EVALUATION AND CONTROL OF ACOUSTICAL ENVIRONMENTS IN 'GREEN' (SUSTAINABLE) OFFICE BUILDINGS

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ABSTRACT

This paper discusses the increasing important issue of the acoustical design of 'green' (sustainable) buildings. Many 'green' buildings have unsatisfactory acoustical environments, according to their occupants. Work done at UBC to evaluate acoustical quality in 'green' office buildings and improve it by engineering control measures is reviewed. The problem of 'green'-building acoustics is introduced and its importance discussed. Details of the acoustical evaluation of six 'green' office buildings by occupant-satisfaction surveys and acoustical measurements are presented, and their implications for the design of 'green' buildings considered. A detailed study of one naturally-ventilated 'green' building is discussed. Pre-treatment survey and measurement evaluation results are presented. It is concluded that inadequate noise isolation due to natural-ventilation openings is a big problem. The design and post-treatment evaluation of noise-control measures to improve the noise isolation in two situations is discussed. Finally, other 'green'-building acoustical issues are noted, and conclusions are drawn as to where future work should be directed.

SOMMAIRE

Cet article présente une question hautement importante qu'est le design acoustique des bâtiments « verts » ou encore durables. De nombreux bâtiments verts possèdent un environnement acoustique insatisfaisant tels que rapportés par leurs occupants. Ici, nous rapportons une revue du programme de recherche accompli à UBC autour de ses bâtiments verts allant de leur évaluation acoustique à la proposition de solutions de contrôle en vue d'améliorer les environnements de travail. Le problème de l'acoustique des bâtiments verts est discuté ainsi que son amplitude. Des précisions sur l'évaluation de six bâtiments verts par des questionnaires et par des mesures sont rapportées suivi d'une discussion sur les implications quant au design de tels bâtiments. L'étude détaillée d'un bâtiment vert ventilé naturellement est discutée. Une enquête prétraitement et les mesures d'évaluation sont présentées. Il est conclu que l'isolation inadéquate du bruit due aux ouvertures créées par les ouvertures des ventilations naturelles pose un réel problème. Le design et l'évaluation post-traitement des mesures mises en place pour le contrôle du bruit sont discutés. Pour conclure, d'autres aspects autour de l'acoustique des bâtiments verts sont notés, et des indications ayant trait aux possibles directions que la recherche dans ce domaine devrait prendre sont suggérées.

1 INTRODUCTION

What does acoustics have to do with sustainable building? Surely, creating acoustical environments in 'green' buildings that the occupants find unsatisfactory *is not sustainable*!

The aim of sustainable ('green') architecture is to create buildings that preserve the environment and conserve natural resources, as well as provide a 'healthy' environment for its occupants. A 'healthy' environment is one that does not cause disease, that promotes well-being and, in the case of workplaces, that enhances productivity. An important aspect of the built environment—often overlooked or undervalued in design—is the acoustical environment. Recent papers [1, 8, 10, 14-16, 22, 23, 25, 26, 30], mainly at acoustical conferences with special sessions on 'green' building, have pointed out that 'green' buildings are often less than satisfactory acoustically, and have reported work devoted to the design, control and/or optimization of their acoustical environments [11, 13-15, 19, 24, 27-29]. The work discussed here was an attempt to investigate this issue more fully, with a focus on 'green' office buildings, and to increase awareness of 'green'-building acoustical issues in the non-acoustical design community.

So, who cares about the acoustical environments in their 'green' buildings? Well…apparently, for example, the occupants of a significant number of recent 'green' buildings at the University of British Columbia (UBC—which aims to be a world leader in sustainability research and practice), who have expressed concerns to the author about the acoustical environment. Of course, poor acoustical environments are not restricted to 'green' buildings; the occupants of numerous conventionally designed, non-'green' UBC buildings have contacted him with acoustical concerns. Acoustical consultants say that they increasingly are asked to resolve acoustical problems in 'green' buildings. In summary, there seem to be a lot of poor acoustical environments in 'green' (and non-'green') buildings; maybe we should do something about it!

To begin to do so has been the objective of recent work at UBC, much of it done in collaboration with Stantec Engineering/Architecture, Vancouver [www.stantec.com]. This paper presents details of the acoustical evaluation of six ‘green’ office buildings, the acoustical evaluation of one naturally-ventilated ‘green’ building (Liu) on the UBC campus, and the design and evaluation of engineered noise-control measures to improve the acoustical performance of Liu natural-ventilation openings. It then discusses other ‘green’-building acoustical issues, draws conclusions and discusses where we should go from here.

