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CONSIDERATIONS FOR THE DESIGN AND ENERGY MODELING OF NEW COMMERCIAL BUILDINGS WITH INCREASED VENTILATION RATES

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ABSTRACT

The 30% more ventilation than ASHRAE 62.1 design criterion has been a long-considered option for design teams pursuing LEED certification to attempt improved indoor air quality for occupants. Emerging research is now discussing the potential cognitive benefits of increasing ventilation rates even further above code minimum levels. This paper outlines key design and modeling questions for practitioners to consider when asked to evaluate the impacts of increased ventilation targets. This paper explores setting performance goals, expected indoor carbon dioxide (CO_2) values, occupancy patterns, energy use, and system sizing implications. A case study example building in Seattle is used to provide building simulation examples and insights.

INTRODUCTION

The Purpose of Ventilation

The primary goal of providing ventilation air in commercial buildings is to ensure the health and comfort of building occupants (Persily 2015). In the U.S., the most common standard for defining ventilation rates and best practices is ASHRAE Standard 62.1. This standard recommends ventilation rates by space type, occupancy, and other measures to provide indoor air quality "that is acceptable to human occupants and that minimizes adverse health effects" (ASHRAE, 2016). Having adequate ventilation in buildings is essential to creating a safe and productive environment.

Benefits of Improved Indoor Air Quality

However, what if *acceptable* air quality is not good enough? Or what if *improved* health is desired, not the minimization of adverse health effects? Numerous studies suggest that increasing ventilation rates beyond the minimum values in Standard 62.1 lead to benefits including a reduction in sick building syndrome symptoms (Fisk et al. 2011) and improved cognitive function (Allen JG et al. 2016). The Allen Harvard study was a double-blind 6-day effort with 24 participants evaluating the change in participant cognitive function scores versus variations in outdoor air quantity, CO_2, and VOCs. The study found that cognitive function scores increased 61% on "green" days (when VOCs were lower than a conventional building) and 101% on "green+" days (when ventilation rates were higher and CO_2 levels were lower) (Allen JG et al. 2016).

If captured, benefits related to improved indoor air quality could provide billions of dollars of annual economic benefits to the U.S. economy (Fisk et al. 2011). The impact to specific businesses and individual facilities is mixed; in some cases, the increased annual operating costs of increased ventilation are estimated to dwarf the employee productivity benefits (MacNaughton et al. 2015).

Using CO_2 to Measure Indoor Air Quality

There is a growing industry effort to monitor and achieve certain CO_2 levels in indoor occupied spaces as a proxy for assuring a high quality indoor environment. Figure 1 illustrates some common and historical recommendations for indoor CO_2 concentrations. Newer building rating systems such as the WELL Building Standard and the RESET standard are going beyond jurisdiction-required design ventilation rates and publishing specific performance-based indoor air quality criteria. Part 2 of Feature 03 of the WELL Building Standard Air concept requires that densely occupied spaces maintain CO_2 levels below 800ppm (WELL Building Standard, 2014). The RESET standard similarly describes a maximum allowable CO_2 level of 1000ppm along with requirements for other indoor air pollutants (RESET Air Quality, 2017), and further prescribes a 600ppm target for "high performance" spaces. Also of note is that as early as 1858, Max Josef von Pettenkofer had proposed a limit on indoor CO_2 at

1000ppm or below (Haghighat et al. 2009). The range of CO_2 targets suggests a lack of consensus across the industry.

