Relationships between Ventilation and Occupant Productivity, Energy and other Societal Costs

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INTRODUCTION

Over the past 15 years, studies concerned with the energy implications of the ventilation rate increases have found sufficient benefits and insufficient negative economic impacts. Standard 62-1989 was adopted and included requirements for effectively increasing the dilution ventilation rates required previously in the 1981 version by about 3 times.

Multiple government and private studies have shown that **improvements in productivity, ranging from 3% - 20%,** can be expected due to improvements in a worker's indoor environment (National Contractors Study, et. al. 1990, 1993, 1995, LBNL-1997, 2000, 2002, 2003, 2011). More recently, some have reduced that range to a more realistic 5% - 10%. This is the magnitude of the benefit that might be captured with help from improved dynamic intake control through HVAC instrumentation and ventilation design. It will be shown that even a **significant fraction of 1% is sufficient to economically justify the needed equipment and energy** to implement ventilation control changes.

The body of this paper will summarize the findings of relevant studies over this period that reflected on the impact of different levels of dilution ventilation. From these, we ask the reader to remember that the **deviations in productivity indicated by levels of ventilation supplied are also applicable to buildings that operate with a large degree of control uncertainty for outdoor air supply and distribution effectiveness.** The objective is to spotlight the importance of ventilation rate "maintenance" under all operating conditions – as required by U.S. codes and professional standards.

Indoor Air Quality (IAQ) is significant to achieving overall improvements in Indoor Environmental Quality (IEQ), which includes several comfort-related factors, the amount of dilution ventilation and the presence or absence of pollutants. Some studies have equated the absence of pollutants to an increase in ventilation air, and vice versa. It has been reported in numerous studies that improving a building's indoor environment will also improve occupant productivity.

Productivity is affected by and includes the performance degradation from: health, sick leave, thermal comfort, lighting, air movement, odors, amount of ventilation supplied to an occupied space, discomfort directly from pollutant loads, etc. Broadly, these are covered by the definition of IEQ, of which IAQ, ventilation and its consistent sufficiency are a key component. Because the effects of most IEQ components are difficult to isolate or measure individually, studies have concentrated on broader terms. It is safe to say that any provision for IEQ adequacy must include a ventilation component.

Because aspects of IEQ and IAQ are normally addressed concurrently and because IAQ is typically not addressed in isolation in new building design, we will for practical purposes equate the research references for IEQ to IAQ, using them almost interchangeably for the purposes of this discussion. In doing so, we also identify the need for more and varied research related to ventilation-specific impacts on productivity and health.

This paper attempts to organize the research materials used according to subject matter. However, many of the studies cover more than one issue and most issues are intertwined to the point that they cannot be separated in the findings (e.g. health issues requiring sick leave vs. overall productivity). Although somewhat arbitrary, the main divisions chosen are: Ventilation and

Performance, Energy Considerations, Health and Healthcare, Student Performance, Implications, and Conclusions.

VENTILATION and WORK PERFORMANCE – THE FINDINGS

Theoretical considerations and empirical data suggest that existing technologies can improve indoor environments in a manner that significantly increases productivity and health. The existing literature contains moderate to strong evidence that characteristics of buildings and indoor environments significantly influence rates of communicable respiratory illness, allergy and asthma symptoms, sick building symptoms, and worker performance.

For the U.S., the estimated potential **annual savings and productivity gains** are $20 to $160 billion from direct improvements in worker performance that are unrelated to health. Health issues add another $17 to $48 billion. This compares to a total energy cost (1995) US commercial buildings of $70 billion. **Better measurement and control of ventilation rates** was identified as one of the methods that both improved IEQ and energy savings. (Fisk 2000a)

Source of Productivity Gain	Potential Annual Health Benefits	Potential U.S. Annual Savings or Productivity Gain (1996 U.S. $)
Reduced Respiratory Illness	16 Million to 37 Million Avoided Cases of Common Cold or Influenza	$6 Billion to $14 Billion
Reduced Allergies And Asthma	8% to 25% Decrease in Symptoms within 53 Million Allergy Sufferers and 16 Million Asthmatics	$1 Billion to $4 Billion
Reduced Sick Building Syndrome Symptoms	20% to 50% Reduction in SBS Health Symptoms Experienced Frequently at Work by ~15 Million Workers	$10 Billion to $30 Billion
Improved Worker Performance from Changes in Thermal Environment and Lighting	Not Applicable	$20 Billion to $160 Billion

Table 1: Estimated potential productivity gains.

