VAV Reheat Versus Active Chilled Beams and DOAS

By Jeff Stein, PE

Steven T. Taylor, PE FASHRAE

Jeff Stein and Steve Taylor are principals of Taylor Engineering, a consulting engineering firm in Alameda, Calif.

There have been a number of articles recently claiming that Dedicated Outdoor Air Systems (DOAS) plus active chilled beam (ACB) systems are superior to Variable Air Volume Reheat (VAVR) systems on energy efficiency, first cost, air quality, etc.[see references 1-4]. The ASHRAE Golden Gate Chapter recently decided to hold a head-to-head competition to put these claims to the test. Three mechanical engineering firms with offices in the Bay Area each provided a Design Development (DD) level design for a real office building currently in design, the U.C. Davis Medical Center Graduate Studies Building (GSB) in Davis, California. One firm designed an ACB+DOAS system, another firm designed a VAVR system, and the third firm designed a hybrid combination of these two systems. A fourth engineering firm then simulated each of the three designs using the EnergyPlus energy simulation program. Finally, a major mechanical contractor provided a detailed HVAC construction cost estimate for each design. The VAV reheat system had both the lowest first costs and the lowest energy costs of the three systems. The analysis also showed that many of the other supposed advantages of ACB+DOAS relative to VAVR, such as improved indoor air quality and a lower floor/floor height, also turned out to be largely overstated. Note that the results of this analysis are only strictly applicable to these three designs and this building and climate, but the conclusions may also apply more broadly.

The GSB Building and the Genesis of the Golden Gate Competition

The U.C. Davis Medical Center Graduate Studies Building (GSB) will be a 56,500 ft^2 office building in Davis, California. The space program is fairly evenly split between private offices, open offices and classroom/conference rooms. Chilled water and hot water will be provided by the campus central plant.

Figure 1. Rendering of Graduate Studies Building

When U.C. Davis first decided to build the GSB, they started with a traditional plans/specifications approach with Firm A as the engineer-of-record. Firm A, which has designed over 1 million square feet of chilled beam buildings, chose an ACB+DOAS design. In early 2012, when the design was in the Design Development stage, the owner decided to switch to a design/build approach and Firm A's design became the bridging documents. One of the design/build teams bidding on the project proposed a VAVR system (designed by Firm B, the authors' firm) and also carried the design through about the DD level in their bid. Another bidder proposed a hybrid chilled beam + VAV reheat system, designed by Firm C. The three designs included equipment schedules, detailed equipment layouts and zoning plans. The team with the hybrid design was awarded the job but the project has since been put on hold. After U.C. Davis selected a design/build team, the ASHRAE Golden Gate chapter decided to use this building for a competition between chilled beams and VAV reheat since it had already been designed with both systems and with a hybrid combination of the two. All three firms were eager to participate. The results of the competition were presented at a seminar sponsored by the ASHRAE Golden Gate Chapter at the Pacific Gas & Electric Energy Center in San Francisco on October 17, 2012.

The Active Chilled Beam Design

The ACB+DOAS design consists of a 100% outside air, constant volume air handler serving two supply risers. The air handler has a chilled water coil with a bypass damper and a hot water coil. The air handler has a variable speed drive primarily for reducing fan speed when the bypass damper is open. The air handler provides the primary air to the active chilled beams. The average DOAS primary airflow rate is about 0.6 cfm/ft^2, which is considerably higher than the minimum ventilation in low occupant density spaces, like offices, but close to the minimum ventilation in higher density spaces like conference rooms and classrooms. A DOAS flow rate higher than the minimum ventilation in low density spaces is often needed to meet the space loads as the capacity of the chilled beams is a function of the primary airflow rates. In densely occupied spaces, it also ensures that space dewpoint does not rise above the surface temperature of the chilled beams, possibly causing condensation. It also improves the indoor air quality compared to code minimum ventilation.

Hot water and chilled water are provided by an existing campus central plant supplying 45^{o}F chilled water to the buildings on campus. However, 45^{o}F typically cannot be supplied to the chilled beams because of the likelihood of condensation and dripping. Therefore, the ACB design includes one set of chilled water pipes supplying 45^{o}F chilled water to the air handler and a separate chilled water heat exchanger and chilled water pump in the building to maintain the chilled water supply temperature to the chilled beams at 57^{o}F. The design engineer felt that a heat exchanger was needed, rather than just a blending valve, as an added layer of protection against condensation.

Each ACB has both heating and cooling coils. The primary air is maintained at 63^{o}F and the ACB heating and cooling coils are then controlled by the thermostat to maintain space conditions.

The ACB design also includes a partially ducted exhaust system—exhaust ducts extend from the air handler down the shafts and into the ceiling return plenum about two thirds of the way from the exhaust shafts to the building skin. This was in response to perceived owner preference for ducted return. However, neither of the other two designs in the design/build competition included ducted return and therefore the return ductwork was not included for any design in the cost model or energy model for the Golden Gate ASHRAE Chapter competition.

