Literature Review of Non-Energy Benefits Associated with Dedicated Outside Air Systems (DOAS)

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Introduction

To better understand the potential non-energy benefits of very high efficiency dedicated outside air systems (also known as very high efficiency DOAS), this literature review summarizes key research, empirical evidence, and studies performed on similar high-performance HVAC approaches that are more prevalent in today's market, such as conventional DOAS. As very high efficiency DOAS improves upon high-performance HVAC approaches used by conventional DOAS, the non-energy benefits summarized in this report can be assumed to manifest to an equal or greater degree with a very high efficiency DOAS approach.

What is very high efficiency DOAS?

Very high efficiency DOAS is a high-performance HVAC approach that minimizes energy consumption by recovering heat with high efficiency heat recovery (>=82% sensible recovery) and a high efficiency heating/cooling system. To maximize performance, this approach includes key design principles, including completely decoupling ventilation air from primary heating and cooling air, downsizing the heating/cooling equipment, and minimizing fan power by minimizing pressure drop and operating ventilation fans at optimal conditions.

More information about very high efficiency DOAS can be found at betterbricks.com/solutions/hvac/dedicated-outside-air-system-doas, or in the BetterBricks' Comprehensive Design Guide.

Overview

This study summarizes key research that supports the potential of very high efficiency DOAS to improve thermal comfort, indoor air quality, occupant productivity and space efficiency, while decreasing operational costs.

These non-energy benefits were found through a literature review of academic sources. Relevant academic literature and reports were initially found by searching Google and academic search engines for the following keywords:

1. Indoor air quality
2. Ventilation
3. DOAS
4. Occupant health
5. Productivity
6. Thermal comfort
7. Occupant control
8. Operational Cost
9. Maintenance
10. Initial Cost

Additional academic sources were identified by cross-referencing studies and authors noted by initial sources.

The inclusion criteria of literature in this study was:
1. Academic article
2. Report or website issued by academic or professional working in the field of DOAS
3. Relevance to answering research question

The exclusion criteria of literature in this study was:
1. Published >25 years ago
2. Report, article, or website that does not cite sources if not primary research

Key themes from the literature review are organized in a causal diagram (Figure 1) to categorize literature review results. This report summarizes literature for the ten relationships in the causal diagram. The sources used in this study can be found in Appendix A.

