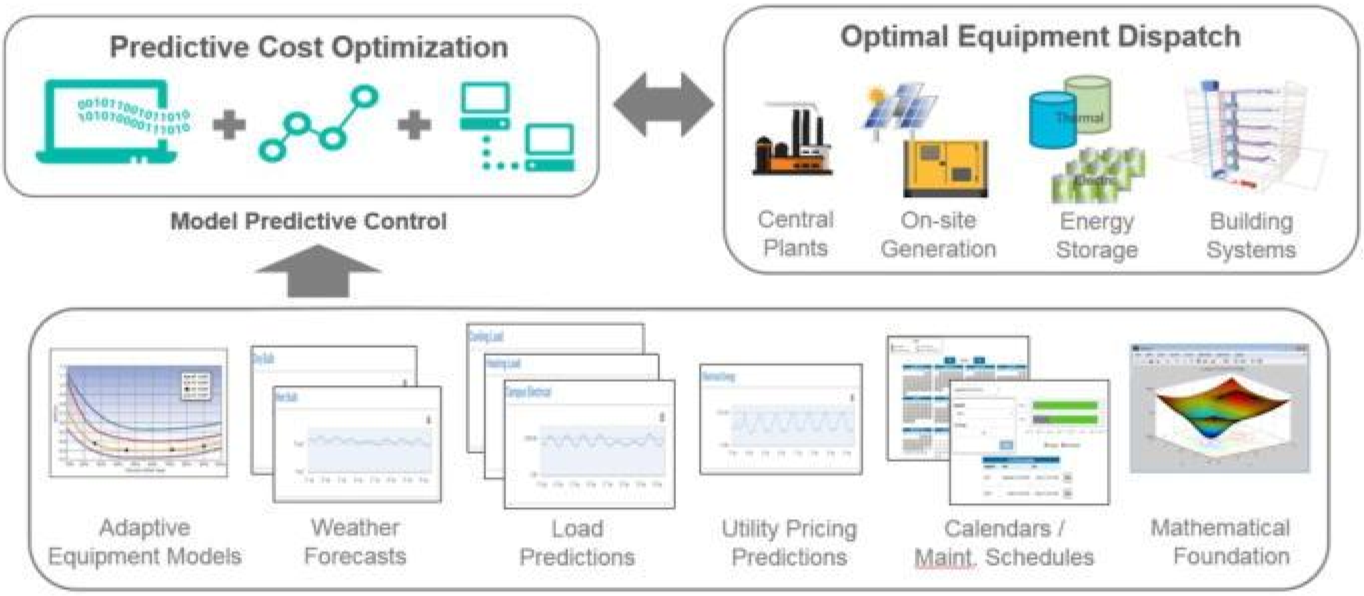

Figure 34. Example of Dynamic Central Plant Optimization Framework for Higher Education Campus (courtesy of Johnson Controls)

8. EDUCATIONAL FACILITIES FOR STUDENTS WITH DISABILITIES

Although a large number of papers exist on students with disabilities, no clear HVAC system design guidelines or criteria were found to address the special requirements of these educational facilities. The intent of this section is to make the designer aware of the special considerations required to address accessibility issues during design, construction, and operation. Close coordination with the architect and other professionals is critical in addressing these requirements.