Figure 2. Schematic of Active Chilled Beam Design

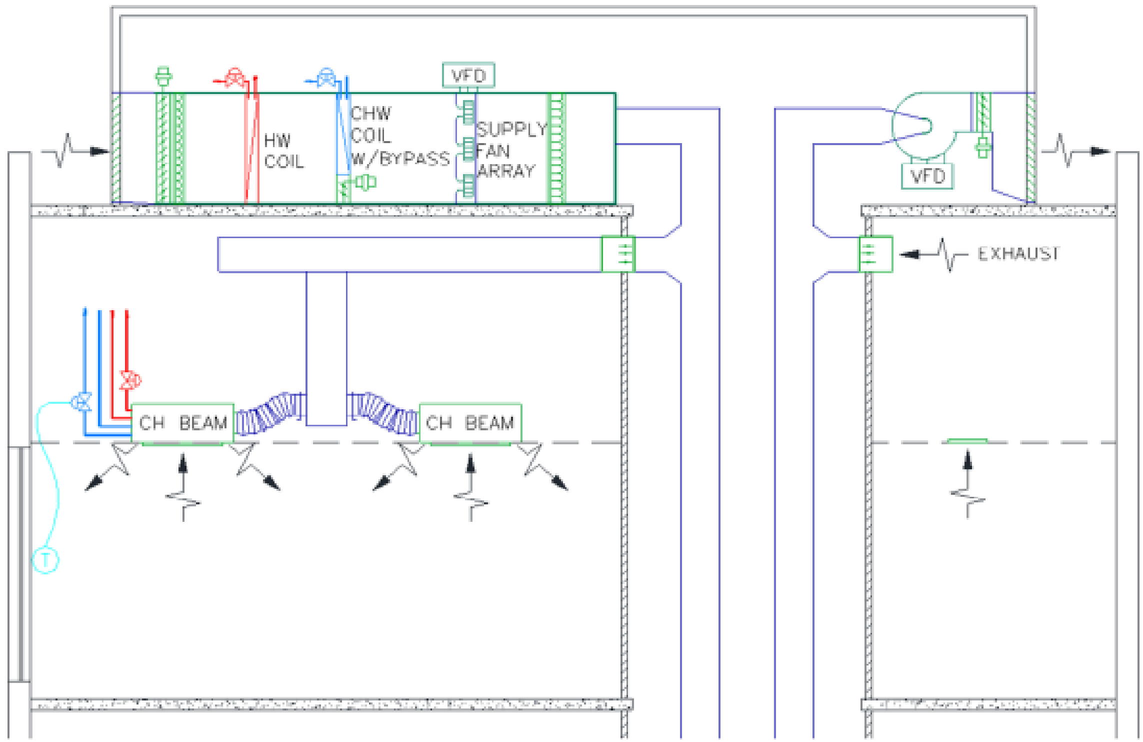
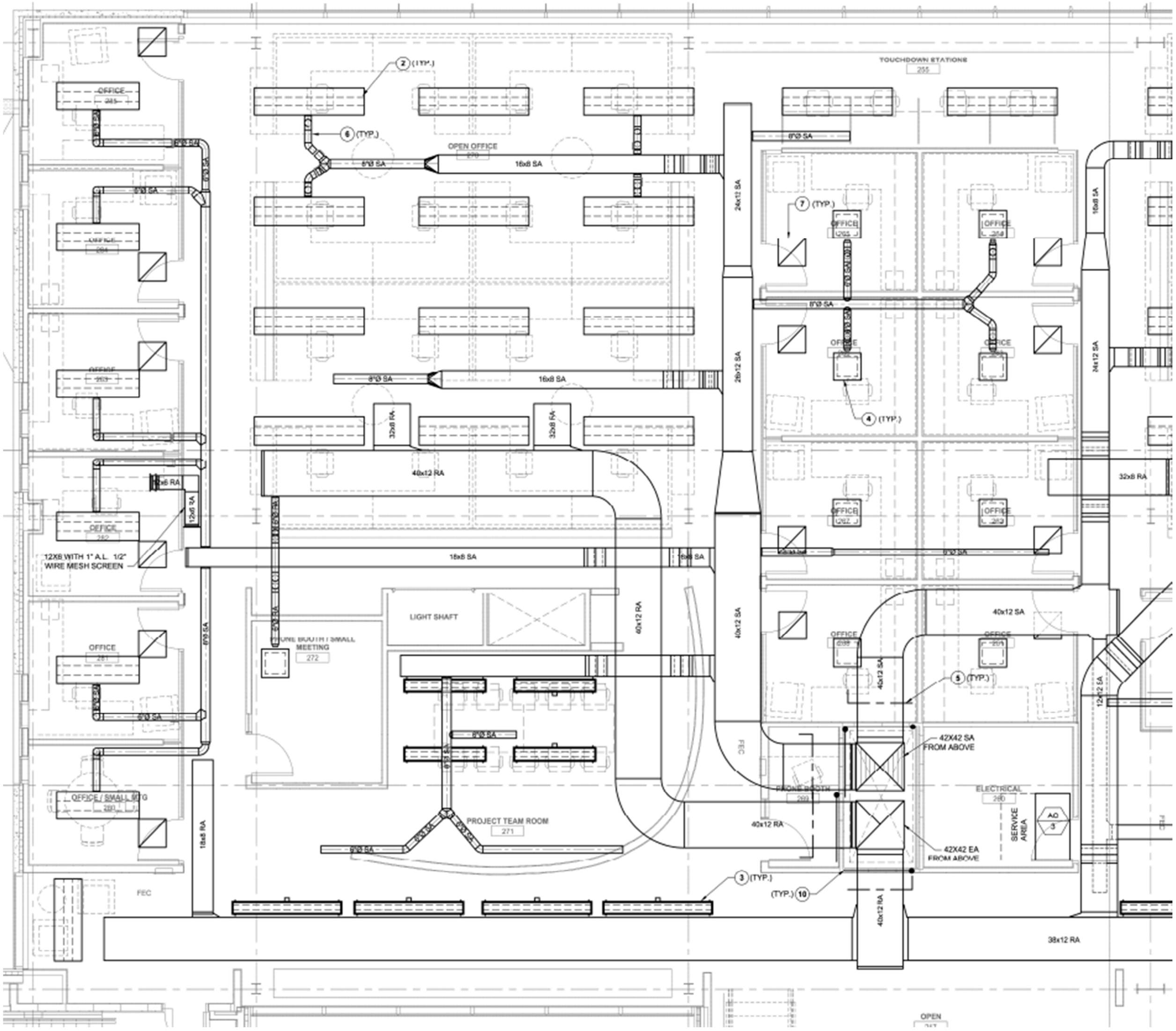


Figure 3. Typical HVAC Floor Plan for ACB Design



The VAV Reheat Design

The VAVR design includes a single VAV air handler with a cooling coil and an airside economizer. Unlike the ACB design, which had two supply risers, the VAVR design only has one supply riser. The air handler is sized for about 0.9 CFM/ft^2 at design conditions. There is no return ductwork, even in the return shaft, and building relief is accomplished with two propeller relief fans.

All zones are served by VAV boxes, most of which have reheat coils. Zones that serve open plan interior spaces that are open to perimeter zones do not have reheat coils because minimum ventilation for both the interior and perimeter can be provided by the perimeter zone reheat box (see Figure 5). The cooling-only VAV boxes have zero minimum flow rates. The reheat boxes use a dual maximum zone control sequence (see Taylor, 2012) with minimum flow rates in the deadband between heating and cooling of about 0.15 cfm/ft^2. High occupant density spaces, such as conference rooms and classrooms, have CO_2 controls that also allow these spaces to have minimum flow rates in deadband of about 0.15 cfm/^{ft2} dynamically reset upwards based on CO_2 concentration.

The air handler supply air temperature is reset from 55°F to 65°F using zone feedback to provide supply air just cold enough to satisfy the worst case zone. Similarly, duct static pressure setpoint is reset to maintain the worst case zone damper nearly wide open (see Taylor, 2007).

