Effective Design of Heating, Ventilation and Air-conditioning Systems for Healthcare Facilities

a report by

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Today's hospital environment requires a healthcare facility's heating, ventilation and air-conditioning (HVAC) systems to provide excellent ventilation effectiveness in order to maintain appropriate indoor air quality, prevent the spread of infection, preserve a sterile and healing environment for patients and staff and to maintain space and comfort conditions. These demands require a healthcare facility's HVAC systems to provide significant quantities of total ventilation air and outdoor air. They also require significant treatment of this ventilation air, including cooling, dehumidifying, reheating, humidifying and filtration of the air to achieve these effective ventilation goals. Future trends indicate that even more treatment of the air will be required to respond further to infection control and bioterrorism issues.

The American Society of Heating, Refrigeration and Air-conditioning Engineers, Inc. (ASHRAE) has recently published the 2003 *HVAC Design Manual for Hospitals and Clinics* ("the Design Manual") to address these challenging design requirements for healthcare facilities. This Design Manual was developed by a group of members of ASHRAE's Special Projects Committee SP-91. The members included design professionals, health specialists, researchers, code officials and representatives of the revision task-force for the American Institute of Architects (AIA) Guidelines for the Design and Construction of Hospitals and Healthcare Facilities, the American Society of Hospital Engineers (ASHE) and the American College of Surgeons (ACS).

The Design Manual has taken the recommendations from all of these informed sources to create a guide that outlines the best practices for design, construction and maintenance of healthcare HVAC systems, including:

- infection control practices to minimise airborne contaminants;
- air distribution effectiveness within spaces served by the ventilation/HVAC systems;
- air quality requirements in the hospital;
- total and outdoor air ventilation requirements;
- room pressure relationships;
- temperature and humidity design criteria;
- filtration practices;
- selection of air-handling systems, distribution systems and control strategies for effective operation;
- system reliability and redundancy recommendations;
- energy-conservative design practices for the healthcare environment; and
- commissioning procedures and operations and maintenance of healthcare HVAC systems.

The Design Manual carefully defines these requirements for each functional space in the healthcare facility, including general medical and surgical nursing units; infectious isolation rooms and protective environment rooms; critical care nursing units; nurseries; labour, delivery and recovery areas; physical therapy areas; surgical suites; accident and emergency departments (A&E) and trauma areas; imaging and radiology areas; laboratory suites; endoscopy suites; offices; foyers; support service areas such as dietary; central sterile services; laundry; materials management and maintenance areas; environmental and linen services; pharmacy and autopsy/morgue areas.

Recommendations for Hospital HVAC Systems

The newly recommended design ventilation rates and design space temperature requirements for healthcare facilities, as recently published in the Design Manual, are listed in *Table 1*. In the US, these requirements are most often met by providing a group of custom-designed air-handling systems to serve the hospital spaces. These air-handling systems must treat the ventilation air by cooling and heating it as required, humidifying it if required and filtering it at significant levels. The systems must also maintain pressurisation requirements and space temperature and humidity setpoint. The most frequently used systems in the healthcare environment are constant volume dual-duct, multizone or terminal reheat systems, as illustrated in *Figures 1* and *2*. However, these significant airflow requirements that are necessary to maintain sterile and healthy environments in healthcare facilities are also the major contributor to