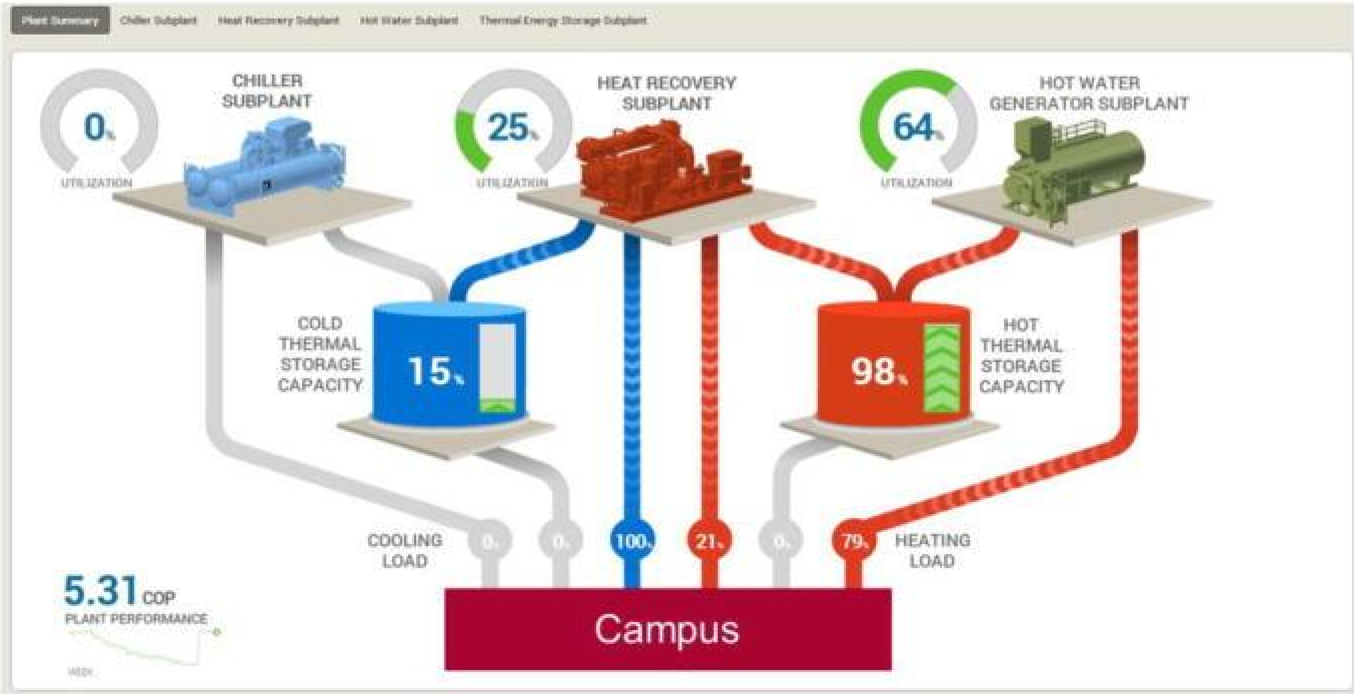

Figure 35. Example of Central Plant Optimization System Operator Dashboard (courtesy of Johnson Controls)

Students' disabilities can be classified by referring to the Individuals with Disabilities Education Act (IDEA), which covers 13 conditions (Understood.org 2019):

- **Specific learning disability (SLD).** Conditions in this group affect a child's ability to read, write, listen, speak, reason, or do math. Issues in this category include
  - Dyslexia
  - Dysgraphia
  - Dyscalculia
  - Auditory processing disorder
  - Nonverbal learning disability
- **Other health impairment.** These conditions limit a child's strength, energy, or alertness. ADHD is one example.
- **Autism spectrum disorder (ASD).** ASD is a developmental disability. It covers a wide range of symptoms and skills, but mainly affects a child's social and communication skills. It can also impact behavior.
- **Emotional disturbance.** Children covered under the term "emotional disturbance" can have a number of mental disorders. These include anxiety disorder, schizophrenia, bipolar disorder, obsessive-compulsive disorder, and depression.
- **Speech or language impairment.** The umbrella term "speech or language impairment" covers a number of communication problems, including stuttering, impaired articulation, language impairment, or voice impairment.
- **Visual impairment, including blindness.** A child who has vision problems is considered to have a visual impairment. This condition includes both partial sight and blindness. If a vision problem can be corrected with eyewear, it does not qualify.
- **Deafness.** Children with a diagnosis of deafness have a severe hearing impairment. They are unable to process language through hearing.
- **Hearing impairment.** This is a hearing loss not covered by the definition of deafness, and can change or fluctuate over time. There is a distinction between being hard of hearing and having auditory processing disorder.
- **Deaf-blindness.** Children with a diagnosis of deaf-blindness have both hearing and visual impairments. Their combined needs exceed those met by programs for the deaf or blind.

- **Orthopedic impairment.** Any impairment to a child's body, no matter the cause, is considered an orthopedic impairment. Cerebral palsy, caused by damage to areas of the brain that control the body, is one example.
- **Intellectual disability.** Children with this type of disability have below-average intellectual ability. They may also have poor communication, self-care, or social skills. Down syndrome is one example of an intellectual disability.
- **Traumatic brain injury.** This is a brain injury caused by an accident or some kind of physical force.
- **Multiple disabilities.** A child with multiple disabilities has more than one condition covered by IDEA. Having multiple issues creates educational needs that cannot be met in a program for any one condition.

Given the varied nature these disabilities, it is difficult to establish a set of HVAC design criteria that will be simultaneously acceptable for each disability. For HVAC system design, each disability may entail specific requirements for thermal comfort design criteria, ventilation and IAQ design criteria, and noise criteria.

Thermal comfort design criteria covering variables such as space temperature, humidity, thermal comfort, etc. for the disabilities described was not found. ASHRAE *Standard* 55 does not provide sufficient information to allow specification of these conditions. Webb and Parsons (1998) investigated thermal comfort levels of people with disabilities, and one of the conclusions (with the subjects tested) was that people with physical disabilities had widely varying responses, making it is necessary to evaluate the needs of people with physical disabilities on an individual or case-by-case basis.

Similarly, ventilation standards for acceptable indoor air quality (e.g., ASHRAE *Standard* 62.1) do not cover these cases, whereas "standard" educational facilities are well covered.

Noise criteria for educational facilities for students with disabilities are mentioned in ANSI *Standard* S.12.60-2010, suggesting that young children and persons with hearing, language, speech, attention deficit, or learning disabilities will benefit from the application of this standard.

Table 20 Key Commissioning Activities for New Building

Phase	Key Commissioning Activities
Predesign	Preparatory phase in which OPR is developed and defined.
Design	OPR is translated into construction documents, and basis of design (BOD) document is created to clearly convey assumptions and data used to develop the design solution. See Informative Annex K of ASHRAE *Guideline* 1.1-2007 for detailed structure and an example of a typical BOD.
Construction	The commissioning team is involved to ensure that systems and assemblies installed and placed into service meet the OPR.
Occupancy and operation*	The commissioning team is involved to verify ongoing compliance with the OPR.

* Also known as acceptance and post-acceptance in ACG (2005).

Table 21 Key Commissioning Activities for Existing Building

Phase	Key Commissioning Activities
Planning	Define HVAC goals
	Select a commissioning team
	Finalize recommissioning scope
	Documentation and site reviews
	Site survey
	Preparation of recommissioning plan
Implementation	Hire testing and balancing (TAB) agency and automatic temperature control (ATC) contractor
	Document and verify TAB and controls results
	Functional performance tests
	Analyze results
	Review operation and maintenance (O&M) practices
	Operation and maintenance (O&M) instruction and documentation
	Complete commissioning report

Source: Adapted from ACG (2005).