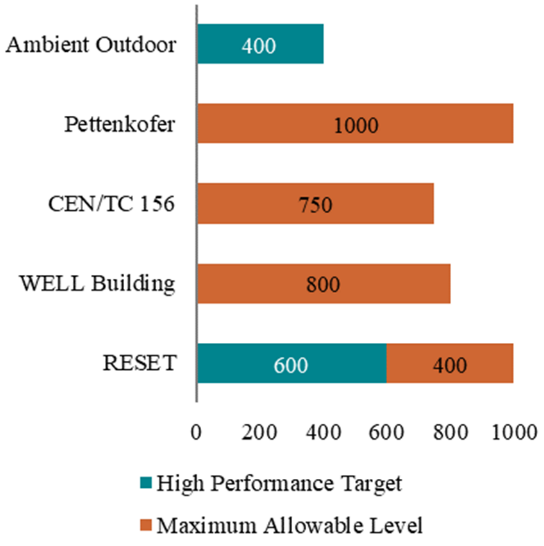

Figure 1: Comparison of Historical Indoor CO_2 Recommended Levels [1,2,3,4]

Practical Challenges

While the research points towards beneficial outcomes from increased ventilation, the upstream translation of these benefits into reliable design and modeling targets is not yet clear. If more ventilation is better, how much is the right amount? Is carbon dioxide concentration an appropriate proxy for indoor air quality? Is increased ventilation the only reliable pollutant mitigation strategy?

Practitioners find themselves in the challenging position of designing and modeling HVAC systems with increased ventilation to achieve a largely undefined state of "better." This paper outlines key design and modeling responses for practitioners to consider when asked to evaluate the impacts of increased ventilation targets. A 100,000sf office building in Seattle, WA is used as the case study example.

DESIGN CONSIDERATIONS

Goal Setting

The first item that should be discussed when considering the design of a building with increased ventilation is the desired outcome. Is the team trying to achieve a LEED credit or a WELL building feature? Or is the team attempting to maintain a certain indoor CO_2 level? Examples of common goals for project teams evaluating increased ventilation are provided in the table below.

Table 1 Examples of Ventilation Goals

EXAMPLE GOAL	DESCRIPTION	RESULTING VENTILATION*
Provide 62.1-2010 ventilation	Industry standard baseline ventilation quantity	17 cfm/person
Provide 62.1-2010 ventilation + 30%	This is the requirement for projects pursuing LEEDv4 EQ Credit Enhanced Indoor Air Quality Strategies, Option 2	22 cfm/person
Provide 62.1-2010 ventilation + 50%	This is the maximum allowed ventilation under some local energy codes (if heat recovery is not provided)	26 cfm/person
Provide 40 cfm/person	This is the value tested in the Harvard study (Allen JG et al. 2016) that led to improved cognitive function scores	40 cfm/person

* These values assume default 62.1 office space type occupant densities, a dedicated outdoor air system (DOAS), and a ventilation effectiveness of 1.0 in both heating and cooling.

Ventilation Rates and Indoor CO_2

The challenge for any project team today in setting a ventilation goal is uncertainty regarding the actual outcome that will be achieved. Increased ventilation is not being provided for the sake of just moving more air through a building – the purpose is improved occupant experience. Thus, what will building occupants experience at a ventilation rate of 17 cfm per person versus at 40 cfm per person? What are the tangible changes in air quality?

One outcome-based metric to consider is the measured indoor CO_2 level resulting from various levels of ventilation. While it is still unclear if CO_2 is to be considered an indoor pollutant (U Satish et al. 2012) or whether increased ventilation is the best method to reduce CO_2 concentration, studies indicate that human performance improves in environments with lower CO_2 levels.

The methodology outlined in Appendix D of ASHRAE 62.1-2016 helps practitioners convert ventilation design criteria in terms of cfm per person into expected steady state indoor CO_2 levels:

$$N / Vo = Cs - Co \qquad \text{(Equation 1)}$$

Where:

- N = CO_2 generation rate per person (0.31 L/min used in chart example)
- Co = Outdoor CO_2 concentration (407ppm in chart example)
- Vo = Outdoor airflow rate per person (L/min)
- Cs = Indoor CO_2 concentration (ppm)

Using Equation 1 and the stated assumptions, Figure 2 shows the corresponding steady state indoor CO_2 level based on the 4 different ventilation rates offered in Table 1.