Figure 4. Schematic of VAV Reheat Design

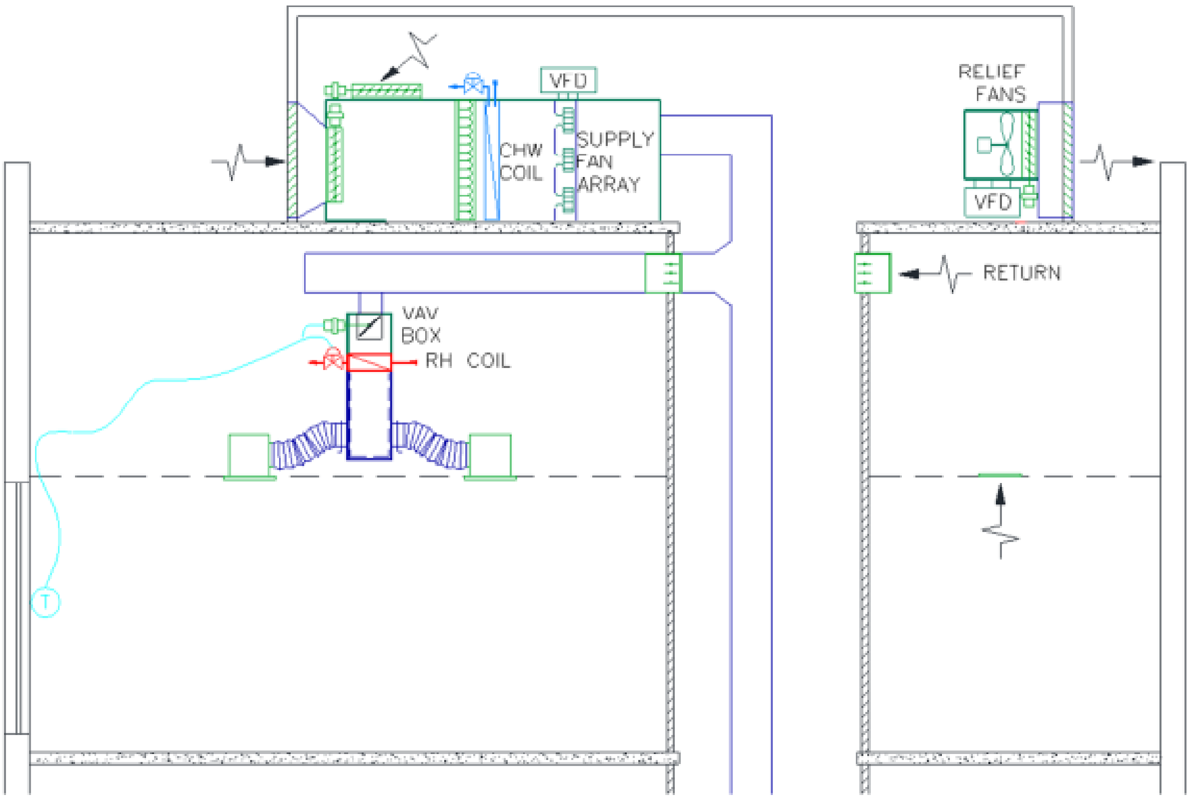
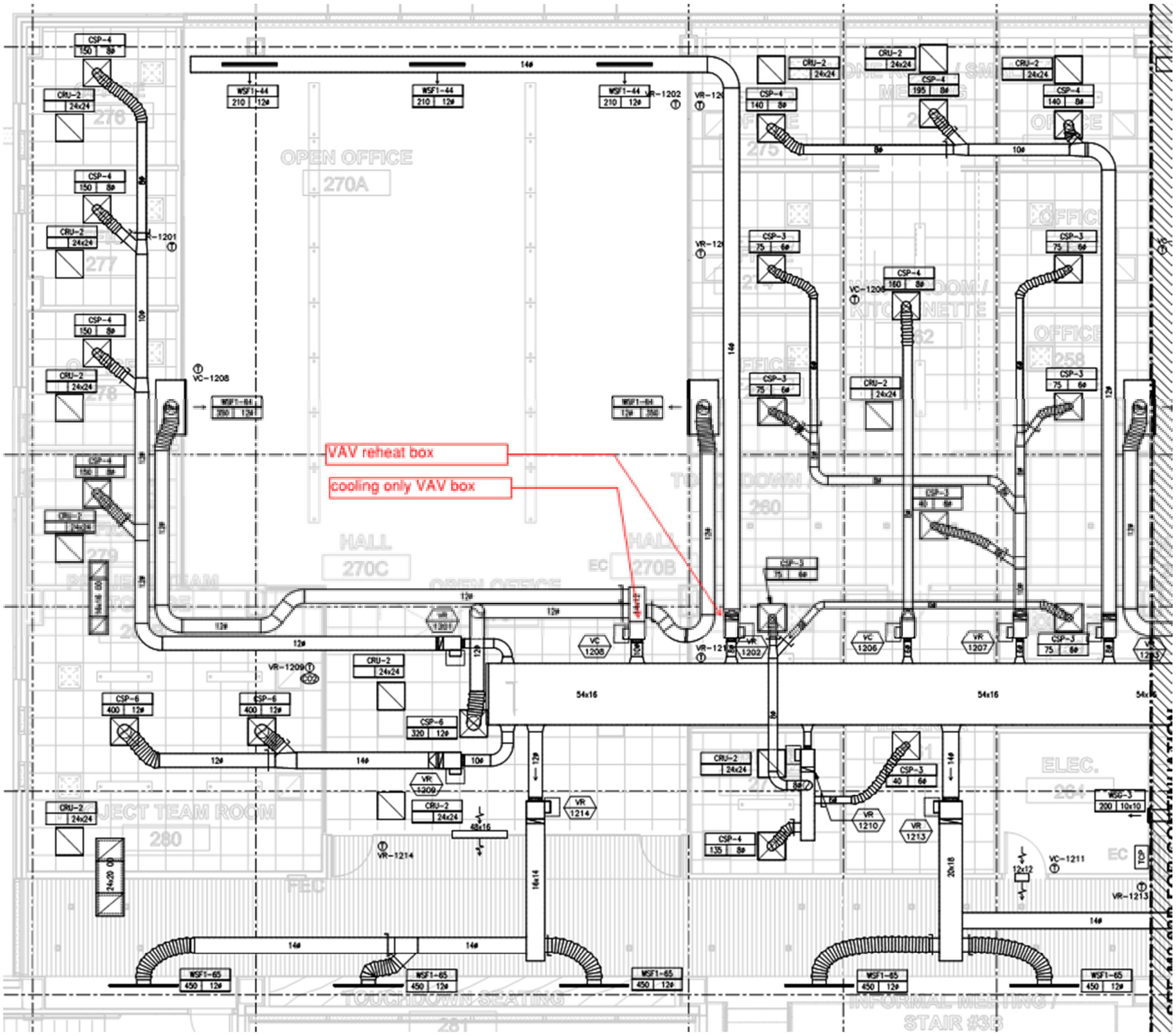


Figure 5. Typical HVAC Floor Plan for VAV Reheat Design



The Hybrid System

The Hybrid system includes a single VAV air handler with a chilled water coil and airside economizer ducted to two supply risers. Interior zones are served by conventional VAV reheat boxes because adding chilled beams to these low load zones would not significantly reduce primary air flow rates. Similarly, conference rooms and classrooms, which have relatively high peak ventilation rates, are served by conventional reheat boxes with CO_2 controls. Chilled beams are only provided in low density perimeter zones where the chilled beams allow significant reduction in the primary airflow rates. Thus about 70% of the total area is conventional VAV reheat and about 30% is hybrid VAV + ACB. The air handler is designed for about 0.7 cfm/ft^2 and 55^{o}F supply air temperature. Like the VAV reheat design, the air handler controls include supply air temperature reset and duct static pressure reset.

The chilled beams are two pipe, cooling-only beams, rather than four pipe beams. Heating is provided by VAV reheat boxes that serve the chilled beams (see Figure 7). Like the ACB+DOAS Design, one set of

45°F chilled water pipes serve the AHU and a second set of 57°F chilled water pipes serve the chilled beams.