More research is required to address educational facilities for students with disabilities.

9. COMMISSIONING

Commissioning (Cx) is a quality assurance process for buildings from predesign through design, construction, and operations. The commissioning process involves achieving, verifying, and documenting the performance of each system to meet the building's operational needs. Given the criticality of issues such as indoor air quality, thermal comfort, noise, etc., in educational facilities and the application of equipment and systems such as DOAS, EMS, and occupancy sensors, it is important to follow the commissioning process as described in Chapter 44 and ASHRAE *Guideline* 0-2013. Technical requirements for the commissioning process are described in detail in ASHRAE *Guideline* 1.1-2007; another useful source is from the AABC Commissioning Group (ACG 2005). Proper commissioning ensures that fully functional systems can be operated and maintained properly throughout the life of the building. Although commissioning activities should be implemented by a qualified commissioning professional or commissioning authority (CA), it is important for other professionals to understand the basic definitions and processes in commissioning.

The following are basic terms used in commissioning:

- **Owner's project requirements (OPR):** a written document that details the functional requirements of the project and the expectations of how it will be used and operated.
- **Commissioning process:** refers to a quality-focused process for enhancing the delivery of a project. The process focuses upon verifying and documenting that the facility and all its systems and assemblies are planned, installed, tested, and maintained to meet the OPR
- **Recommissioning:** an application of the commissioning process to a project that has been delivered using the commissioning process.
- **Retrocommissioning** (also called **existing building commissioning**): applied to an existing facility that was not previously commissioned.
- **Ongoing commissioning:** an extension of the commissioning process well into the occupancy and operation phase.

Commissioning: New Construction

Table 20 shows the phases of commissioning, as defined in ASHRAE *Guideline* 1.1-2007.

ACG (2005) refers to the following HVAC commissioning processes for new construction:

- Comprehensive (starts at the inception of a building project from the predesign phase till postacceptance)
- Construction (takes place during construction, acceptance, and postacceptance; predesign and design phases are not included in this process)

Commissioning is an important element in new construction. LEED® for Schools (USGBC 2009a) requires as a prerequisite (Energy and Atmosphere, prerequisite 1) verification that the project's energy-related systems are installed and calibrated and perform according to the OPR, BOD, and construction document. Additional credits (Energy & Atmosphere, and Enhanced Commissioning) can be obtained by applying the entire commissioning process (or comprehensive HVAC commissioning), as described previously.

Commissioning Existing Buildings

HVAC commissioning in existing buildings covers the following:

- Recommissioning
- Retrocommissioning (RCx)
- HVAC systems modifications

Although recommissioning and retrocommissioning differ, the methodology for both is identical. Retrocommissioning applies to buildings that were not previously commissioned. Recommissioning is initiated by the owner of a previously commissioned building, and seeks to resolve ongoing problems or to ensure that the systems continue to meet the facility's requirements. There also could have been changes in the building's occupancy, design strategies, equipment or equipment efficiency, occupant comfort, or IAQ that can initiate the need for recommissioning. Typical recommissioning activities are shown in Table 21.

Commissioning is also an important element in existing buildings. USGBC (2009b) *LEED® for Existing Buildings & Operation Maintenance* awards up to six credits for commissioning systems in existing buildings in the Energy and

Atmosphere (EA) section.

Table 22 Selected Case Studies from *ASHRAE Journal*

Project Name	Facility Type	Location	Description	Publ. Date
University of California, Merced, Sierra Terraces	Higher ed.	Merced, California	Dormitory	May-10
De Anza College, Kirsch Center for Environmental Studies	Higher ed.	Cupertino, California	Classrooms, labs, open study stations	May-10
The Kahnawake Survival School (KSS)	K-12	Kahnawake, Québec, Canada	High school, community center, public assembly	May-10
Whitmore Lake High School	K-12	Whitmore Lake, Michigan	Gymnasium, cafeteria, natatorium, media center, commons area, and classrooms	May-10
Ann Arbor Skyline High School	K-12	Ann Arbor, Michigan	Classrooms, learning communities, gymnasiums, cafeteria/commons, lab spaces, decentralized administration, auditorium, black-box theater, and natatorium	May-11
St. John's School	K-12	Saint-Jean-sur-Richelieu, Québec, Canada	Science rooms with laboratories and a library	May-11
Université de Sherbrooke, Campus Longueuil	Higher ed.	Longueuil, Québec, Canada	Classrooms, offices, labs, gathering areas, etc.	May-12
Maple School District, Northwestern High School	K-12	Maple, Wisconsin	Classrooms, labs, auditorium, gymnasium, and district offices	May-12
St. Clair County Community College: North Building	Higher ed.	Port Huron, Michigan	Faculty offices and instructional classrooms.	Sep-12
Jarvis Hall, The University of Wisconsin-Stout (UW-Stout)	Higher ed.	Menonomie, Wisconsin	Labs, vivarium, clean rooms, classrooms, offices, and greenhouse	Oct-12
Hamilton Heights Elementary School	K-12	Arcadia, Indiana	Elementary school (grades 3-6). Includes classrooms and administrative offices.	Mar-13
University of California, Davis	Higher ed.	Davis, California	Student services. Academic advising center, computer center, recreation room, laundry room, service desk, mail center, and convenience store.	Apr-13
The Segundo Services Center (SSC) at University of California, Davis (UCD)	Higher ed.	Davis, California	Student service center	Apr-13
Portland State University Academic and Student Recreation Center,	Higher ed.	Portland, Oregon	Academic and student recreation center	May-13
City College of San Francisco	Higher ed.	San Francisco, California	Classrooms, administrative offices, specialized laboratories, computer lab, study spaces, childcare/family training center, meeting rooms, and a café,	May-13
McGill University McIntyre Pavilion	Higher ed.	Montreal, Québec, Canada	Research and teaching facility. Includes laboratories, library, and classrooms.	Aug-13
Vancouver Island University (VIU)	Higher ed.	Duncan, British Columbia, Canada	Classrooms, science labs, offices, meeting rooms, and a cafeteria	Dec-13
Davis Building University of Findlay	Higher ed.	Findlay, Ohio	University level science education. Includes 19 science laboratories, a 112-seat lecture hall, one computer lab, 15 faculty offices, one conference room, and one student lounge.	May-14
Energy Environment Experiential Learning University of Calgary	Higher ed.	Calgary, Alberta, Canada	Post-secondary classroom and laboratory building. Includes classrooms, offices, teaching and research labs for biology, chemistry, earth sciences, chemical, civil, and mechanical engineering students.	Sep-14
Otto Maass Laboratory Building	Higher ed.	Montreal, Québec, Canada	Education and research in chemistry. Includes teaching and research laboratories, classrooms, lounge, and large	Nov-14