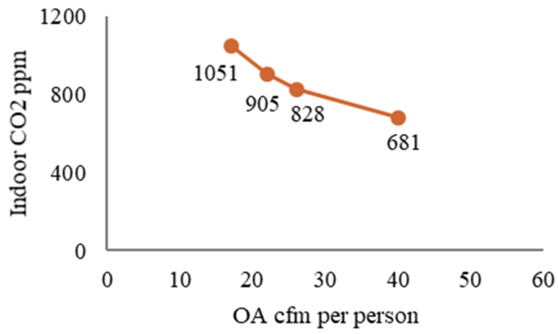

Figure 2 OA per person and Resulting Indoor CO_2

For a project with a goal of providing the code minimum office ventilation rate at the default office occupancy, the peak indoor CO_2 level is expected to be ~1050ppm. For a project with a goal of providing 40 cfm per person, the peak indoor CO_2 level is expected to be ~680ppm. Note that at higher or lower metabolic rates, the CO_2 generation rate per person will change and the resulting indoor CO_2 level will vary.

The resulting CO_2 levels in Figure 2 assume peak conditions at design occupancy density for office space. Assuming only 75% of occupants are present yet the DOAS system provides the same volume of outside air, the ventilation per person increases and the corresponding indoor CO_2 levels decrease as shown in Figure 3. Thus, systems without the ability to reduce airflow based on actual occupancy will likely achieve lower peak CO_2 levels than expected.

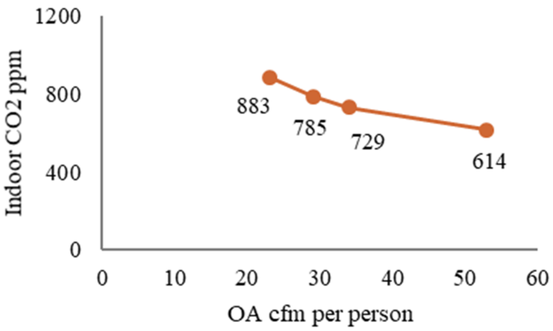

Figure 3 OA per person and Resulting Indoor CO_2 with 75% Occupancy

Impact of Occupancy Patterns

Another important ventilation design consideration that could influence the overall project ventilation design criteria relates to how various spaces will be occupied. The rise and fall of indoor CO_2 concentrations is not instantaneous. The expected occupancy of a space dramatically affects modeled hourly CO_2 levels.

IESVE-2017 simulation software was used to evaluate how occupancy affects the predicted indoor CO_2 level on a typical day. Figure 4 shows a typical office zone of ~2,500sf with a default occupant density at 200sf per person leading to a peak occupancy of ~12 people. Using code minimum ventilation and a default ASHRAE office occupancy schedule, the peak CO_2 concentration of ~900ppm is not achieved until 4pm.

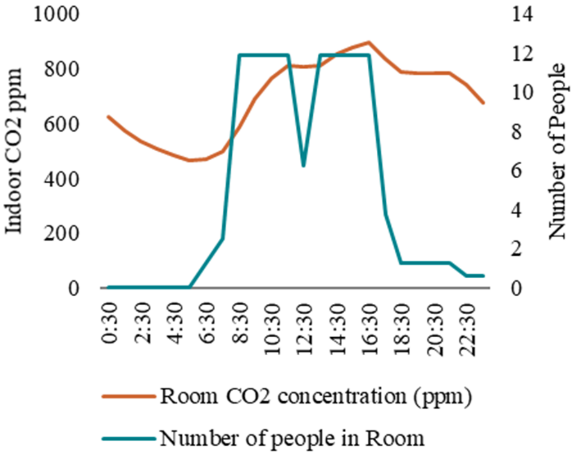

Figure 4 Modeled Default Daily Profile for Typical Office Space CO_2 Concentration with Minimum Ventilation

Even under 95% occupancy, it takes time for CO_2 to accumulate in the space, meaning that occupants do not immediately experience the peak CO_2 condition. Using the default occupancy profile, modeling shows that office occupants would experience CO_2 concentrations within 100ppm of the peak CO_2 condition for approximately 60% of annual occupied hours (7am – 6pm, M-F). Annual bin data is shown in Figure 5 below.