Relationship Diagram

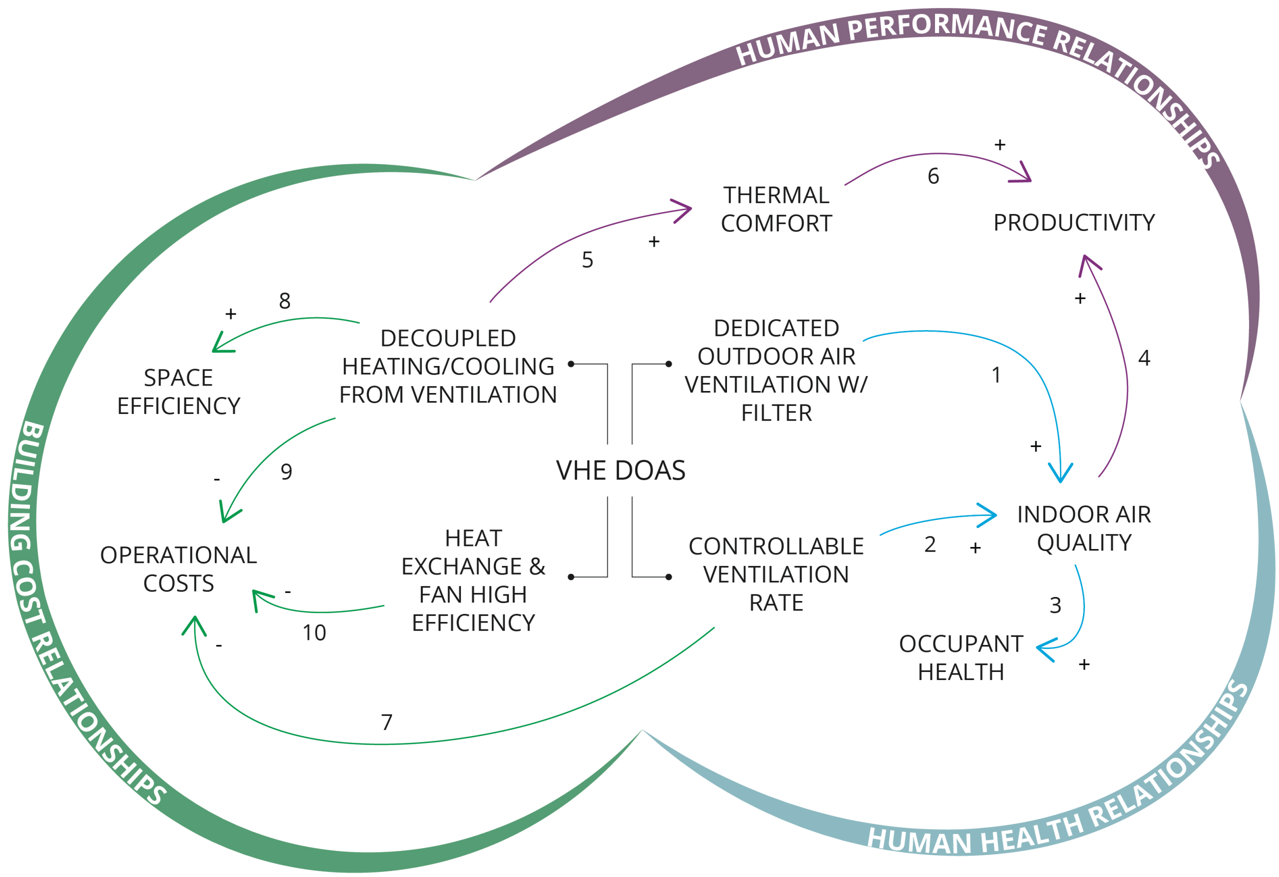

Figure 1. Relationship Diagram

Key components of very high efficiency DOAS are identified as: 1) decoupled heating/cooling from ventilation, 2) dedicated outdoor air ventilation w/ filter, 3) controllable ventilation rate, & 4) heat exchange and fan with high efficiency.

Arrows depict relationships between VHS DOAS key components and non-energy elements. Each relationship is assigned a number 1-10. (+) Indicates positive association, (-) Indicates inverse association. For example, controllable ventilation rates increase indoor air quality (relationship #2) and decrease operational costs (relationship #7).

Relationship Summaries

(1) 100% outdoor air ventilation w/filter → Indoor Air Quality

Bringing 100% outdoor air into a space dilutes concentration of indoor pollutants, prevents recirculation of contaminated air, and ensures required outdoor ventilation rates are met.

Bringing 100% outdoor air into a building has the potential to significantly reduce the adverse effects of indoor air pollutants by reducing their concentration in indoor air (Gerardi 2010). This benefit is realized only if the outdoor air brought into the building does not contain high concentrations of common outdoor pollutants such as particulate matter, ozone, and nitrogen oxides. These outdoor pollutants are associated with pediatric asthma, pulmonary inflammation, and decreased lung function and can enter buildings in high levels (Laumbach 2010, Angkana 2011). MERV 13 filters are highly effective in filtering particulate matter and airborne bacteria and viruses, and can reduce accumulation of pollutants indoors by up to 95%.

Recirculating inside air and low outside air ventilation rates can increase the rate of infection disease transmission (Wargocki 2002). Since a DOAS system does not mix outdoor air with return air like traditional systems, there is little risk that pathogens or pollutants from one space will travel to another space. If there is an indoor pollutant, its concentration in the air will be diluted through a continuous supply of outdoor air to that space. A DOAS system also simultaneously controls ventilation and latent loads through one closed system, and avoids moisture related indoor air quality issues by making it easier to control humidity (Mumma 2002).

While high ventilation rates of outdoor air have been shown to lead to improved air quality and health outcomes (Fisk 2017, Tarantini 2017), it is difficult for traditional ventilation systems, such as VAV, to ensure that outdoor air is being delivered at the rates specified by ASHRAE minimum standards. Often, based on site measurements, outdoor air ventilation rates into a space do not comply with the ASHRAE Standard (Mendell 2013, Fisk 2017, Allen 2016). Air distribution to a space with VAV is dependent on heating and cooling demands and other factors that make it difficult to determine how much fresh, outdoor air is delivered to a space (Mumma 1998). Air delivered to a space also only contains a variable fraction of fresh air, which makes it even more difficult to determine how much outdoor air is delivered. With DOAS systems, it is much easier to ensure that minimum outdoor air ventilation requirements are met (http://doas-radiant.psu.edu/).

(2) Controllable Ventilation Rate → Indoor Air Quality

Building occupants generate pollutants and odors through performing indoor activities, so regulating ventilation rates based on occupant density is important to ensure proper dilution of indoor pollutants.