Table 1: Recommended Ventilation Rates/Temperatures

Functional space	Pressure relationship to adjacent areas	Minimum air changes of outdoor air per hour	Minimum total air changes per hour	Design temperature °F (°C)	Design relative humidity
Operating theatres	P	5	25	68–75 (20–23.9)	30–60
Delivery rooms	P	5	25	68–75 (20–23.9)	30–60
Recovery rooms	P	2	6	68–75 (20–23.9)	30–60
Intensive-care rooms	O	2	6	70–75 (21.1–23.9)	30–60
Nursery suites	P	5	12	75–80 (23.9–26.7)	30–60
Trauma rooms (crisis)	O	3	15	70–75 (21.1–23.9)	30–60
Trauma rooms (A&E)	P	2	6	70–75 (21.1–23.9)	30–60
A&E waiting rooms**	N	2	12	70–75 (21.1–23.9)	30–60
Radiology waiting rooms**	N	2	12	70–75 (21.1–23.9)	30–60
Procedure rooms	N	3	15	70–75 (21.1–23.9)	30–60
Bronchoscopy/triage rooms**	N	2	12	70–75 (21.1–23.9)	30–60
Patient rooms (general)	O	2	6	70–75 (21.1–23.9)	30–60
Protective environment rooms	P	2	12	70–75 (21.1–23.9)	30–60
Airborne inf. isolation room	N	2	12	70–75 (21.1–23.9)	30–60
Labour/delivery/recovery/postpartum rooms	O	2	6	70–75 (21.1–23.9)	30–60
X-ray (surgery/critical care/catherisation)	P	3	15	72–78 (22.2–25.6)	30–60
X-ray (diagnostic)	O	2	6	72–78 (22.2–25.6)	30–60
Laboratory (general/bact./cytology/microbiol./hist./nuclear medicine/pathology)**	N	2	6	70–75 (21.1–23.9)	30–60
Laboratory/biochem./media transfer	P	2	6	70–75 (21.1–23.9)	30–60
Physical therapy	N	2	6	72–80 (22.2–26.7)	30–60
Central supply soiled**	N	2	6	72–78 (22.2–25.6)	30–60
Clean**	P	–	6		
Steriliser room**	N	–	10	– –	– –
Food preparation**	O	2	10	– –	– –
Laundry	N	2	10	– –	– –

Key: P = positive; N = negative; O = neutral

*** All air to be exhausted directly to outdoors.*

Source: American Society of Heating, Refrigerating and Air-conditioning Engineers, Inc. (ASHRAE), HVAC Design Manual for Hospital and Clinics, *SP-91, 2003.*

the significant energy usage of healthcare facilities. The total and outdoor air change requirements are almost always significantly greater than those required to meet space hourly heating and cooling load requirements and maintain space comfort. As a result, the HVAC systems are constantly using significant fan energy to move the air from the air-handling system throughout the facility, and significant energy to cool and dehumidify and then reheat the ventilation air delivered to the spaces in order to maintain space temperature and humidity requirements. The outdoor air requirements also result in significant energy used for outdoor air cooling, dehumidification, heating and dehumidification, depending on the climate.

Energy Impact of the HVAC Systems in a Healthcare Facility

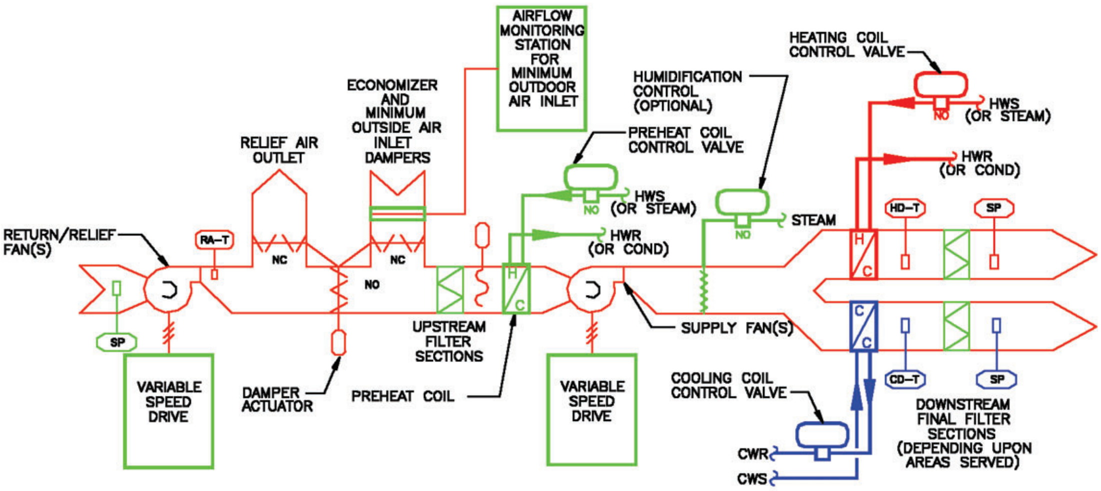
The impact that these HVAC systems have on the consumption of energy resources in healthcare facilities using traditional healthcare HVAC systems is illustrated in *Table 2*. This table was developed using a Department of Energy (DOE) 2.1 computer model of an actual hospital evaluated in several climates.