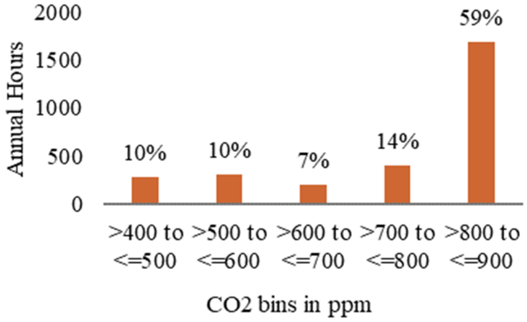

Figure 5 Annual Occupied Hours per CO_2 bin for Typical Office Space

With a more varied occupancy schedule that only ever peaks at 75% of design values, the peak CO_2 concentration occurs during unoccupied hours and the space never exceeds 770ppm, even when using code minimum ventilation. This case is shown in Figure 6 below.

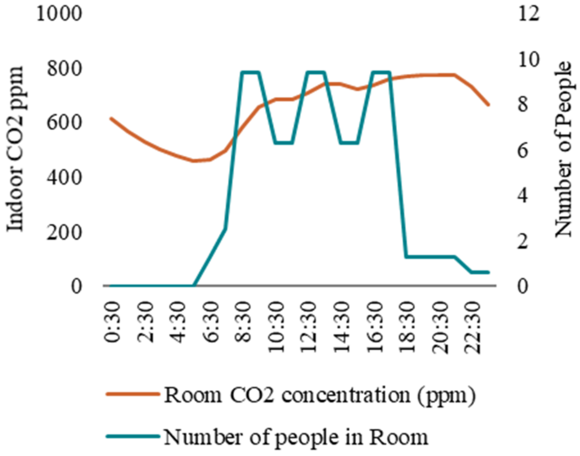

Figure 6 Modeled Varied Daily Profile for Typical Office Space CO_2 Concentration with Minimum Ventilation

Figure 6 also illustrates the challenge of modeling CO_2 concentrations: surprisingly, the peak CO_2 is observed after occupied hours. The model includes a small but non-zero occupancy after hours which continues to add CO_2 to the space even though the ventilation system is off. Using the increased ventilation target of 40 cfm per person and the default ASHRAE occupancy schedule for office spaces, the space CO_2 concentration peaks at ~640ppm as shown in Figure 7.

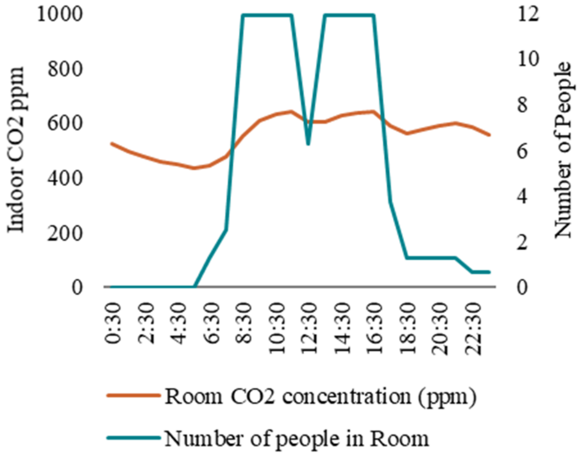

Figure 7 Modeled Default Daily Profile for Typical Office Space CO_2 Concentration with 40 cfm per person

Modeled vs Measured

As discussed above, the presence and impact of high CO concentrations varies with occupant diversity and may not be intuitive. The nuances of modeled indoor CO_2 concentrations can be challenging. The limited data publicly available often includes existing buildings with less airtight envelopes, limiting the ability to link indoor CO_2 concentrations to ventilation rates. Newer, airtight buildings often include CO_2 monitoring, but that data is less available. Interestingly, one study on several small commercial buildings in the Pacific Northwest (Montgomery, et. al), focused on indoor CO_2 concentrations before and after a retrofit to DOAS ventilation systems and found that while CO_2 concentrations improved, the existing buildings did not specifically show problematic CO_2 concentrations. A summary of their results is shown in Table 2.

