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Perceptions in the U.S. building industry of the benefits and costs of improving indoor air quality

Abstract How building stakeholders (e.g. owners, tenants, operators, and designers) understand impacts of Indoor Air Quality (IAQ) and associated energy costs is unknown. We surveyed 112 stakeholders across the United States to ascertain their perceptions of their current IAQ and estimates of benefits and costs of, as well as willingness to pay for, IAQ improvements. Respondents' perceived IAQ scores correlated with the use of high-efficiency filters but not with any other IAQ-improving technologies. We elicited their estimates of the impacts of a ventilation–filtration upgrade (VFU), that is, doubling the ventilation rate from 20 to 40 cfm/person (9.5 to 19 l/s/person) and upgrading from a minimum efficiency reporting value 6 to 11 filter, and compared responses to estimates derived from IAQ literature and energy modeling. Minorities of respondents thought the VFU would positively impact productivity (45%), absenteeism (23%), or health (39%). Respondents' annual VFU cost estimates (mean = $257, s.d. = $496, median = $75 per person) were much higher than ours (always <$32 per person), and the only yearly cost a plurality of respondents said they would pay for the VFU was $15 per person. Respondents holding green building credentials were not more likely to affirm the IAQ benefits of the VFU and were less likely to be willing to pay for it.

M. Hamilton, A. Rackes, P. L. Gurian, M. S. Waring

Department of Civil, Architectural and Environmental Engineering, Drexel University, Philadelphia, PA, USA

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M. S. Waring
Department of Civil, Architectural and Environmental Engineering, Drexel University, 3141 Chestnut St.
Philadelphia, PA 19104, USA
Tel.: 011-215-895-1502
Fax: 011-215-895-1363
e-mail: msw59@drexel.edu

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Practical Implications

The survey elucidated the state of knowledge among U.S. building industry stakeholders on the costs and benefits of Indoor Air Quality (IAQ), including showing that a majority doubt or are uncertain of the benefits of IAQ improvements and also overestimate their costs. Educating stakeholders on the known benefits and relatively low cost of improving IAQ could have the effect of increasing the number of IAQ-related upgrades in the building stock. Given that green building professionals, who presumably have already received some IAQ-related education, were no more likely to believe beneficial and were less likely to pay for ventilation and filtration upgrades than other respondents, the indoor air community may need to reconsider and/or redesign existing education and outreach strategies.

Introduction

The benefits of improving Indoor Air Quality (IAQ) for health, productivity, and other measures have been documented in the technical literature by a number of studies over the past few decades. For instance, research suggests that measurable improvements in overall building occupant welfare are associated with several types of basic heating, ventilating, and air-conditioning (HVAC) enhancements, including increased ventilation rates (VRs) and greater filtration of particulate matter (PM).

Strong evidence for improved IAQ affecting occupant welfare and productivity comes from VR studies (Clausen et al., 2011). For instance, higher incidences of airborne disease infections in commercial and institutional buildings are associated directly with low VRs (Li et al., 2007) and indirectly with high indoor carbon dioxide (CO_2) levels, which are a proxy for lower VRs (Myatt et al., 2004). Also, increased VRs in offices (up to 25 l/s/person) are associated with reduced Sick Building Syndrome (SBS) symptoms (Apte et al., 2000; Fisk et al., 2009; Sundell et al., 2011), as well as with reduced absenteeism in offices (Milton et al., 2000) and classrooms (Mendell et al., 2013; Sundell et al., 2011). Higher VRs have also been linked to higher productivity in offices (Seppänen et al., 2006) and better performance on computerized testing of cognitive ability in English primary schools (Bakó-Biró et al., 2012), although the generalizability of these findings is unclear.

Although it has been demonstrated that reduced VOC source strength and increased VRs have similar impacts on perceived air quality (Wargocki et al., 2002), there remains some uncertainty regarding specific causal pathways. Moreover, increased VRs alone may not be sufficient to improve IAQ. One study found that increased ventilation in a call center with dirty filters led to increased complaints of SBS symptoms, but that increased ventilation with a clean filter reduced the number of reported symptoms (Wargocki et al., 2004). Also, there is no available information on how VRs impact long-term health outcomes, such as cancer, pulmonary disease, myocardial infarction, or endocrine disruption.

Particles are another important determinant of IAQ impacts, and most exposure to outdoor PM occurs indoors (Jenkins et al., 1992; Klepeis et al., 2001; Lioy et al., 1988; Wallace, 1993). Although the precise mechanisms by which PM exposure affects human health are unclear (Phalen and Wolff, 2000), exposure to outdoor PM has established associations with acute and chronic health endpoints. Increases in outdoor $PM_{2.5}$ have been correlated with increased cardiovascular and respiratory diseases (Dominici et al., 2006; Pope et al., 2009), chronic bronchitis (Abbey et al., 1994), and increased mortality (Dockery and Pope, 1994; Dockery et al., 1992; Pope, 2002; Pope et al., 1995; Schwartz et al., 1996). Some studies have associated urban-level exposure impacts to predicted changes in exposure inside buildings (Bekö et al., 2008; Hänninen et al., 2005), but others maintain that there is a lack of understanding of the health effects of outdoor PM once indoors (Clausen et al., 2011).

Modeling suggests that higher efficiency filtration in the supply airstream reduces the level of outdoor PM that enters indoor environments (Bekö et al., 2008; Fisk et al., 2002; Hänninen et al., 2005; Waring and Siegel, 2008). Several case studies have shown that increased filtration leads to reductions in PM, but none have significantly linked improvements in health endpoints, even short-term and self-reported ones, *directly* to the use of higher efficiency filtration (Skulberg et al., 2005). Some evidence suggests that employing high-efficiency particulate air (HEPA) filters in residential buildings reduces markers used to predict future adverse coronary events (Allen et al., 2011; Brauner et al., 2008).

Not only is there evidence that improving IAQ results in a measurable benefit in terms of health and productivity, there is also an indication that these improvements are cost-effective. In one study, Fisk et al. (2011) modeled several IAQ improvements in the U.S. office building stock, including increased VR, the addition of airside economizers and controls, better temperature control, and dampness and mold countermeasures, and determined the potential annual net benefit to be $20 billion. In a related effort, Fisk et al. (2012) performed a benefit–cost analysis of changes in the amount of outdoor air supplied to U.S. office buildings and estimated net annual economic benefits of between $13 billion and $38 billion. It was further noted that by using economizers and thus increasing time-averaged VRs, it was possible to achieve well-being benefits while saving energy at the same time, as was also suggested by Rackes and Waring (2014) in a proof-of-concept study of optimal VRs.