The example facility is a 305,000 square foot (28,335m^2), full-service metropolitan healthcare facility with all the typical healthcare facility functions: surgery suites, recovery suites, labour/delivery areas including nurseries and Caesarean-section suites, cardiac catherisation areas, radiology, mammography, nuclear medicine areas, laboratory areas, physical and occupational therapy areas, out-patient examination and surgery areas, dietary, laundry, nursing floors, A&E and waiting areas, maintenance services, offices and special services.

The annual energy usage for this facility in 2002 was 255,320 British thermal units (BTU) per square foot per year (2.89 x 10^6 kilojoules [kJ] per m^2 per year) at an annual cost of US$779,840 or US$2.56 per square foot per year (US$27.52 per m^2 per year).

The energy rates in 2001 for the example facility were US$0.055 per kilowatt hour for electricity and US$5 per million BTU (US$4.74 per million kJ) for natural gas. *Table 2* was created using these rates. As illustrated in *Table 2*, depending on the climate, between 35% and 54% of the annual energy costs of the typical healthcare facility are related to the

Figure 1: General Air-handling System Schematic – Dual-duct or Multizone Air-handling Units



operation of the healthcare HVAC systems, primarily related to treatment of ventilation air. This includes ventilation fan energy, outdoor air cooling and dehumidification, outdoor air heating and humidification, as well as cooling of ventilation of air and thermal mixing and reheating required to maintain space comfort. However, there are methods suggested in the new Design Manual to achieve the ventilation requirements in order to maintain a healthy and comfortable environment in an energy-conservative manner.

Use of Variable Air Volume Supply and Return-air Systems

In most locations, health codes will allow a reduction in minimum total airflow rates and minimum outdoor airflow rates during unoccupied periods. Significant energy savings can be achieved by designing the air-handling systems serving these spaces as variable air volume (VAV) tracking systems, as illustrated in *Figures 2* and *3*. The AIA and ASHRAE allow ventilation rates to be reduced to 25% of the occupied period rates, as long as continuous directional control and space pressurisation is maintained at all times and the full (occupied) ventilation air change rates can be re-established at any time. A key component of this energy-conservative design is that most areas in healthcare facility spaces are not occupied 24 hours a day, seven days per week, although most current healthcare ventilation systems operate under that premise. Usually, only about 15% to 20% of the hospital is actually occupied constantly.

Several factors should be evaluated when determining how effective the use of a VAV HVAC system will be in serving certain spaces of a healthcare facility:

- hours of operation of the spaces being served by the HVAC system;
- magnitude of the difference between the required minimum ventilation air changes per hour (see *Table 1*) and the airflow required to meet space-sensible cooling load requirements;
- requirements for continuous directional control – positive, negative, neutral or no requirement (see *Table 1*).

For example, in spaces that are occupied for 24 hours daily (i.e. A&E, 24-hour laboratories or pharmacy areas, intensive-care units and patient rooms, etc.) and/or where the space-sensible cooling airflow requirements are not significantly different to the required minimum ventilation air change rate requirements, reducing airflow will probably not reduce energy consumption greatly. However, in spaces where no continuous directional control or minimum ventilation air change rates are required, where there are significant unoccupied hours or where space-sensible cooling airflow requirements are significantly different to the required minimum ventilation air requirements, then significant reductions in energy consumption can be achieved through use of VAV control of the HVAC systems, as illustrated in *Figures 2* and *3*. This is especially true when the airflow rates can be reduced substantially during unoccupied periods. Most spaces in healthcare facilities fall into these categories.