Table 2 Measured CO_2 Rates in Existing Commercial Buildings

TYPE	OCCUP-ANCY	AREA FT2 (M2)	EXISTING OCCUPIED CO_2	POST RETROFIT OCCUPIED CO_2
Office	M-F, 7am-6pm	11,600 (1,080)	-	500
Office	M-F, 8am-5pm	13,200 (1,225)	615	565
Restaurant	Variable	1,600 (162)	900	740
Office w/ Garage	M-F, 9am-5pm	5,600 (520)	620	545
Restaurant	M-F, 11am-9pm Sa-Su, 9am-9pm	1,150 (110)	760	-
Office	M-F, 9am-5pm	5,900 (550)	-	500
Office	M-F, 8am-5pm	24,300 (2,260)	480	560

This table highlights the acute need for better measurement and diagnosis of issues prior to the application of increased ventilation as a panacea for occupant performance optimization.

Impact of Occupant Density

The calculation of ventilation rates in Standard 62.1 is based on both floor area and occupant density. As a result, as the occupant density of a space increases, the total outdoor air provided per person decreases. Table 2 highlights how the total quantity of ventilation air per person changes based on occupant density when project goals are based on Standard 62.1. As shown in Table 3, in more densely occupied spaces, the jump from 62.1+50% to the absolute target of 40 cfm per person becomes much more dramatic. Taking care to understand how project goals and thresholds change based on being defined relative to code versus defined as absolute values is important.

Table 3 Ventilation Air per Person based on Occupant Density

OA TARGET	OA PER PERSON AT 200 SF PER PERSON	OA PER PERSON AT 75 SF PER PERSON
62.1-2010	17	9.5
62.1-2010 + 30%	22.1	12.4
62.1-2010 + 50%	25.5	14.3
40 cfm per person	40	40

The chart in Figure 8 illustrates the resulting peak daily CO_2 value for spaces with increased occupant density at minimum ventilation. The peak CO_2 value increases with occupant density as the contribution of the ventilation quantity based on floor area (Ra) decreases. Any ventilation goal based on 62.1 will have a varying peak CO_2 value based on occupant density; a ventilation goal based on a cfm per person value will not.

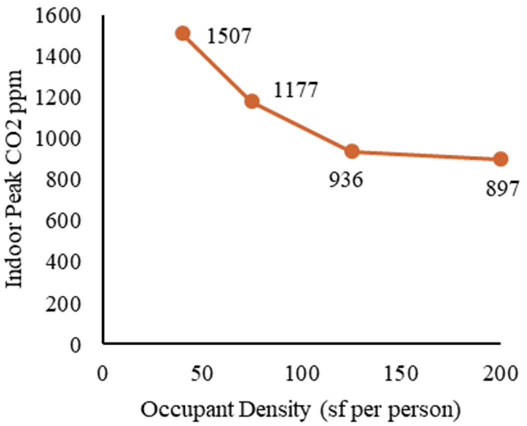

Figure 8 Expected Indoor CO_2 Peak Concentration as a Function of Occupant Density

Thus, in setting ventilation design targets, it is useful for the design team to try to understand 1) expected peak occupant density rather than typically calculated maximum occupancy, 2) expected building occupancy patterns during daily use rather than following typical design guidance, and 3) for what percentage of operating hours the air quality goals are expected to be met or exceeded.

Energy Use

Another obvious factor for the design team to consider is how increased ventilation affects annual building energy use. As with most building design criteria, the impact of increased ventilation varies based upon the building type, building location, and HVAC system strategies.

For the ~100,000sf case study office building in Seattle, WA, using a DOAS with a 50% effective heat recovery ventilator, the overall impact of increased ventilation is shown in Table 4 below. No DCV was assumed. The increase in total building energy use for the sample building ranges from 3% to 13% depending on the goal. The changes to heating, cooling, and fan energy use are also provided. Note that results will differ significantly based on climate and building type, thus these specific results should not be used as suggestive of the outcome in other scenarios.

