Rescuing New Construction from Widgetitis with Simple HVAC Design

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ABSTRACT

New commercial facilities waste more energy than people would expect in this era of stringent energy codes. This is primarily due to large central systems that have devolved from the century-old concept of the central air handling system.

Central systems are designed to cool some spaces while heating others at the same time. Wasteful constant volume central systems from the 1950s gave way to less wasteful variable air volume systems in the 1970s. However, variable air volume systems' need to sequence controls for temperature, ventilation, humidity, and fan speed make them too complex to operate efficiently. This complexity requires expertise that facility managers and even engineers and contractors do not typically have, and therefore these systems become major energy wasters. Variable air volume systems can be designed and controlled to operate efficiently but ask any auditor: This is a rare find.

This paper includes data from various sources demonstrating the systemic waste that is virtually unavoidable with central air handling systems, especially when compared to much simpler single zone systems. Findings indicate system type and control are at least as critical as equipment specifications and physical building characteristics, the latter of which are typically the focus of new construction programs.

This paper includes numerous proven system concepts that are as inherently prone to efficiency as status quo central variable air volume systems are prone to waste. The objective of this paper is to serve as a guide to substantially improve new construction programs for low energy use and high customer satisfaction.

Energy Codes and New Construction

In recent years, the adoption of more stringent energy codes and standards has accelerated, resulting in diminishing returns on incremental cost and savings associated with more efficient equipment and appliances. Building energy performance features required by energy codes are reaching physical and economic limits. For example, direct digital control systems are designed to—and, per code, must—trim out the fat associated with wasted fan energy, simultaneous heating and cooling, and ventilation control. Building envelope requirements may already be pushing levels beyond cost effectiveness based on today's fuel costs and equipment efficiency requirements. Finally, there are absolute limits that are being approached such as high efficiency boilers, which have a 100 percent theoretical efficiency limit and lighting power densities which, like the LED exit sign, represent the end of the road in lighting efficiency.

Are the days of new construction programs therefore numbered as impacts from cost-effective measures asymptotically approach zero? Possibly, but that day is far beyond the horizon. There is plenty of room to design and build systems that are cost-effective, simple and save energy over established baselines—but they break the mold.

Historical HVAC

Modern HVAC system design began in the 1880s with the development of the first high-rise, steel-frame buildings in Chicago (Wulfinghoff 2011). Ventilation systems were required at the time to prevent the spread of airborne pathogens in these early crowded buildings. Soon crude tubular heat exchangers using steam and cooling coils repurposed from the meat packing industry were inserted into the air stream for heating and cooling.

Typical systems featured a very large fan to draw fresh air from the roof and push return air through the building to the basement level, where the fan and heat exchangers are situated. Air drawn in from outdoors is pushed out via the stack effect in bathrooms with gravity exhaust systems. Ventilation is supplied by a central system with zone (room) controls provided by individuals using hand valves on steam radiator coils and operable windows.

In the 1950s, cars were big, energy was cheap, and building HVAC systems were designed accordingly. Full cooling was incorporated in buildings by central systems with the use of constant volume reheat systems. Constant volume reheat systems provide air for cooling to all zones all times of the year. Heat is added at the zone level, typically referred to as “reheat”, to offset the cooling or even push the zone into heating as needed to maintain temperature. This is an obvious waste of energy—both in cold weather when cooling is free and in warm weather when it is not.

Following the oil embargo and energy shocks of the 1970s, efficiency and fuel use in buildings suddenly gained scrutiny and the variable air volume system was the solution. Rather than sending a constant flow of conditioned air to temperature-control zones and then mixing or reheating supply air, the variable air volume system would first control the volume of air delivered to the space. This provides a means to control temperature by lessening the amount of reheat required to control space temperature.

Even with this giant leap in energy-saving potential, there remained vast opportunities for savings through sophisticated control algorithms, which were made possible with the acceleration and proliferation of direct digital controls. Up until this point (1970s – 1980s), control systems were pneumatic. The control “wires” were tubes with varying air pressure controlled by complex devices that were ingenious but crude. Digital controls allow for nearly unlimited and infinite control strategies that must be orchestrated in harmony to provide comfortable and safe environments for building occupants.