Scientific literature was reviewed by a group of European scientists, called EUROVEN, with expertise in medicine, epidemiology, toxicology, and engineering. The group reviewed 105 papers published in peer-reviewed scientific journals …Based on the data in papers judged conclusive, the group agreed that **ventilation is strongly associated with comfort** (perceived air quality) **and health** [Sick Building Syndrome (SBS) symptoms, inflammation, infections, asthma, allergy, short-term sick leave], and that an **association between ventilation and productivity** (performance of office work) **is indicated**. The group also concluded that increasing outdoor air supply rates in non-industrial environments improves perceived air quality….. The group concluded additionally that the literature indicates …. that improper maintenance, design, and functioning of air-conditioning systems contributes to increased prevalence of SBS symptoms. (Wargocki 2002) These findings help justify the additional use of control instrumentation for fault detection purposes.

Potential **direct productivity gains estimated at 0.5% to 5%,** reflect the significant uncertainty involved. In many non-industrial workplaces, the cost of **workers' salaries and benefits exceeds energy costs by approximately a factor of 100.** Consequently, there should be strong motivation to change building designs or operations if the changes improved worker performance by even a significant fraction of a percent or reduced sick leave by a day or more per year. While employers may be tempted to neglect energy efficiency when seeking to improve health and productivity, the most desirable measures are those that improve IEQ and simultaneously save energy. (Fisk 2002) This conclusion sounds much like the goals from maximizing the precision of outdoor air intake rate control, which contributes to achieving both objectives.

A preliminary estimate of the total annual expenditures for IAQ problem prevention and mitigation activities in the United States is approximately $16 billion with **a range of $12 billion to $20 billion**. While not precise, this estimate does indicate that the level of expenditure is **substantial.** It is also apparent that **expenditures are growing….** (Levin 2005, LBNL-58694) The best way to avoid IAQ problems, based on the primary historical causes, is to assure that sufficient outdoor air is supplied - under all operating conditions.

In a study by the Technical University of Denmark's International Centre for Indoor Environment and Energy, the relationship between Productivity, IAQ and SBS (Sick Building Syndrome) symptoms was evaluated. Their study determined that removing a pollution source from a space or increasing the outdoor air supply rate improved the perceived air quality, reduced the intensity of general SBS symptoms such as headaches, and improved the performance of office work. (Wargocki 2002) Changes in the outdoor air supply rate can be manifested by inadequate control design, instrumentation quality, control sequencing, all of which offer opportunities for problem avoidance.

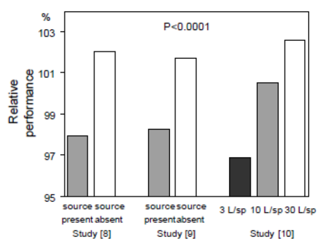


Fig 2. Perceived air quality, intensity of general SBS symptoms and relative performance of office tasks as a function of the presence or absence of the pollution source, or the outdoor air supply rate

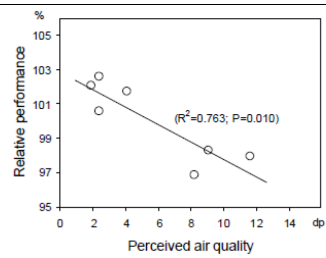


Fig 4. Relative performance of office tasks as a function of the air quality

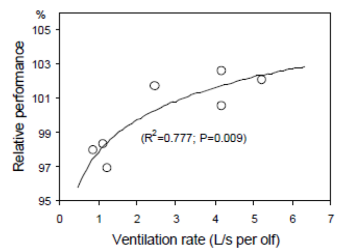


Fig. 6. Relative performance of office tasks as a function of the outdoor air supply rate

> *"Based on the results obtained, quantitative relationships were established showing that the **performance of office work can be increased by 1.1% for every 10% reduction in the proportion of persons dissatisfied with the air quality**, by 1.6% for every twofold decrease of pollution load, and by 1.8% for every twofold increase of the ventilation rate (outdoor air supply rate*)."

These relationships can be used to roughly estimate the effects of ventilation rate changes for improved air quality on office productivity. They also demonstrate the importance of knowing and maintaining an adequate volume of outdoor air, based on the combination of both space population and floor area.

ICIEE conducted three separate **studies showing an increase of productivity at 5 percent or more through IAQ improvements.** Results clearly justify increased initial and operating costs, and provide a strong economic incentive for designing indoor environments with outdoor air of a higher quality and volume than the minimum prescribed by ventilation codes and standards. (Wargocki 2002)

A cost-benefit analysis of measures used to improve air quality in an existing air-conditioned office building (11581 m^2, 864 employees) was carried out by Djukanovic, Wargocki and Fanger in 2002 for hot, temperate and cold climates and for two operating modes: Variable Air Volume (VAV) with economizer; and Constant Air Volume (CAV) with heat recovery. The annual energy cost and first cost of the HVAC system were calculated for various levels of air quality (10-50% dissatisfied). This was achieved by changing the outdoor air supply rate and the pollution loads.