Table 4 Annual Energy Use Impact of Example Ventilation Goals

OA TARGET	HEATING % CHANGE	COOLING % CHANGE	FAN % CHANGE	TOTAL % CHANGE
62.1-2010	-	-	-	-
62.1-2010 + 30%	+6%	-6%	+16%	+3%
62.1-2010 + 50%	+10%	-9%	+27%	+5%
40 cfm/person	+29%	-23%	+73%	+13%

The heating increase is due to increased heating at both the DOAS unit and terminal fan coil units. The decrease in cooling energy use is a result of increased minimum outside air during swing seasons, a huge benefit in Seattle's mild climate. The increase in fan energy is simply the result of moving more air through the building.

When the average occupant density in the building is higher (75 sf per person versus 200 sf per person for the results shown in Table 3), the percentage change in results are similar until the 40cfm per person goal is analyzed. Per the values shown in Table 3, the actual ventilation per person jumps from only 9.5 cfm per person at the 62.1-2010 base to the flat 40 cfm per person. Because of this quadrupling of ventilation, the overall building energy use increases by over 40% as zone heating skyrockets. This result highlights how design teams need to be acutely aware of how ventilation criteria are defined in densely occupied buildings.

Relative to a LEED energy model baseline (where under 90.1-2010, increased ventilation cannot be modeled in the baseline case), there are numerous strategies that can be combined to offset the energy impact of the increased ventilation. Examples include:

- More efficient heating or cooling sources;
- Increased heat recovery via more efficient ERVs or heat recovery chillers with relief air heat recovery;
- More efficient DOAS and terminal unit fans (or elimination of terminal unit fans through passive heating and cooling zone units if loads allow); or
- Use of demand control ventilation to ensure over-ventilation does not occur during periods of low occupancy.

As one example, in the test building, the 50% effective ERV was replaced by a heat recovery chiller (HRC) used to recover heat from an exhaust air relief coil. With this design, heat that is bypassed by the ERV during hours when the DOAS unit does not need it can be captured via the relief air coil and be utilized at zone terminal units (if needed). These results of this design change are shown in Table 5 below. Using a heat recovery chiller in lieu of an ERV provides savings versus the base case in every scenario except the 40cfm per person case where a 1% increase in energy use occurs.

Table 5 Annual Energy Use Impact of a Different Heat Recovery Approach with Increased Ventilation

OA TARGET	HEAT RECOVERY APPROACH	TOTAL % CHANGE*
62.1-2010	ERV	-
62.1-2010	HRC	-6%
62.1-2010 + 30%	ERV	+3%
62.1-2010 + 30%	HRC	-5%
62.1-2010 + 50%	ERV	+5%
62.1-2010 + 50%	HRC	-4%
40 cfm/person	ERV	+13%
40 cfm/person	HRC	1%

* All % changes are relative to the 62.1-2010 with ERV base case.

Extra efficiency measures such as replacing an ERV with a heat recovery chiller that can be used to neutralize the energy impact of increased ventilation come at increased first cost. Also, while obvious, instead of being "neutralizing measures," these measures could be implemented in the minimum ventilation building and provide additional energy savings to achieve superior overall energy performance of the minimum ventilation building. In the example above, a heat recovery chiller could be used in the base minimum ventilation building and provide a 6% energy savings. This is an attractive savings measure for project teams pursuing very high performance or net zero energy building projects.

While additional ventilation may constitute a small drag on reaching specific energy targets or achieving code compliance, studies have found the overall energy cost to be minimal compared to the bigger picture economic benefits of decreased absenteeism, reduced sick building syndrome, and increased occupant performance (Fisk et al. 2011 and MacNaughton et al. 2015).