These benefits and costs associated with improving IAQ have attained some consensus within the indoor air research community. However, it is not clear whether the likely magnitudes of these benefits and costs are established in the perceptions of actual building stakeholders, including tenants, owners, operators, and designers/consultants. As such, we surveyed 112 building stakeholders of their perceptions of their IAQ and estimates of the benefits to occupant well-being and energy-related costs of a specific IAQ ventilation–filtration upgrade (VFU), and also of their willingness to pay for the VFU. We also compared their estimates to our own best estimates to identify any discrepancies between these views, allowing one to use these findings to increase awareness of the benefits and costs of improved IAQ to shrink any knowledge gaps between the research and stakeholder communities.

Methodology

We conducted a survey to (i) characterize stakeholder perceptions of their current IAQ state and importance of IAQ in their commercial buildings; (ii) quantify differences in their IAQ perceptions as they relate to building characteristics, potential IAQ-improving technologies, and stakeholder groups; (iii) assess perceived benefits and costs of a specific upgrade of building ventilation and filtration that exceed current standards and should, according to the literature, be expected to improve IAQ; (iv) assess willingness to pay for the upgrade for different types of stakeholders; and (v) ascertain the extent to which IAQ is used in the marketing of commercial space to be leased. Drexel University Institutional Review Board (IRB) approval was obtained for all survey work in this article.

Survey instruments

A series of semi-structured interviews was completed initially to ascertain whether our questions captured information well and to make sure critical points were not overlooked. The semi-structured interviews were conducted on a convenience sample of 20 individuals recruited by email or word of mouth. Each interview was conducted by phone and lasted ~35–45 min; upon completion, participants were provided a $20 gift card. With subjects' permissions, interviews were recorded and were then coded by hand, compiled, and used to develop the structured, online stated preference survey.

For the structured survey instrument, four categories of stakeholders were identified as critical to decision-making in the market: (i) building owners; (ii) property and facilities managers; (iii) tenants; and (iv) mechanical system designers and consultants. Because respondents were likely to have experience with multiple buildings, they were asked to answer the survey questions based on 'the last mechanically ventilated building [they] had worked with', which was called their 'reference building' thereafter. Respondents were recruited via trade shows, direct email invitations, professional networks, and word of mouth. Respondents were provided a $20 gift card for completing the online survey. The online survey was administered between late 2013 and early 2014, and it is reproduced in full in the Appendix S1.

The survey had five sections. The first section consisted of questions about basic demographic information of each respondent and their reference building (e.g. building type and IAQ-related technologies utilized). In the second section, questions examined respondents' opinions about the definition, importance of, and impacts of IAQ in general, as well as their perceptions of their current state of IAQ, any actions that had been taken to improve it, and maintenance frequency in their reference building. Also, respondents were asked to rate the IAQ in their reference building, and this rating provided the basis for the metric 'perceived IAQ' that was utilized as a dependent variable in later analyses.

In the third section, respondents were presented with an upgrade package and asked to estimate the benefits and costs of implementing it in their reference building. Respondents were first asked to consider the 'current minimum standards' for IAQ to be those resulting from the American Society for Heating, Refrigeration, and Air-conditioning Engineers (ASHRAE) Standard 62-2001 for offices and informed that this specified a minimum VR of 20 cfm/person (9.5 l/s/person) and a minimum efficiency reporting value (MERV) 6 filter. They were then asked to consider 'improved air quality' to be that resulting from doubling the VR to 40 cfm/person (19 l/s/person) and installing a MERV 11 filter. These two improvements define what we call the 'ventilation-filtration upgrade' (VFU).

The fourth section covered stated and perceived organizational willingness to pay (WTP) for the specified VFU in terms of percent increase in energy costs and added cost in US dollars (USD) per occupant per year. Lastly, the fifth section queried respondents on the extent and manner in which IAQ has been marketed during the commercial building leasing and buying process.

Technical estimates for energy consumption

To compare our technical estimates to respondents' estimates of the energy costs of improving IAQ with the VFU, we estimated the operating cost impacts of the VFU for a group of seven building energy use simulation models implemented in EnergyPlus software (U.S. DOE, 2012). These models were based on U.S. Department of Energy (DOE) Commercial Reference Building models (Deru et al., 2011), modified to reflect other HVAC system types and to match energy use reported in the Commercial Buildings Energy Consumption Survey (CBECS). The seven models spanned from a small (3500 ft^2 or 325 m^2) single-zone office with a system equivalent to a residential furnace to a medium-sized (53 600 ft^2 or 4982 m^2) office with a central boiler and chiller serving three variable air volume (VAV) air handlers. All models had an occupant density of five occupants per 1000 ft^2 (~100 m^2), similar to the U.S. median in offices (Rackes and Waring, 2013).

For these building models, we developed a corresponding pre- and a post-VFU version. In the pre-VFU version, the VR was specified as 20 cfm/person and the system static pressure was determined with default EnergyPlus HVAC template objects, which was 600 Pa for single-zone unitary systems and 1000 Pa for variable air volume (VAV) systems. In the post-VFU version, the VR was 40 cfm/person, and the system static pressure was increased by 100 Pa to account for the difference between a MERV 6 and 11 filter. In practice, pressure drop across filters varies greatly and depends on fan type, system characteristics, and PM loading, but 100 Pa is the difference between the minimum and final resistances required for MERV 6 (150 Pa) and 11 (250 Pa) filters in ASHRAE Standard 52.2, which defines MERV (ASHRAE, 2007).

Each of these before and after models was run in 15 cities representing 12 climate subzones (2A, 2B, 3A, 3B, 3C, 4A, 4B, 4C, 5A, 5B, 6A, and 6B), eight census divisions, and 14 U.S. states. Results were annual changes in electricity and natural gas consumption resulting from the VFU in each location. These were combined with estimates from the U.S. Energy Information Administration (EIA) on electricity (U.S. EIA, 2014a) and natural gas (U.S. EIA, 2014b) prices by state, as of February 2014, to estimate the changes in energy operating costs in USD from implementing the VFU. For our comparison to survey answers, we used these to calculate both the energy cost change as a percent of the building's total energy expenditures, and the real added annual cost per occupant in USD.