50% occupant dissatisfaction was noted as "typical" for the 56 office buildings studied in the European Audit project in 9 countries (Bluyssen et al., 1996).

The economic benefits of the increased productivity were calculated assuming an hourly office worker salary of $19.4 /hour (U.S. Department of Labor, 2000). Thus a 1% increase in productivity would result in an economic benefit of $0.194 /hour per person. The change in ventilation required to affect a 1% increase in productivity (or avoid a 1% loss) is approximately 10 L/s/p ± 25%, as demonstrated in the Seppänen analysis of 2006, *Ventilation Rates in Offices and Work Performance* (below).

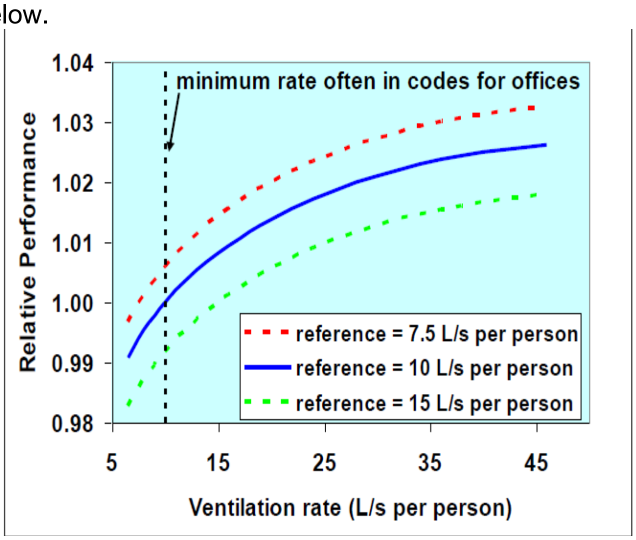
With these assumptions, the **annual benefit due to improved air quality was always at least 10 times higher than the increase in annual energy and maintenance costs**. The **payback** time of the HVAC first costs involved in improving the air quality was always **less than 4 months**. (Djukanovic 2002)

Djukanovic's analysis was based on computer simulation requiring a number of assumptions regarding operating effectiveness. In actuality, equipment, controls and instrumentation must be selected and prudently applied under dynamic operating conditions in order to achieve desired results. Our extended analysis also indicates that **increasing the precision of outdoor air control to overcome the large uncertainties in indirect measurement are well worth the investment.** The key to ensuring a constant supply of ventilation air is **measuring and controlling the rate of intake**, in both VAV and Constant Volume systems as both are subject to most of the same forces that influence intake rates (e.g. mixed air, wind, stack effects, etc.)

In a series of laboratory simulation experiments with exposures of up to 5 hours the **performance of simulated office work was increased** by removing common indoor sources of air pollution, or **by increasing the rate at which clean outdoor air was supplied per person (3-30 L/s/p)**. The resulting pollutant levels affected the headache and difficulty in thinking clearly and the perception of IAQ. These findings were validated in two 8-week field intervention experiments, which were carried out in call-centers in northern Europe and in the hot humid tropics. The results of field experiments show that **IAQ had a larger effect on the actual performance of office work in the field than would be predicted from the laboratory experiments**. (Wyon 2006)

Ventilation Rates in Offices and Work Performance - Speed of call center work & speed and accuracy of various tasks. Results from the Statistical Analyses of Nine Studies with 26 Data Points is described below.

1.0 base = 13.8 cfm/p



Based on this relative performance change, we can expect a 3% swing in productivity should airflow rates vary from 5 to 15 L/s/p, or about the equivalent of a ± 50% change in outdoor airflow rate, based on a 10 L/S/P or 20 cfm/p control set point. This scenario is entirely possible with a combination of equipment malfunction, measurement errors, control sequence improperly applied, etc. (Seppänen 2006)

A recent 2011 study provides quantitative estimates of the benefits and costs of providing different amounts of outdoor air ventilation in U.S. offices. For four scenarios that modify ventilation rates, the authors estimated changes in sick building syndrome (SBS) symptoms, work performance, short-term absence, and building energy consumption.