			lecture hall.	
Valley View Middle School	K-12	Snohomish, Washington	Public middle school (grades 7 and 8)	May-15
Discovery Elementary School	K-12	Arlington, Virginia	Public middle school (grades K-5)	May-18
University of Illinois, Frederick Seitz Materials Research Laboratory	Higher ed.	Urbana, Illinois	Five major AHUs and eight smaller ones were replaced and consolidated with two central dual-path (outdoor and return air), low-velocity AHUs. Sixty lab exhaust fans were replaced with three high-plume fans with DOAS and heat pipe heat recovery.	March-20
Frederick Douglass High School	K-12	Lexington, Kentucky	Geothermal field that serves as building's heat source/sink system for heat pump system.	March-20
Alice West Fleet Elementary	K-12		A water-source heat pump system using a geothermal well field. Uses variable-flow DOAS. Incorporated CO_2 scrubbers into ventilation system and demand control ventilation	May-21
Dalhousie IDEA and Design Buildings	Higher ed.	Halifax, Nova Scotia, Canada	Modular water-to-water heat pumps feed in-floor radiant heating and cooling using thermally active building structure (TABS) in design building, and in-floor radiant heating with chilled-water fan-coils in IDEA building	Sep-21
Gamble Montessori High School	K-12	Cincinnati, Ohio	Renovation of 100-year-old school building to WSHP system paired with DOAS	Oct-21
Kentucky Community and Technical College	Higher ed.	Commonwealth of Kentucky	Energy reduction and water consumption; resolve mechanical system issues and replace obsolete equipment; enhance efficiency through BAS and integrate BAS into state-managed building; develop data analytics platform	Apr-22
Adlai E. Stevenson High School	K-12	Lincolnshire, Illinois	High school addition achieving net zero, using VRF units, DOAS, DCV, enhanced control sequences, and PV designed to produce all energy consumed.	Jun-22
Interdisciplinary Life Science Building (ISLB)	Higher ed.	Baltimore, Maryland	High-performance laboratory using DOAS, energy recovery, and active chilled beams; decoupling ventilation from space sensible loads; high-performance fume hoods.	Jul-22

*

* All articles are available from technologyportal.ashrae.org; ASHRAE members have free access (must be logged in).

HVAC systems modifications can vary from minor modifications up to complete reconstruction of all or part of building's HVAC system. The process for this type of project should follow the process described previously for new construction.

10. SEISMIC- AND WIND-RESTRAINT CONSIDERATIONS

Seismic bracing of HVAC equipment should be considered. Wind restraint codes may also apply in areas where tornados and hurricanes necessitate additional bracing. This consideration is especially important if there is an agreement with local officials to use the facility as a disaster relief shelter. See Chapter 56 for further information.

11. COVID-19 PANDEMIC INFORMATION

In 2020 ASHRAE established the ASHRAE Epidemic Task Force to help deploy ASHRAE's technical resources to address the challenges of COVID-19 and future epidemics as it relates to the effects of heating, ventilation, and air-conditioning systems on disease transmission in health care facilities, educational facilities, the workplace, home, public, and recreational environments. This information can be found at www.ashrae.org/technical-resources/resources.

12. SELECTED CASE STUDIES

Tables 22 and 23 list selected case studies of educational facilities as published in *ASHRAE Journal* and *High Performance Building* Magazine respectively.