VAV Occupied and Unoccupied Period Control for Non-critical Care Spaces

Many of the spaces in a healthcare facility (such as dining areas, out-patient administrative offices, maintenance areas, many out-patient therapy areas and many common areas) do not have continuous pressurisation control requirements. These areas can be served easily by a traditional VAV air-handling system and can reduce energy consumption substantially through use of occupied and unoccupied period control strategies.

Table 2: Typical Hospital Component Energy Costs – Traditional Constant Volume Ventilation Systems

Component	% of Total Energy Costs										
	NE (Boston)	Mid-Atl. (Phila.)	SE (Atlanta)	Florida (Miami)	Midwest (St. Louis)	Upper Ctrl. (Chicago)	North (Minapls.)	South Ctrl. (Houston)	Southwest (Tuscon)	S. Calif. (Los Ang.)	Northwest (Seattle)
Lighting	12%	12%	12%	11%	11%	12%	11%	11%	13%	13%	13%
Cost	$89,445	$89,445	$89,445	$89,445	$89,445	$89,445	$89,445	$89,445	$89,445	$89,445	$89,445
Miscellaneous Electrical	13%	13%	13%	12%	13%	13%	13%	12%	14%	14%	15%
Cost	$98,860	$98,860	$98,860	$98,860	$98,860	$98,860	$98,860	$98,860	$98,860	$98,860	$98,860
OA Cooling/ Dehumidification	1%	1%	2%	7%	1%	1%	1%	5%	1%	4%	1%
Cost	$4,625	$7,355	$18,915	$56,750	$8,420	$7,350	$5,780	$35,320	$5,875	$32,945	$7,350
Space Sensible/ Ventilation Air Cooling	8%	8%	11%	17%	7%	7%	6%	14%	12%	9%	5%
Cost	$53,570	$63,125	$82,625	$142,515	$58,875	$54,860	$51,360	$112,460	$85,450	$60,335	$61,330
Cooling - Fan Heat/Thermal Mixing	2%	2%	3%	4%	2%	2%	2%	3%	3%	2%	1%
Cost	$13,395	$15,780	$20,655	$35,630	$14,720	$13,715	$12,840	$28,115	$21,360	$15,085	$7,835
OA Heating/ Dehumidification	4%	3%	3%	1%	5%	5%	6%	1%	1%	1%	3%
Cost	$31,320	$24,210	$20,525	$5,600	$36,730	$37,150	$46,060	$10,715	$8,220	$1,485	$18,715
Space Heating/ Reheating/Thermal Mixing	24%	24%	18%	13%	23%	23%	24%	17%	18%	19%	24%
Cost	$181,450	$172,250	$142,750	$108,525	$182,890	$182,215	$196,450	$127,800	$128,000	$139,350	$164,750
Cooling Towers/ Condenser Water Pumping	3%	4%	5%	8%	4%	4%	3%	7%	5%	5%	3%
Cost	$24,940	$31,250	$40,970	$71,750	$30,430	$29,570	$27,410	$57,745	$34,600	$33,945	$18,015
Chilled Water/Heating Water Pumping	4%	4%	5%	5%	4%	4%	4%	5%	5%	5%	4%
Cost	$32,130	$31,955	$36,430	$42,790	$33,970	$32,740	$32,030	$39,550	$36,870	$37,490	$29,035
Ventilation Fans	20%	20%	20%	17%	19%	19%	19%	18%	21%	21%	22%
Cost	$148,535	$148,535	$148,535	$148,535	$148,535	$148,535	$148,535	$148,535	$148,535	$148,535	$148,535
Heating Auxiliaries	5%	5%	5%	2%	7%	6%	7%	4%	4%	4%	5%
Cost	$43,660	$40,390	$37,180	$23,620	$51,920	$48,940	$53,860	$34,980	$28,025	$26,830	$33,590
DHW Heating/Sterilizers/	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%
Cost	$3,895	$3,895	$3,895	$3,895	$3,895	$3,895	$3,895	$3,895	$3,895	$3,895	$3,895
Dietary/Sterilizers	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%
Cost	$8,920	$8,920	$8,920	$8,920	$8,920	$8,920	$8,920	$8,920	$8,920	$8,920	$8,920
Thermal Distribution	2%	2%	1%	1%	2%	2%	2%	1%	1%	1%	2%
Cost	$11,875	$11,015	$9,260	$6,680	$12,230	$12,220	$13,430	$930	$7,840	$8,090	$10,330
TOTAL	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**
Costs (US)	**$746,620**	**$746,985**	**$758,965**	**$843,515**	**$779,840**	**$768,415**	**$788,875**	**$797,270**	**$705,895**	**$705,210**	**$700,605**