The estimated annual economic benefits were **$13 billion** from increasing minimum ventilation rates (VRs) from 8 to 10 L/s per person, $38 billion from increasing minimum VRs from 8 to 15 L/s per person, and $33 billion from increasing VRs by adding outdoor air economizers for the 50% of the office floor area that currently lacks economizers. **The estimated $0.04 billion in annual energy-related benefits of decreasing minimum VRs from 8 to 6.5 L/s per person are very small compared to the projected annual costs of $12 billion. Benefits of increasing minimum VRs far exceeded energy costs** while adding economizers yielded health, performance, and absence benefits with energy savings. (Fisk 2011a)

To help you put these numbers in perspective, let us equate the differentials in VRs to ventilation control errors. We do not have the information to estimate energy costs from the excessive positive errors, but the $12 Billion loss in productivity from a realistic -25% control error, is significant.

VR – L/s/p	VR – CFM/p	**% difference**	$ Billion
8 – 10	16 - 20	**+ 25%**	$13
8 – 6.5	16 - 13	**- 25%**	**($12)**

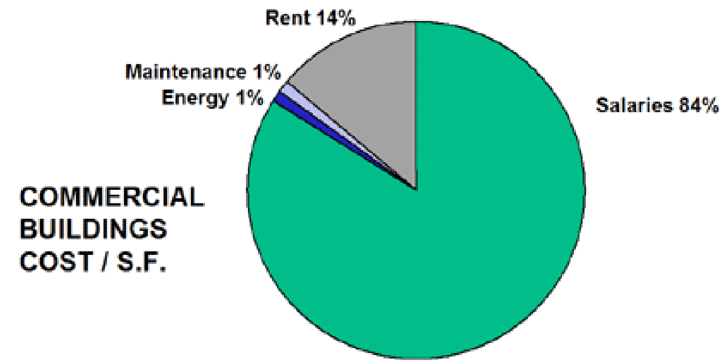
This study recommended four remedial measures in U.S. offices—increasing low ventilation rates, improving temperature controls so that offices don't get too hot in winter, performing dampness and mold remediation, and adding economizers—would reduce adverse health effects and health care costs, decrease absence rates, improve thermal comfort, and improves work performance. The projected societal economic benefits of non-overlapping combinations of these remedial measures range from $17 billion to $26 billion per year. (Fisk 2011b)

PRODUCTIVITY vs. ENERGY - COST COMPARISONS

Several significant organizations have already concluded that building management policies that ignore the IAQ impact can have a negative financial effect that far outweighs the minor savings projected from those policies. For example, NIBS and the Naval Facilities Engineering Command, as early as 1997, stated in their *Whole Building Design Guide*:

> *"Because worker salaries exceed building energy, maintenance and annualized construction costs by a large factor, the cost-effectiveness of improvements in indoor environments will be high even when the percentage improvements in health and productivity are small…* ***The resulting benefit-to-cost ratios were very high, approximately 50 to 1...for increased ventilation…"*** (WBDG attributed to Fanger 1998)

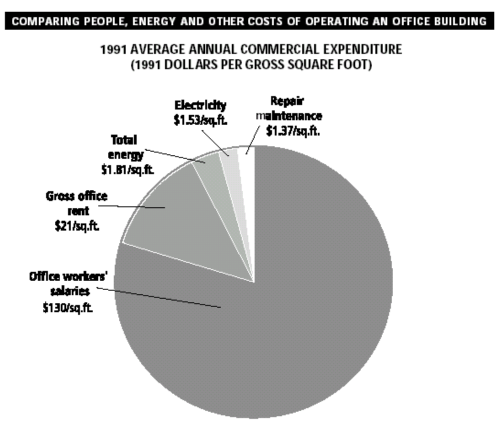
A 1% productivity savings can nearly offset a company's entire annual energy cost.



*Based on two recent field studies – one in schools and one in retail. H.M.G. 1999

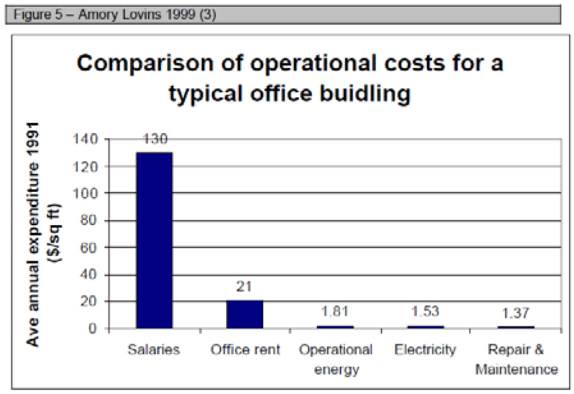
WBDG/NIBS go on to propose:

> **"…a 'productivity' increase of 1% will completely offset the building's entire energy bill.** This implies that it is crucial that interventions made in the name of energy efficiency do not negatively impact occupant satisfaction and productivity."