The quality of indoor air, which has large implications on occupant health (section 3) and productivity (section 4), is highly influenced by a variety of occupant generated pollutants. Carbon Dioxide, CO_2, has been linked to decreased cognitive performance and increased rate of Sick Building Syndrome Symptoms (Allen 2016, Vehvilainen 2016, Apte 2000) and has been shown to make people more exhausted when CO_2 concentration is beyond 3,000 ppm (Kajtar 2011). CO_2 is produced at a rate of 35,000 – 50,000 ppm per breath, which is 100 times higher than the concentration typical outdoor air (WSU Energy Program Report 2013). Nitrogen dioxide is an indoor pollutant that is also produced by human activity and is typically generated by heating and cooking appliances. Nitrogen dioxide can cause serious damage to the respiratory tract and exacerbate asthma (Gerardi 2010). Volatile organic compounds (VOCs) are also known indoor irritants which often have unpleasant odors and have been linked to headaches, respiratory problems, and cancer (Fisk 2004). While VOCs are predominantly emitted by indoor furniture and building materials, use of cleaning products, perfumes, and even human metabolism can introduce VOCs inside buildings.

Increasing outdoor air ventilation rates diminish the concentration of indoor air pollutants and pathogens through dilution (Fisk 2017). Despite the health implications of indoor air contaminants, ASHRAE designates required ventilation rates based on perception of indoor air quality rather than relative risk of exposure (Lin 2014). The ASHRAE Standard 62.1 per person ventilation rates are based on bioeffluent concentration with which 80% or more of the occupants do not express dissatisfaction with air quality (ANSI/ASHRAE 62.1-2019). Many studies have shown benefits in health and performance when increasing ventilation rates beyond ASHRAE standards (Satish 2012, Mendell 2013, MacNaugton 2015, Allen 2016, Fisk 2017).

Unfortunately, many buildings do not ventilate according to even ASHRAE standards in practice. A study of 162 classrooms in 28 Californian schools in three school districts found that all school districts had median ventilation rates lower than the 7.1 liter per second (l/s) (or 15 cubic feet per minute (cfm)) per person standard in California (Mendell 2013). Increasing classroom ventilation rates in these classrooms to the California standard was shown to decrease illness-related absence by 3.4%. Further increasing ventilation rates above the standard was shown to provide further reduction in illness-related absence. These results echo other studies that increased ventilation rates greatly benefit occupant health and reduce illness-related absence in work and school settings (Mendell 2005, Wyon 2004, Wargocki 2000, Fisk 2017, Allen 2016). There could be a threshold to the benefits of increased ventilation rates on reduced illness related absence, with one study not finding a difference in the rate of absence when comparing ventilation rates of 34 and 90 cfm/person (Myatt 2002).

(3) Indoor Air quality → Occupant Health

Indoor pollutants can cause morbidity in building occupants, but diluting these pollutants through increased ventilation can reduce the effects of these pollutants on occupant's health.

There are many indoor air pollutants that cause physiological reactions, illness, and disease. These pollutants can be classified as gases, volatile organic compounds, particulate matter, infectious agents, and allergens (Gerardi 2010). The most common building-related illnesses with a clear clinical diagnosis are respiratory infections and asthma (Gerardi 2010). Infections can stem from viral, bacterial, fungal, or animal protein sources. Sick Building Syndrome (SBS) is a common acute condition triggered by indoor pollutants with symptoms ranging from irritation of sinuses, dull headache, rash, and fatigue (Geardi 2010). SBS symptoms typically subside when exposure to indoor irritant ends. Increase in ventilation rates in office settings has shown to decrease SBS symptoms (Heerwagen 2000, Apte 2000, Shan 2016).

Asthma is an ailment associated with poor indoor air quality and disproportionally impacts low-income and racial minority children (Gauderman 2005). A major factor in the development and exacerbation of asthma is exposure to indoor allergens and irritants, with as much at 40% of the excess asthma in minority children attributed to exposure to indoor allergens (Lanphear 2001). A study found that improving indoor air quality through enhancing exterior envelope, replacing off-gassing indoor materials, and installing energy recovery ventilators with continuous fresh air supply reduced asthma-related clinical visits from 62% to 21% (Takaro 2011).

Multiple studies have indicated that increasing ventilation rates with outdoor air reduces the spread of airborne infectious disease by diluting bacterial and viral load in indoor air. A literature review performed by Seppanen et al. identified three studies that have studied the prevalence of respiratory illness in relation to ventilation rates (Seppanen 1999). The studies took place in military barracks, a jail, and nursing home, and evaluated ventilation rate changes between 2.5 versus 20 cubic feet per minute (cfm) per person, 8 versus 26 cfm per person, and 4 versus 8 cfm per person respectively. In all three studies, lower ventilation rates yielded an increase in the rate of illness, ranging from 50% to 370%. Another literature review of indoor airflow and transmission rates of infectious diseases performed by a panel of medical experts and building scientists concluded that the spread of infectious diseases, such measles, tuberculosis, chickenpox, influenza, smallpox, and SARS, increases with decreased ventilation (Li 2006). This panel was not able to provide conclusive recommendations on ventilation rates based on the findings of available studies, but an inverse relationship between infection rate and ventilation rate was observed.

