

# FACTORS AFFECTING VENTILATION, INDOOR-AIR QUALITY AND ACOUSTICAL QUALITY IN 'GREEN' AND NON-'GREEN' BUILDINGS: A PILOT STUDY

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## ABSTRACT

*This paper discusses a pilot project involving the direct monitoring of ventilation, indoor-air quality and the acoustical conditions in selected nominally 'green' and non-'green' buildings located on a university campus. The objectives were to measure parameters quantifying these three aspects of indoor environmental quality, determine the relationships between them and the building-design concepts, and evaluate the implications of the results for ventilation-system design, especially in 'green' buildings. Measurements were made in rooms, with and without acoustical treatment, in buildings with natural ventilation or mechanical (displacement and/or mixed-flow) ventilation systems. Measurements were made of ventilation rates (air changes per hour), indoor air quality (respirable-fibre, total-VOC and ultrafine-particulate concentrations), and the acoustical conditions (noise levels and reverberation times). Correlations between the environmental results, the building concept, the ventilation concept and the building window status were explored. In rooms with natural ventilation, low-frequency noise and total sound-pressure levels were lower; however, the rooms had higher ultrafine-particulate counts and lower ventilation rates. Rooms with mechanical ventilation had higher low-frequency and total sound-pressure levels, higher ventilation rates and fibre concentrations, but lower concentrations of ultrafine particulates. It was concluded that, in general, mechanical ventilation can provide better indoor air-quality, but that HVAC noise is an issue if the system is not properly designed. In 'green' buildings, noise levels were acceptable when the windows were closed, but increasing the ventilation rate by opening the windows resulted in higher noise levels. The results suggest that the acceptability of environmental factors in buildings depends on the degree of compliance of the design and its implementation with standards and design guidelines (i.e. for ventilation, air quality, thermal comfort, etc.), whether the original design concept is 'green' or non-'green'.*

## KEYWORDS

green building, conventional building, ventilation quality, indoor-air quality, acoustical conditions, mechanical ventilation, natural ventilation

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## INTRODUCTION

A primary purpose, and a design goal, of a building are to provide a comfortable, healthy and productive environment for the occupants. In sustainably-designed ('green') buildings, an additional goal is to meet objective sustainability and energy-efficiency targets. There are four key elements of a building that combine to create the indoor environment: the structure (including the windows in the building envelope), the heating, ventilation and air-conditioning (HVAC) concept/system, the outdoor environment and the occupants' activities.

The role of the HVAC system is to control the temperature, air velocity, mean radiant temperature and air humidity. Some systems (such as constant-volume, variable-air-volume and displacement) provide supply air to dilute and exhaust contaminants and stale air from the environment, as well as providing thermal comfort. Ventilation air is clean outdoor air delivered to occupied areas of a building which, in conjunction with the air exhausted from the space, dilutes and removes air contaminants. The ventilation system must maintain the indoor air at a satisfactory, healthy level. In some common systems, the supply air is used for heating or cooling the space. In this case, part of the total supply air must always be fresh and clean; the proportion of fresh air to the total supplied varies with occupant-usage patterns.

Aspects of the indoor environment that directly influence the occupants of a building are ventilation, indoor-air quality (IAQ) and the acoustical conditions, as well as thermal conditions and lighting (neither considered in this work). There exist close relationships between the various factors, and each influences the others. Higher ventilation rates in rooms with mechanical ventilation systems may lead to higher background noise. In a naturally-ventilated room, airflow paths may reduce noise isolation between two rooms. The absence of noise from HVAC equipment may result in inadequate speech privacy. Acoustical treatment may improve acoustics, but could impair ventilation and IAQ, and may even compromise the 'green' design if non-'green' materials are used. The use of radiant slabs for temperature regulation to reduce energy consumption through the high heat-capacity of concrete slabs may result in lower sound absorption and poorer acoustical conditions.

The reduction of energy consumption and the application of 'green'-building design principles such as natural ventilation are considered very seriously in building design nowadays. The ultimate objective of the pilot research reported here was to understand better the impact of a building's ventilation-system concept on the indoor environmental quality—with respect to ventilation, indoor air and acoustics. In order to evaluate these environmental factors, rooms in both 'green' and non-'green' (conventional) buildings were chosen such that different types of ventilation concepts/systems—mixed-flow, displacement and natural—were involved.