Table 23 Selected Case Studies from *ASHRAE High Performing Buildings* Magazine

Project Name	Facility Type	Location	Description	Publ. Date
The Environmental Discovery Center at Indian Springs Metropark	Higher ed.	White Lake, Michigan	Classrooms, laboratories, and a multipurpose room.	Spring 2008
Great Seneca Creek Elementary School	K-12	Germantown, Maryland	Elementary School	Summer 2008
OHSU Center for Health & Healing	Higher ed.	Portland, Oregon	Mixed-use facility for wellness, medical research, clinics, surgery, classrooms, and ground floor retail and underground parking.	Winter 2009
Two Harbors High School, Lake Superior School District	K-12	Two Harbors, Minnesota	Educational, High School	Spring 2009
Bethke Elementary School	K-12	Timnath, Colorado	10-month school includes classrooms, gym, cafeteria, media center, and office.	Winter 2010
Ohlone College Newark Center for Health Sciences and Technology	Higher ed.	Newark, California	Community college. Includes classrooms, labs, fitness center, and café.	Winter 2010
Richardsville Elementary School	K-12	Richardsville, Kentucky	Elementary school. Includes gymnasium and cafeteria.	Fall 2012
Sustainable Urban Science Center	K-12	Philadelphia, Pennsylvania	High school (9th–12th grades) science laboratory and classroom building.	Winter 2012
Evie Garrett Dennis Campus Phase One	K-12	Denver, Colorado	Elementary through high school campus.	Spring 2012
University of Florida William R. Hough Hall (Graduate Business Studies Building)	Higher ed.	Gainesville, Florida	Classroom and office building. Includes classrooms, seminar/meeting rooms, and study/lounge space for graduate business students, and staff offices and support spaces.	Spring 2012
Kiowa County Schools (formerly Greensburg K-12 Schools)	K-12	Greensburg, Kansas	K-12 Public School	Summer 2012
Kensington High School for the Creative and Performing Arts	K-12	Philadelphia, Pennsylvania	High school (9th-12th grades). Includes 200-person theater and related back of stage facilities, instrumental classroom with private practice rooms, choral room, dance studio, library and related facilities, regulation sized gymnasium with shower and locker rooms, cafeteria and full-service kitchen, two visual art studios, two science laboratories, broadcasting studio, and general purpose classrooms.	Winter 2013
University of California, Davis Health and Wellness Center	Higher ed.	Davis, California	Student health care. Includes exam, treatment, education, office, and laboratory spaces.	Winter 2013
Clemson University Lee III	Higher ed.	Clemson, South Carolina	University academic building. Includes studio space, seminar rooms, and faculty/administrative offices.	Summer 2013
Sandy High School	K-12	Sandy, Oregon	Public high school (9th-12th grades). Includes two gymnasiums; auditorium; full-service kitchen; district-wide IT and server room; career technology education spaces (i.e., automotive, arts, metal, and construction arts).	Spring 2014
The Hal and Inge Marcus School of Engineering	Higher ed.	Lacey, Washington	Education: classrooms, thermal engineering labs, materials lab, environmental lab, computer-aided drafting lab, solar lab, faculty offices, and assembly spaces.	Spring 2014
Haywood Community College Creative Arts Building	Higher ed.	Clyde, North Carolina	Community college/education creative arts building. Includes clay, wood, jewelry, and fiber studios/shops.	Spring 2014
Chemeketa Community College	Higher ed.	Salem, Oregon	Higher education. Includes science labs (biology, chemistry, and anatomy), classroom, training, and faculty space for health professions (dental hygiene, nursing, and pharmacy technology).	Spring 2014

Health Sciences Complex Addition				
Locust Trace AgriScience Center	Higher ed.	Lexington, Kentucky	Agricultural vocational/technical school. Includes academic building, greenhouse, animal surgical area, riding arena, stalls, barn, and farm equipment.	Winter 2015
Oakland University Human Health Building	Higher ed.	Rochester, Michigan	Mixed use university building including classrooms, offices, and teaching labs.	Winter 2015
Zero Net Energy Center	Higher ed.	San Leandro, California	Educational training facility. Includes lecture rooms, classrooms, training labs, offices, lobby, break rooms, and computer rooms.	Summer 2015
Hollis Montessori School	K-12	Hollis, New Hampshire	New classroom building: 1022 m^2 with four classrooms for primary and elementary students	Fall 2015

*

* All included and additional articles are available from www.hpbmagazine.org.

REFERENCES

ASHRAE members can access *ASHRAE Journal* articles and ASHRAE research project final reports at technologyportal.ashrae.org. Articles and reports are also available for purchase by nonmembers in the online ASHRAE Bookstore at www.ashrae.org/bookstore.

ACG. 2005. *ACG commissioning guideline*. AABC Commissioning Group, Washington, D.C.

AIHA. 2010. Laboratory ventilation. ANSI/AIHA *Standard* Z9.5-2012. American Industrial Hygiene Association, Fairfax, VA.

Anderson, D.R., J. Macaluso, D.J. Lewek, and B.C. Murphy. 2004. *Building and renovating schools: Design, construction management, cost control*. R.S. Means, Kingston, MA, and John Wiley & Sons, New York.

ANSI/AHRI. 2015. Performance rating of DX dedicated outdoor air system units. *Standard* 920. Air-Conditioning, Heating, and Refrigeration Institute, Arlington, VA.

ANSI. 2010. Acoustical performance criteria, design requirements and guidelines for schools. *Standard* 12.60-2010. American National Standards Institute, Washington, D.C.

ASHRAE. 1988. *Active solar heating systems design manual*.

ASHRAE. 1991. *Active solar heating systems installation manual*.

ASHRAE. 2008. *30% advanced energy design guide for K-12 school buildings*.

ASHRAE. 2010. *Thermal comfort tool*.

ASHRAE. 2011. *50% advanced energy design guide for K-12 school buildings*.

ASHRAE. 2015. *Combined heat and power design guide*.