(4) Indoor Air quality → Productivity

Reducing concentration of indoor air pollutants through increased ventilation has been shown to increase productivity and reduce sickness related absenteeism in school and office settings.

Over the past 20 years, building envelopes have become more airtight and energy efficient due to increasingly stringent building regulations (Allen 2016). While tighter envelopes reduce the number of air changes per hour due to infiltration of outside air, and therefore reduce energy consumption, low ventilation rates are associated with increased concentration of indoor pollutants that can be detrimental to human health and productivity. Common harmful pollutants that are typically found in high levels in conventional buildings include volatile organic compounds, dust particles, nitrogen dioxide, and carbon dioxide. Reducing these indoor air contaminants has been shown to increase mental cognition and productivity in office (Clements-Croome 2008, Wyon 2004) and school (Fisk 2017) settings in several academic studies. A study by Seppanen et al. found that work performance increased at a rate of 0.8% with every 10 cfm/person increase in ventilation between 14 to 30 cfm/person, but the benefit of increased ventilation was not as great over 30 cfm/person (Seppanen 2006).

Another study by Allen et al. comparing cognitive performance of office workers in variously ventilated spaces similarly found that increased ventilation and lower CO_2 concentrations improves indoor air quality and significantly improves productivity (Allen 2016). The study used a validated, computer-based cognitive test to assess office worker performance. Ventilation rate, CO_2, and VOC were all found to impact performance on the test. CO_2 concentration had a major impact on cognitive function scores. Average cognitive scores for seven out of nine cognitive domains decreased as CO_2 increased (Allen 2016). To contextualize this study, background outdoor CO_2 concentrations are typically 350-400 ppm (https://www.esrl.noaa.gov/). ASHRAE Standard 62.1 suggests an airflow rate of 20 cfm/person, which corresponds to a CO_2 concentration of 945 ppm, commonly stated as 1000 ppm (https://compass.astm.org/). This standard is commonly required by local building codes that use ASHRAE standards (Allen 2016). In Allen's study, changes in CO_2 concentrations from 550 ppm to 945 resulted in 15% reduction in cognitive test scores. Changes in concentrations from 550 to 1400 ppm, resulted in 50% decreases in cognitive scores. (Allen 2016). Overall, a 21% decrease in typical participant cognitive score across all nine cognitive function domains was seen with 400 ppm increases in CO_2 concentrations. This is particularly concerning since many spaces far exceed the 1000 ppm standard. In one study, 45% of 435 classrooms in Washington and Idaho exceeded this threshold, and reported that elevated CO_2 concentrations were associated with increases in student absences (Allen 2016). These findings suggest a benefit in cognitive performance from, at a minimum meeting the suggested 1000 ppm CO_2 concentration standard, or even lowering CO_2 concentrations below these ASHRAE standards.

Reduced ventilation can cause health effects, such as mucosal and allergy symptoms (Fisk 2017). Enhanced ventilation in buildings can improve performance of workers by reducing absenteeism and improving health overall (MacNaughton 2015). Healthier buildings reduce sick time and increase productivity (Miller 2009). Good ventilation and the absence of organic compounds leads to happier, healthier workers.

(5) Decoupled heating/cooling from Ventilation → Thermal Comfort

DOAS allows for better control of humidity and when coupled with radiant heating and cooling can provide superior uniformity of air and radiant temperature.

Thermal comfort is defined as the subjective assessment of one's thermal satisfaction of the environment and is affected by environmental and personal factors. The four environmental factors that contribute to thermal comfort are air temperature, radiant temperature, air speed, and humidity (Lechner 2014). The personal factors are metabolic rate and clothing insulation (Lechner 2014). The most common physiological symptoms that cause a negative perception of thermal comfort are feeling too hot or too cold, but dryness of skin, nose, throat, nasal congestion, itchy skin, and headache have been found to directly correlate with temperature and relative humidity (Amin 2015, Ormandy 2012).

DOAS can provide thermal and environmental comfort through eliminating drafts and reducing fan noise. If supply air is located at the ceiling in a DOAS system, the air for ventilation is distributed at a low velocity and warms to room temperature 12 to 15 inches below the ceiling plane, eliminating cold drafts and vertical air variations common in VAV systems (Mumma 2002). Acoustic comfort is also improved because DOAS has a lower airflow rate than traditional all-air systems, resulting in reduced fan noise (Mumma 2002).