For the percent change in energy operating costs, we wanted the denominator to reflect realistic energy expenditures, which may not be captured by our idealized EnergyPlus reference models. Therefore, we divided the cost increases derived from modeling the VFU by the average commercial building energy expenditure reported to CBECS (U.S. EIA, 2006) for each location's census region and heating and cooling degree day bin, all on an area-normalized basis. (Because the change in expenditure from the VFU was calculated with 2014 energy costs but the total energy expenditure was in 2003 USD, the percent increase in costs due to the VFU may be slightly overstated.) For the added annual cost per occupant, the change in energy operating costs was simply normalized by the number of occupants.

Technical estimates for productivity, SBS impacts, absenteeism, and PM changes

To compare our technical estimates to respondents' estimates of the welfare benefits of improving IAQ with the VFU, we estimated its associated productivity, SBS impacts, and absenteeism changes. These estimates were based solely on the change in VR due to the VFU and did not include filtration effects. The productivity estimate was from Seppänen et al. (2006), who used a fractional polynomial model to account for the VR–productivity relations from seven field and three laboratory studies, and our calculation used the functional form for the response from Fisk et al. (2011). We note that most of the field studies used by Seppänen et al. (2006) were conducted in settings like call centers that have higher occupant density and easily quantifiable measures of performance such as call response time. While they report that the relation of increased productivity and increased VR is statistically significant at a 95% confidence level up to ~32 cfm/person (~15 l/s/person), the exact percent increase for other tasks per added unit of ventilation is uncertain, especially for less repetitive types of office work.

For changes in SBS prevalence rate with VR, the Fisk et al. (2009) equation was employed. Those authors screened and analyzed eight existing studies in which questionnaires about SBS symptoms were administered to occupants under different VRs. All of the included studies were in office buildings, and all but two included data from more than one site or trial. The SBS symptoms varied by study, but in all cases, the occupants did not know the true VR when they filled out the questionnaire.

The absenteeism impact was estimated with an exponential response model (Fisk et al., 2011, 2012) that extrapolated from the results of a study of VR and short-term absence in 40 buildings (Milton et al., 2000). Fisk et al. (2012) noted that the absenteeism relation was formulated from results of only one study (albeit including 40 buildings) and may be more uncertain than those for productivity and SBS prevalence, which were based on multiple studies.

Although we did not compare them to respondents' estimates, we determined the PM-related impacts due to the combined effects of the filtration upgrade and the VR increase. Generally, the former tends to reduce the indoor concentration of outdoor PM, while the latter has the opposite effect because it introduces more outdoor PM. There is also a third, subtler effect on PM: if the HVAC system total supply airflow rate is constant, an increase in VR will reduce the air recirculation rate and thus the total effective filtration (presuming, as is common, that only the total supply air is filtered and ventilation air is not also filtered). PM calculations were time-averaged (El Orch et al., 2014; Riley et al., 2002), with size-integrated removal rates relying on specific assumptions and methods that have been previously described (Rackes and Waring, 2013). To estimate a reasonable range of PM percent reductions due to filtration, calculations were performed for both urban and rural PM size distributions (Jaenicke, 1993) and for total supply airflows corresponding to 0.64 cfm/ft^2 (3.3 l/s/m^2), which is the median from the U.S. Environmental Protection Agency BASE study for supply flows measured at the diffusers (Persily and Gorfain, 2008), and 0.30 cfm/ft^2 (1.5 l/s/m^2), which is a typical lower limit for air distribution design. This calculation ignored any indoor PM formation due to terpene oxidation (Youssefi and Waring, 2012, 2014) by ozone, hydroxyl radicals, or nitrate radicals (Waring, 2014; Waring and Wells, 2014).

Results and Discussion

Survey demographics

For the 112 respondents, demographics and reference building categorizations are listed in Table 1. The most common respondent role was consultant or designer (38%), followed by property or facilities manager (24%), building owner (21%), and tenant (18%). Within the building owner category, about one-third leased their building to other tenants, while two-thirds occupied the building themselves. Approximately one-third of respondents reported holding some kind of green building certification, such as from the U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) program. A majority of respondents' reference buildings were office buildings (60%), although other types were represented. Most buildings were in an urban (54%) or suburban (45%) environment.

Respondents were recruited via mailing lists from trade shows and through personal and professional networks. This process began in our location (Philadelphia, PA) and was later expanded geographically. All respondents were from the U.S., and 77% were from the Mid-Atlantic or northeastern U.S., including Pennsylvania (55%), New Jersey (10%), Delaware (5%), Connecticut (3%), New York (3%), and Virginia (1%). There was a substantial minority from California (10%), and one respondent each from Colorado,

Table 1 Respondent and reference building demographics (total $n = 112$)

	n	Percent
Respondent's role		
Building owner	23	21
Property or facilities manager	27	24
Tenant	20	18
Consultant or designer	42	38
Holds any green building certification		
Yes	36	32
No	74	66
Undisclosed	2	2
Building type		
Office	67	60
Retail	9	8
Education	15	13
Other	21	19
Building location		
Urban	60	54
Suburban	50	45
Rural	2	2
Approximate building age		
0–5 years	20	18
6–15 years	21	19
16–30 years	31	28
31–50 years	20	18
51–100 years	18	16
100–200 years	2	2
(mean = 31.3 years, s.d. = 26.7 years)		
Climate zone		
2	4	4
3	10	9
4	69	62
5	27	24
6	2	2

Florida, Illinois, and Texas. Eleven percent of respondents did not indicate their location, and we note that a respondents' state was not necessarily the same one where his or her reference building was located. Because this work used a convenience sample, there is no single sample frame and it is not possible to calculate a non-response rate.

Perceptions of current IAQ and standard compliance

When asked to rate the IAQ in their reference building with designations corresponding to a Likert scale from 1 to 5, with 'poor IAQ' corresponding to 1 and 'excellent IAQ' to 5, most respondents rated their current IAQ as 'good' (i.e. a rating of 3). The overall distribution was fairly normal, with a mean of 3.18 and a standard deviation (s.d.) of 0.98 (Figure 1a). This response will be referred to as 'perceived IAQ' henceforth.