The specific objective of this research was to undertake a preliminary investigation of the relationship between ventilation performance, IAQ and acoustical quality in a nominally-'green' and in non-'green' buildings. In particular, it was to determine the physical factors affecting these three environmental aspects, the relationships between them and the building-design concept, and the implications of the results for ventilation-system design, especially in 'green' buildings. Of course, the environmental quality perceived by a building's occupants also depends on their ability to control their environments (Brown and Cole 2009, Fang *et al.* 2004, Field and Digerness 2008, Kaczmarczyk *et al.* 2004), but this was not considered here. Offices, labs and classrooms, with or without mechanical ventilation, and with or without acoustical treatment, in four buildings were selected and monitored; the results in different cases were compared to determine the factors that influence them. Full details of the study are reported in (Khaleghi 2008).

Following are details of how the environmental aspects were characterized:

- Ventilation: air-exchange rate (air changes per hour, ACH); ventilation rate was quantified by measuring the air flow entering the rooms. At the time of monitoring, the numbers of occupants were not at their usual levels; thus, CO<sub>2</sub> levels were not measured in this study;
- IAQ: respirable-fibre particle concentration; ultra-fine particles < 0.1 µm (two measures: ratio of indoor-to-outdoor particulate concentration (PC) and indoor PC – 20% of outdoor PC). Indoor air should have lower concentrations of ultrafine particulate matter than outdoor due to the ability of the building itself to filter particulate matter. Therefore, the ratio of indoor to outdoor ultrafine particulate matter should be less than 1.0 unless there is an indoor source of ultrafine particles. The second measure was used since all of the buildings were very close to one another, and the reference (outdoor) particulate concentration was calculated as an average, and normalized to allow comparisons between rooms. An efficient building filtration should remove ~ 80% of ambient ultrafine particulate matter; therefore, indoor – 20% of outdoor was investigated as an indicator of how PC varies between rooms with different ventilation systems—in other words, it is a more sensitive way of comparing PC values between rooms.); total volatile organic compounds (TVOC concentration);
- Acoustical quality: background-noise level; mid-frequency reverberation time; average mid-frequency surface-absorption coefficient.

## METHODS

### *Site selection*

Four buildings on the University of British Columbia (UBC) campus, with rooms which were adjacent—and, thus had similar outdoor environmental conditions—were selected for monitoring. Study rooms were chosen which were easy to access, and which included different HVAC systems, furnishings and acoustical treatments. In total, 17 rooms were selected—six with natural or displacement ventilation and eleven with overhead mixed-flow ventilation. One building (Kaiser) was a sustainably-designed (nominally-‘green’) building with LEED® Silver certification; its sustainable-design features include natural ventilation, water conserving washrooms, rooftop photovoltaic panels, and the use of concrete thermal ceiling slabs, non-toxic wood products and recycled building materials.

The other buildings (CEME, LPC, McLeod) were designed as conventional (non-‘green’) buildings. All buildings were located next to campus roads; the vehicles using them generated a low level of noise and air pollution—the buildings were in relatively quiet and clean external environments compared to a downtown location.

In view of the fact that the acoustical conditions in any room are a function of its geometry, furnishings and furniture density, and its acoustical treatment, the rooms investigated were divided into four main groups:

- Group I: Small rooms—these were small offices or study rooms with up to two occupants, and floor areas <20 m<sup>2</sup>. Two of these rooms had natural ventilation, five had mechanical ventilation, with high or low furnishing density, and carpets and acoustical-tile ceilings;

- Group II: Small classrooms—these rooms were generally larger than the rooms in the first group, with floor areas of 20–50 m<sup>2</sup>; one had a mechanical ventilation system, one natural ventilation, and they had the main distinction that they contained desks and chairs, and acoustical ceilings;
- Group III: Large rooms with substantial acoustical treatment—this category included two large-volume rooms—a student laboratory and a seminar room—with floor areas >80 m<sup>2</sup>, ventilated by displacement ventilation systems or natural ventilation; they had high furniture densities, acoustical-tile ceilings and were carpeted;
- Group IV: Large rooms with some acoustical treatment—these rooms covered a wide range of student laboratories (floor areas 90–300 m<sup>2</sup>) with different types of acoustical treatment and furnishings. Two rooms had ‘hybrid’ (natural + supplemented mixed-flow) ventilation, and four rooms had mechanical ventilation.