VAV Occupied and Unoccupied Period Control for Critical Care Spaces

As discussed, in areas of the healthcare facility where continuous directional pressurisation control is required (either positive or negative) and significant minimum airflow rates are required during occupied periods, significant reductions in energy usage and costs can be achieved by reducing airflow rates during unoccupied periods. *Figure 3* illustrates the method for achieving these savings when using a VAV reheat supply and return tracking system. The same procedures would apply equally well to dual-duct or multizone systems. These tracking systems will require some additional maintenance to ensure that the return-air terminal airflow stations do not become plugged with lint or dust and may need to be designed with pre-filters ahead of the return-air tracking terminal unit.

Conclusions

In comparing the energy usage of traditional systems (see *Table 2*) with VAV tracking systems (see *Table 3*) in all of the examined geographical locations, the total energy costs in the hospital can be reduced by over 37%. In all cases, electrical consumption was reduced by over 30% and thermal consumption from 50% to 75% of that used for traditional constant volume air-handling systems. The cost to implement these changes to existing air-handling systems in a typical hospital would be US$1,250,070. This would indicate a simple payback from 3.7 to 4.8 years depending on the area in which the projects were implemented.

If these energy-conservative strategies were designed

Figure 2: Variable-volume Air-handling System Schematic – Terminal Reheat Systems