Figure 6. Schematic of Hybrid ACB + VAV Reheat Design

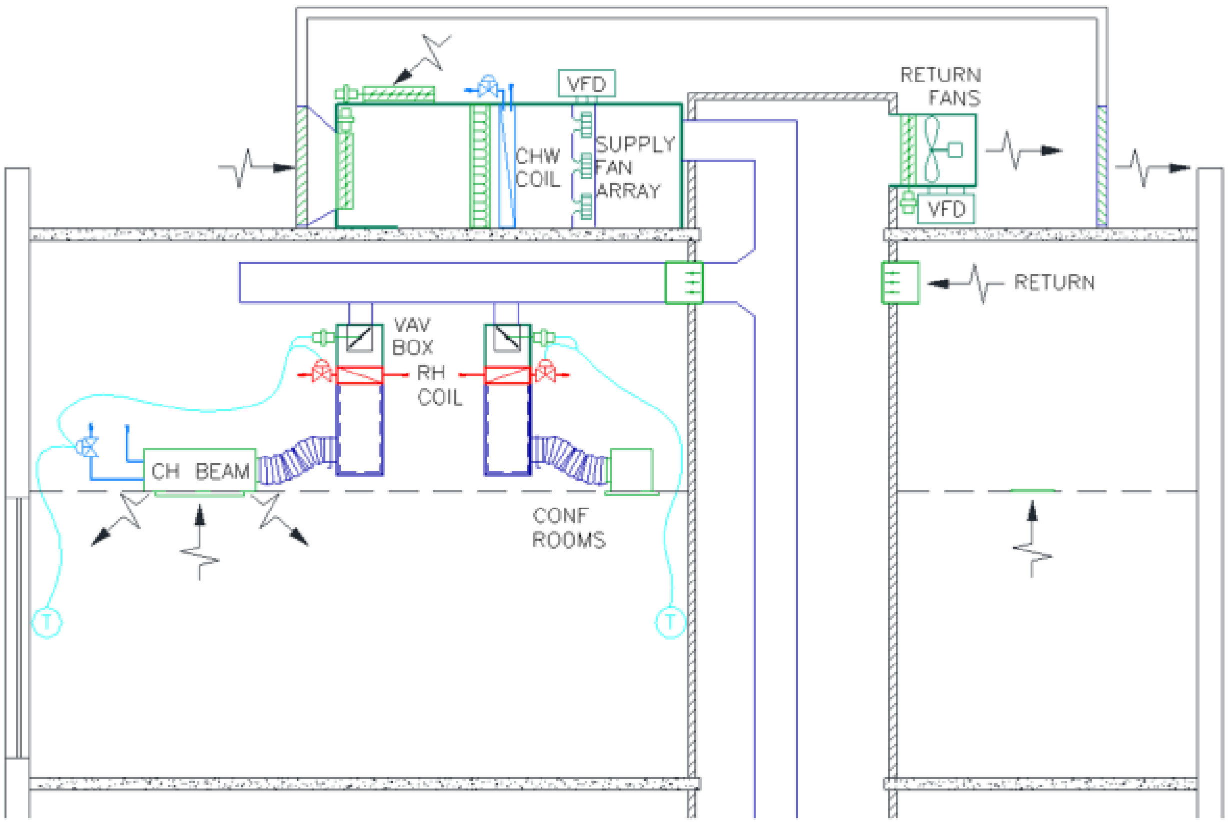
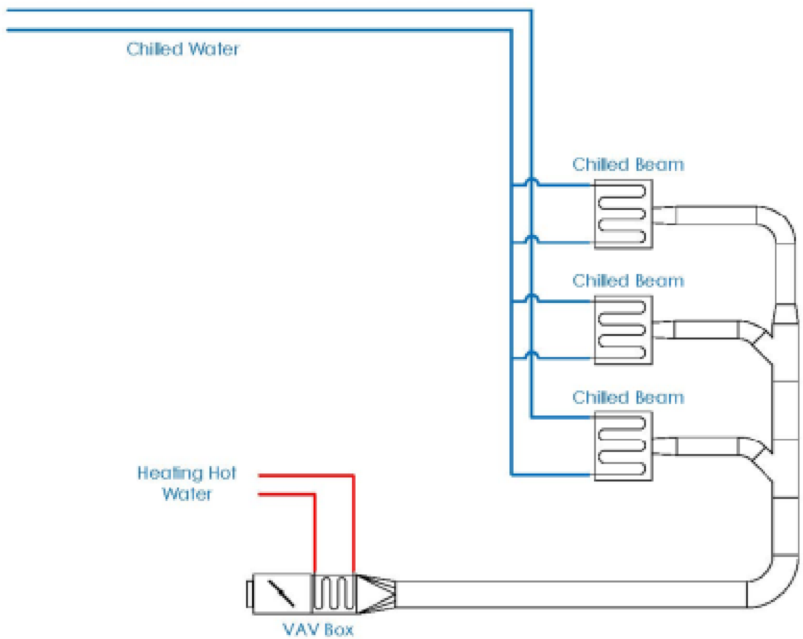


Figure 7. Schematic of Hybrid Zone



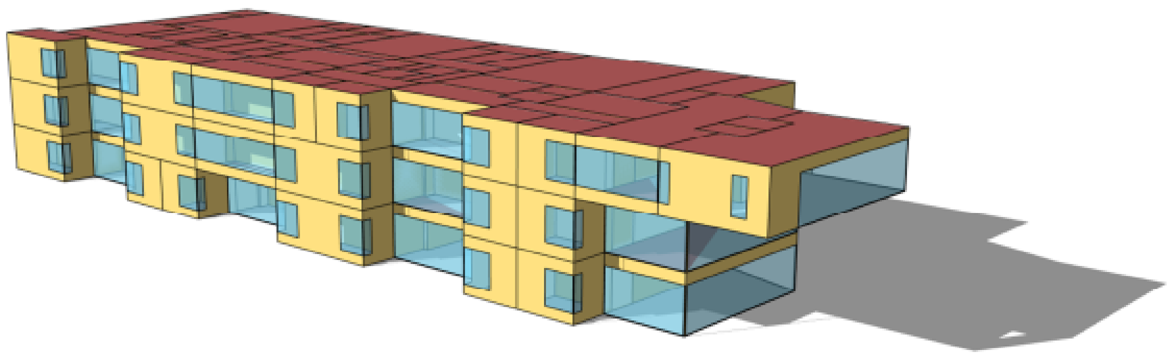
The Energy Model

Each of the three designs was simulated with EnergyPlus. EnergyPlus was chosen because it has an explicit chilled beam module. Other simulation programs such as EnergyPro and eQUEST do not have a chilled beam module and therefore typically approximate chilled beams with induction units. EnergyPlus does not explicitly allow chilled beams served by VAV reheat boxes. Therefore, the Hybrid Design was approximated using two systems serving the ACB zones: VAV with HW reheat boxes and four pipe fan coil units with zero zone fan energy operating in sequence; whatever load the VAV box could not meet was met by the four pipe fan coil.

Lighting power density was modeled using the prescriptive requirements of ASHRAE 90.1-2007 Occupant density and receptacle power density was modeled using the defaults in ASHRAE 90.1-2007 User's Manual Table G-B (e.g. 275 ft^2/person and 0.75 W/ft^2 for offices). Schedules for HVAC, lighting, occupants and receptacles were modeled using the defaults in ASHRAE 90.1-2007 User's Manual Tables G-E to G-M.

The campus central cooling and heating plants are modeled per the baseline modeling assumptions in ASHRAE 90.1-2007 Appendix G for chilled water and hot water plants.

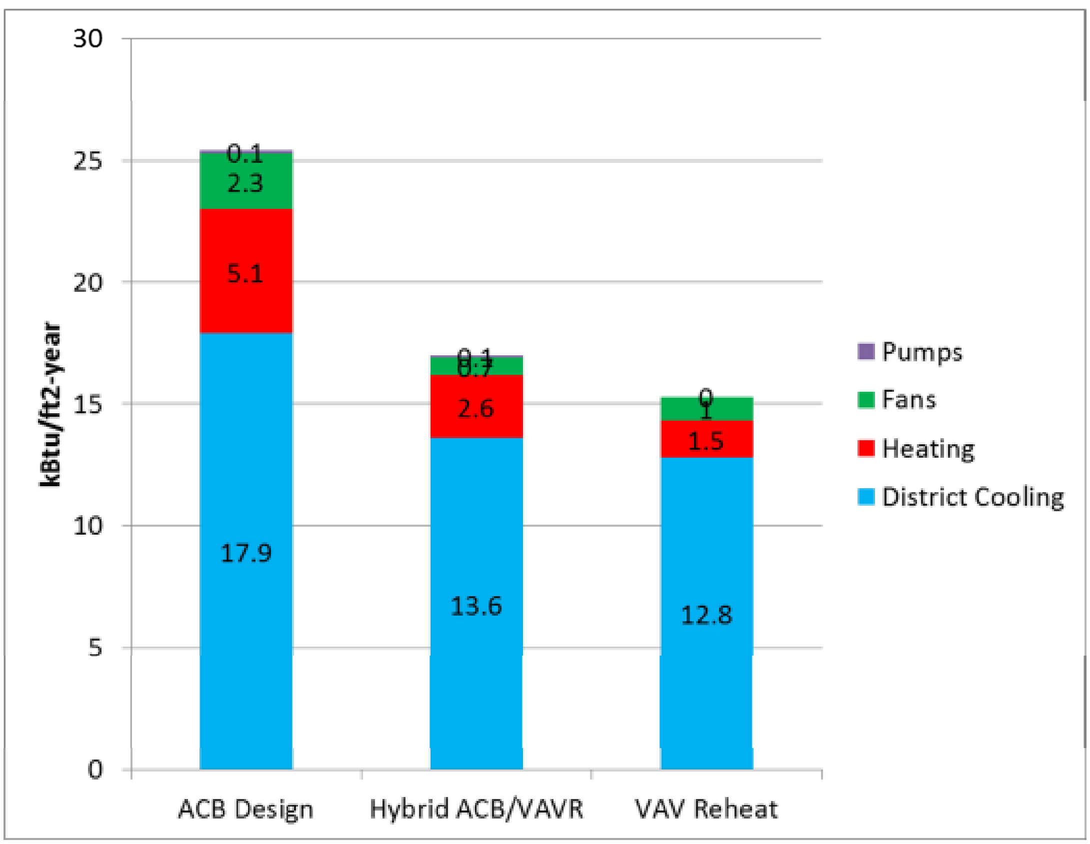
Figure 8. 3D Image from EnergyPlus Model