In the end, 17 rooms were selected for study. The rooms were surveyed regarding their HVAC-system design (see Khaleghi, 2008 for details), dimensions and surface finishes, as well as their furnishing densities and absorptions, the types and amounts of acoustical treatment (carpet, ceiling, wall)—details of how these were calculated are found in Khaleghi, 2008). The rooms had a wide range and mix of characteristics, but in general were chosen such that pairs of rooms were only substantially different with respect to one characteristic, for comparison. Based on their ventilation-system concepts, rooms were divided into three categories: natural, displacement and mixed-flow. On the basis of their building-design concepts, the rooms were also divided into three other categories: conventional, hybrid and ‘green’ (e.g. naturally-ventilated). The hybrid category consisted of rooms which had mechanical (displacement or overhead mixed-flow) ventilation systems, but were located in the nominally-‘green’ building (Kaiser). Some of the labs and offices in this building had hybrid design. In general, the non-‘green’ rooms had mechanical ventilation, acoustical ceilings and relatively-high furnishing densities. Some of the hybrid rooms did not have operable windows to the outdoors, and had displacement or mixed-flow ventilation. The rooms with mechanical ventilation were conditioned by means of the supply air; radiant slabs were used to regulate temperature in rooms with displacement ventilation systems. The study rooms with ‘green’ construction concept had operable windows to control the ventilation rate. Moreover, radiant slabs, in conjunction with the windows, had the role of controlling the thermal conditions in these rooms.

## ***Environmental factors***

### ***Ventilation***

In mechanically-ventilated rooms, ventilation performance was measured as air-flow rate using a thermo-anemometer (Velocicalc® Plus Model 8360, TSI Inc., Shoreview MN). The probe of the air-velocity meter was placed 0.025 m in front of the air-supply grill; the application factor of the guide vanes at the opening was chosen as 0.78 (ACGIH 1992). The air velocity was converted to air changes per hour using the room volume. In rooms with natural or displacement ventilation the air-exchange rate was determined using tracer-gas decay as per Bearg (1993). Briefly, a portable infrared-spectrometer gas analyzer (MIRAN IA, Foxboro, Nortex, ON) was used to measure the tracer-gas (SF<sub>6</sub>) concentration over time, after a steady-state concentration of SF<sub>6</sub> was introduced into the room. The number of air changes per hour was calculated from:

$$I = \left( \frac{1}{\Delta t} \right) \ln \left( \frac{C_1}{C_2} \right)$$

where  $C_1$  and  $C_2$  were the concentrations of SF<sub>6</sub> at times  $t_1$  and  $t_2$ , with  $\Delta t = t_2 - t_1$ .

### **IAQ**

- Respirable-fibre concentration: Airborne fibres (those with lengths >5 µm, width <3 µm and length-to-width ratio >3:1) were collected onto a 25-mm mixed cellulose-ester filter and counted using a modification of asbestos-airborne fibre count NIOSH 7400 (<http://www.cdc.gov/niosh/pdfs/7400.pdf>, accessed May 2007);
- Ultra-fine-particulate concentration (UPC): A P-trak ultra-fine-particle counter (TSI model 8525, Shoreview MN) was used to measure the counts of particles <1 µm. Measurements were taken over the entire room, with a data-logging interval of 10 s;
- TVOC: A ppb RAE PID detector model PGM 7240 (RAE Systems, San Jose CA) was used to measure TVOC concentration indexed to isobutylene.

### **Acoustical conditions**

The following acoustical parameters were measured:

- Background-noise level: The equivalent continuous sound-pressure level was measured, in octave bands from 31.5 to 8000 Hz, over the entire room, using a sound-level meter (model NA-29E, RION Co. Ltd., Tokyo, Japan). Total levels were calculated in unweighted ( $L_{eq}$ ) and A-weighted ( $L_{Aeq}$ ) decibels, as well as in terms of Noise Criterion (NC) (Design Standards 2003);
- Reverberation time: Reverberation time was measured, using a real-time analyzer (model NE830, Norsonics AS, Tranby, Norway), in octave bands from 125 to 8000 Hz, at four positions in smaller, and six positions in larger, rooms and the results averaged in each band. The times in the 1000-Hz octave band were used to characterize the mid-frequency reverberation ( $T_{mid}$ ). As a measure of the amount of sound absorption in the room, mid-frequency average surface-absorption coefficients ( $\alpha_{mid}$ ) were calculated from  $T_{mid}$  and the room dimensions, using diffuse-field theory. These include the absorption of the furnishings, as well as the room boundaries.