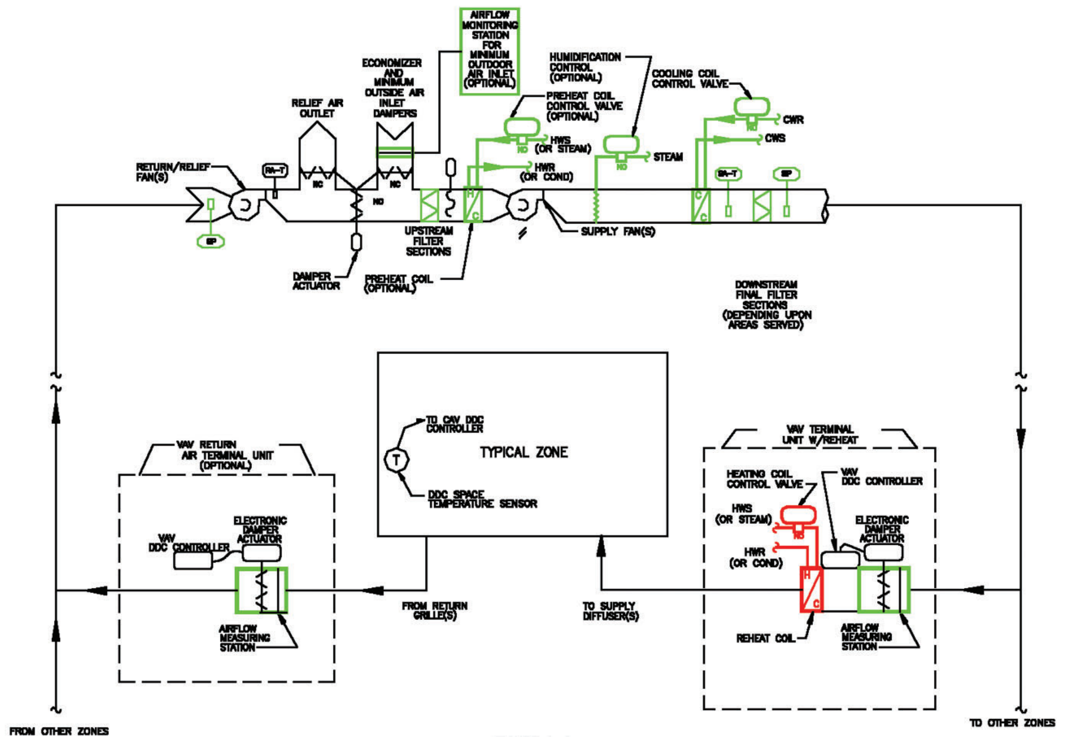


Figure 3: Critical Care Area Schematic – Typical for Directional Pressurisation Control Areas

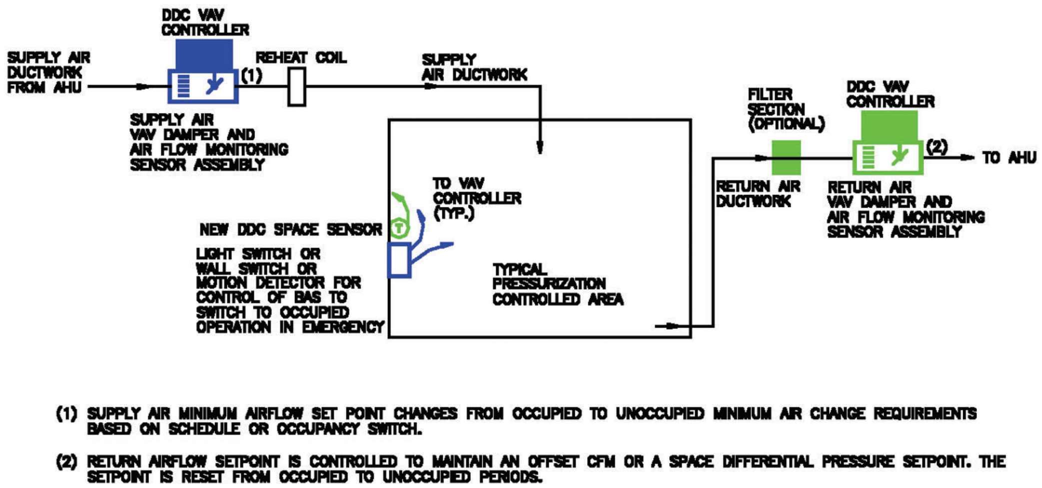


Table 3: Typical Hospital Component Costs (VAV Tracking Ventilation Systems)