Most respondents reported that the IAQ in their building met or exceeded ASHRAE's minimum standards (Figure 1b). (For all relevant questions, a note at the bottom of the prompt reminded, 'For example, for offices ASHRAE Standard 62-2001 specifies a minimum ventilation rate of 20 cfm/occ and a MERV 6 filter'.) Only 9% thought their building did not comply with the standard. A plurality believed that maintenance was carried out strictly according to guidelines (44%), and equal proportions believed that maintenance was carried out less or more frequently than dictated by guidelines, or did not know (19% each). For this question, certain maintenance procedures (including filter change, visual inspection of coil and cleaning, and outdoor air damper check) were suggested to respondents to clarify the scope of the question. For answers to these questions, differences among stakeholder groups (e.g. owners vs. tenants) were not significant when a chi-squared test of independence was performed on a cross-tabulation of the data.

When asked whether their reference building had IAQ problems (Figure 2a), a large majority of respondents (81%) reported that there were none. Of those who did, different stakeholder groups were equally likely to indicate that there were problems in their reference building. Among the 19% reporting problems, the most commonly cited types (respondents could indicate up to three) were ventilation-related issues (57% of the 19% who had reported problems, or 11% of all respondents), followed by outdoor air pollution (24% of those reporting problems, or 4% of all respondents). Those reporting problems cited temperature and odor-related problems next most frequently (19% each), followed by VOCs and humidity (14% each), and dust and mold (10% each).

Reported use of IAQ technologies

Respondents were also given a list of specific IAQ-related technologies or practices and asked to select all that were present in their reference building (Figure 2b). Airside economizers were the most frequently cited (62% of respondents), followed by high-efficiency filters (51%) and demand control ventilation (45%). Only 8% of respondents indicated that none of these technologies were in their reference building; an additional 11% did not know. These self-reported values are somewhat uncertain, as the majority of respondents (at least the 62% who were not designers or consultants) may not be familiar with all of the technologies or whether they were actually present. Also, as these values were not drawn from a representative sample, caution should be used in their interpretation. That being said, in the case of economizers, the reported percentage was reasonably close to 50%, the percentage of commercial buildings with economizers according to CBECS (Fisk et al., 2012; U.S. EIA, 2003).

Relating perceived IAQ to respondent and building characteristics and use of technologies

To identify which factors may have some effect on the perceived IAQ ratings, a number of contingency tables were run between the dependent variable of perceived

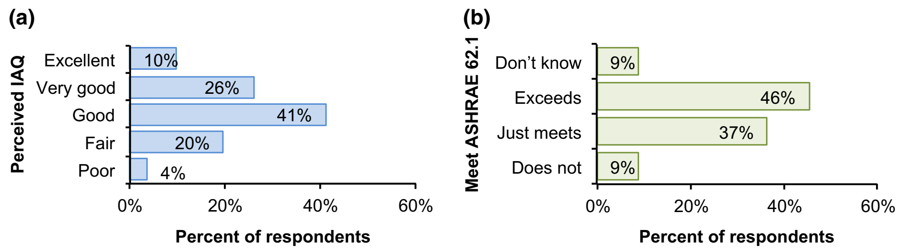

Fig. 1 Respondent reported (a) perceived Indoor Air Quality (IAQ) and (b) perceived meeting of ASHRAE Standard 62.1 in reference building (n = 112)

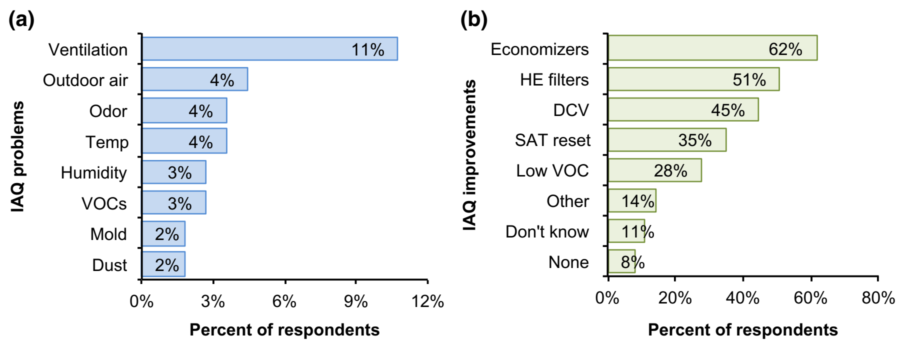

Fig. 2 (a) Reported occurrence of Indoor Air Quality (IAQ) problems and (b) reported use of IAQ-influencing technologies for all respondents (n = 112). Respondents could select multiple options for both questions. Temp = temperature; VOCs = volatile organic compounds; HE filters = high-efficiency filters; DCV = demand controlled ventilation; SAT reset = supply air temperature reset; low VOC = low VOC emitting building materials

IAQ and (i) whether the respondent indicated the building currently had IAQ problems; (ii) whether any actions had been taken to improve IAQ; (iii) ownership of the building; (iv) whether the respondent held a green building certification; (v) location of the building (urban vs. non-urban); (vi) the approximate building age (binned); (vii) reported frequency of maintenance; (viii) reported compliance with ASHRAE standards; and (ix) reported use of specific technologies from Figure 2b in the reference building (individually).

Chi-squared statistics were computed to assess these effects (Table 2). A significant negative relationship with perceived IAQ ratings was found for the variables 'Problems with current IAQ' and 'Reported ASHRAE compliance.' That is, both the perceived presence of current IAQ problems and failure to meet ASHRAE standards were associated with lower perceived IAQ. Lower perceived IAQ ratings were also significantly associated with older buildings and with urban buildings. The only technology for which there was a significant relationship with perceived IAQ was the use of high-efficiency filters. The use of demand controlled ventilation (DCV) was almost significant, even though strictly speaking, DCV can periodically reduce VRs and degrade IAQ (Rackes and Waring, 2013). The use of economizers and low VOC furnishings did not correlate with respondents' perceived IAQ ratings.

As an additional step, a multiple linear regression was run for perceived IAQ as the dependent variable against the predictor variables (i) urban vs. non-urban; (ii) binned building age; (iii) maintenance frequency; and (iv) use of specific individual technologies (Table 3). The regression model was significant (F (4,105) = 8.72, $P < 0.001$) and accounted for about 22% of the variance in perceived IAQ ($R^2 = 0.249$, adjusted $R^2 = 0.221$). In agreement with the contingency tables, the predictor variables 'urban/non-urban' and 'building age' had a negative effect on perceived IAQ, with respondents more likely to report poor perceived IAQ for urban and for older buildings. A higher reported frequency of maintenance was associated with higher perceived IAQ, as was the use of high-efficiency filters (again, the only technology that had a statistically significant effect on perceived IAQ).