To investigate individual environmental aspects and the factors that influence them, the seventeen rooms in this pilot study were stratified according to characteristics such as surface finish, acoustical treatment, furnishings, ventilation concept and window status (open or closed), and strata averages calculated and compared. Relationships between the environmental factors and concepts involved in the building design were investigated using point-biserial (Glass and Hopkins, 1995) and Pearson correlation analysis.

## **RESULTS: INDIVIDUAL ENVIRONMENTAL FACTORS**

Tables 1-3 summarize the study rooms by group, as well as the measured ventilation, IAQ and acoustical results. In particular, Table 1 shows the building design concept (construction concept and type of ventilation system), the basic physical characteristics of the test rooms (volumes, surface areas, presence and locations of radiant slabs, window statuses during monitoring), furnishing densities and absorptions, and the amounts of acoustical treatment. Table 2

**TABLE 1.** Study rooms by group, and design-concept and physical data (CW=closed windows, OW=open windows).

Group	Room	Room volume (m <sup>3</sup> )	Room surface area (m <sup>2</sup> )	Construction concept	Ventilation system	Radiant slabs	Window status	Furnishings		Acoustical Treatment (% coverage)		
								Density (0=low, 1=high)	Absorption (NRC) (0=low, 1=high)	Carpet	Ceiling	Wall
I	Kaiser 5008	35	64	1	2	0	0	0.23	0.20	16	0	0
I	Kaiser 5015	35	64	1	2	0	0	0.57	0.22	16	0	0
I	CEME 2208	35	65	0	2	0	0	0.68	0.17	19	19	0
I	McLeod 417	37	77	0	2	0	0	0.07	0.09	0	0	0
I	Kaiser 4044 (CW)	45	77	2	0	2	0	0.65	0.20	0	0	0
I	Kaiser 4044 (OW)	45	77	2	0	2	1	0.65	0.20	0	0	0
I	Kaiser 4016 (CW)	45	77	2	0	2	0	0.57	0.22	0	0	0
I	Kaiser 4016 (OW)	45	77	2	0	2	1	0.57	0.22	0	0	0
I	LPC 313	130	63	0	2	0	0	0.67	0.15	0	26	0
II	Kaiser 3028 (CW)	100	135	2	0	2	0	0.23	0.21	0	0	13
II	Kaiser 3028 (OW)	100	135	2	0	2	1	0.23	0.21	0	0	13
II	CEME 1206-08	120	160	0	2	0	0	0.43	0.09	0	28	0
III	McLeod 418	225	266	0	2	0	0	0.72	0.20	32	32	0
III	Kaiser 4025	560	510	1	1	2	0	0.87	0.39	33	0	0
IV	McLeod 228	520	577	0	2	0	0	0.88	0.09	0	34	17
IV	McLeod 202	470	577	0	2	0	0	0.88	0.09	0	34	17
IV	Kaiser 4060	920	790	1	1	2	0	0.62	0.37	0	0	5
IV	Kaiser 4065	270	286	1	1	2	0	0.56	0.29	0	0	0
IV	CEME 1212	170	215	0	2	0	0	0.36	0.09	0	33	0
IV	CEME 2212	340	340	0	2	0	0	0.52	0.09	0	0	0

**TABLE 2.** Study rooms by group, and measured background-noise and reverberation-time ( $T_{mid}$ ) results. N/A indicates unavailable results (CW=closed windows, OW=open windows).