DOAS decouples sensible and latent loads, allowing for better control of temperature and relative humidity than traditional VAV systems (Mumma 2002). Although humidity control in the Pacific Northwest is not usually a significant issue, there are substantial indoor air quality benefits for more humid climates. The ventilation system in DOAS addresses humidity independently of heating and can quickly respond to humidity control needs, which keeps environmental conditions in a thermally acceptable range (Mumma 2002). Superior control of humidity also prevents damp spots in ceiling tiles, insulation, carpet and walls, preventing likelihood of mold growth (Mumma 2002).

Under cooling conditions, DOAS paired with radiant cooling has been shown to improve thermal comfort. During radiant cooling, heat is expelled through radiant heat loss as opposed to convection and sweating and there is reduction in draft and vertical temperature difference (Tian 2008). Radiant cooling paired with displacement ventilation can lead to discomfort, because the cold air delivered at high velocities with displacement ventilation can create undesirable cold drafts. This problem can be significantly reduced if most of the cooling load is handled by the radiant system. Radiant heating also improves thermal comfort over convection systems, because radiant heating provides a more equal distribution of heat in a space as large surfaces near the occupant, such as floor surfaces and furniture, warm and radiate heat (Imai 2015).

(6) Thermal Comfort → Productivity

Thermal discomfort can lead to reduced production in office and school settings.

Investing in buildings that improve an occupant's sense of thermal comfort is important, because an improved sense of thermal comfort can increase mental performance and productivity (Zeiler 2009). Studies have found that temperature influences performance (Cui 2013, Seppanen 2006, Lee 2012, Fisk 2004). One study of a US office building found that cognitive function of employees decreased when exposed to consistently cold temperatures. The same reduction appeared when exposed to consistently warm temperatures (Cui 2013, Lee 2012). Several studies have found that perceived thermal comfort in classrooms showed improvements of productivity and performance (Zeiler 2009, Zomorodian 2016). The optimal temperature range for cognitive function was found to be between 22-26 degrees Celsius (71.6-78.8 ° F) (Seppanen 2006). Optimal temperatures for performance can vary due to the type of task (Zeiler 2009, Heerwagen 2000, Tarantini 2017, Chang 2019, Schellen 2012). Furthermore, study subjects engaged in creativity-oriented tasks perform better in slightly warmer environment than average while those performing critical thinking tasks did better in spaces on the cooler end of the comfort spectrum (Heerwagen 2000, Chang 2019).

Thermal comfort can also vary by gender. A study looking at the influence of gender on comfort asked participants to perform simulated office tasks and analyzed temperatures on the body while recording their perception of comfort. The study found that women were 4.5 times more likely to complain about cold extremities and their skin temperatures were significantly cooler than the male participants. The male participants in this study showed higher overall performance in the cooler environments than the female subjects (Schellen 2012). Another study conducted in Germany measured how the effects of temperature on cognitive performance varied based on gender (Chang 2019). This experiment had over 500 individuals perform math, verbal, and cognitive reflection tasks while only altering the temperature. The findings show that women had higher scores in warmer temperatures and the males performed better in lower temperatures. However, the impact was significantly higher for the women with a 1.76% increase in performance at the higher temperature. The change in men's performance was not statistically significant (Chang 2019).

(7) Controllable Ventilation Rate → Operational Costs

Controlling ventilation rates can significantly reduce energy use by reducing the need to condition air during low-occupied times of the day.

Providing variable ventilation rates to a space based on changes in occupancy can be achieved through a strategy referred to as demand-controlled ventilation (DCV). ASHRAE standard 90.1 defines DCV as a system that provides "automatic reduction of outdoor air intake below design rates when the actual occupancy of spaces served by the system is less than design occupancy" (ASHRAE 2010d). Since CO_2 is proportional with human occupancy and activity, reduction in ventilation rates are commonly controlled by demand control dampers (DCD) that respond to CO_2 sensors integrated into the thermostat or located elsewhere within the space (Lin 2014).

DCDs can save considerable amounts of energy and operating costs because they reduce ventilation rates during unoccupied or low occupied times. A 2011 Department of Energy study examined the energy and cost implications of DCDs by running simulations for four different buildings types in various climates with roof top unit heat pump systems. The report found that DCDs are most effective in heating-dominated climates because they reduce ventilation load, however reduction in fan run time was shown to be the predominant cause of reduced energy consumption (Wang 2011). The payback period of the DCD controller using energy costs at the time of report publication was three years. Typical energy cost savings can range on average between 5 to 27 percent (WSU Energy Program Report 2013), but savings up to 35% was shown using DCD for a stand-alone retail building in Seattle (Wang 2011).