2. ACOUSTICAL EVALUATION OF SIX ‘GREEN’ OFFICE BUILDINGS

2.1 Objectives, Methodology and Study Buildings

The objective of this work was to evaluate six ‘green’ office buildings acoustically, to learn design lessons. It involved meetings with the designers, performing an occupant-satisfaction survey (using a web-based survey developed by the Center for the Built Environment at the University of California at Berkeley (www.cbe.berkeley.edu—Figure 1 shows the questions pertaining to the acoustical environment), analyzing the acoustical responses, walking through the building, planning acoustical measurements, performing and analyzing the acoustical measurements, and considering the design implications of the results.

The study involved six very different nominally-‘green’ office buildings, all designed to prevailing sustainable-development principles, evaluated 1-5 years after occupancy. Descriptions can be found elsewhere [www.ecosmart.ca/index.cfm?bd=kbdet.cfm&id=58]. All buildings had mainly glass façades for day-lighting, with sun shades and operable windows, and contained a mix of private and shared offices, and open-office cubicles.

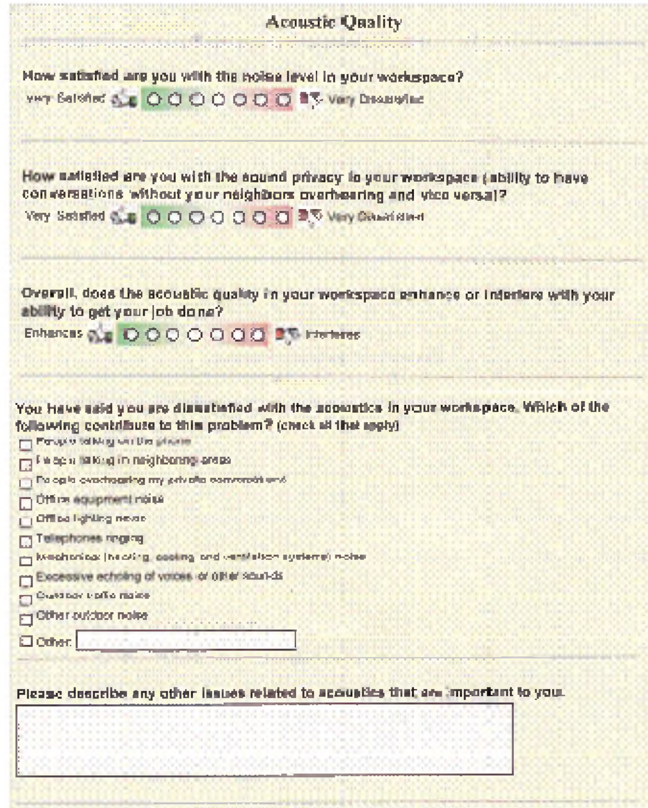

Figure 1: Occupant-satisfaction survey, CBE, UC Berkeley: acoustical quality.

2.2 Measurements and Acceptability Criteria

The objective here was to use physical-acoustical measurements to evaluate the acoustical environment, to explain the survey results, which identified situations (workplaces and building conditions) of high and low occupant satisfaction. Workplaces at which measurements were performed were chosen to correspond to high and low occupant satisfaction. In general, these included desks in open-plan, shared and private offices, which were located in quiet and noisy areas, near and far from operable windows. Furthermore, measurements were made under building conditions expected to correspond to high and low satisfaction (windows or doors closed or open, quiet or noisy external source). Table 1 shows the four acoustical parameters that were measured. Of particular interest is Speech Intelligibility Index [2] which quantifies speech intelligibility and privacy. Also shown are the acceptability criteria used to evaluate each aspect of the acoustical environments in these office buildings, chosen from information in various sources [3-5, 7].

2.3 Results

Designer meetings

Following are the main points relevant to acoustics learned from the designers at the meetings with them: LEED® certification is often a goal that influences design; design often does not involve specialized acoustical expertise—acoustical consultants deal with ‘special cases’; quantitative acoustical design targets are never set; designers are aware

Table 1: Acoustical measurement parameters and acceptability criteria.

Measurement parameter	Acceptability criterion
Background noise level, NC in dB	NC 30-35 in meeting, conference rooms NC 35-40 in workspaces
Reverberation time (mid-frequency), RT_{mid} in s	< 0.75 s for comfort, verbal communication
Speech Intelligibility Index, SII	> 0.75 for high speech intelligibility < 0.2 for high speech privacy
Noise Isolation, NIC in dB	NIC 35-40 for executive offices, conference rooms NIC 30-35 for general offices, meeting rooms

of acoustical issues; external noise (and pollution) concerns may rule out a fully-natural ventilation concept; 'green' buildings often have operable windows, which causes noise concerns if there's an external noise source; low noise levels resulting from absence of a forced-air system result in low speech privacy; client's wishes (e.g. for open-office design) may affect design; budget short-falls at the end of the project may affect acoustical quality; obtaining good noise isolation involves lined return-air ducts, upholstered furniture, acoustical ceilings, carpet, open-office partitions; some buildings are designed for any occupant—the internal 'fit-up' (e.g. acoustical treatments) is done later by contractors for tenants (often on limited budgets); designers often believe their building is well designed, and is successful with its occupants.