Digital control allowed for innovative methods to save energy compared to early energy codes that adopted the 1989 edition of ASHRAE 90.1 Energy Standard for Buildings Except Low-Rise Residential Buildings. The 2004 edition of ASHRAE 90.1 advanced the sophistication of digital control system algorithms, a new baseline that wiped out most of the “savings” associated with the previously sophisticated algorithms. These algorithms would clamp down further on simultaneous heating and cooling, minimize fan power, and provide variable ventilation control – at least, in theory.

Plants and Systems

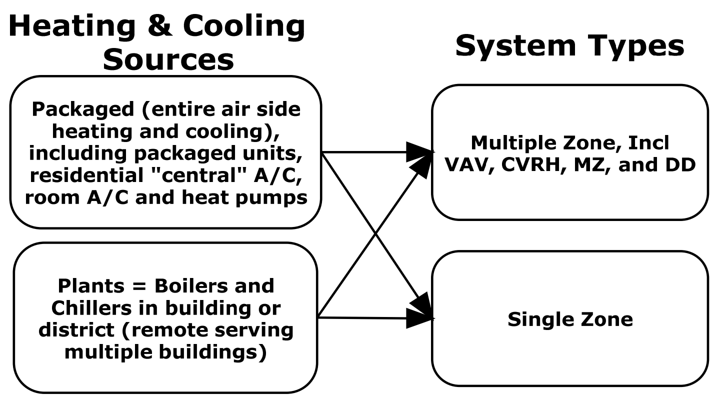
Heating and cooling plants generally refer to boilers and chillers. Plants may be specific to one building or they may be centralized district plants serving a network of buildings such as a downtown or college campus.

Systems refer to air-side equipment that delivers heating, cooling and ventilation to rooms / temperature control zones. There are central systems that serve multiple zones and there are systems that serve single zones.

Heating and cooling can be generated by boiler and chiller plants or by the air-side system itself (packaged equipment, which includes the heat exchangers, refrigerant compressors, and burners needed for cooling and heating).

Packaged equipment can serve both as single-zone and multiple-zone (centralized) systems, and boiler and chiller plants can also serve single-zone and multiple-zone air handling systems. This is depicted in Figure 1. The efficiencies of heating and cooling sources vary substantially—which has been the focus of energy efficiency programs since their inception—but the focus of this paper is on the systems. In reality, system type has as much or more impact on energy consumption than heating and cooling source efficiencies. For example, a code-compliant air-cooled chiller may have an efficiency measured by coefficient of performance (COP)[1] of 2.8. A compliant water-cooled chiller may be twice as efficient with a COP of 6.1. Simultaneous heating and cooling can—and, in many cases, does—easily wipe out the difference and then some, considering heating energy is also wasted.

Figure 1. Heating and Cooling Sources and Systems



VAV = variable air volume, CVRH = constant volume reheat,
MZ = constant volume multizone, DD = constant volume dual duct

Current Building Stocks and Performance

Numerous energy modeling and end-use energy analyses for commercial buildings have been completed. These include the NREL Benchmark study presented at the 2008 ACEEE Summer Study conference (Torcellini et al. 2008) and the Arthur D. Little studies, Volume I (Westphalen & Koszalinki 2001), Volume II (Westphalen & Koszalinski 1999) and Volume III (Roth et al. 2002), which primarily present theoretical energy consumption by buildings and, importantly, HVAC systems that operate per design intent.

When analyzing new construction design alternatives, energy modelers must use code-compliant control sequences in their building simulations. However, code-compliant sequences and actual sequences in the field are two different things. As a result, theoretical simulations do not tell the whole story. Modelers cannot—and should not—arbitrarily insert wasteful control

[1] COP is the ratio of Btu extracted from the conditioned space divided by Btu input to the cooling equipment, typically electrical Btu at 3,413 Btu/kWh. It is the output divided by the input.

sequences or design “flaws” when determining impacts for commercial new construction programs. But these flaws are ubiquitous, although random and varying. The presence of flaws is evinced from Commercial Building Energy Consumption Survey (EIA CBECS 2003) and Michaels Energy’s benchmarking of facilities. The flaws are specifically identified in numerous retrocommissioning findings from Michaels’ investigations of existing buildings. These actual data and findings paint a clear picture that contrasts with building simulations: Buildings with central air handling systems serving multiple zones are much more prone to systemic waste.