Group	Room	Background Noise Level			$T_{mid}$ (s)
		$L_{eq}$ (dB)	$L_{Aeq}$ (dBA)	NC (dB)	
I	Kaiser 5008	64.8	47.8	43	0.78
I	Kaiser 5015	60.2	44.6	38	0.78
I	CEME 2208	59.8	39.0	33	0.29
I	McLeod 417	59.2	46.3	39	1.73
I	Kaiser 4044 (CW)	56.0	43.1	39	0.45
I	Kaiser 4044 (OW)	57.0	44.4	40	0.45
I	Kaiser 4016 (CW)	55.5	38.3	34	0.45
I	Kaiser 4016 (OW)	55.9	44.1	38	0.45
I	LPC 313	63.8	50.2	45	0.38
II	Kaiser 3028 (CW)	53.2	38.5	31	0.80
II	Kaiser 3028 (OW)	61.8	50.4	45	0.80
II	CEME 1206-08	61.8	41.8	36	0.54
III	McLeod 418	60.2	38.2	33	0.31
III	Kaiser 4025	59.6	48.1	45	0.48
IV	McLeod 228	59.4	43.4	37	0.57
IV	McLeod 202	57.7	42.0	36	0.57
IV	Kaiser 4060	N/A	N/A	N/A	0.89
IV	Kaiser 4065	57.2	44.6	37	1.02
IV	CEME 1212	51.8	39.3	33	0.54
IV	CEME 2212	54.4	41.7	36	1.76

summarizes the background-noise and reverberation-time measurement results. Table 3 shows the ventilation and IAQ results. In some cases accurate results were unavailable due to equipment malfunction, poor quality experimental conditions or inaccessible rooms. Following is a summary of the main observations made from the analysis of the results:

### ***Ventilation***

Whatever type of ventilation system is involved, the ventilation performance depends on the correct design and selection of the equipment. As expected, the ventilation performance (rate and quality) was different from room to room. In rooms with mechanical ventilation, as was the case for the delivered airflow, the ventilation rate covered a broad range of values, from completely inadequate to completely satisfactory (2.7–15 ACH) (ASHRAE 2004).

In naturally-ventilated rooms, the main factor influencing the supply and ventilation air was the status of the windows (open or closed). The ventilation rates were very low (1.0–3.8 ACH); with windows closed, the rate dropped (0.1–1.5 ACH). Factors which affected the ventilation in naturally-ventilated rooms are the outdoor temperature and the existence of ‘ventilators’ (ventilation ducts, channels or openings) allowing airflow between the rooms and the adjacent environments (to an atrium or a negative-pressure room) (Larsen and Heiselberg, 2008).

**TABLE 3.** Study rooms by group, and measured ventilation and IAQ results. N/A indicates unavailable results (CW=closed windows, OW=open windows).

Group	Room	Ventilation rate (air changes per hour)	Fibre conc. (fibres per ml)	VOC Indoor - outdoor conc. (ppb)	Ultrafine-particulate concentration (ppm)	
					Indoor/ outdoor ratio	indoor - 20% outdoor
I	Kaiser 5008	4.8	1.87	91	0.53	1017
I	Kaiser 5015	15.0	N/A	118	0.44	727
I	CEME 2208	3.0	3.44	3	0.37	485
I	McLeod 417	2.7	1.40	34	0.71	1590
I	Kaiser 4044 (CW)	1.5	1.81	52	0.72	1617
I	Kaiser 4044 (OW)	N/A	1.81	33	0.90	2170
I	Kaiser 4016 (CW)	0.7	N/A	21	N/A	N/A
I	Kaiser 4016 (OW)	3.8	N/A	N/A	0.79	1825
I	LPC 313	10.0	2.10	97	0.79	6705
II	Kaiser 3028 (CW)	0.1	0.58	12	0.84	1984
II	Kaiser 3028 (OW)	1.0	0.58	13	0.88	2102
II	CEME 1206-08	4.4	1.26	0	0.35	517
III	McLeod 418	3.1	0.64	18	0.62	1297
III	Kaiser 4025	0.8	2.10	44	0.75	1698
IV	McLeod 228	3.5	2.92	6	0.55	1090
IV	McLeod 202	2.8	3.00	10	0.51	952
IV	Kaiser 4060	N/A	0.82	19	0.66	1422
IV	Kaiser 4065	3.1	0.82	24	0.85	1997
IV	CEME 1212	7.3	5.90	0	0.33	361
IV	CEME 2212	3.5	1.17	23	0.79	1299

### IAQ

In non-industrial buildings such as those studied here, IAQ problems arise in the room when there is an inadequate amount of ventilation air being provided, given the amount of contaminants present. Following are the main observations made from the statistical analysis of the various IAQ factors reported in Table 3:

- Respirable-fibre dust – The main factors affecting the fibre concentration were the type and quantity of furnishings, and the amount of acoustical treatment—the type of ventilation system was of secondary importance. When stratified into two groups (mechanical and natural ventilation), the data in Table 3 suggest that fibre concentration was greater in naturally-ventilated rooms than in rooms with mechanical ventilation, due to the lower ventilation rate. The number of fibres increased with the amount of acoustical treatment. Carpets increased the number of fibres slightly. A high level of room activity increased fibre concentration;
- Ultra-fine particles – The average value of indoor PC – 20% of outdoor PC was lower in mechanically-ventilated rooms than in rooms with natural ventilation (with closed or open windows). The ratio was higher in naturally-ventilated rooms;



- Total VOCs – Higher TVOCs were measured in carpeted or furnished rooms. On average, naturally-ventilated rooms in nominally-‘green’ buildings had lower TVOC concentrations than rooms with mechanical ventilation. The major factors affecting the emission and concentration of TVOCs were the type and quantity of furnishings, and the amount of acoustical treatment; the type of ventilation system was of secondary importance. The highest TVOC concentration was in a room under renovation.

### Acoustical Quality

In naturally-ventilated rooms, the acoustical conditions depended completely on the window status; the background-noise level was low when the windows were closed; opening the windows to increase the ventilation rate led to higher mid- and high-frequency noise.

In rooms with mixed-flow ventilation, the velocity of the air at the duct outlet had a significant effect on the background-noise level. In these rooms, it was observed that, in spite of high ventilation rates in some of the rooms, the background-noise level—especially at low and mid frequencies—was lower than in similar rooms with less air-flow. This suggests that the correct duct design and air velocity have more impact on the background-noise level than simply the rate of air delivered to the room. Furthermore, in rooms with displacement systems with nearby exhaust fans (to enhance air movement between inside and adjacent rooms), the acoustical conditions were unsatisfactory, especially at low and mid frequencies. This was observed even when the fans and associated ducts were acoustically treated. This suggests that acoustically lining a duct directly adjacent to supply or exhaust openings is not always an adequate solution for noise reduction, although this is a common practice in the design of ductwork systems by mechanical engineers.

Besides having different HVAC systems, other main attributes of the rooms were the types and densities of their acoustical treatments and furniture. As expected,  $T_{mid}$  decreased and  $\alpha_{mid}$  increased with the amount of sound-absorbing material (*i.e.* acoustical ceiling, carpet, wall absorption and furniture). Apparently acoustical treatment is effective at reducing reverberation.

## RELATIONSHIPS BETWEEN FACTORS

The investigations were planned to answer five research questions, as follows:

1. *What are the effects of furnishing density and absorption on reverberation time, average surface-absorption coefficient and TVOC concentration?* Table 4 shows the correlation coefficients between furnishing density and absorption, and  $T_{mid}$ ,  $\alpha_{mid}$  and TVOC concentration ratio. With increased furnishing density,  $T_{mid}$  decreased and  $\alpha_{mid}$  increased, as expected. The main factors affecting the TVOC concentrations in the rooms were the

**TABLE 4.** Correlation coefficients between furnishing density/absorption and reverberation time ( $T_{mid}$ ), average surface-absorption coefficient ( $\alpha_{mid}$ ) and VOC indoor-outdoor concentration ratio.

	$T_{mid}$	$\alpha_{mid}$	VOC indoor-outdoor concentration ratio (ppb)
Furnishing density	-0.53	0.72	0.06
Furnishing absorption	-0.17	0.16	0.20

type and quantity of furnishings, and acoustical treatment. The effect of furnishing density on VOC concentration was very low. This correlation was greater with furnishing absorption, but was still small. In fact, the effect of acoustical treatment—especially carpets and acoustical ceilings—on VOC concentration, was much more significant than that of furnishings. Again, acoustical treatment is apparently effective.