ASHRAE. 2017 *ASHRAE design guide for dedicated outdoor air systems (DOAS)*.

ASHRAE. 2018. *Achieving zero energy—Advanced energy design guide for K-12 school buildings*. www.ashrae.org/technical-resources/aedgs/zero-energy-aedg-free-download.

ASHRAE. 2019. The commissioning process. *Guideline* 0-2019.

ASHRAE. 2007. HVAC&R technical requirements for the commissioning process. *Guideline* 1.1-2007.

ASHRAE. 2014. Measurement of energy and demand savings. *Guideline* 14-2014.

ASHRAE. 2012. Instrumentation for monitoring central chilled-water plant efficiency. *Guideline* 22-2012.

ASHRAE. 2019. Safety standard for refrigeration systems. ANSI/ASHRAE *Standard* 15-2019.

ASHRAE. 2019. Designation and safety classification of refrigerants. ANSI/ASHRAE *Standard* 34-2019.

ASHRAE. 2017. Method of testing general ventilation air cleaning devices for removal efficiency by particle size. *Standard* 52.2-2017.

ASHRAE. 2020. Thermal environmental conditions for human occupancy. ANSI/ASHRAE *Standard* 55-2020.

ASHRAE. 2019. Ventilation for acceptable indoor air quality. ANSI/ASHRAE *Standard* 62.1-2019.

ASHRAE. 2019. Energy standard for buildings except low-rise residential buildings. ANSI/ASHRAE/IESNA *Standard* 90.1-2019.

ASHRAE. 2020. Standard method of test for the evaluation of building energy analysis computer programs. ANSI/ASHRAE *Standard* 140-2020.

ASHRAE. 2020. Standard for the design of high-performance green buildings except low-rise residential buildings. ANSI/ASHRAE/USGBC/IES *Standard* 189.1-2020.

ASHRAE. 2020. Method of testing ultraviolet lamps for use in HVAC&R units or air ducts to inactivate micro-organisms on irradiated surfaces. ASHRAE *Standard* 185.2-2020.

ASHRAE. 2021. Ventilation of health care facilities. ASHRAE *Standard* 170-2021.

ASHRAE. 2022. *Educational Facilities Design Guide for Education Facilities: Prioritization for Advanced Indoor Air Quality.*

Beaufait, R. 2018. Paving a path for zero energy schools. *ASHRAE Journal* (May):36-42.

BetterBricks. 2009. *Bottom-line thinking on energy in commercial buildings: Schools*. BetterBricks, Northwest Energy Efficiency Alliance, Portland, OR.

Bahnfleth, W.P. 2020. Reducing infectious disease transmission using UVGI. ASHRAE Short Course.

Bluyssen, P.M., M. Ortiz, and D. Zhang. 2021. The effect of a mobile HEPA filter system on "infectious" aerosols, sound and air velocity in the SenseLab. *Building and Environment* 188. dx.doi.org/10.1016/j.buildenv.2020.107475.

Bolinger, M. 2009. Financing non-residential photovoltaic projects: Options and implications. Lawrence Berkeley National Laboratory *Report* LBNL-1410 E. emp.lbl.gov/reports.

California Energy Commission. 2006. *Displacement ventilation design guide: K-12 schools*.

Chen, Q., and L. Glicksman. 2003. *System performance evaluation and design guidelines for displacement ventilation*. ASHRAE.

Cory, K., J. Coughlin, and C. Coggeshall. 2008. Solar photovoltaic financing: Deployment on public property by state and government. NREL *Technical Report* NREL/TP-670-43115. www.nrel.gov/docs/fy08osti/43115.pdf.

Cramm, K. 2020. Designing HVAC systems for school gyms. *ASHRAE Journal* (August):48-53.

Dell'Isola, A.J. 1997. *Value engineering: Practical applications*. R.S. Means Company, Kingston, MA.

DiBerardinis, L.J., J.S Baum, M.W. First, G.T. Gatwood, and A.K. Seth. 2013. *Guidelines for laboratory design—Health and safety considerations*, 4th ed. Wiley, New York.

Ebbing, E., and W. Blazier, eds. 1998. *Application of manufacturers' sound data*. ASHRAE.

EPA. 2000. *Indoor air quality—Tools for schools*, 2nd ed. U.S. Environmental Protection Agency, Washington, D.C.

EPA. 2010. *Laboratories for the 21st century (Labs21).* U.S. Environmental Protection Agency, Washington, D.C. lbt.i2sl.org.

Esberg, G. 2010. Dispelling the cost myth. *High Performing Buildings* (Winter):30-42.

EVO. 2018. *International performance measurement and verification protocol (IPMVP)*. Efficiency Valuation Organization, Washington, D.C. www.evo-world.org/en/products-services-mainmenu-en/protocols/ipmvp.

FEMP. 2008. *Measurement and verification for federal energy projects*, v. 3.0, Federal Energy Management Program, Washington, D.C.

FEMP. 2021 *BLLC 5.3-21: Building life cycle cost program*. Federal Energy Management Program, Washington, D.C. www.nist.gov/services-resources/software/building-life-cycle-cost-programs.

Glazer, J. 2006. Evaluation of building performance rating protocols. ASHRAE Research Project RP-1286, *Final Report*.

Harriman, L.G., G.W. Brundrett, and R. Kittler. 2001. *Humidity control design guide for commercial and institutional buildings*. ASHRAE.