Simulation Results

The results of the EnergyPlus simulations are shown in Figure 9. The VAV Reheat Design uses 40% less HVAC energy than the ACB Design and the Hybrid Design uses 33% less HVAC energy than the ACB design. The VAV Reheat savings relative to the ACB Design are across the board: VAV Reheat has 28% less cooling energy than ACB, 70% less heating energy, 60% less fan energy, etc.

Figure 9. Simulated HVAC Energy Use Intensities (Site Energy)



Understanding the Simulation Results

Further analyses of the designs reveals that the simulation results are not surprising.

Fan Power

Table 1 shows that the VAV Reheat design has about 40% higher fan power at design conditions than the ACB+DOAS design. However, the ACB+DOAS fan power is constant at part load while the VAV Reheat fan power goes down very quickly at part load, thanks to the near cube law relationship between fan speed and fan power.

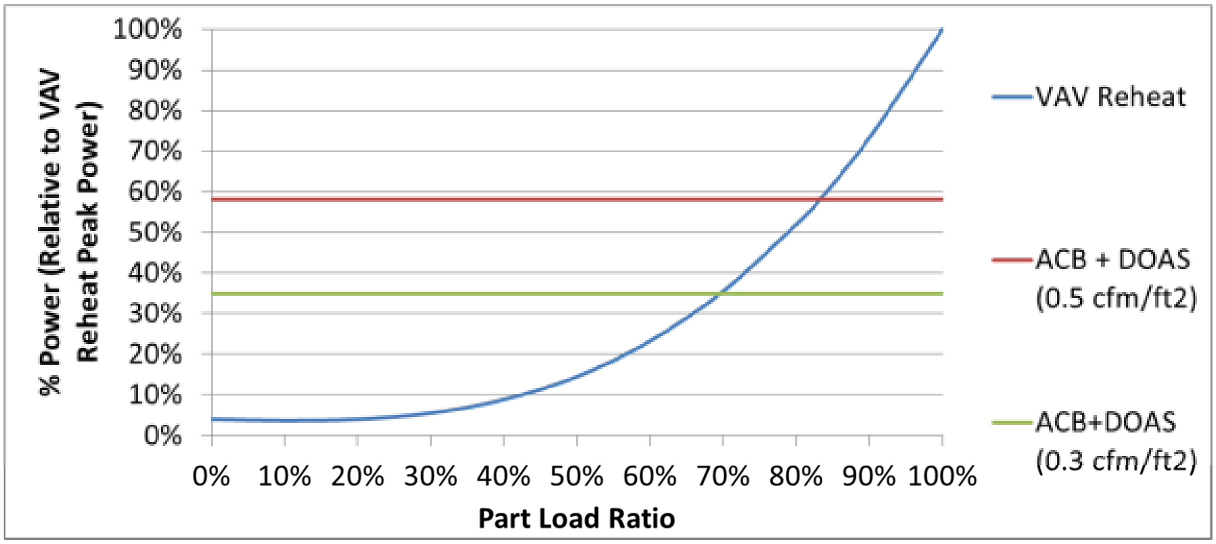
Table 1. Design Fan Power

	ACB + DOAS (0.5 cfm/ft^2)	VAV Reheat
CFM	30,000*	50,000
CFM/ft2	0.53	0.88
Ext. Static Press.	1.8	2.3
Int. Static Press.	2.0	1.7
Total Static Press.	3.8	3.9
Fan Efficiency	69%	69%
Brake Horsepower	26	44

*There was some confusion as to the primary airflow rate in the GSB ACB+DOAS Design. 30,000 cfm (0.5 cfm/ft^2) was used in the energy model but 36,000 (0.6 cfm/ft^2) was used in the cost model. Had the energy model used 0.6 cfm/ft^2 then the ACB+DOAS energy performance would have been slightly worse. Had the cost model used 0.5 cfm/ft^2 then the ACB+DOAS costs would have been slightly better. In both cases the difference is most likely "in the noise".

As Figure 10 shows, the VAVR Design uses less fan power than the ACB+DOAS Design whenever the part load ratio (airflow fraction required to meet the load) is less than about 83%, which is almost all of the time. The annual average airflow rate in the VAV Reheat simulation was about 60% of peak flow, which explains why the VAV Reheat Design used less than half of the fan energy of the ACB+DOAS Design. Figure 10 also shows that even if the ACB+DOAS Design had been reduced to 0.3 cfm/ft^2 it would still use more fan energy compared to a VAVR system with an average annual flow rate of 60%. A primary airflow rate of 0.3 cfm/ft^2 is about the lowest possible with an ACB+DOAS system in order to meet latent loads with the primary air and the sensible loads with the chilled beams. Furthermore, there is reason to believe that the 60% average part load ratio in the Energy Plus model is probably unrealistically high. The default ASHRAE schedules for office occupancy call for a nearly constant occupancy schedule of 95% and a nearly constant lights and receptacles schedule of 90%. ASHRAE Research Project 1515 (reference 7) suggests that realistic schedules are smaller than this and that a realistic annual average part load ratio for office buildings is closer to 40% than 60% [Taylor, 2012]. At 40% part load ratio, the 0.5 cfm/ft^2 ACB+DOAS design uses 6 times as much fan energy as the VAVR design and the 0.3 cfm/ft^2 ACB+DOAS design uses 4 times as much.

Figure 10. Supply Fan Power versus Part Load Ratio



Cooling Energy

In non-economizer conditions (outside air temperature > return air temperature) the ACB+DOAS Design has a higher cooling load than the VAVR Design because it has a higher outside air load (0.5 cfm/ft^2 compared to 0.15 cfm/ft^2). In economizer conditions, the ACB+DOAS Design also has higher mechanical cooling loads because it does not have an air economizer while the VAVR Design does have an air economizer and thus benefits from economizer free cooling. The ACB+DOAS Design also has higher reheat/recool loads than the VAVR Design because the fixed primary airflow rate (0.5 cfm/ft^2) and fixed supply air temperature (63°F) means the ACB+DOAS Design is always providing about 6 Btuh/ft^2 of cooling even when the actual load is lower. The VAVR Design, on the other hand, provides no more than about 3 Btuh/ft^2 at minimum flow, even if the supply air temperature is fixed at its minimum of 55°F. Thus the ACB+DOAS Design has a higher cooling load under all conditions compared to the VAVR Design.

In this building all mechanical cooling loads are met by the campus central plant so the cooling efficiency is the same for all three designs. Thus the ACB+DOAS Design <u>must</u> have higher cooling energy than the VAVR Design – the loads are higher and the cooling plant efficiency is the same (or worse when pump energy is included). To take advantage of the warmer chilled water supply temperature required by the chilled beams, a medium temperature chilled water plant is required, preferably with an integrated water-side economizer. One lesson learned from this analysis is that connecting to a 45°F central plant loses all cooling efficiency benefits of medium temperature systems like chilled beams or radiant cooling.