Component	NE (Boston)	Mid-Atl. (Phila.)	SE (Atlanta)	Florida (Miami)	Midwest (St. Louis)	Upper Ctrl. (Chicago)	North (Minapls.)	South Ctrl. (Houston)	Southwest (Tuscon)	S. Calif. (Los Ang.)	Northwest (Seattle)
	% of Total Energy Costs										
Lighting (T-8 Lamps)	20%	20%	20%	18%	19%	19%	18%	18%	20%	21%	23%
Cost	$89,445	$89,445	$89,445	$89,445	$89,445	$89,445	$89,445	$89,445	$89,445	$89,445	$89,445
Miscellaneous Electrical	22%	22%	22%	20%	21%	21%	20%	20%	22%	23%	25%
Cost	$98,860	$98,860	$98,860	$98,860	$98,860	$98,860	$98,860	$98,860	$98,860	$98,860	$98,860
OA Cooling	0%	1%	1%	4%	1%	0%	0%	3%	1%	3%	0%
Cost	$1,015	$2,615	$3,800	$18,445	$2,605	$1,980	$1,850	$12,335	$3,555	$12,940	$2,000
Space Sensible/ Ventilation Air Cooling	6%	8%	10%	17%	7%	6%	6%	14%	11%	10%	4%
Cost	$27,570	$36,205	$48,690	$86,885	$32,015	$29,525	$27,150	$68,935	$49,615	$43,200	$17,430
Cooling - Fan Heat/Thermal Mixing	2%	2%	3%	4%	2%	2%	1%	4%	3%	2%	1%
Cost	$6,890	$9,050	$12,175	$21,720	$8,000	$7,380	$6,795	$17,235	$12,405	$10,800	$4,360
OA Heating/ Humidification	5%	4%	3%	0%	5%	6%	7%	1%	1%	0%	3%
Cost	$22,710	$18,370	$10,195	$1,100	$25,500	$26,010	$34,480	$4,730	$6,460	$700	$13,650
Space Heating / Reheating/ Thermal Mixing	13%	13%	9%	3%	13%	13%	15%	6%	6%	8%	13%
Cost	$59,720	$54,285	$38,360	$17,125	$62,290	$62,030	$72,250	$38,925	$36,500	$34,500	$51,350
Cooling Towers/ Condenser Water Pumping	3%	5%	5%	9%	4%	4%	3%	7%	5%	5%	3%
Cost	$14,880	$18,975	$24,520	$42,435	$17,770	$16,980	$15,805	$34,570	$23,400	$19,610	$10,380
Chilled Water/Heating Water Pumping	8%	4%	8%	9%	8%	8%	8%	9%	9%	8%	7%
Cost	$32,130	$31,955	$36,430	$42,795	$33,970	$32,740	$32,030	$39,550	$36,870	$37,490	$29,030
Ventilation Fans	12%	13%	12%	13%	12%	12%	12%	13%	14%	13%	13%
Cost	$56,520	$57,910	$60,220	$67,440	$57,880	$57,245	$57,465	$62,815	$63,600	$56,375	$54,905
Heating Auxiliaries	5%	4%	3%	1%	5%	5%	6%	2%	4%	4%	4%
Cost	$20,995	$17,500	$13,640	$5,450	$23,045	$22,580	$26,050	$10,445	$9,200	$9,035	$15,515
DHW Heating/Sterilizers	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%
Cost	$3,895	$3,895	$3,895	$3,895	$3,895	$3,895	$3,895	$3,895	$3,895	$3,895	$3,895
Dietary/Sterilizers	2%	2%	2%	1%	1%	2%	2%	1%	2%	2%	2%
Cost	$8,920	$8,920	$8,920	$8,920	$8,920	$8,920	$8,920	$8,920	$8,920	$8,920	$8,920
Thermal Distribution	1%	1%	1%	0%	1%	1%	1%	1%	1%	0%	1%
Cost	$5,900	$5,500	$4,600	$1,800	$6,100	$4,600	$5,615	$1,770	$1,790	$2,025	$3,425
TOTAL	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**
COST (US)	**$449,450**	**$453,485**	**$453,750**	**$506,315**	**$470,295**	**$462,190**	**$480,610**	**$492,430**	**$444,515**	**$427,795**	**$403,165**
Savings Over (US)	**$297,070**	**$293,500**	**$293,745**	**$337,345**	**$307,545**	**$306,315**	**$308,265**	**$308,800**	**$260,380**	**$277,411**	**$267,440**
Traditional Systems	**36%**	**39%**	**39%**	**40%**	**40%**	**39%**	**39%**	**35%**	**37%**	**59%**	**40%**

and implemented as part of a new project, the additional incremental costs would only be US$620,245 for a simple payback ranging from 1.3 years to 2.3 years for the additional incremental cost. Therefore, use of VAV air-handling systems with supply/return air-tracking/pressurisation control systems for zones that require directional pressurisation control and traditional VAV air-handling systems for other areas in the healthcare facility can reduce the annual energy costs by between 36% and 40% while still achieving the effective ventilation goals required for healthy and comfortable hospital environments. ■