Perceptions of the benefits of the VFU package

Respondents were asked whether three types of benefits, that is, (i) general health benefits; (ii) a decrease in (relative) absenteeism; and (iii) an increase in productivity, would result from moving from current minimum standards to improved air quality via the VFU package in their reference building (Figure 3). The options were 'Yes', 'No', and 'Don't know'. A plurality indicated that improving IAQ with the VFU would

Table 2 Chi-square statistics computed for contingency tables for variable of perceived Indoor Air Quality (IAQ) and each other listed variable (n = 112)

	Pearson chi-square value	df	Asymp. sig. (2-sided)	Association
Variable				
Problems with current IAQ?	24.060	4	<0.010	Negative
Actions taken to improve IAQ?	5.491	4	0.241	Positive
Respondent owns building?	0.943	4	0.918	Positive
Green building certification	4.729	4	0.316	Positive
Urban?	13.365	4	0.010	Negative
Building age (binned)	25.483	12	0.013	Negative
Reported frequency of maintenance	13.284	12	0.349	Positive
Reported ASHRAE compliance	60.828	12	<0.010	Positive
Technologies Utilized				
Economizers	4.902	4	0.298	Positive
Demand control ventilation (DCV)	8.613	4	0.072	Positive
Supply air temperature reset	4.669	4	0.323	Positive
High-efficiency (HE) filters	12.369	4	0.015	Positive
Low VOC furnishings	2.587	4	0.629	Positive
None (no technologies utilized)	5.431	4	0.246	Negative

Table 3 Results of forward stepwise regression on dependent variable of perceived Indoor Air Quality (IAQ)

Independent variable	Unstandardized coefficients	Standard error	Standardized coefficients	t	Sig.
(Constant)	3.509	0.289		12.145	0
Urban/non-urban	−0.544	0.174	−0.275	−3.130	0.002
Building uses high-efficiency filters	0.424	0.168	0.216	2.519	0.013
Approximate building age (binned)	−0.223	0.088	−0.218	−2.523	0.013
Maintenance frequency	0.208	0.085	0.211	2.459	0.016

result in health benefits (39%) and productivity increases (45%), but a minority (23%) of respondents thought there would be a decrease in absenteeism. Therefore, for all three benefits, a majority of respondents either thought the benefit would not result from the VFU or were unsure.

In our respondent set, a majority of building market stakeholders did not perceive a strong connection between ventilation and filtration interventions to improve IAQ and advance positive impacts. Given the manner in which the question was posed, which was improving IAQ ‘above the current minimum standards’, along with the large fractions of respondents that thought their reference building currently met or exceeded minimum standards, the overall response suggests a strong degree of deference in the industry to the minima established by the standard. Interestingly, this view was also reflected in our semi-structured interviews, in which several subjects did not recognize that standards were meant to establish *minimum* acceptable operating levels and equated ‘good indoor air quality’ to operating conditions in which ASHRAE standards were met (but not necessarily exceeded).

Several observations may be made regarding these data based on cross-tabulations with other categorical variables:

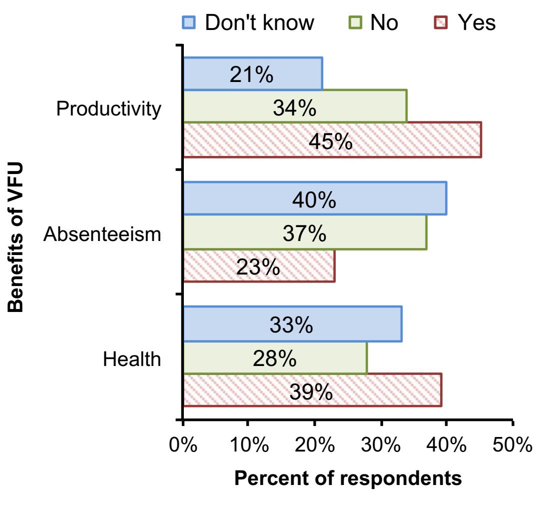

Fig. 3 Respondent perceptions of whether three prompted benefits would result from our specified ventilation–filtration upgrade (VFU), which doubles ventilation from 20 to 40 cfm/occ (9.5 to 19 l/s/occ) and increases filtration from a minimum efficiency reporting value (MERV) 6 to 11 filter (n = 112)

- Perceptions of whether the VFU would lead to health, absenteeism, or productivity benefits in the reference building were not significantly related to perceived IAQ (chi-squared statistics for these tabulations were not significant).
- Respondents with older reference buildings were more likely to believe there would be health benefits associated with improving the IAQ above current

minimum standards; $\chi^2(3, n = 112) = 7.862$, $P = 0.049$.

- Respondents with urban reference buildings were more likely to believe there would be productivity benefits associated with improving IAQ above current minimum standards; $\chi^2(1, n = 112) = 7.560$, $P = 0.006$.
- Tenants and property and facilities managers were more likely to believe there would be IAQ-related productivity benefits than other stakeholder groups; $\chi^2(3, n = 112) = 8.123, P = 0.044$.
- The affirmative perception of IAQ-related benefits did not vary significantly by whether a respondent possessed any type of green building certification (again using a chi-squared test of independence). However, specific types of green certifications were not considered separately.

The minority of respondents who affirmed that there would be a decrease in absenteeism or an increase in productivity was asked to estimate percent changes for the respective impact, and those were compared to our technical estimates (Table 4). In general, these respondents strongly overestimated the productivity benefits of the VFU. The median building industry estimate was a 10.0% increase, and responses skewed upward, with a mean of 15.4%, s.d. of 11.7%, and a range from 0% to 60%. (One respondent said there would be a productivity increase but then estimated its magnitude to be 0%.) Our technical estimate was much smaller at 1.4%. However, directly comparing market responses to the technical estimate may be misleading, as the survey question was general while the technical estimate used quantitative relationships of task improvements measured in particular settings. Conversely, respondents who thought a decrease in absenteeism would result from the VFU tended to underestimate its magnitude. The median industry estimate of reduced relative absenteeism was a 10% decrement, with a mean of 15.8%, s.d. of 12.9%, and a range from 3% to 50%. The technical estimate of 28% was thus a larger decrease than most respondents estimated.