Source: *Natural Capitalism: Creating the Next Industrial Revolution*, p. 90

Figure 5 – Amory Lovins 1999 (3)

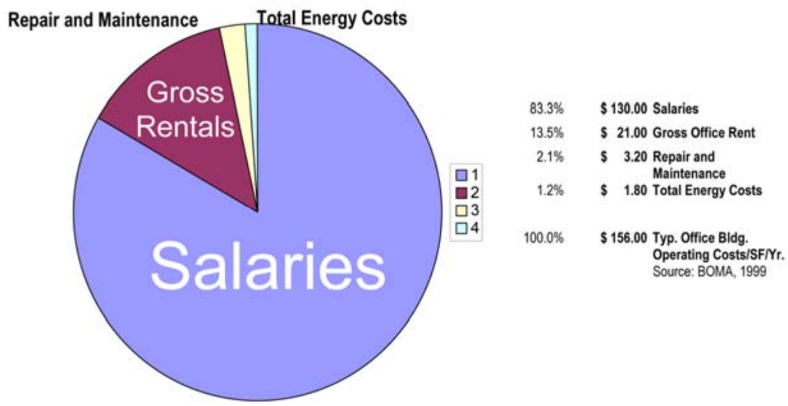


(MN State Budget proposal documents, 2002-2007 Capital Budget)

In many non-industrial workplaces, the cost of workers' salaries and **benefits exceeds energy costs by approximately a factor of 100,** first identified by Woods and Jamerson in 1989. Consequently, businesses should be strongly motivated to change building designs or methods of operation if these changes improve worker performance by even a significant fraction of a single percent of their salaries, or reduced sick leave by one day or more per year.

With this magnitude of benefits-to-cost ratio, there should be little hesitation from building owners and operators to comply with our national standards for ventilation and IAQ. While some employers may be tempted to neglect energy efficiency when seeking to improve health and productivity, the most desirable measures (or packages of measures) are those that improve IEQ/IAQ and simultaneously save energy (Wargocki 2000).

The smart building operator will provide his system with a control system and input devices sufficiently accurate and reliable to allow optimizing adjustments for changing conditions. This would enable the system to be controlled at the most cost-effective points of operation without sacrificing the benefits of providing improved IAQ.



(BOMA 1999)

HEALTH & HEALTHCARE

The papers reviewed in this study indicate that higher ventilation rates will, on average, improve occupants' health, reduce absences, and improve perceived air quality. The papers provide **considerable evidence of benefits from increasing office ventilation rates above those specified in ANSI/ASHRAE Standard 62-1999**. (Milton 2000)

IEQ Variables	Health/Productivity Outcomes					
	Sick Building Syndrome Symptoms[a]	Allergy and Asthma	Communicable Respiratory Illness (Short-term Sick Leave)[b]	Task Performance or Productivity	Economic Gains	Total Papers
Ventilation Rate/CO_2 Concentrations	(1, 12, **18**, 22, 23)	(22)	**(13, 18)**	(23)	**(6, 13)**	7p

Taken together, these three papers (in BOLD #) increase the strength of available scientific evidence that **IEQ substantially affects health and productivity**.

6.
Fisk, W.J. 2000. "Health and productivity gains from better indoor environments and their relationship with building energy efficiency." Annual Review of Energy and the Environment 25(1):537–66.

13.
Milton D.K., P.M. Glencross, M.D. Walters. 2000. "Risk of sick leave associated with outdoor ventilation level, humidification, and building related complaints." Indoor Air 10(4):212–21.

18.
Seppanen, O.A., W.J. Fisk, M.J. Mendell. 1999. "Association of ventilation rates and CO_2 concentrations with health and other human responses in commercial and institutional buildings." Indoor Air 9(4):226–52.

While more research is clearly needed, the message to architects and engineers is to **pay attention to IEQ, in particular to ensuring minimum ventilation rates, because many studies have found that ventilation rates influence health, satisfaction with indoor air quality or absences.**

Perceived air quality, Sick Building Syndrome (SBS) symptoms and productivity were studied in a normally furnished office space (108 m3) ventilated with an outdoor airflow of 3, 10 or 30 L/s per person, corresponding to an air change rate of 0.6, 2 or 6 h-1. **Increasing ventilation decreased the percentage of subjects dissatisfied with the air quality** ($P < 0.002$. It also eased difficulty in thinking clearly ($P < 0.001$) and made subjects feel generally better ($P < 0.0001$). The performance of four simulated office tasks improved with increasing ventilation rates, and the effect reached formal significance in the case of text-typing ($P < 0.03$). **For each two-fold increase in ventilation rate, performance improved on average by 1.7%.** This study shows the benefits for health, comfort and productivity of ventilation at rates well above the minimum levels prescribed in existing standards and guidelines. (Wargocki 2000)