Data from CBECS only include heating and cooling sources, not systems. These heating and cooling sources as shown in Figure 1 are identified in CBECS as either central plant (boiler, chiller, and district for either or both heating and cooling), or various packaged options for heating and cooling. Michaels’ experience is backed by Arthur D. Little II, which indicates buildings with central plants are predominantly served by central air handling systems. Little II specifies that 46 percent of the conditioned floor space was served by central variable air volume systems; 29 percent was served by constant volume multiple-zone systems, and 25 percent was served by single-zone fan coil units.

Furthermore, data for Arthur D. Little I were collected from 1986 to 1995. Many of the constant volume multiple zone systems will since have been converted to or replaced with variable air volume systems. The upshot: Buildings with central heating and cooling plants represented in CBECS data can be said to be primarily served by central air handling systems, with a significant majority of the conditioned floor area served by variable air volume systems, which industry practice confirms is today’s “standard.”

Data presented in Table 1 and Figure 2 demonstrate the energy waste inherent with central air handling systems. The “Unitary, Fossil Heat” systems include packaged units, residential central air conditioning and furnaces, room air conditioners, and space heaters. The Heat Pump column represents air-source, water-source with boiler and cooling tower, and ground-source heat pumps.

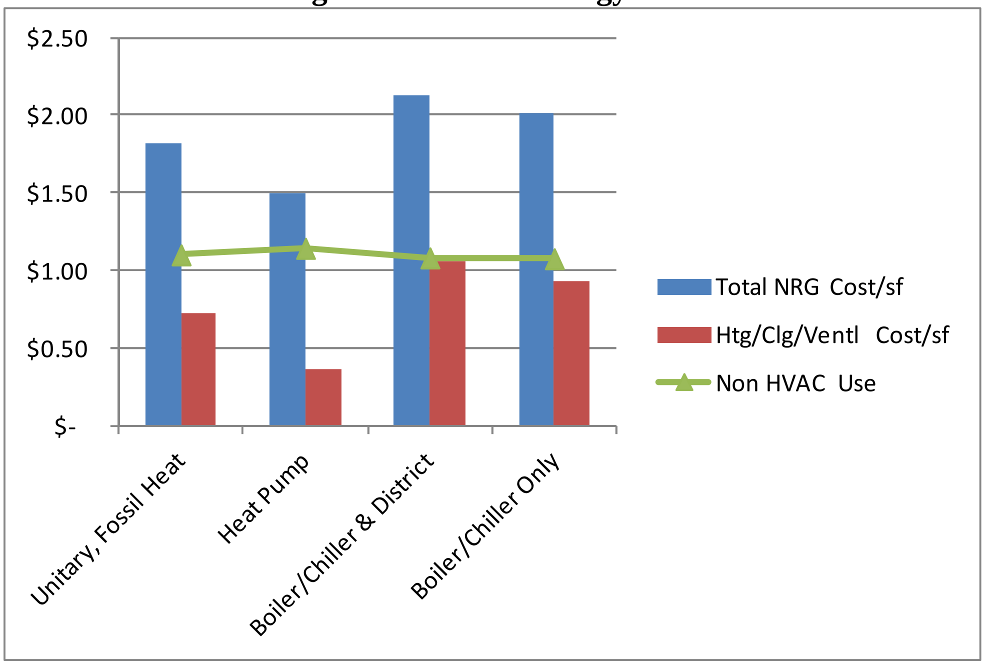
Buildings represented in the sample include office, public assembly, outpatient healthcare, and education with a minimum of 25,000 square feet of floor area and one to three floors. This study focuses on facilities in the upper Midwest and similar climates for purposes of developing new construction programs for the region. The sample was drawn from East and West North-Central, Midwest, Mid-Atlantic, and New England. States in these regions are north of and include Kansas, Missouri, Illinois, Indiana, Ohio, Pennsylvania, and New Jersey.