Perceptions of the cost of the VFU package

Survey subjects were next asked to estimate the costs of VFU implementation. Subjects were asked to estimate: (i) the percent increase in their reference building's energy costs and (ii) the added annual cost per occupant in USD. We did not ask the respondents to limit their answers about cost per occupant to energy use only, so it possible that some included capital or maintenance costs in their estimates. However, we think it likely that most did base their estimates only on added energy expenses given that the cost question directly followed the energy increase question.

A wide range of answers was given for both questions, indicating that respondents generally did not have a good understanding of the costs associated with the VFU in their reference building. For the percent increase in energy costs, estimates for respondents in all climate zones ranged from 0% to 75%, with a mean of 15% (s.d. = 14.3%) and a median of 15% (Figure 4a). The median for respondents in each climate zone was approximately 2–4 times higher than the median technical estimate in that climate zone (Table 4). Indeed, for most climate zones, the range of responses was above and barely overlapped the range of technical estimates. For example, in climate zone 4, the median technical estimate was a 4.0% increase in energy costs, while the median increase given by respondents in climate zone 4 was 15.0%.

The estimates for the added cost of the VFU in dollars per person per year ranged from \$0 to \$2500 with a mean of \$257 (s.d. = \$496) and a median of \$75 (Figure 4b). For a few climate zones, survey participants reported median values that were reasonably close to the median technical estimate (e.g. \$25.00 vs. \$15.50, respectively, for climate zone 5), but in others, they were much larger (e.g. \$275.00 vs. \$10.48, respectively, for climate zone 3). Overall, respondents greatly overestimated the cost per person, with approximately 65% saying it would be over \$30, which was the maximum of the range of our technical estimates in any climate or office type. In addition, the distributions were quite skewed, with about 17% saying the cost would be more than \$300 a person, or more than ten times the maximum technical estimate. There was a correlation between estimates of percent increase in energy costs and added cost per person (Spearman's rho = 0.348, $P < 0.001$). That is, respondents who answered high to one question generally answered high to the other, although not necessarily by a ratio that represented the particular energy costs and occupant densities in the reference buildings (as these values are unknown).

Individual stakeholder groups had different estimates of the costs associated with employing the VFU (Figure 5a). Tenants in particular often most overestimated the costs associated with making technological IAQ improvements, but their estimates varied widely and were sometimes lower than other groups. Building owners and property and facility managers had reasonably similar estimates from the standpoint of their central tendencies, although each group had quite different ranges of dispersion. While designers and consultants' median estimates were the lowest of the four groups, their estimates were still higher than most of our best estimate models.

Interestingly, there were not significant relationships between perceptions of IAQ-related benefits and perceptions of associated costs for the VFU among all respondents. Respondents' estimates of energy costs and estimates of added cost per occupant were

Table 4 Comparison of technical estimates and industry responses of benefits and costs of our specified ventilation-filtration upgrade (VFU), which doubles ventilation from 20 to 40 cfm/occupant (9.5 to 19 L/s/occupant) and increases filtration from a minimum efficiency reporting value (MERV) 6 to 11 filter. SD = standard deviation.

	Technical Estimate[a]		Industry Response [b]		
Benefits	*Values or range*		*Median (min to max)*	*Mean (SD)*	*n*
Productivity[c]	1.4%		10.0% (0% to 60%)	15.4% (11.7%)	49
Absenteeism[c]	−28%		−10.0% (−3% to −50%)	−15.8% (12.9%)	25
SBS symptoms[c]	−24%				
Indoor $PM_{2.5}$[d]	−52% to −37%				
Indoor PM_{10}[d]	−55% to −39%				
Energy increase[e]	*Median (min to max)*	*Mean (SD)*	*Median (min to max)*	*Mean (SD)*	*n*
Climate zone 2	4.1% (2.7% to 7.7%)	4.7% (1.6%)	17.5% (10% to 30%)	18.8% (8.5%)	4
Climate zone 3	2.3% (−1.6% to 8.4%)	2.7% (2.6%)	8.5% (0% to 30%)	9.7% (8.9%)	10
Climate zone 4	4.0% (−2.4% to 9.1%)	4.1% (3.0%)	15.0% (0% to 75%)	16.4% (17.4%)	69
Climate zone 5	5.5% (0.2% to 9.9%)	5.4% (3.0%)	10.0% (3% to 25%)	13.2% (6.7%)	27
Climate zone 6	8.1% (−2.1% to 11.6%)	6.8% (4.2%)	15.0% (10% to 15%)	15.0% (7.1%)	2
Cost increase[f]	*Median (min to max)*	*Mean (SD)*	*Median (min to max)*	*Mean (SD)*	*n*
Climate zone 2	$16.08 ($11.74 to $20.51)	$16.40 ($2.24)	$100 ($80 to $200)	$126.67 ($64.29)	3
Climate zone 3	$10.48 (−$5.36 to $21.38)	$8.96 ($7.09)	$275 ($0 to $2500)	$572.70 ($799.53)	10
Climate zone 4	$14.09 (−$8.85 to $30.98)	$14.19 ($10.25)	$100 ($0 to $2000)	$265.95 ($472.33)	58
Climate zone 5	$15.50 ($0.55 to $30.59)	$15.61 ($8.96)	$25 ($2 to $2000)	$133.83 ($402.74)	24
Climate zone 6	$20.98 (−$5.54 to $28.21)	$16.91 ($10.53)	$90 ($80 to $100)	$90.00 ($14.14)	2

[a]Based on 14 simulations each in climate zones 2 and 6, 28 simulations each in zones 3 and 4, and 21 simulations in zone 5
[b]Benefit market estimates based only on respondents who believed the benefit existed
[c]Based on ventilation rate change alone
[d]Based on ventilation rate and filtration efficiency changes
[e]Percent increase in energy operating costs; increases due to VFU normalized by average commercial building energy expenditure from CBECS (U.S. EIA, 2006)
[f]Added annual cost per occupant; USD/occupant-yr