Khankari, K. 2021. Analysis of spread of airborne contaminants and risk of infection. *ASHRAE Journal* (July).

Kavanaugh, S.P., and K. Rafferty. 1997. *Ground-source heat pumps*. ASHRAE.

Kramer, H., G. Lin, C. Curtin, E. Crowe, and J. Granderson. 2020. *Proving the business case for building analytics*. Lawrence Berkeley National Laboratory (LBNL), October. dx.doi.org/10.20357/B7G022.

Krieth, F., and Y. Goswami. 2007. *Handbook of energy efficiency and renewable energy*. CRC Press, Boca Raton, FL.

Kowalski, W. 2009. *Ultraviolet germicidal irradiation handbook*. Springer-Verlag, Berlin.

Laboratory Benchmarking Tool (LBT). 2019. lbt.i2sl.org/.

Maor, I., and T.A. Reddy. 2008. Near-optimal scheduling control of combined heat and power systems for buildings, Appendix E. ASHRAE Research Project RP-1340, *Final Report*.

McIntosh, I.B.D., C.B. Dorgan, and C.E. Dorgan. 2001. *ASHRAE laboratory design guide*. ASHRAE.

Meckler, M., and L. Hyman. 2010. *Sustainable on-site CHP systems: Design, construction, and operations*. McGraw-Hill, Columbus, OH.

MFMA. 2005. *Humidity and environmental recommendations*. Maple Flooring Manufacturers Association, Oakbrook Terrace, IL. www.maplefloor.org/TechnicalInfo/Position-Statements/Humidity-and-Environmental-Recommendations.aspx.

NAFA. 2012. *Recommended practices for filtration for schools*. National Air Filtration Association, Madison, WI. www.nafahq.org/wp-content/uploads/Schools-Secured.pdf.

NAFA. 2021. *Recommended practices for filtration for commercial spaces*. National Air Filtration Association, Madison, WI. www.nafahq.org/wp-content/uploads/Commercial-Office-Spaces-Secured.pdf.

NCSU. 2018. *DSIRE database of state incentives for renewables & efficiency*. North Carolina State University, under National Renewable Energy Laboratory Subcontract XEU-0-99515-01. www.dsireusa.org.

Neuman, D.J. 2003. *Building type basics for college and university facilities*. John Wiley & Sons, Hoboken, NJ.

New Buildings Institute. 2007. *Core performance guide: A prescriptive program to achieve significant, predictable energy savings in new commercial buildings*. New Buildings Institute, White Salmon, WA.

NRC. 1996. *Guide for the care and use of laboratory animals*. National Research Council, National Academy Press, Washington, D.C.

Orlando, J.A. 1996. *Cogeneration design guide*. ASHRAE.

Petchers, N. 2002. *Combined heating, cooling & power handbook: Technologies & applications*. Fairmont Press, Inc. Lilburn, GA.

RETScreen. 2021. *RETScreen® international: Empowering cleaner energy decisions*. Natural Resources Canada. www.retscreen.net/ang/home.php.

R.S. Means. 2023a. *Means mechanical cost data*. R.S. Means Company, Inc., Kingston, MA.

R.S. Means. 2023b. *Means maintenance and repair cost data*. R.S. Means Company, Inc., Kingston, MA.

Rumsey, P., and J. Weale. 2006. Chilled beams in labs. *ASHRAE Journal* 49(1):18-25.

Ryan, W. 2004. *Targeted CHP outreach in selected sectors of the commercial market*. Report prepared by the University of Illinois at Chicago Energy Resource Center for the U.S. Department of Energy, Energy Efficiency and Renewable Energy Program.

Salazar, J., D.P. Wyon, B. Moreno, S. Espinoza, and P. Wargocki. 2018. Reducing classroom temperature in a tropical climate improved the thermal comfort and the performance of elementary school pupils. *Indoor Air* 28(6):892-904.

Schaffer, M.E. 1993. *A practical guide to noise and vibration control for HVAC systems*. ASHRAE.

Seibert, K.L. 2010. An energy education. *High Performing Buildings* (Winter):44-55.

Siebein, G.W., and R.M. Likendey. 2004. Acoustical case studies of HVAC systems in schools. *ASHRAE Journal* 46(5):35-47.

Skistad, H., E. Mundt, P.V. Nielsen, K. Hagstrom, and J. Railio. 2002. *Displacement ventilation in non-industrial premises*. Federation of European Heating and Air-Conditioning Associations (REHVA), Brussels.

Su, C., J. Lau, and F. Yu. 2017. A case study of upper-room UVGI in densely-occupied elementary classrooms by real-time fluorescent bioaerosol measurements. *International Journal of Environmental Research and Public* Health 14(1):51. dx.doi.org/10.3390/ijerph14010051.

Tartarini, F., S. Schiavon, T. Cheung, and T. Hoyt. 2020. CBE thermal comfort tool: Online tool for thermal comfort calculations and visualizations. *SoftwareX* 12. dx.doi.org/10.1016/j.softx.2020.100563.

Understood.org. 2019. *The 13 conditions covered under IDEA*. Understood.org USA, New York. www.understood.org/en/articles/conditions-covered-under-idea.

UL. 2021. Guidance on the use of integrated indoor air quality sensors. *Standard* 2906. UL Solutions,

USGBC. 2009a. *LEED® 2009 for schools—New construction and major renovations*. U.S. Green Building Council, Washington, D.C.