In U.S. residences, rates of ventilation depend on the quantity of accidental cracks and holes in building envelopes and ducts, on weather conditions, and on window and exhaust fan use. Even in mechanically-ventilated commercial buildings, HVAC systems very rarely include integral systems for measuring and controlling minimum rates of outside air supply; thus, **ventilation rates are poorly controlled.** The minimum **ventilation rates measured in surveys of such buildings often differ substantially** from the minimum ventilation rates specified in the applicable codes [Seppanen et al. 1999, Fisk et al. 1992, Lagus Applied Technologies 1995, Teijonsalo et al. 1996, and Turk et al. 1989 cited by orig. author].

While the **problems associated with measurement and control of outside air ventilation rates have been recognized for many years**, there has been little progress toward overcoming the problems. The **large range of ventilation rates among buildings** suggests an opportunity to improve health and satisfaction with air quality by increasing ventilation rates in buildings with low ventilation rates and decreasing ventilation rates in buildings with high ventilation rates.

Due to the dose-response relationships between ventilation rates and health outcomes (Seppanen et al. 1999), the average level of health symptoms and satisfaction with air quality might be improved without increasing the total ventilation rate of the building stock or increasing the associated energy use. **Consequently, research and technology transfer in needed on energy-efficient means of measuring and controlling building ventilation rates.** (Fisk 2000b, LBNL-47458)

In a survey of 100 U.S. office buildings, 23 percent of office workers experienced frequent symptoms of Sick Building Syndrome (SBS) such as respiratory ailments, allergies and asthma. The **impact has been usually hidden in sick days, lower productivity and medical cost, but the economic impact is enormous, with an estimated decrease in productivity around 2 percent nationwide,** resulting in an annual cost to the United States of approximately **$60 billion**

Risk Factor	Percent Change (95% Confidence Limits)	
	Total Sick Leave Within Hourly Workers	Short-Term Sick Leave Within Office Workers
Lower Ventilation Rate	130% (54% to 244%)	53% (22% to 92%)

Table 1: Association of (one) suspected risk factors with sick leave

Outcome	Annual Cost (Savings) Per Employee*
Ventilation Energy Costs 25 cfm/worker × $3.22/cfm/year	$80
Sick Leave Costs Sick Leave avoided (1.5 days per workers)	($480)
Net Savings	($400)
*Assumes Hourly Compensation of $40.	

Table 2: Potential economic costs and benefits of increasing the ventilation rate by 25 cfm (12 L/s) per person.

Confirmation of these results in a study with better ventilation rate measurements is desirable. (Kumar 2002, LBNL-51289)

25% of the studies reviewed in one collaborative paper were considered to be conclusive with regard to the association between building **ventilation and the transmission of airborne infection**. There is **strong and sufficient evidence to demonstrate the association between ventilation, air movements in buildings and the transmission/spread of infectious diseases** such as measles, tuberculosis, chickenpox, influenza, smallpox and SARS.

The evidence of the association between **ventilation, the control of airflow direction in buildings, and the transmission and spread of infectious diseases was** strong and sufficient, **supporting the use of negatively pressurized isolation rooms** for hospital patients with these diseases, in addition to the use of other engineering control methods. (Li, et.al. 2007)

STUDENT PERFORMANCE

The U.S. Environmental Protection Agency's (EPA), Indoor Environments Division, Office of Radiation and Indoor Air published *Indoor Air Quality and Student Performance* in August of 2000. Among the conclusions they presented were good indoor air quality **contributes to a favorable learning and a sense of comfort, health, and wellbeing** for school occupants. These factors combine to assist a school in its core mission - educating children. (EPA 2000)

It only makes sense that **children can not perform as well when they are sick or absent** from school. Indoor air quality problems can result in absences **because of respiratory infections, allergic diseases from biological contaminants**, or irritant reactions to chemicals used in virtually every part of the school. Other sources support this.

Some conditions in the school environment are closely associated with the incidence of sick building syndrome and asthma symptoms, (Smedje 1999, Daisy 1999) and **asthma-related illness is one of the leading causes of school absenteeism**, **accounting for over 10 million missed school days per year** (Asthma and the Environment 1999). In addition, persons with asthma or other sensitivities **may have reduced performance in the presence of environmental factors that trigger their asthma**.