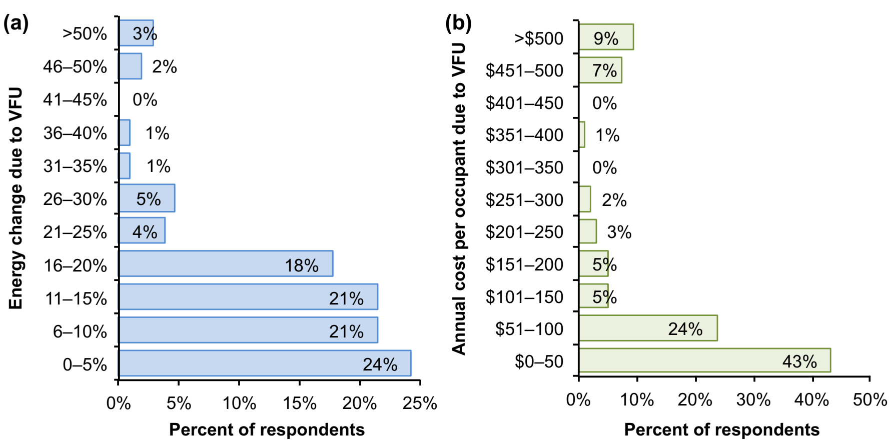

Fig. 4 Respondents' estimate required (a) percent energy change and (b) added annual cost per occupant (in USD) to improve Indoor Air Quality with our specified ventilation–filtration upgrade (VFU), which doubles ventilation from 20 to 40 cfm/occ (9.5 to 19 l/s/occ) and increases filtration from a minimum efficiency reporting value (MERV) 6 to 11 filter (n = 97)

cross-referenced with the affirmative perception of queried benefits (health, absenteeism, or productivity). No results were significant (when utilizing a chi-squared test), nor were they significant for the cross-tabulation of cost estimates with the use of specific IAQ-related technologies (e.g. economizers) or with generic green building certification.

Willingness to pay for improved IAQ

In this section, respondents were queried about their organization's willingness to pay (WTP) for the VFU. To assess WTP, respondents were randomly presented with one of five annual USD costs per person ($15, $50, $150, $500, or $1500) and asked whether their organization would likely be willing to pay this cost (Figure 5b). Across all cost categories, 5–25% of respondents indicated they did not know whether their organization would pay or not. For a cost of $15 per person, a plurality of respondents (a majority, excluding the unsure) thought their organization would be willing to pay for IAQ improvements. However, for all cost categories greater than $15, a majority of respondents indicated their organization would not be likely to pay for such an upgrade.

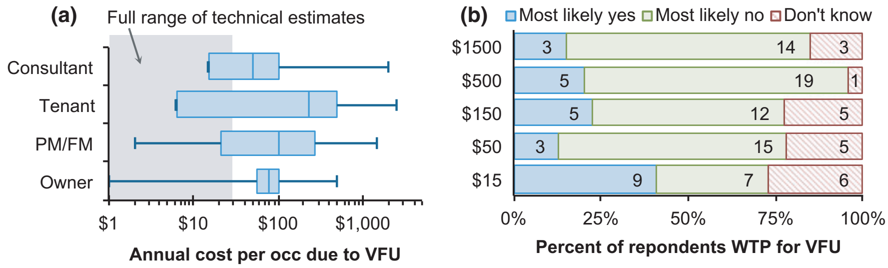

Fig. 5 (a) Stakeholder group differences in estimated added annual cost per occupant to improve Indoor Air Quality with, as well as in the shaded region the range of our technical best estimates (*x*-axis on log scale) and (b) perceived organizational willingness to pay (WTP) by prompted cost for our specified ventilation–filtration upgrade (VFU), which doubles ventilation from 20 to 40 cfm/occ (9.5 to 19 l/s/occ) and increases filtration from a minimum efficiency reporting value (MERV) 6 to 11 filter (n = 112). PM/FM = property or facilities managers

To identify factors that may affect WTP, responses across all cost categories were pooled and recoded into a dichotomous variable 'Likely to pay,' which was coded positively only if a respondent had answered 'Yes' to the prompted WTP question. A forward binary logistic regression (using the likelihood ratio method) was run on the 'Likely to pay' variable using different predictors. The resulting regression model was significant (omnibus $\chi^2 = 41.698$, df = 5, $P < 0.001$) and explained approximately 41% of the variance in 'Likely to pay' (Cox and Snell $R^2 = 0.410$). Respondents were more likely to pay if they owned their building, thought there would be productivity benefits, or thought the added cost per person would be high. Of course, the higher the USD of the prompt, the less likely respondents were to say they would pay. Interestingly, those with some type of green building certifications were also significantly less likely to pay. In theory, these respondents should be familiar with the research findings about IAQ impacts, and their skepticism suggests that green building certification programs may need to better convey the benefits of better filtration and increased ventilation.

The meaning of 'would the organization managing the building be likely to pay' depends on whether the respondent is a representative of the reference building. Owners likely responded based on what they themselves would pay, while other stakeholders presumably responded with what they thought owners were likely to pay. To further isolate the impact that ownership has on stated likelihood to pay, a binary logistic regression was run on 'Likely to pay' with ownership as the only predictor variable. The regression model was significant (omnibus $\chi^2 = 10.615$, df = 1, $P = 0.001$) and was able to explain ~11% of the variance in stated likelihood to pay for improved IAQ (Cox and Snell $R^2 = 0.109$). Thus, owners indicated a significantly greater willingness to invest in the VFU than tenants believed they would be—by about a factor of five, according to the odds ratio given by the model. Of course, this is only a stated WTP. Perhaps owners were overly generous in their self-estimation, but it may also be the case that tenants would be surprised by their building owners' receptiveness to implementing IAQ improvement measures.

Marketing of IAQ

In the final portion of the survey, respondents were asked about the marketing of IAQ during the leasing and buying of commercial space. Building owners and property and facilities managers were asked about their own marketing practices, while tenants and consultants were asked to reflect on their experiences when others were doing the marketing to them. Most owners or owner representatives did not report marketing IAQ (34% claimed to), and most tenants reported not having seen owners attempting to command higher rents as a result of better IAQ (21% of tenants and consultants said they have seen this, 48% said they have not, and 31% had no knowledge of this). Figure 6 shows that nearly four in ten owners and facilities and property managers believe that 10% or fewer of all tenants consider IAQ during the buying or leasing process.