While DCV offers significant energy and operational cost savings, it is difficult to ensure that the outdoor air ventilation requirements are met per ASHRAE standard 62.1 with traditional, multi-space variable air volume (VAV) systems (O'neill 2019). This is because in multi-space VAV, outdoor air is mixed with indoor air. As this mixed air is distributed to rooms, it is difficult to quantify and ensure that the appropriate fraction of outdoor air is distributed to each room. A study conducted at the University of Nebraska assessed DCV control strategies in multi-space VAV systems and concluded that either they do not comply with the ASHRAE ventilation standards or there is no way to ensure compliance (Lin 2013). In fact, another study found that in some cases, spaces using DCV with multi-space VAV can be up to 90% under ventilated with outdoor air (fraction of outdoor air is not meeting min standard) -- for example only 2 cubic feet per minute (cfm) per person of outdoor air will be provided, when 20 cfm per person is required (Mumma 2002).

With DOAS, it is much easier to ensure that proper outdoor air ventilation requirements are met since 100% outdoor air is delivered to a space (Mumma 2002). Implementing DCV ventilation in DOAS is simple and effective, and can significantly reduce operational costs through reducing need to condition outdoor air and fan run time.

(8) Decoupled heating/cooling from Ventilation → Space Efficiency

Decoupling heating and cooling from ventilation significantly reduces size of equipment and ducts.

The gross volume of air required for DOAS can be up to 80% less than traditional variable air volume (VAV) systems (Cheng 2019). The reduction in air volume for DOAS is due to the decoupling of heating and cooling from ventilation air. Traditional mixing systems combine heating, cooling, and ventilation using large volumes of air to satisfy all of those needs. When multiple spaces are being served with a VAV system, 20-70% more outdoor air is required compared with DOAS to meet ventilation requirements (http://doas-radiant.psu.edu/). This is to assure that the proper amount of outdoor air enters a space (http://doas-radiant.psu.edu/).

For DOAS, the reduction of circulating air volume can offer significant space savings compared with VAV (or CAV) systems due to reduced duct and equipment sizes. The reduced need for outdoor air in DOAS systems can reduce chiller and pump sizes (http://doas-radiant.psu.edu/). The reduction in air flow rates, which are 15 to 20% lower in DOAS systems (http://doas-radiant.psu.edu/), allow for a down-sizing of air distribution systems when compared with similar forced air heating and cooling systems that include ventilation air. Reducing ductwork size leads to reductions in plenums and mechanical shafts. Reducing the plenum depth has implications on total building cost due to potential reductions in floor-to-floor heights and required construction materials – especially with respect to the area of building enclosure. Furthermore, reducing mechanical shaft size frees up floor area for programmatic uses and provides more planning flexibility (http://doas-radiant.psu.edu/). When compared with traditional forced air systems, DOAS typically reduces HVAC space requirements by 33% (https://ghtltd.com/raise-ceiling-heights-with-a-doas-system/).

(9) Decoupled heating/cooling from Ventilation → Operational Costs

DOAS reduces volume of outdoor air required and total volume of circulating air compared with traditional systems, reducing amount of energy required to condition outdoor air and run larger fans.

Traditional, multi-space variable air volume (VAV) HVAC systems deliver a variable amount of outdoor air to each space due to mixing with indoor air. Per the multiple space equation of ASHRAE 62.1, 20-70% more outdoor air is required than DOAS in order to ensure that the required amount of outdoor ventilation is delivered to a space (http://doas-radiant.psu.edu/). This larger air volume needs to be cooled and dehumidified in the summer and heated in the winter, which is energy intensive and costly (Mumma 2003).

Pumps and fans required a significant amount of energy, and they consume 20% to 60% of the total HVAC electrical energy demand (Chinery 2014). Fans for VAV systems are much larger than DOAS systems, since large flow rates are required to achieve sensible heating loads for VAV systems (http://doas-radiant.psu.edu/). DOAS systems can have air flow rates that are 15-20% smaller than VAV systems (http://doas-radiant.psu.edu/). Providing ventilation, especially during low occupied times, is therefore very costly with VAV, since running the fans takes a considerable amount of energy. Smaller fans used with DOAS save a significant amount of operating costs (Chinery 2014).

A cost analysis performed by Dr. Stanley Mumma, a scholar in DOAS, determined that mechanical costs can be reduced by 23% annually when switching from a VAV system to a DOAS system that uses radiant heating and cooling (http://doas-radiant.psu.edu/). A hypothetical 6 story, 31,000 sf office building in Philadelphia was used as the study model, and compliance with ASHRAE energy conservation standard 90.1-2004 was assumed. Mumma concluded that reductions in cost due to duct size, chiller size, air handling unit size, plenum depth, and integrated thermal and fire suppression piping leads to a cost savings of $2/sf (http://doas-radiant.psu.edu/).