Table 1. CBECS 2003 Energy Data

	Unitary, Fossil Heat	**Heat Pump**	**Boiler/Chiller & District**	**Boiler/Chiller Only**
N	80	10	43	35
Sample sf	4,545,206	766,871	3,989,977	3,736,045
Represented sf	103,965,178	124,865,000	860,797,295	698,000,500
kWh/sf	15.58	13.92	14.78	14.64
Fossil kBtu/sf	33.04	13.50	81.89	67.80
Heating kBtu/sf	34.82	12.97	70.72	56.18
Cooling kBtu/sf	6.53	6.28	4.72	5.67
Ventl kBtu/sf	8.66	2.46	11.96	10.82
Cooling/Ventl kWh/sf	4.45	2.56	4.89	4.83
Total Energy Cost/sf	$1.82	$1.50	$2.13	$2.01
Htg/Clg/Ventl Cost/sf	$0.72	$0.36	$1.05	$0.93
Non-HVAC Use	$1.10	$1.14	$1.08	$1.07

To achieve a relative comparison among various fuels, a cost of 10 cents per kWh and 80 cents per therm equivalent of fossil fuel is used in this analysis. As shown, the non-HVAC energy consumption is very similar for all subcategories, at about $1.10 per square foot among the buildings with differing heating and cooling sources.

Figure 2. CBECS Energy Data



In recent years, Michaels has provided ASHRAE Level II audits for several hundred facilities in the upper Midwest. The most common facility type for comparison purposes is K-12 schools. Energy intensity data for 34 schools of varying heating and cooling sources and air handling systems similar to the CBECS data are provided in Table 2 and Figure 3. Like the CBECS data, facilities with single-zone systems perform substantially better than facilities with large central air handling systems, even though large central systems are likely to have more efficient heating and cooling sources. The data set is limited, with larger buildings trending toward higher energy intensities.

Arthur D. Little II also provides a clear performance differential between central systems, including constant and variable volume, versus distributed single zone system energy performance. The data show the auxiliary systems alone for central variable air volume systems consume nearly 12 kWh per square foot while single-zone fan coil units only account for a little more than 8 kWh per square foot.

Similarities between CBECS, Michaels' and Arthur D. Little II data are presented in Figure 4. Energy intensity differences are nearly the same, but Michaels' data show single-zone systems using 22 percent less than central systems, as opposed to a 14 percent difference in CBECS. Because the Little II data are provided in Btu only, the fossil fuel split is unknown. However, the energy intensities provided indicate the fan coil / single zone systems use 30 percent less than central plant and variable air volume.

Table 2. Upper Midwest School Energy Intensity (Michaels Data)

	Buildings	Square Feet	Energy Cost	Cost/sf
Gas Central + Cooling	10	1,588,309	$2,290,634	$1.44
Gas Single Zone + Cooling	18	878,526	$1,003,530	$1.14
Ground Source Heat Pump	6	464,500	$499,044	$1.07

Figure 3. Upper Midwest School Energy Intensity Scatter Plot (Michaels Data)