2. *What is the effect of ventilation rate on environmental quality?* Table 5 shows the correlation between ventilation rate and the environmental factors. By increasing the ventilation rate, the total background noise—in unweighted and A-weighted decibels (and at all octave-band frequencies)—increased. Although the magnitudes of these correlations were not large (especially for NC), at lower frequencies they were appreciable. The influence of ventilation rate on the fibre and TVOC concentrations in the rooms was positive. This was due to the fact that the majority of rooms with acoustical treatment and high furnishing density were in buildings with higher ventilation rates. Moreover, the negative correlation coefficient shows that by increasing the ventilation rate (and the concomitant use of filters) the ultra-fine particulate concentration decreased in the rooms.
3. *What is the impact of the ventilation-system concept on the ventilation and environmental qualities?* The results with correlation coefficient  $\geq 0.3$  between the ventilation-system concept and environmental factors are shown in Table 6. Following are the main results:
  - in rooms with natural ventilation: the levels of unweighted, low-frequency and total noise were lower; the number of air changes per hour was lower; the fibre concentration was lower (due to the type of furnishings); the ratio of indoor-to-outdoor ultra-fine particulate concentration was higher (due to no filtration and inadequate control of outdoor air);
  - in rooms with displacement ventilation systems: total A-weighted sound-pressure levels (and those at mid-frequency) were higher; the NC level of the noise was higher (because of nearby exhaust fans);
  - in rooms with mixed-flow ventilation systems: the unweighted, total (and low-frequency) noise levels increased with air changes per hour; the fibre concentration

**TABLE 5.** Correlation coefficients between ventilation rate and environmental factors.

	Background-noise level			Fibre concentration (fibres per mL)	VOC indoor-outdoor concentration ratio	Indoor/outdoor ultrafine particulate concentration ratio
	$L_{eq}$ (dB)	$L_{Aeq}$ (dBA)	NC			
Ventilation rate	0.27	0.21	0.13	0.42	0.66	-0.41

**TABLE 6.** Correlation coefficients (with magnitude  $\geq 0.3$ ) between ventilation concept and environmental factors.

Ventilation concept	Background-noise level			Ventilation rate (air changes per hour)	Fibre concentration (fibres per mL)	Indoor/outdoor ultrafine particulate concentration ratio
	$L_{eq}$ (dB)	$L_{Aeq}$ (dBA)	NC			
Natural	-0.36	-	-	-0.43	-0.32	+0.59
Displacement	-	+0.31	+0.30	-	-	-
Mixed-flow	+0.36	-	-	+0.45	+0.38	-0.91

was higher (due to the type of furnishings); the ratio of indoor-to-outdoor PC was significantly lower.

It was also found that, in rooms with mechanical-ventilation systems, total unweighted (and low-frequency) noise levels increased with the ventilation rate.

4. *What is the effect of construction concept on ventilation and environmental qualities?* The relationships between construction concept (*i.e.* non-‘green’, hybrid or ‘green’) and noise level, ventilation rate and IAQ were investigated. The results with correlation coefficient  $\geq 0.3$  are presented in Table 7. It was observed that:
- in non-‘green’ buildings: the NC noise level was lower than in hybrid and ‘green’ buildings; this was mainly due to the presence of rooms with displacement ventilation (with exhaust fans), and of naturally-ventilated rooms with open windows in other groups; the ratio of indoor-to-outdoor PC was lower; the VOC concentration in the rooms was lower;
  - in hybrid rooms: unweighted and A-weighted low, mid and total noise levels were higher; NC levels were higher; ventilation rates (air changes per hour) were higher; the VOC concentration was higher;
  - in ‘green’ rooms, total unweighted sound-pressure levels were lower; the number of air changes per hour was lower; fibre concentrations were lower (due to the absence of acoustical tile and carpets, and low furniture density); ratios of indoor-to-outdoor particulate concentration were higher.
5. *What is the effect of window status on ventilation and environmental qualities in naturally-ventilated rooms?* As shown in Table 8, window status had a strong influence on background noise and air quality in naturally-ventilated rooms. By opening the windows, the levels of noise in all frequency bands and, therefore, total unweighted and A-weighted noise levels, increased noticeably. This effect was greatest at mid and high frequencies. In addition, with windows open, the indoor – 20% outdoor PC was greatly increased, due to the introduction of high volumes of unfiltered air into the rooms by opening the windows.

**TABLE 7.** Correlation coefficients (with magnitude  $\geq 0.3$ ) between construction concept and environmental factors.