(10) Highly efficient heat exchange → Operational Costs

Rotary wheels and counter-flow fixed plate exchangers are the most energy efficient air-to-air heat exchangers and fixed plate exchangers can run with virtually no cross-contamination.

There are several types of heat recovery systems, including fixed plate, heat pipe, rotary wheel and run-around coil (Mardiana-Idayu 2012). Rotary wheels and fixed plate exchangers are the most energy effective, with typical efficiency at 80%+ and 70-90% respectively, while heat pipe and run-around efficiencies are typically under 80% (O'Conner 2016).

Rotary wheels and fixed plates are commonly used for their high efficiency (O'Conner 2016). In a rotary wheel, heat exchange between exhaust and supply air occurs in ducts located in a rotary wheel that spins to aide heat exchange. Due to the rotation mechanism, there is a greater risk with fresh air contamination by exhaust air with rotary wheels, which can occur through cross-flow and carryover leakage (Mardiana-Idayu 2012). Fixed plate exchangers consist of thin metal plates spaced apart to allow airstreams to pass adjacent to each other and heat exchange occurs through the metal plates. Since the airstreams are completed separated, there is no risk of cross contamination (O'Conner 2016).

ASHRAE has recommended significant increases in ventilation rates during the COVID-19 pandemic (ASHRAE Report April 2020). While increasing outdoor ventilation can reduce the concentration of indoor pollutants and pathogens, there are significant energy and cost implications associated with bringing significantly more unconditioned air into a building (Greenheck 2020). An ASHRAE-issued report recommended that highly efficient heat exchangers be used to offset this energy demand (ASHRAE Report June 2020). Although an increase in energy and operational costs will result from increased outdoor ventilation rates, the penalty for this change in operations with very high efficiency DOAS is not as high as traditional systems, due to the highly efficient heat exchanger and smaller fan sizes.

Appendix A

Primary Author	***Year***	***Title***	***Source***
ASHRAE	2020	ASHRAE Position Document on Infectious Aerosols. April 14 2020	Report
ASHRAE	2020	Practical Guidance for Epidemic Operation of Energy Recovery Ventilation Systems Authored by ASHRAE TC 5.5. June 9, 2020	Report
ASTM Compass	2020	Standard Guide for Using Indoor Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation	Website: https://compass.astm.org/EDIT/html_annot.cgi?D6245+18#s00034
GHT Consulting Engineers	2020	Raise Ceiling Heights with a DOAS System	Website: https://ghtltd.com/raise-ceiling-heights-with-a-doas-system/
GreenHeck	2020	HVAC Operational Adjustments Can Help Mitigate the Spread of COVID-19	Report
NOAA Global Monitoring Laboratory	2020	Standard Guide for Using Indoor Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation	Website: https://compass.astm.org/EDIT/html_annot.cgi?D6245+18#s00034
Chang, Tom	2019	Battle for the thermostat: Gender and the effect of temperature on cognitive performance	Plos One Vol. 14(5)
Cheng, Fanyong	2019	A robust air balancing method for dedicated outdoor air system	Energy & Buildings Vol. 202 pp. 1-13
O'neill, Zheng	2019	Energy savings and ventilation performance from CO2-based demand controlled ventilation: Simulation results from ASHRAE RP-1747 (ASHRAE RP-1747)	Science and Technology for the Built Environment Vol. 0 pp. 1-25
MacNaughton, Piers	2018	The Impact of Working in a Green Certified Building on Cognitive Function and Health	Building & Environment Vol. 114 pp. 178-186
Fisk, William	2017	The ventilation problem in schools: Literature review	Indoor Air Vol. 27(6) pp. 1039-1051