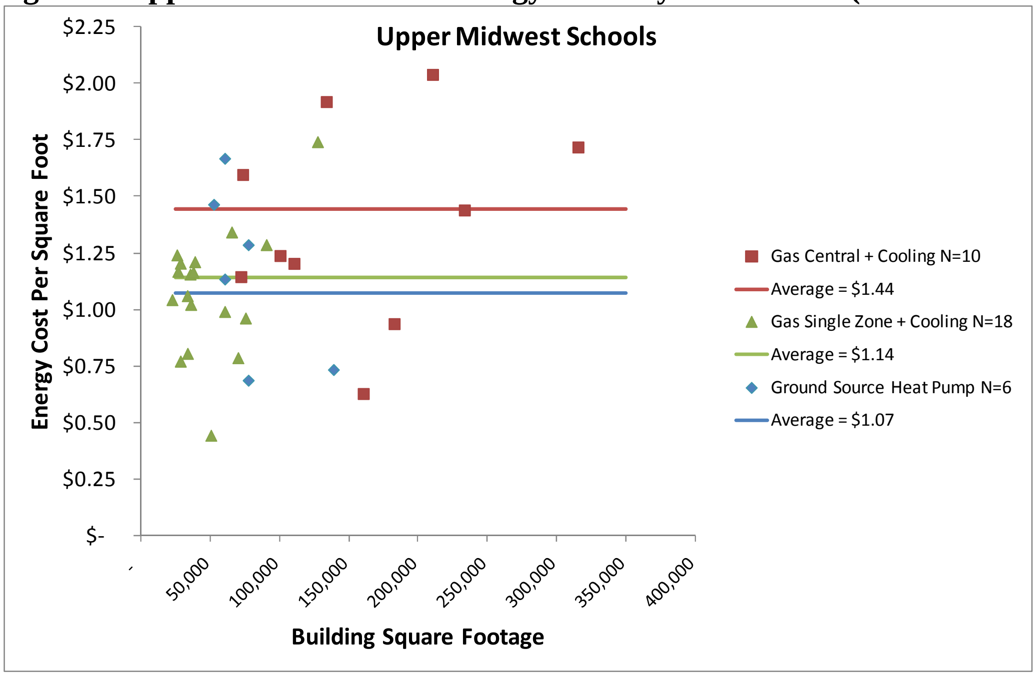
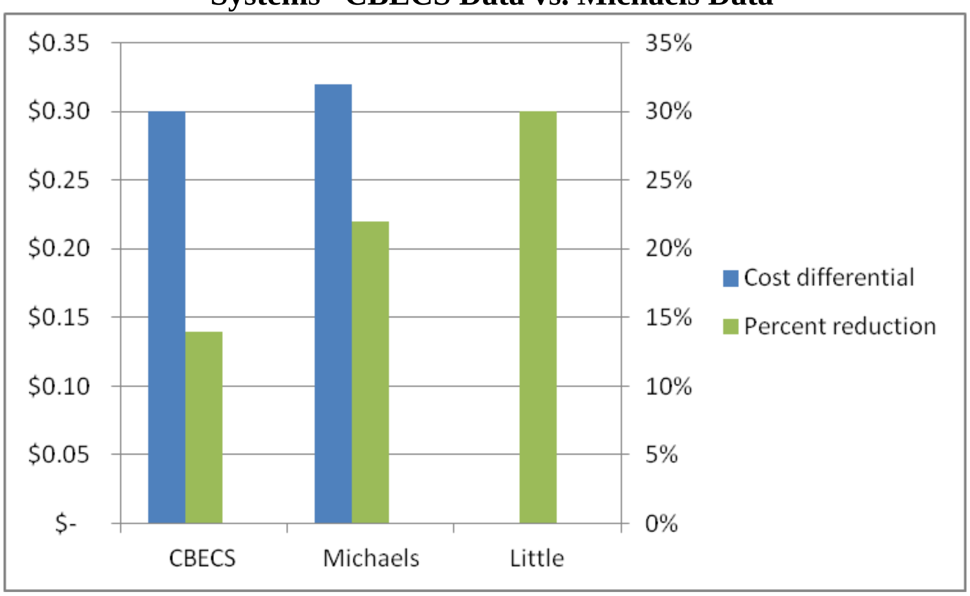


Figure 4. Reductions in Energy Intensity from Single-Zone Compared to Multiple Zone Systems– CBECS Data vs. Michaels Data



Problems with Multiple-Zone Systems

In the 1970s, when energy efficiency and consumption became an issue, designers and the industry should have abandoned the multiple-zone system rather than muddying a misguided concept with the added complexity of variable volume systems. While variable air volume systems can be designed and controlled to operate efficiently, the combination of HVAC system needs, system complexity, and brutal cost competitiveness make the odds of a high performance and efficient variable volume system very unlikely.

The needs for HVAC systems include at least two and sometimes three things: temperature control, ventilation for occupants, and humidity control. Temperature control with variable air volume systems includes sequencing of air flow, central air handler discharge air temperature, and some source of heat in the temperature control zone. In the absence of energy codes and standards, this temperature control aspect, which was the original design feature, is an order of magnitude easier than "advanced" algorithms mentioned previously. Modern energy codes and standards are written assuming that digital control systems have tremendous flexibility and capability, and this is correct. The problem is, writing detailed sequences and then fulfilling those sequences correctly is very difficult.

Temperature Control Complexity

Typical sequences, just at the variable air volume box that controls air flow to the zone for conditions ranging from full cooling to full heating, include: (1) modulating the flow of 55F air down to minimum flow as the cooling load decreases, (2) sequencing the heating valve open until it is full open as the heating load increases, and (3) modulating box flow to open again, increasing the flow of warmest air possible. Less common, though better for both comfort and controls, is when the heating coil is not integral with the box, but instead on the perimeter where it is independent of the air flow. Another option is the fan-powered box where the supply flow includes room-circulated air for heating at constant volume, regardless of airflow from the central air handler.