Motivation can often overcome small burdens of environmental stress so that children's performance may not decline. However, **continued environmental stress can drain children's physical and mental resources** and ultimately affect their performance. Evidence from office workers suggests that when individuals experience just two symptoms of discomfort, they begin to perceive a reduction in their own performance. That perception increases as the number of symptoms increases, averaging a 3% loss with 3 symptoms, and an 8% loss with 5 symptoms. (Raw 1990). It follows that **when large numbers of students and staff experience signs of discomfort related to the air inside their school, teaching and learning performance will likely degrade over time.**

All of these "building-related illnesses" (BRI's) result from the lack of effective indoor environmental quality management. In extreme cases, schools sometimes have to be closed until problems are investigated and solved.

There is widespread concern that indoor environments can affect occupants' health, comfort and performance. Indoor environments in schools are of particular concern because:

1) *Schools are seen as particularly **likely to have environmental deficiencies** that could lead to poor indoor environmental quality (IEQ). In particular, **chronic shortages of funding** in schools contribute to inadequate operation and maintenance of facilities.*
2) ***Children breathe higher volumes of air** relative to their body weights and are **actively***

> ***growing**. Thus, they have **greater susceptibility** to environmental pollutants than adults do. Children also **spend more time in school** than in any other indoor environment outside the home. Adverse environmental impacts on the learning and performance of students in schools could have important immediate and lifelong effects (GAO, 1995).*

The available evidence indicates that **lower outdoor air ventilation rates**, known to cause generally higher concentrations of the pollutants produced indoors, **were related to reduced performance among occupants** (Wargocki, 2000; Smedje, 1996 - Heath 2003)

The **most persuasive available evidence suggests that some aspects of IEQ, including low ventilation rate** and less daylight, may **reduce the performance of occupants**, including students in schools. Sufficient evidence is available to justify actions to safeguard IEQ in schools. (McCoy 2002, Kumar 2002)

In exploring system options for schools that would overcome the IAQ deficiencies recorded in traditional systems, Charles A. McCoy and Scott C. Bernth wrote about their experience with VAV (Variable Air Volume) systems in Indiana. (McCoy 2002) The authors noted that many technology **innovations have emerged to offset the drawbacks of VAV**, specifically for our discussion: "Highly accurate airflow measuring stations on the AHUs automatically fine-tune the outside airflow, and compensate as needed…"

Equipment for VAV systems is more complex and more expensive than other ventilation alternatives. However, **cost savings from the system's energy-efficiency and load-balancing capabilities usually result in a relatively short payback time**, allowing the school district to enjoy a net gain in long-term energy savings. The use of VAV designs in modern schools has increased dramatically in recent years and **means are required to insure that the needed ventilation rates are maintained under all operating conditions**. (ASHRAE 2010)

Student attendance in American public schools is a critical factor in securing limited operational funding. Student and teacher attendance influence academic performance. One study explored the association of student absence with measures of indoor minus outdoor carbon dioxide concentration (ΔCO_2). Absence and ΔCO_2 data were collected from 409 traditional and 25 portable classrooms from 22 schools located in six school districts in the states of Washington and Idaho. **Forty-five percent of classrooms** studied had short-term indoor CO_2 concentrations above 1000 ppm. A **1000 ppm increase in ΔCO_2** was associated ($P < 0.05$) with a 0.5% – 0.9% decrease in annual average daily attendance (ADA), corresponding to a **relative 10–20% increase in student absence**. Annual ADA was **2% higher** ($P < 0.0001$) **in traditional classrooms**.

This study provided motivation for larger school studies to i**nvestigate associations of student attendance, and occupant health and student performance, with... more accurately measured ventilation rates.** Technological interventions such as improved automated control systems could provide continuous ventilation during occupied times, regardless of occupant thermal comfort demands.

The **high prevalence of low ventilation rates**, combined with the growing evidence of the positive impact that sufficient ventilation has on human performance, suggests an **opportunity for improving design and management of school facilities**. (Shendell, et.al. 2006)

Two independent field intervention experiments were carried out in mechanically ventilated classrooms receiving 100% outdoor air. **Outdoor air supply rate and filter condition were manipulated** to modify indoor air quality, and the performance of schoolwork was measured. The conditions were established for one week at a time in a blind crossover design with repeated measures on children in two classes. The children indicated that the air was fresher but otherwise perceived little difference when the outdoor air supply rate increased from 3.0 to 8.5 L/s (6.4–18 cfm) per person, while the speed at which they performed two numerical and two language-based tasks improved significantly. **A significant effect of ventilation rate was observed in 70% of all the statistical tests for an effect on work rate, but there were no significant effects on errors.** The unbalanced design also made it impossible to test for an interaction between filter condition and ventilation rate. **These results indicate the importance of improving indoor air quality and ventilation in classrooms**. (Wargocki 2007, RP-1257)

VENTILATION and PRODUCTIVITY– IMPLICATIONS

A substantial body of scientific evidence suggests that providing ventilation rates, at or above the minimum rates prescribed in current U.S. building codes, is a priority in order to maintain occupant health, work and school performance. Careful attention to ventilation system design features, controls, instrumentation, operational practices, and maintenance practices that affect building ventilation rates is desirable.