Heating Energy

Similar to cooling energy, the ACB+DOAS Design has to use more heating energy than the VAVR design because the zone reheat load is higher as described above and because the outside air heating load is higher. In the winter the ACB+DOAS Design must heat 0.5 CFM/ft^2 of outside air while the VAVR Design only has to heat 0.15 cfm/ft^2 of outside air, three times as much outside air load.

Also, as with the cooling loads, the heating loads are met by the campus central plant so the heating efficiency is the same for all three designs. Thus it is not surprising that the ACB+DOAS model uses more than twice as much heating energy as the VAVR model. To take advantage of the reduced temperature hot water required by the chilled beams in heating mode, a condensing boiler plant is required. As with cooling, connecting to a conventional central plant loses all heating efficiency benefits of chilled beams. Note that the VAVR design and the Hybrid design can also take advantage of condensing boilers but not to the extent of the ACB+DOAS design because they have smaller hot water coils.

The HVAC Cost Model

A major mechanical contractor used the DD level drawings of each design to estimate the HVAC installed costs for each design. As noted above, the cost of the return ductwork on the floors and in the return shaft in the ACB+DOAS design was not included in the cost estimate because return ductwork is not required for the ACB+DOAS design and was not included in either of the other two designs. As shown in Table 2, The ACB+DOAS Design costs more than twice as much as the VAVR Design and the Hybrid Design is about half way between the other two. The ACB+DOAS design is so much more expensive that even if it used no HVAC energy at all it would still take 80 years to pay back the incremental first cost compared to VAVR.

The cost breakdown in Table 2 sheds some light on the cost differential. The VAVR Design uses 30% more sheet metal than the ACB+DOAS Design but the ACB+DOAS Design uses 30 times more chilled water piping and 5 times more hot water piping. One reason the VAVR hot water piping costs are so much lower is because the VAV boxes are grouped close to the duct mains in order to minimize hot water piping (Figure 5). In the ACB+DOAS design the hot water piping must run out to every chilled beam. The ACB+DOAS equipment cost is double the VAVR equipment cost. This is due primarily to the cost of the active chilled beams themselves and to the added pumps and heat exchanger used for the secondary chilled water circuit. The ACB+DOAS subcontractor cost is also double the VAVR subcontractor cost. This is due to the higher controls costs (e.g. more chilled water valves, humidity sensors, etc.), higher insulation costs (for all that extra piping) and higher test and balance costs.

Table 2. HVAC Cost Model Results

	VAVR	**Hybrid**	**ACB +DOAS**
Total HVAC Cost ($)	1,371,000	1,980,000	3,341,000
Total HVAC Cost ($/SF)	25	37	62
PARAMETER COMPARISON			
Material Cost ($)	215,179	279,703	576,496
Labor Cost ($)	584,058	877,138	1,509,349
Equipment Cost ($)	319,695	380,297	608,118
Sub-contractors ($)	252,067	442,862	647,037
lbs of ductwork	38,000 lbs	33,224 lbs.	28,612 lbs.
linear feet of chilled water pipe	310 feet	5,963 feet	10,244 feet
linear feet of heating hot water	2,085 feet	2,330 feet	9,630 feet

There are a number of other potential costs that are not included in these figures which could make the ACB+DOAS Design even more expensive relative to VAVR. One example is seismic bracing for the chilled beams. General contractors have reported that they have been caught off guard by the amount of seismic bracing required for chilled beams and the resultant impact on other utilities. Another potential additional cost is lighting. The chilled beams take up much more ceiling space than conventional diffusers. This increases the cost of coordination between mechanical and electrical trades and potentially the cost of lighting fixtures.

Other Factors

The VAVR system was clearly better on both energy efficiency and HVAC costs compared to the ACB+DOAS system, but what about the other supposed advantages of ACB+DOAS?

Floor-to-Floor Height

The impact of the HVAC system on the floor-to-floor height is primarily a function of the size of the supply mains on the floors. The bigger the mains, the more floor-to-floor height is required. Other HVAC components, such as VAV boxes, rarely affect the floor-to-floor height because they are usually smaller than the mains and can be tucked up between beams, while supply mains must run under the beams.

On a typical floor of the GSB, the ACB+DOAS Design has four supply mains each sized at 40x12, for a total supply main area of 13 ft^2 per floor (see Figure 11). On the same floor the VAVR Design has one 54x16 main and one 30x16 main for a total supply main area of 9 ft^2 (See Figure 12). So in this case the ACB+DOAS Design has larger supply mains and thus has no advantage in terms of floor-to-floor height.

Figure 11. ACB+DOAS 2nd Floor Supply Mains

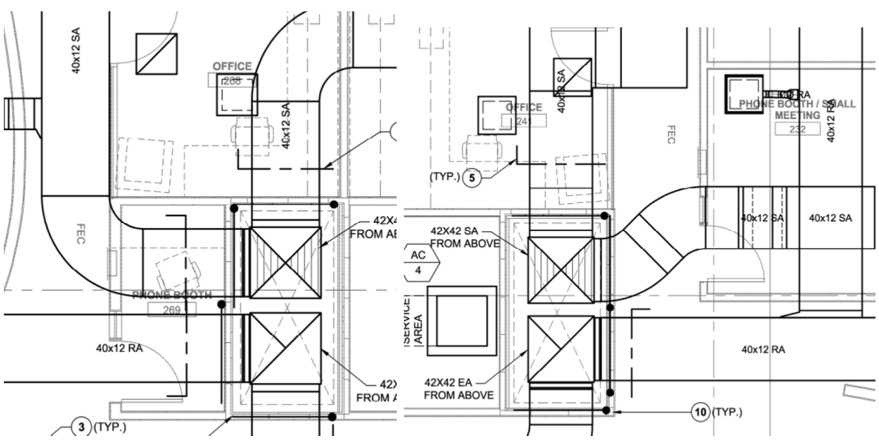
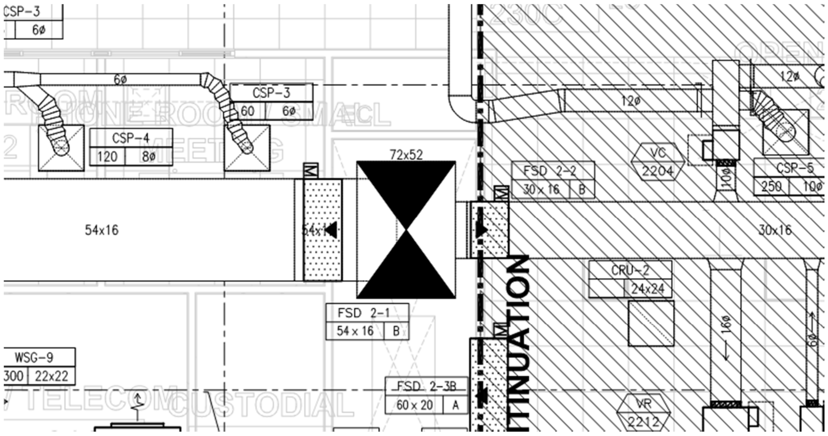