Central system discharge air temperature is reset to avoid or minimize simultaneous heating and cooling—excessive cooling at the unit, free or not, will cause undue heating in the zone(s). Resetting the discharge air temperature can also be sequenced in different ways. Temperature can be reset as high as possible in both heating and cooling seasons, or it can be reset as high as possible in the cooling season, and remain at 55F in the heating season, adding minimal heat at the central unit and allowing for minimal fan power, but this can create comfort problems when systems are poorly understood and designed to be cheap.

Ventilation Control Complexity

Ventilation control with variable volume systems is extremely complicated considering that the volume of fresh air delivered to a zone depends on the outdoor air damper position, the percent flow of the unit, and the box controller's percent open at the zone. On top of this is the complication of return air from other zones which must be accounted for to provide adequate ventilation. It is so complicated that ASHRAE has developed a complex iterative process just to determine the minimum box position (percent open) for each zone. What is happening in other zones contributes to the volume of "unused" outside air in the zone in question. This is horrifically complex, requiring either complex computational fluid dynamics or guesswork for air distribution, and then guesswork for occupancy patterns – and, having done that, it will only determine the minimum flow rate for zones to ensure adequate ventilation at all times.

Humidity Control

In most occasions, dehumidification is provided by driving the dew point down to desired setpoint, which is typically 55F during warm moist periods of the year. The dew point must always be less than or equal to the actual sensible temperature, and so return air, which is likely sufficiently dry, must be cooled from about 75F to 55F and possibly reheated in the zone because of minimum flow requirements discussed in the previous section.

Fan Energy and Airflow

Central variable air volume systems move large volumes of air over long distances, requiring a lot of sheet metal for ductwork and associated cost. Nearly all the air supplied to zones is returned to the system in a central location and delivered back to the zones. Even though codes and standards require either variable speed drives or variable pitch fan blades for part-flow control, as well as static pressure reset to minimize fan power – which, if done properly, is very competitive with single-zone systems – this rarely occurs, per our findings. Of 13 facilities with the potential for static pressure reset controls that we investigated, all 13 lacked this control.

Non-Performance

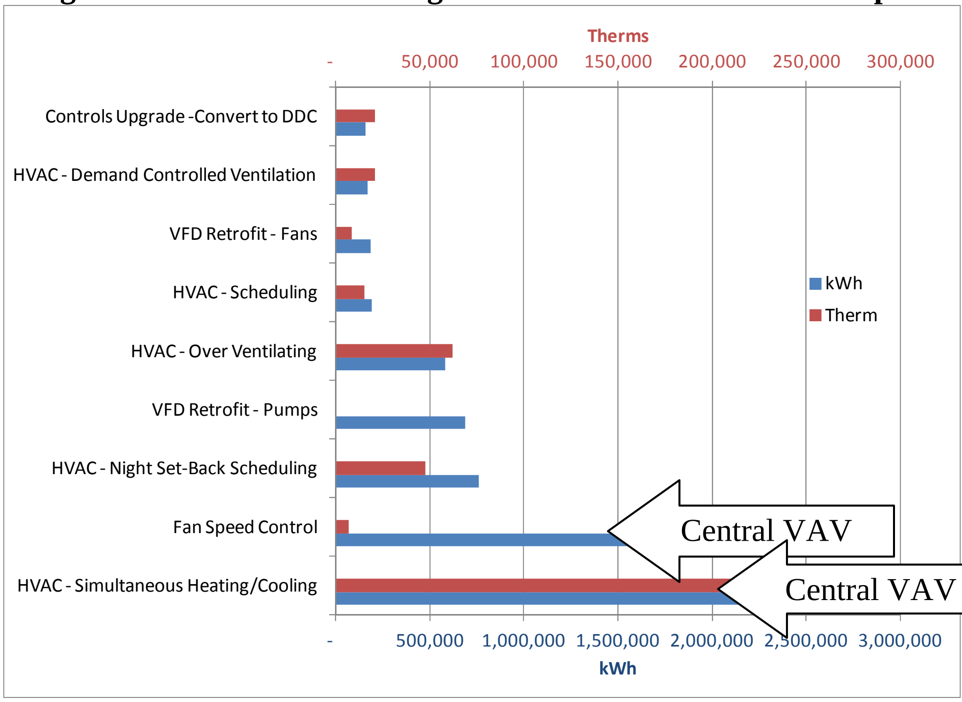
The findings in CBECS, Arthur D. Little II and Michaels' benchmarking energy intensity data indicate that the complexities and inherent design challenges with central air handling systems are significant and real. Michaels' retrocommissioning experiences validate the pitfalls and associated impacts inherent in large central variable air volume systems.