USGBC 2009b. *LEED® 2009 for existing buildings and operation maintenance*. U.S. Green Building Council, Washington, D.C.

U.S. DOE. 2009. *EnergySmart schools*. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy.

U.S. DOE. 2014. *Office of Energy Efficiency and Renewable Energy (EERE)*. U.S. Department of Energy, Washington, D.C. www.energy.gov/eere.

U.S. DOE. 2015. *M&V guidelines: Measurement and verification for performance-based contracts*, v. 4.0. U. S. Department of Energy, Federal Energy Management Program, Washington, D.C. www.energy.gov/sites/prod/files/2016/01/f28/mv_guide_4_0.pdf.

Volz, J, and M. Branham. 2022. Driving energy savings with data. *ASHRAE Journal* 64(4, April):60-63.

Wargocki, P., J. Porras-Salazar, and S. Contreras-Espinoza. 2019. The relationship between classroom temperature and children's performance in school. *Building and Environment*. dx.doi.org/10.1016/j.buildenv.2019.04.046.

Wargocki, P., and D.P. Wyon. 2007. The effects of moderately raised classroom temperatures and classroom ventilation rate on the performance of schoolwork by children (RP-1257). *HVAC Research* 13(2):193-220.

Wargocki, P, and D.P. Wyon. 2013. Providing better thermal and air quality conditions in school classrooms would be cost-effective. *Building and Environment* 581-589.

Webb, L.H., and K. C. Parsons. 1998. Case studies of thermal comfort for people with physical disabilities. *ASHRAE Transections* 104(1A).

Wright, G. 2003. The ABC's of K-12. *Building Design & Construction*, June.

Zhao, W., S. Lestinen, P. Mustakallio, S. Kilpelainen, J. Jokisalo, and R. Kosonen. 2021. Experimental study on thermal environment in a simulated classroom with different air distribution methods, *Journal of Building Engineering* 43. dx.doi.org/10.1016/j.jobe.2021.103025.

BIBLIOGRAPHY

ASHRAE. 2010. *ASHRAE greenguide: The design, construction and operation of sustainable buildings*, 3rd ed. J.M. Swift and T. Lawrence, eds.

ASHRAE. 2021. Weather data for building design standards. ANSI/ASHRAE *Standard* 169-2021.

ASHRAE. 2019. *Standard 90.1-2016 user's manual*.

Barbose, G., N. Darghouth, S. Weaver, and R. Wiser. 2013. *Tracking the sun VI: An historical summary of the installed price of photovoltaics in the United States from 1998 to 2012*. U.S. Department of Energy's Lawrence Berkeley National Laboratory.

CHPS. 2016. *Best practices manual*. Collaborative for High Performance Schools, CA.

Darbeau, M. 2003. ARI's views on ANSI S-12.60-2002. *ASHRAE Journal* 45(2):27.

Harriman, L.G., and J. Judge. 2002. Dehumidification equipment advances. *ASHRAE Journal* 44(8):22-27.

Lan, L., L. Xia, R. Hejjo, D.P. Wyon, and P. Wargocki. 2020. Perceived air quality and cognitive performance decrease at moderately raised indoor temperatures even when clothed for comfort. *Indoor Air* 30:841-859.

Lilly, J.G. 2000. Understanding the problem: Noise in the classroom. *ASHRAE Journal* 42(2):21-26.

Megerson, J.E., and C.R. Lawson. 2008. Underfloor for schools. *ASHRAE Journal* 50(5):28-30, 32.

Moxley, R.W. 2003. Prioritizing for preschoolers. *American School & University* (November).

Mumma, S.A. 2001. Designing dedicated outdoor air systems. *ASHRAE Journal* 43(5):28-31.

Nasis, R.W., and R. Tola. 2002. Environmental impact. *American School & University* (November).

Nelson, P.B. 2003. Sound in the classroom—Why children need quiet. *ASHRAE Journal* 45(2):22-25.

Perkins, B. 2001. *Building type basics for elementary and secondary schools*. John Wiley & Sons, New York.

Rodríguez, C.M., M.C. Coronado, and J.M. Medina. 2021. Thermal comfort in educational buildings: The Classroom-Comfort-Data method applied to schools in Bogota, Colombia. *Building and Environment* 194(May).

Schaffer, M.E. 2003. ANSI standard: Complying with background noise limits. *ASHRAE Journal* 45(2):26.

Sadrizadeh, S., R. Yao, F. Yuan, H. Awbi, W. Bahnfleth, Y. Bi, G. Cao, C. Croitoru, R. de Dear, F. Haghighat, P. Kumar, M. Malayeri, F. Nasiri, M. Ruud, P. Sadeghian, P.Wargocki, J. Xiong, W. Yu, and B. Li. 20252. Indoor air quality and health in schools: A critical review for developing the roadmap for the future school environment. *Journal of Building Engineering*. dx.doi.org/10.1016/j.jobe.2022.104908.

U.S. DOE. 2002. *National best practices manual for building high performance schools*. U.S. Department of Energy, Washington, D.C. www.epa.gov/iaq/schools/high_performance.html.

Watch, D. 2001. *Building type basics for research laboratories*. John Wiley & Sons, New York.

Wolf, M., and J. Smith. 2009. Optimizing dedicated outdoor-air systems. *HPAC Engineering* (December).

Wulfinghoff, D.R. 2000. *Energy efficiency manual*. Energy Institute, Wheaton, MD.

The preparation of this chapter is assigned to TC 9.7, Educational Facilities.