Figure 12. VAVR 2nd Floor Supply Mains



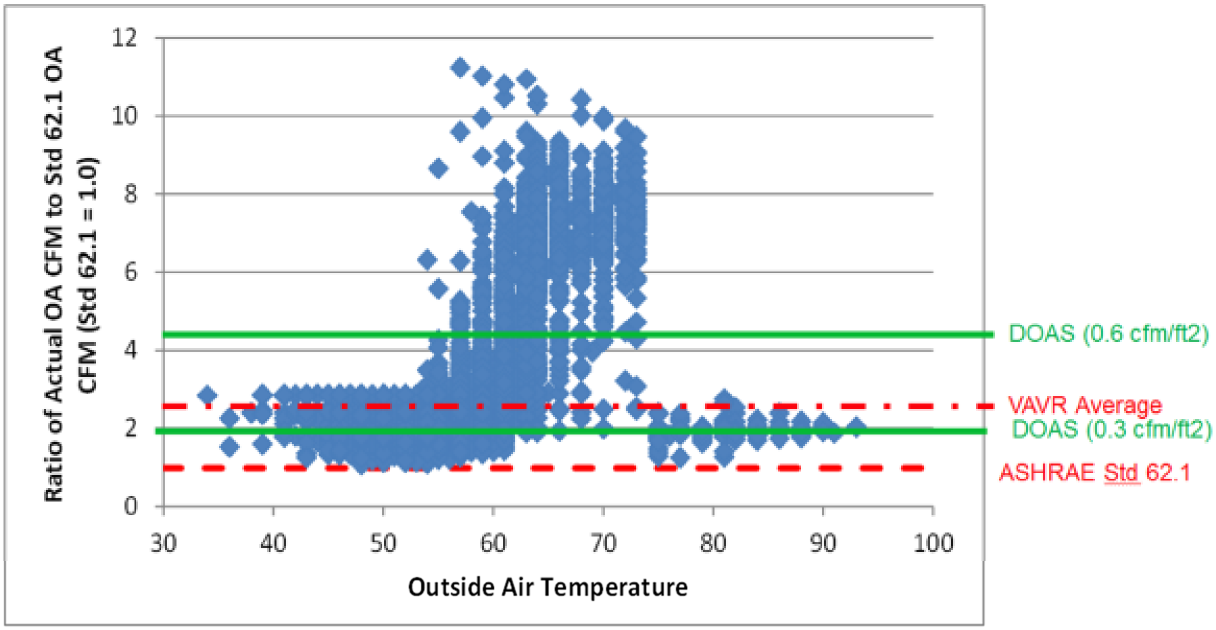
The ACB+DOAS supply mains are larger because they are sized for a lower velocity. To mitigate the fan energy penalty of a constant volume system relative to a VAV system, an ACB+DOAS system must use lower duct velocities compared to a VAVR system. In this case, the VAVR supply mains are sized at about 2000 ft/min while the ACB+DOAS mains are sized at about 900 ft/min. VAVR mains can be sized for a higher velocity because they are variable volume and the actual flow rate is almost always well below the design flow. VAVR supply mains can be sized up to about 2500 ft/min with minimal impact on annual fan energy or noise risk.

An ACB+DOAS design might have a floor-to-floor advantage over VAVR with different design choices. For example, if the ACB+DOAS system had been designed for 0.3 cfm/ft^2 instead of 0.6 cfm/ft^2 and the duct mains sized at 1500 ft/min then the duct mains would be about 30% smaller than a comparable VAVR system sized at 2500 ft/min. Of course an ACB+DOAS system at 0.3 cfm/ft^2 and 1500 fpm would still have more than double the annual fan energy of a VAVR system at 0.9 cfm/ft^2 and 2500 fpm (see Figure 10).

Indoor Air Quality

Proponents of ACB+DOAS argue that it provides better indoor air quality than VAVR because it uses higher design ventilation rates. What this argument fails to capture, however, is the IAQ benefits of the airside economizer in a VAVR design. As part of the competition a detailed eQuest simulation of the GSB was performed to determine how the ventilation rates of the designs compared to each other and to ASHRAE Standard 62.1 in every space and every hour of the year. See Taylor (2012) for details of the ventilation analysis. Figure 13 shows that the actual outside air flow in the VAVR Design met or exceeded the outside airflow required by Standard 62.1 every hour of the year and that the annual average outside airflow is 260% larger than Standard 62.1 rates including multiple space inefficiencies. Figure 13 also shows that a DOAS system at 0.6 cfm/ft^2 does indeed provide more outside air than a VAVR system averaged over a year but a DOAS system designed at 0.3 cfm/ft^2 does not. Ventilation for the hybrid design was not simulated but it will be worse than the VAVR because it has the same design minimum outside airflow rate but less economizer benefit because of the lower airflow rates in the chilled beam zones.

Figure 13. Hourly and Annual Average Ventilation Compared to ASHRAE 62.1

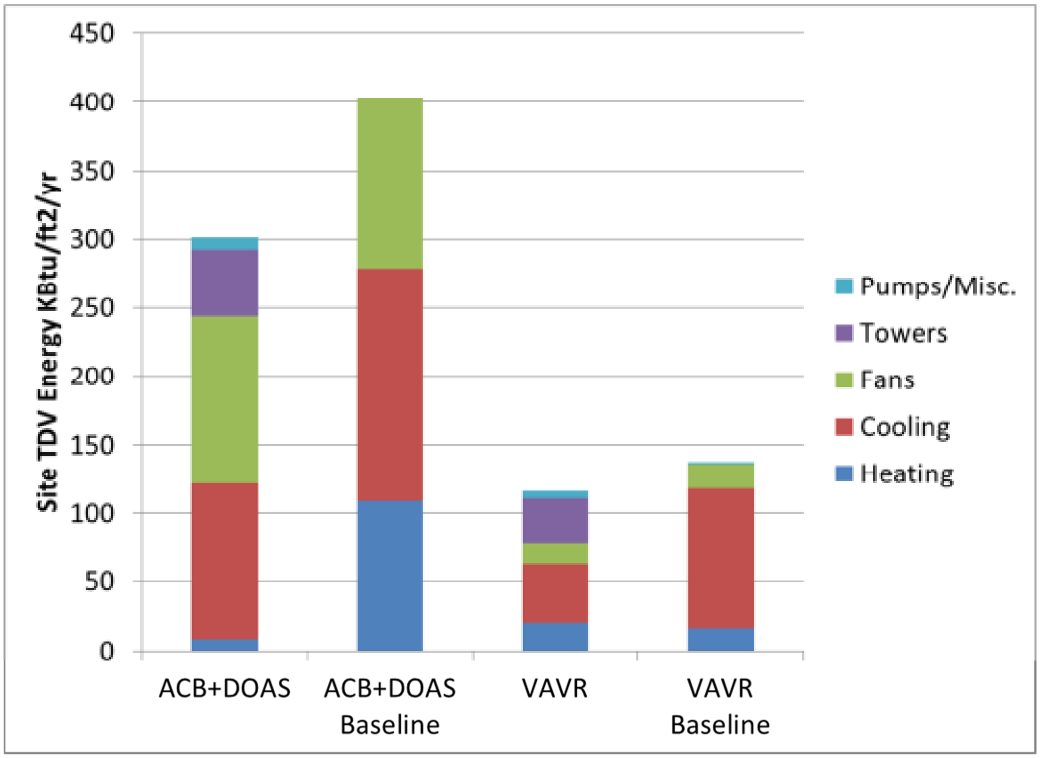


Another IAQ issue related to chilled beams is the potential for mold and mildew growth due to condensation on chilled beam cooling coils. While ACB systems are designed not to condense, condensation can occur due to humidity sensor drift, incorrectly programmed control sequences, building engineers unfamiliar with chilled beams, unexpected space latent loads, etc. VAVR of course is not vulnerable to this potential IAQ risk. Another downside of ACB systems is that they do not work well with operable windows because of the risk of humid outside air condensing on the chilled beams. Chilled beams are available with vertical coils and condensate drip pans but this can reduce capacity per foot (at the same water temperature) so more linear feet of beam is required, further increasing the cost, and of course there is the cost of piping all the drip pans to drains.