The Energy Solutions Center, a Washington, DC-based non-profit organization promoting the efficient use of natural gas, contracted with Michaels Energy to produce a report on the energy-saving potential, best practices, and persistence issues surrounding retrocommissioning projects and programs (Ihnen & Weitner 2011). As part of the study, Michaels quantified savings by measure for 22 recent projects. Savings totals are dominated by correcting common flaws in variable air volume system control. The results are shown in Figure 5.

Simultaneous heating and cooling findings for these studies fell primarily into two categories. First is minimum zone flow set too high and associated discharge temperature to the flow-control box set too low, resulting in excessive cooling such that reheat is required to maintain space temperature. This is very common. Second is poor humidity control with excessively low unit discharge air temperatures used year-round or nearly year-round. Outside of those two most frequent findings, Michaels also observed ventilation systems, used to supply tempered fresh air to zone terminal heating and cooling equipment, being controlled to supply 70F degree air all year, sometimes after it has been cooled to the desired 55F dew point. In these cases, the air is reheated and sent on its way to zones that require cooling. The ventilation air is cooled, reheated, and then cooled again in these zones.

Another significant waste of energy with central systems is when they serve rogue zones. Rogue zones are unique zones dominated by non-weather loadings. These include equipment or server rooms, or possibly even a zone with a poor temperature sensor location. In these cases, the rogue zone needs cooling all the time and sometimes nearly full design flow of design cool air temperature. This essentially drives the entire system into full cooling mode, resulting in excessive reheat energy for all or nearly all other zones served by the system. One Michaels retrocommissioning project involved the removal of one temperature sensor from such a system, resulting in 40 percent annual natural gas savings at the utility meter.

Figure 5. Retrocommissioning Measures with the Greatest Impact



Solution

The HVAC design and construction industry, led by energy efficiency programs, must migrate to systems that are as prone to minimized waste as the devolved central systems are prone to virtually inescapable and unnecessarily excessive losses. The core of efficient system design is the single-zone system. Single-zone systems, combined with appropriate ventilation design features, provide much lower waste—both in probability and magnitude—due to the following features:

- Avoidance or minimization of simultaneous heating and cooling
- Reduced fan power from moving less air over less distance with less fan static pressure required
- Much simpler and more precise ventilation control, as ventilation in one zone is not a function of “unused air” in other zones
- Efficient humidity control, where needed, from a dedicated outdoor air ventilation system

Ventilation air for these systems is provided by an energy recovery unit, with or without supplementary heating and cooling, providing 100 percent outdoor air to temperature control zones. A ventilation system with supplemental heating and cooling is known as a dedicated outdoor air system; this is used when an area with low internal gains such as a laboratory needs a high volume of ventilation, or when humidity control during the cooling season is an issue.

Ventilation systems serving buildings where humidity control is not critical, such as with offices or schools, many times do not need specific humidity control because (1) dehumidification requirements almost always coincide with hot ambient weather conditions, allowing zone cooling systems to effectively control humidity in most cases; and (2) heavy occupancy zones such as conference rooms present sufficient sensible loads to require cold enough supply air to control humidity . In fact, many, if not most, commercial buildings such as these turn boilers off in the cooling season. However, it is always the responsibility of the designer to account for internal and external (ventilation) moisture gains to the space. Occupant-dense spaces may need humidity control in the cooling season.

Facilities with critical humidity control requirements such as libraries, museums, hospitals, laboratories, and auditoriums should have true dedicated outdoor air systems which include energy recovery and dehumidification of ventilation air, which is the primary source of moisture in most of these facilities.

Unlike central air handling systems, ventilation control with single-zone systems using dedicated 100 percent ventilation air is easy. Ventilation to individual rooms including classrooms and offices can be controlled by occupancy sensor with open/shut control. Ventilation in zones with widely varying occupancy can be controlled by continuously adjusting ventilation air flow using CO2 control. The central 100 percent outdoor air system volume and fan speed control is simply controlled with supply duct static pressure. As demand for fresh air increases, fresh air supply duct pressure drops and the fan speeds up.