In contrast with owners' perceptions of tenants' considerations of IAQ, nearly half of tenants (48%) claim to consider IAQ 'indirectly' during the buying or leasing process, either via building location, age, or green building certifications. Additionally, 26% claimed to consider it 'directly', while the remaining 26% reported 'no consideration'. Despite this, only 21% of the 62 tenants and consultants indicated they had seen owners asking for higher rents for better IAQ. Of these 13 respondents, most indicated that they trusted claims from owners that a building had 'better IAQ'; 54% were either 'confident' or 'very confident', while 38% were 'neutral'. In short, although reports of using improved IAQ as a real estate selling point are relatively rare, when they are made, a slim majority here found them credible.

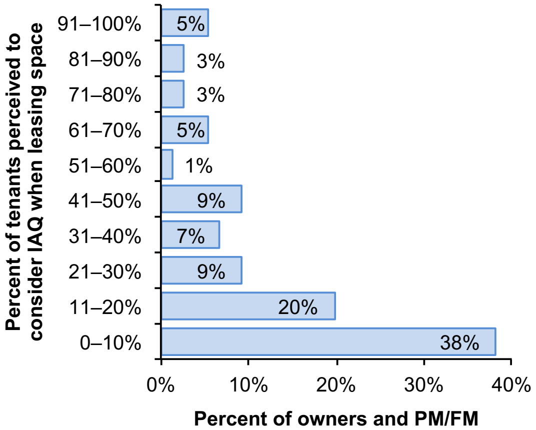

Fig. 6 Binned percentage of tenants considering Indoor Air Quality (IAQ) when leasing space, as estimated by building owners and property and facilities managers (PM/FM) (n = 50)

Study design and limitations

Our study was not designed to test specific hypotheses, but rather to assess the perceptions of building industry respondents, which we recorded regardless of their basis or accuracy. In our view, the fact that all responses are self-reported is appropriate for a study on perceptions. However, it imposes limits on the ability to identify associations between IAQ perceptions and other factors, like whether a building is old or compliant with ASHRAE 62-2001, because these are also self-reported. Some factors (building age) are probably reasonably reliable when self-reported, whereas others (standard compliance) may not be. In particular, real VRs in buildings are difficult to assess accurately, so it is unlikely that people had any basis to truly evaluate their own perceptions for this question.

Our results should thus be interpreted with these nuances in mind, recognizing that the conclusions herein apply to the self-reported, perceived state of the world of our respondents. For example, the *self-reported* use of high-efficiency filters and frequent HVAC maintenance were both associated with better *perceived* air quality. We do not know whether these practices were really in place in the reference buildings where people said they were, or if better perceived IAQ was due to verifiably better IAQ, so we cannot conclude from our study that high-efficiency filters and frequent maintenance are associated with better air quality. However, we do not need a survey to make that conclusion; the benefits of filtration and maintenance are already established. The conclusion from this work is that those benefits appear to be appropriately *reflected in the perceptions of market actors*—regardless of the mechanism.

Readers may still question whether different stakeholders have different types of knowledge and whether many lack sufficient IAQ-related knowledge to respond in an informed manner. The answers to these questions are certainly ‘yes’, and in a sense these levels of knowledge are part of what we were trying to evaluate in this study. However, where we thought respondents’ lack of knowledge would be a limitation, we tried to construct the survey to minimize the impact, for example, by asking all respondents to keep in mind a reference building they knew well, and repeatedly supplying the definition of relevant ASHRAE standards. Furthermore, the particular knowledge of different stakeholder groups confounds expectations about their responses. For instance, designers and consultants are more likely to understand the meaning of and compliance with ASHRAE standards but may have less knowledge about the state of IAQ or actual technologies employed, having spent less time in their reference buildings than members of other groups. As another example, owners or tenants who deal with energy billing should have better context with which to evaluate energy-related financial impacts.

Moreover, in some of the central findings of the survey, variations among stakeholder groups were different than one might expect based on prior assumptions about their level of knowledge; that is, those expected to be more knowledgeable about technologies, standards, or building science did not express opinions more similar to the technical IAQ consensus. For example, while designers and consultants were generally closer to the technical estimates on cost, tenants and property and facility managers were more likely to believe that the VFU would increase productivity. Similarly, those with green building certificates were not more likely to see *any* benefits of the VFU, despite the emphasis in many certification programs on improving indoor environments by increasing the VR above the standard minimum.

One final caveat is important. Because the survey respondents were drawn using convenience sampling, there may be sources of bias that are impossible to quantify, and results might not be entirely representative of the stakeholder population at large. Also, as about three quarters of responses were from the Mid-Atlantic and Northeastern U.S., the perceptions of stakeholders in other parts of the country may be underrepresented, if regional differences exist.

Conclusions

The findings of this study suggest that a very substantial portion of commercial building stakeholders do not recognize the benefits of good IAQ or the efficacy of ventilation and filtration in achieving it. Majorities of respondents either did not think or know that that these measures could lead to increased productivity (55%), absenteeism (77%), and any health benefits

(61%). Our results also suggest an abiding faith in minimum requirements set by standards. To the extent that benefits of exceeding the current standards were recognized, an association with productivity outcomes appeared more firmly established than associations with absenteeism or any health outcome. Perhaps most strikingly, those with green building certifications were less likely than the surveyed population at large to recognize a connection between productivity, absenteeism, or health benefits and increased ventilation or filtration. Even among respondents that did recognize a benefit, quantitative estimates of the benefit varied widely and often showed little agreement with our technical best estimates based on the IAQ literature.

Respondents were not much better at estimating the costs of the proposed VFU, and energy cost percent increase estimates were a factor of ~2–4 times higher than our modeling estimates. Cost increases expressed in annual USD per person overlapped the range of technical estimates but were in many cases higher by orders of magnitude. When asked about willingness to pay for the VFU, the only cost for which a plurality of respondents said they would pay was quite low ($15 per person), but encouragingly within the range of our best estimate of cost. Taken together, these results suggest that better information about the benefits (greater than people think) and costs (less than people think) of IAQ improvements could induce building stakeholders to adopt them. In some cases, inclusion of additional technology in buildings to sense and report risks related to IAQ might be warranted, as even with education, stakeholders and occupants may not recognize impacts of IAQ components that they cannot physically perceive. Thus, encouraging greater investment in improving IAQ in the workplace likely requires bridging the gap of understanding of stakeholders about the real benefits and costs of improved IAQ.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:
Appendix S1. Indoor air quality survey.

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