Primary Author	Year	Title	Source
Maula, Henna	2017	The effect of low ventilation rate with elevated bioeffluent concentration on work performance, perceived indoor air quality, and health symptoms	Indoor Air Vol. 27(6) pp. 1141-1153
Tarantini, Mariantonietta	2017	A Co-Citation Analysis on Thermal Comfort and Productivity Aspects in Production and Office Buildings	Buildings Vol. 7(2) pp. 36
Allen, Joseph	2016	Associations of Cognitive Function Scores with Carbon Dioxide, Ventilation, and Volatile Organic Compound Exposures in Office Workers: A Controlled Exposure Study of Green and Conventional Office Environments	Environmental Health Perspectives Vol. 124(6) pp. 805-
O'Conner, D	2016	A Review of Heat Recovery Technology for Passive Ventilation Applications	Renewable and Sustainable Energy Reviews Vol. 54 pp. 1481-93
Shan, X	2016	Comparing mixing and displacement ventilation in tutorial rooms: Students' thermal comfort, sick building syndromes, and short-term performance	Building and Environment Vol. 102 pp. 128-137
Vehvilainen, Tommi	2016	High indoor CO2 concentrations in an office environment increases the transcutaneous CO2 level and sleepiness during cognitive work	Journal of Occupational and Environmental Hygiene Vol. 13(1) Page: 19-29
Zomorodian, Zahra	2016	Thermal comfort in educational buildings: A review article	Renewable and Sustainable Energy Vol. 59 pp. 895-906
Amin, Nor	2015	Architectural Evaluation of Thermal Comfort: Sick Building Syndrome Symptoms in Engineering Education Laboratories	Procedia Social and Behavioral Sciences Vol. 204 pp. 19-28
Imai, Shigeru	2015	Comparison of Thermal Comfort by Radiant Heating and Convective Heating	Journal of Engin, Project, and Production Management Vol. 5(1) pp. 26-35

Primary Author	Year	Title	Source
MacNaugton, Piers	2015	Economic, Environmental and Health Implications of Enhanced Ventilation in Office Buildings	International Journal of Environmental Research and Public Health Vol. 12(11) pp. 14709-14722
Chinery, Mark	2014	Using Sensor-based Demand Controlled Ventilation to Realize Energy Savings in Laboratories	Thesis, Department of the Air Force Air University
Lechner, Norbert	2014	Heating, Cooling, and Lighting	Print Book
Lin, Xingbin	2014	Evaluation on the Validity of the Assumptions Underlying CO2-Based Demand-Controlled Ventilation by a Literature Review	ASHRAE Transactions, Volume 120, Part 1
Cui, Weilin	2013	Influence of indoor air temperature on human thermal comfort, motivation and performance	Building and Environment Vol. 68 pp. 114-122
Lin, Xingbin	2013	ASHRAE 1547-RP Final Report CO2-Based Demand Controlled Ventilation for Multiple Zone HVAC Systems	Report
Mendell, MJ	2013	Association of classroom ventilation with reduced illness absence: a prospective study in California elementary schools.	Indoor Air Vol. 23(6) pp. 515-528
WSU Energy Program Report	2013	Measuring Carbon Dioxide Inside Buildings – Why is it Important?	Report
Lee, M	2012	Student learning performance and indoor environmental quality (IEQ) in air-conditioned university teaching rooms	Building and Environment Vol. 49(C) pp. 238-244
Mardiana-Idayu, A	2012	Review on heat recovery technologies for building applications	Renewable and Sustainable Energy Reviews Vol. 16 pp. 1241-55

Primary Author	Year	Title	Source
Ormandy, David	2012	Health and thermal comfort: From WHO guidance to housing strategies	Energy Policy Vol. 49 pp. 116-121
Satish, Usha	2012	Is CO 2 an Indoor Pollutant? Direct Effects of Low-to-Moderate CO 2 Concentrations on Human Decision-Making Performance	Environmental Health Perspectives Vol. 120(12) pp. 1671- 1677
Schellen, L	2012	The influence of local effects on thermal sensation under non-uniform environmental conditions — Gender differences in thermophysiology, thermal comfort and productivity during convective and radiant cooling	Physiology & Behavior Vol. 107(2) pp. 252-261
Angkana, Roy	2011	The effects of outdoor air pollutants on the costs of pediatric asthma hospitalizations in the United States, 1999 to 2007	Medical Care Vol. 49(9) pp. 810-7
Kajtar, Laszlo	2011	Influence of carbon-dioxide concentration on human well-being and intensity of mental work	Healthy Buildings: Creating a Healthy Indoor Environment for People, Proceedings
Takaro, Tim	2011	The Breathe-Easy Home: The Impact of Asthma-Friendly Home Construction on Clinical Outcomes and Trigger Exposure	American Journal of Public Health Vol. 101(1) pp. 55-62
Wang, W	2011	Energy Savings and Economics of Advanced Control Strategies for Packaged Air-Conditioning Units with Gas Heat	Pacific Northwest National Laboratory Report
Gerardi, D	2010	Building-Related Illness	Clinical Pulmonary Medicine Vol. 17(6) pp. 276-281
Laumbach	2010	Acute effects of motor vehicle traffic-related air pollution exposures on measures of oxidative stress in human airways	Annals of the New York Academy of Sciences Vol. 12031(1) pp. 107-112
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