LEED Energy Points

There is one area that the ACB+DOAS Design significantly outperformed the VAVR Design: LEED energy points. How could a system that uses twice as much HVAC energy score more LEED energy points? The answer is that the two systems are not compared to the same baseline model by EnergyPro, the software most commonly used to demonstrate compliance with the California Title 24 energy code and to determine LEED energy credits. The Title 24 modeling rules state that the baseline model shall have the same outdoor air ventilation rate as the proposed model. EnergyPro interprets this to mean the same percentage of outside air. EnergyPro also considers ACB+DOAS to be a single zone system and thus compares it to constant volume, 100% outside air, packaged single zone units. On the other hand, EnergyPro compares the VAVR Design to a packaged VAV reheat system with the same minimum ventilation rate. Figure 14 shows that the ACB+DOAS Design uses 25% less HVAC energy than its EnergyPro-generated baseline while the VAVR Design only uses 15% less HVAC energy than its baseline. However, it also shows that the ACB+DOAS baseline is 3 times higher than the VAVR baseline! Fortunately, the California Energy Commission is currently revising the Title 24 modeling rules so that the HVAC design and ventilation rate in the baseline model are fixed regardless of the proposed HVAC design or proposed ventilation rate.

Figure 14. EnergyPro HVAC Energy Simulation Results



Other Downsides of ACB versus VAVR

Water Leaks – In addition to the condensation risk, ACB systems also have a much higher risk of chilled and hot water leaks than VAVR systems because they have so much more piping, particularly over tenant spaces.

Maintenance - It is possible with VAVR systems to locate many boxes in corridors or non-critical spaces outside the zones they serve, so that maintenance or repairs can be done without disrupting the occupied space; but no such option exists for ACBs.

Lighting – Lighting quality and efficiency may be compromised due to restrictions in fixture location imposed by chilled beams.

Flexibility for Future Tenant Improvements – Rigidly secured and piped chilled beams are much more expensive to relocate than VAVR diffusers, which do not require seismic bracing and are generally connected with flex duct. Not only will HVAC cost be higher for tenant improvements but other trades' costs are also likely to be higher as a result of the "forest" of seismic bracing supporting the ACBs.

LEED EQ Credit 5 (Indoor Chemical and Pollutant Source Control) – This credit is generally achievable with a VAVR system since it requires that all supply air be filtered, but not with an ACB system because the secondary air induced through chilled beams is unfiltered.

Thermal Comfort – When the zone minimum cooling output exceeds the cooling load then the zone is overcooled and driven to the reheating setpoint (e.g. 70°F). When the minimum zone output is less than the zone load then the space temperature drifts up to the cooling setpoint (e.g. 74°F). Most people are more comfortable at the cooling setpoint than at the heating setpoint in summertime when they are wearing summer attire (see ASHRAE RP 1515). Thus reducing the zone minimum cooling output improves comfort. As discussed above, the ACB+DOAS Design has a higher minimum zone cooling output than the VAVR Design and thus is likely to be less comfortable.

What If Scenarios

In this competition VAVR is the clear winner but are there other applications or designs for which ACB+DOAS or a hybrid design using ACB would be lower first cost or lower energy cost?

Lower Primary Airflow – An ACB+DOAS primary airflow rate of 0.3 cfm/ft^2 instead of 0.5 or 0.6 cfm/ft^2 would reduce the cooling load in hot weather and the reheat load in cold weather but it would increase the cooling load in mild weather (less free cooling). The net result would likely be lower annual energy use than 0.6 cfm/ft^2 but would lowering the primary airflow rate allow the beams to achieve the necessary cooling capacity and provide sufficient latent capacity and meet the air quality objectives?

Two-Pipe Chilled Beams – Using a two-pipe beam that can switch between heating and cooling, rather than a four pipe beam, would reduce first costs but not enough to make ACB less expensive than VAVR and it would have no real impact on energy performance.

ACB+Recirculation – What if an airside economizer was added to the ACB+DOAS design so that the system remained constant volume at 0.5 cfm/ft^2 but the outside airflow component could be modulated between 0.15 cfm/ft^2 and 0.5 cfm/ft^2 in order to minimize the heating and cooling penalty of the higher flow rates? This scenario was simulated with EnergyPlus during the competition. As expected, the ACB+Recirculation energy use went down but still was considerably higher than the VAVR energy use and the ACB+Recirculation is even more expensive with the economizer. And of course the system is no longer DOAS and thus loses most of the supposed advantages of DOAS systems.

Heat Recovery – What if, instead of an air economizer, the ACB design included a heat exchanger between the exhaust air and the outside air? In many climates, like most of California, the added supply and exhaust fan energy from the added pressure drop of the heat exchanger would outweigh most or all of the energy savings from heat recovery. Even if heat recovery was a net energy saver it would not save as much as the ACB+Recirculation option above which is still less efficient than VAVR. And of course adding heat recovery only makes ACB+DOAS more expensive.

Waterside Economizer – A waterside economizer will not help the ACB+DOAS design catch up to VAVR in terms of fan energy or mechanical cooling load but it will allow the ACB+DOAS to meet the cooling load more efficiently. It is important to recognize, however, that a waterside economizer is usually less efficient than an airside economizer due to the cooling tower and pump energy required and due to the fact that it has three temperature approaches (compared to no approaches for an air economizer) that determine when the economizer is available and what fraction of the load it can serve. There is the approach of the tower to the ambient wetbulb (which gets worse as the wetbulb goes down), the approach across the heat exchanger, and the approach from the chilled beam to the supply air. Chilled beams also generally have a low chilled water ΔT (e.g. 6^{o}F) which limits waterside economizing.

Multiple Chillers – To have any chance of competing with a VAVR system on energy use the ACB+DOAS design must have separate high and low temperature chillers—low temperature (e.g. 45^{o}F) chillers to serve the air handlers and high temperature chillers (e.g. 57^{o}F) to serve the chilled beams. This will improve the mechanical cooling efficiency of the ACB design but will also significantly increase the first cost and complexity of the system.

Other Hybrid Designs – The hybrid design in this competition failed to compete with the VAVR design on energy or first cost but there are other hybrid designs that might fare better. Livchak (2012) suggests adding parallel or series fan powered boxes to the ACB in order to reduce primary air. While this will reduce the heating/cooling penalties associated with high primary air it will also increase fan energy and maintenance (due to all the small fans) and will likely not result in lower total energy than VAVR and will reduce indoor air quality. It will also significantly increase the first cost of the ACB design, which as noted above would already take 80 years to pay for itself even if it used no energy at all.

Conclusions

In this competition, VAVR was the clear winner versus ACB+DOAS. VAVR had much lower first costs, much lower energy costs, and similar floor-to-floor heights. These conclusions strictly apply only to the analyzed systems and this building, which is in a relatively mild climate. However, in the last 5 years the authors' firm has conducted detailed life cycle cost analyses comparing several ACB variations to VAVR for several buildings across the country and has yet to come across a single case where ACB was more efficient or lower cost. The authors' firm has also reviewed lifecycle cost analyses by other firms that appear to have gone out of their way to make VAVR look bad by using unnecessarily high design flow rates and static pressures, single maximum zone controls with high minimums, fixed supply air temperature, etc. A common technique to inflate the VAVR energy use is to make it minimally compliant with ASHRAE 90.1-2004 or 90.1-2007, conveniently ignoring the facts that 90.1 has raised the bar for VAVR since 2007 and that a good VAVR design can far exceed 90.1. A well-designed VAVR system (including dual maximum zone controls, supply air temperature reset, duct static pressure reset and CO2 controls in high density spaces) is hard to beat. Many others engineers have come to similar conclusions (see Murphy, 2011). It is possible that an ACB design with low primary airflow and with medium temperature chilled water and a waterside economizer might be more efficient than VAVR in some applications, such as a building with high sensible loads in a more extreme climate where outdoor air economizers are not as effective. But it is it is doubtful ACB can ever compete with VAVR on a first cost or lifecycle cost basis. The added costs of the piping and beams for ACBs are simply too high and well-designed VAVRs are simply too efficient.

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