System Sizing

As with energy use, there is a negative impact to the project budget to design building systems to accommodate additional ventilation. This cost can be seen in equipment sizing, sheet metal costs, as well as in lost usable area due to increased shaft sizes. The table below shows the change in peak building heating and cooling loads as well as DOAS airflow relative to the minimum ventilation case for the example ventilation goals. The changes in load are calculated assuming the energy recovery ventilator is operating.

Table 5 Peak Building Loads with Changing Ventilation Goals

OA TARGET	PEAK BUILDING HEATING LOAD % CHANGE	PEAK BUILDING COOLING LOAD % CHANGE	DOAS AIRFLOW % CHANGE
Provide 62.1-2010 ventilation	-	-	-
Provide 62.1-2010 ventilation + 30%	+9%	+2%	30%
Provide 62.1-2010 ventilation + 50%	+15%	+4%	50%
Provide 40 cfm/person	+37%	+10%	135%

While the changes in heating and cooling loads for the +30% and +50% ventilation cases could be considered to be within the safety factor of designed equipment, the change for the 40 cfm per person case is substantial. Similarly, the overall increase in the size of the DOAS unit is significant. These load and unit sizing increases carry downstream to the sizing of the ventilation duct, central plant equipment, and distribution pumping.

Additionally, given that the goal of providing increased ventilation is to limit indoor CO_2 levels, there may be additional costs incurred for monitoring of various spaces to verify that the additional ventilation is achieving the desired results, thus justifying the increased energy use and equipment size. This type of measured building level data, complemented by known design parameters and occupancy data will be incredibly valuable to the industry as further research on buildings with increased ventilation levels is conducted.

Finally, if additional efficiency measures are added to the project to make up for the lost energy savings associated with increased ventilation, these costs should also be considered. To truly optimize the design, teams must consider the full range of potential impacts when setting ventilation goals.

Additional Considerations

Importantly, increased ventilation may not be the only method to achieve enhanced indoor air quality. This paper does not discuss or attempt to quantify the impact of a variety of other options for air quality improvement or control such as operable windows, varied infiltration rates, CO_2 scrubbers, plant walls, distribution effectiveness, or the appropriateness of ventilation rate requirements. These alternate solutions present exciting opportunities for air quality improvements with potentially more limited energy consumption impacts; however, analysis of their utilization and effectiveness is only just beginning.

CONCLUSION

Increasing ventilation rates in buildings is one potential approach to improve indoor air quality and occupant experience in buildings. The energy impacts associated with increased ventilation rates vary depending on the air quality goal but are non-trivial in the example building and climate evaluated. Design teams should carefully consider and evaluate the importance of the air quality goals with respect to the building occupancy type, expected occupancy patterns, and the associated energy penalties.

While the energy consumption impacts may be limited in some cases, there are substantial impacts to mechanical equipment sizing and control strategies. Design teams should carefully consider the cost impacts of larger and more complex systems with respect to air quality goals. Appropriately evaluating the impact of increased ventilation, as well as other air quality improvement strategies will require the creation of a much larger aggregated database of building air quality measurements and occupancy patterns.

In the larger context of high performance buildings and climate change, the interest in indoor air quality is a critical issue. Lower overall building energy use will mandate tighter envelopes, making indoor air quality control even more critical. The drive for better cognitive function could lead unwary practitioners to unnecessarily increase ventilation rates (and subsequent energy use), equipment size, and system complexity. As ventilation rates rise and envelope loads decrease, ventilation energy consumption will have a bigger impact. It will be critical for future engineers and modelers to optimize for both cognitive function and energy use- and this balance will only get harder as ambient (exterior) CO_2 levels continue to rise.

Given current industry data and experience, designing and modeling buildings for increased ventilation is challenging. A lack of information regarding building occupancy patterns and the effectiveness of how well ventilation rates achieve air quality targets could lead to over or under supply of outside air and thus the over or under design of mechanical systems.

Building practioners make decisions based on science, engineering principles, and relevant experience. Simply increasing outdoor air quantities without having confidence in the end result presents little value for practitioners, owners, or occupants.

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