There are design and construction options for these systems any designer and contractor would be comfortable with:

- Central plants with condensing boilers and chillers
  - Fan coil units with hot water/chilled water coils
  - Water source heat pump with condensing boilers
- Packaged and split cooling systems with direct-expansion cooling and gas-fired or heat pump heating
  - Packaged single-zone with gas-fired heating and direct-expansion cooling
  - Condensing furnaces with efficient condensing units for cooling
  - Water-source heat pumps with boiler and tower
  - Ground-source heat pumps
  - Air-source heat pumps / variable refrigerant volume

These systems are compared to packaged variable air volume systems per ASHRAE 90.1-2007, Appendix G in the results section below.

Results

Single-zone systems are compared against baselines drawn from ASHRAE 90.1-2007 Appendix G. Single-zone system models are based on the ASHRAE 50% Advanced Energy

Design Guide; all of the systems are modeled for the same 15,000 sf office building. Only HVAC systems are compared against one another. The gas-heating baseline system is variable air volume with direct-expansion cooling with ASHRAE 90.1 2007 baseline equipment performance. Demand ventilation savings are not modeled. The electric-heat option uses an air-source heat pump with baseline efficiencies as well. System cost estimates were provided by a design-build contractor.

Simple payback based on incremental cost for these systems is not encouraging. However, simple payback famously fails to tell an adequate story about system performance and cost effectiveness. Instead, 20-year operating cost (a fixed-term proxy for life-cycle cost) shows us the true cost of each option in present-value dollars[2]. By committing to an option, end users are effectively committing to spending that present-value dollar amount right now. Figures 6 and 7 show that the present-value cost of each option is less than the baseline, leading to a different recommendation than their simple payback would suggest.

Figure 6. System Life Cycle Cost and Energy Comparison – Gas Heat

System type	Total system capital costs	Life-cycle costs	Total annual energy cost	Life-cycle savings over baseline (%)	Energy cost savings over baseline (%)	Simple payback (years)
VAV system with DX cooling (ASHRAE)	$ 220,500	$ 539,469	$ 24,599	--	--	--
Packaged single zone system with furnace and DX	$ 136,825	$ 402,156	$ 23,466	25%	5%	(73.8)
4-pipe fan coil w/ condensing boiler and air-cooled chiller	$ 385,500	$ 425,419	$ 14,618	21%	41%	16.5
Furnace with split-system DX	$ 224,300	$ 307,504	$ 16,020	43%	35%	0.4
VAV w/ condensing boiler and air-cooled chiller	$ 278,700	$ 383,016	$ 16,228	29%	34%	7.0
Water-source heat pump	$ 371,000	$ 399,588	$ 15,698	26%	36%	16.9

Figure 7. System Life Cycle Cost and Energy Comparison – Electric Heat

System type	Total system capital costs	Life-cycle costs	Total annual energy cost	Life cycle savings over baseline (%)	Energy cost savings over baseline (%)	Simple payback (years)
Packaged single-zone heat pump (ASHRAE)	$ 136,200	$ 551,340	$ 29,062	0%	0%	--
Air-source heat pump	$ 177,185	$ 278,491	$ 17,104	49%	41%	3.4
Ground-source heat pump	$ 385,900	$ 224,760	$ 13,881	59%	52%	16.4
Variable refrigerant volume	$ 391,500	$ 348,858	$ 14,787	37%	49%	17.9

Note that variable air volume systems are controlled per ASHRAE 90.1-2007 requirements, which, as has been discussed, never happens in practice. Single-zone systems also rarely operate ideally per code; however, there are major inescapable differences—their design makes simultaneous heating and cooling nearly impossible, and they offer low fan energy and precise ventilation control.

[2] Based on a real discount rate (does not include inflation) of 3%.

Conclusion

The variable air volume system is the rotary internal-combustion aircraft engine, with dozens of moving parts requiring perfect design, construction, maintenance and tuning, while the single-zone system resembles the turbo fan engine with one very robust moving part. Today's digital controls make it much easier for building codes to require complex control algorithms than it is for building operators to implement them and realize the purported energy savings. As an energy efficiency industry and HVAC design industry, we can continue to fool ourselves that designers, engineers, controls contractors, commissioning agents and end users will become experts with these complex systems when the market demands the cheapest, fastest construction humanly possible; or, we can make it easy on ourselves and end users and abandon these albatrosses in favor of single-zone systems that are as difficult to mess up as variable air volume systems are as difficult to use efficiently.

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