Construction concept	Background-noise level			Ventilation rate (air changes per hour)	Fibre concentration (fibres per mL)	Indoor/outdoor ultrafine particulate concentration ratio	VOC concentration (ppb)
	$L_{eq}$ (dB)	$L_{Aeq}$ (dBA)	NC				
Non-‘green’	-	-	-0.32	-	+0.40	-0.47	-0.33
Hybrid	+0.35	+0.42	+0.39	+0.41	-	-	+0.46
‘Green’	-0.36	-	-	-0.43	-0.34	+0.59	-

**TABLE 8.** Correlation coefficients (with magnitude  $\geq 0.3$ ) between environmental factors and ‘windows open’ in naturally-ventilated rooms.

Background-noise level			Indoor-20% outdoor particulate concentration
$L_{eq}$ (dB)	$L_{Aeq}$ (dBA)	NC	
+0.66	+0.77	+0.71	+0.77

## Discussion

This study involved one nominally-‘green’ (sustainably designed, LEED®-certified) building (Kaiser) involving mixed ventilation concepts. However, there is no one definition of ‘green’. The results of correlating the environmental factors and the building-design concept, with ‘green’ defined as those rooms in Kaiser with natural ventilation, and hybrid as those with displacement ventilation, suggest that, in general, higher air-flow rates result in higher HVAC noise (unweighted and A-weighted), especially at lower frequencies. Excessive mid-frequency noise was more noticeable in rooms with displacement ventilation, in which the exhaust fan is located in or close to the room. The noise-monitoring results indicate that acoustical treatment of the airflow path between the fan and the room cannot make any significant improvement in this case.

Generally, natural ventilation promotes lower HVAC noise; however, no significant control of air quality was observed in the naturally-ventilated rooms. In ‘green’ buildings, the indoor environment was highly influenced by the status of the windows.

It was observed that mechanical ventilation was effective in the dilution and removal of contaminants from indoor air. Non-‘green’ buildings provided better IAQ; however, the acoustical quality of the rooms depended strongly on the quality of the ventilation-system design. Moreover, rooms with hybrid construction concept had unacceptable acoustical and indoor-air qualities if the ventilation system and surface finishes were not properly selected and designed.

## CONCLUSION

This novel pilot study investigated environmental quality, the factors that influence them, their relationships, and how they relate to concepts associated with the building design. The main results of this study are as follows:

1. Acoustical treatment reduced reverberation times, but also resulted in lower air quality in rooms. Rooms with acoustical ceilings and carpets had higher TVOC and fibre concentrations. In fact, the highest TVOC concentrations were measured in rooms with non-‘green’ or hybrid construction concepts, and mechanical ventilation systems.
2. ‘Green’ rooms with natural ventilation had unacceptable particle concentrations. Due to the lack of air filtration with natural ventilation, the particle concentration in the indoor environment is a direct function of the outdoor concentration when there is significant air exchange between the indoor and outdoor environments (through building openings or windows). Therefore, in buildings in the vicinity of high traffic or industrial zones, particle concentrations can lead to unsatisfactory air quality in naturally-ventilated rooms.
3. Mechanical ventilation provided better IAQ, but higher HVAC noise levels—IAQ and noise level are directly associated.

Another observation related to the acoustical environment, drawn from the study, is that the use of radiant slabs in ‘green’ buildings as a temperature-regulation strategy may restrict the use of acoustical ceilings or carpets. The absence of sound-absorbing materials results in less sound absorption and increased reverberation, and an amplification of existing noise levels, creating a noisy environment. However, the density and absorption of furnishings can

make a noticeable contribution to the reduction of reverberation. Wall absorption can also be a solution, especially when acoustical ceilings cannot be used.

The results of this pilot study suggest that optimum building design would use a mechanical ventilation system, with a ventilation rate conforming to current standards. Mechanical ventilation is not necessarily noisy, if its components are designed and selected carefully. Selecting correct air velocities and duct sizes, using duct liners and silencers, using flow straighteners, placing grilles, diffusers and registers far from elbows and branch takeoffs, avoiding ventilation grilles in doors, etc., are strategies which improve the acoustical performance of HVAC systems by keeping noise levels in acceptable ranges (ASHRAE 2005). Furthermore, careful selection of the amount, type and location of acoustical treatments (using 'green' materials which are contaminant-free, and using wall absorption in combination with radiant ceiling slabs) promotes acceptable IAQ and acoustical qualities.

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