1. When possible, given a building's design, maintain building ventilation rates at or above the minimum rates specified in current applicable codes and professional standards (ASHRAE 2010, IMC 2009).

    - Periodic or **continuous monitoring of outdoor air intake flow rates** is recommended to assure that the amount of **ventilation actually delivered is consistent with the design and operational intent**.

    - The outdoor air intake system should be designed so that reasonably accurate measurements of intake flow rates are possible. [LBNL Impacts of Building Ventilation on Health and Performance, http://eetd.lbl.gov/ied/sfrb/vent-practices.html] **The typical reliance solely on the building design and occasional air balancing to maintain desired ventilation rates is not recommended because available data indicate that building and building subspace ventilation rates, in practice, are very often well below or above code requirements and professional standards** [Persily 2004, NISTIR-7145].

    - Commissioning, periodic re-commissioning, and maintenance of building ventilation systems are recommended to assure that the desired ventilation rates are maintained. To enable commissioning, **adequate access must be provided** to air handler components **for measurements or instrumentation** and maintenance. The commonly reported ventilation equipment failures and control system problems, particularly in commercial buildings, point to the need for this ongoing commissioning and maintenance. Permanently mounted airflow **measurement devices can be employed to provide automated feedback on ventilation status and performance, which can be compared to fault conditions** for alarming and maintenance.

2. In hot humid climates, the ventilation air can be a large source of moisture-laden air. In these climates, dehumidification systems must be able to remove sufficient moisture to prevent high levels of indoor humidity during peak and off-peak thermal load conditions. **Systems must also be capable of maintaining a net pressurization flow to counter moisture infiltration** and to provide a **net drying effect** to previously wetted surfaces in exterior wall cavities.

3. Reducing the sources of indoor pollutants, for example through selection of low emitting building materials, furnishings, and consumable supplies and frequent changing of filters, diminishes the amount of ventilation needed to maintain low indoor pollutant concentrations. Increasing the ventilation rate may increase energy consumption and therefore must be controlled as precisely as possible for maximum efficiency. **Reductions in ventilation requirements require even greater measurement**

accuracy, as the controlled amount must never go below that required for pressurization or an uncontrollable negative pressure situation may be created.

Many building designers and operators tend not to consider airflow measurement a significant factor in the system's ability to provide consistently comfortable and energy efficient working environments. Without reliable pressurization control, temperature and humidity fluctuations due to infiltration can be more frequent than hourly occurrences. The cost for inadequate control systems is counted in energy dollars that are otherwise squeezed by budget-minded operations management.

Reliable and continuous measurement of key airside components for direct feedback control is essential for accomplishing IEQ objectives reliably and in the most cost-effective manner. More precise and consistent control inputs would therefore make spaces more comfortable for the occupants and more energy efficient for the building manager.

CONCLUSIONS

People in industrialized countries spend more than 90% of there lives in an artificial indoor environment (home, transportation, work). This makes the indoor environment much more important for people health and comfort than the outdoor environment. In typical office buildings the cost of people is a factor 100 higher than energy costs, which make the performance of people at their work significantly more important than energy costs.

The task is to optimize indoor environmental conditions for health, comfort and performance while conserving energy, since **more than one third of current global energy consumption is used to maintain indoor environments**. Detailed field investigations of the indoor environment in hundreds of large office buildings in many parts of the world have documented that the indoor environmental quality is typically rather mediocre, with many people dissatisfied and many suffering from sick-building syndrome symptoms. Recent studies under laboratory conditions and in the field have shown a significant influence of the indoor environment on people's productivity.

Also studies on occupant sick leave shows a very high loss of work time and performance, which have significant economic consequences. ….Recent studies showing that comfortable room temperatures, increased ventilation above normal recommendation, reduction of indoor pollution sources and **more effective ventilation increases the performance of people**. **The results indicate (a potential) increase of productivity of 5-10 %**. (Olsen 2005)

Those individuals focused solely on energy should be silenced by common sense and the pursuit of improvements in broader objectives: PRODUCTIVITY & HEALTH. Instead of concentrating on the energy cost alone, we should be looking at the greater positive impacts that are expected (by orders of magnitude larger).

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