Occupant-satisfaction surveys

The Berkeley survey asks occupants to rate their general satisfaction with the building and with their workspace, with the office layout, with the office furnishings, with thermal comfort, air quality, lighting, acoustical quality and with the washrooms. Occupants rated quality on a scale of -3 (maximum dissatisfaction) to +3 (maximum satisfaction).

Figure 2 shows the results of the occupant-satisfaction surveys done in five of the six buildings. Also shown (Ref) are the average scores from all buildings ('green' and non-'green') surveyed using the CBE survey. In general, satisfaction ratings were positive indicating satisfaction. Occupants were very satisfied with their buildings and workspaces, with the furnishings, office layouts, cleanliness and maintenance and with the washrooms. They were generally very satisfied with the lighting, and somewhat satisfied with air quality. Satisfaction with thermal comfort varied from somewhat satisfied to somewhat dissatisfied. Occupants were generally dissatisfied with the acoustical environment, which often received the lowest rating. Speech privacy was found to the biggest acoustical issue. The main sources of dissatisfaction with acoustical quality were: lack of privacy; HVAC noise; phone ringing; external noise; people moving and talking; office equipment; reverberation. Concerns were least in private offices, and greatest in open-plan and shared offices. They were greatest near (external) walls, and least far from walls.

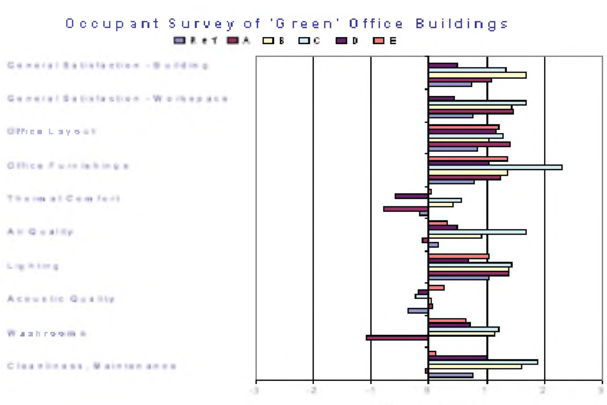

Figure 2: Occupant-satisfaction-survey results for 'green' office buildings.

Acoustical measurements

Following are the main results of the acoustical measurements:

- Background Noise Level: NC 26-34 (unoccupied, natural ventilation); NC 35-42 (unoccupied, forced-air ventilation); NC 45-60 (external noise, windows open); NC 40-60 (occupied);
- Reverberation Time: open-office areas: 0.6-1.0 s (low absorption); 0.2-0.4 s (high absorption); private offices: 0.4-0.7 s (low absorption); 0.2-0.4 s (high absorption); hallways, atriums: 0.9-2.4 s;
- Speech Intelligibility (private office, across desk, casual voice): 0.3-0.6 (forced-air ventilation, low absorption); 0.7-0.8 (natural ventilation, high absorption);
- Speech Privacy. Between open-office cubicles, casual voice): 0.3-0.6 (forced-air ventilation, low absorption); 0.7-0.8 (natural ventilation, high absorption). Outside-inside private office (door open, casual voice) = 0.7;
- Noise Isolation: into closed offices = NIC 25-30 (door closed), = NIC 9-15 (door open); between work areas = NIC 7-20.

Design implications

The main acoustical design implications of the results related to low background-noise levels, inadequate speech privacy, excessive reverberation, inadequate noise isolation between workplaces in open and shared work areas, and inadequate internal and external wall isolation. Following are details, divided into 'universal' issues applicable to any building, and specific 'green'-building issues:

'Universal' design issues:

- a design approach that assumes that acoustical issues are minimal and can be dealt with using the non-specialist knowledge of the design team, may not result in occupant satisfaction with the acoustical environment;
- locating an office building next to an external noise source makes noise complaints likely;
- operable windows significantly reduce the sound isolation provided by the building envelope, resulting in noise complaints;
- adequate sound isolation from outside to inside offices requires good acoustical design;
- shared offices inevitably lead to speech-privacy concerns. Private offices readily provide adequate speech privacy;
- open-plan office areas are acoustical challenges that require good acoustical design; the required speech privacy depends partly on the expectation and activities of the occupants;
- buildings with insufficient sound-absorbing materials have excessive reverberation, resulting in an acoustical environment which feels 'noisy', in which intermittent sounds (e.g., telephone ringing, door slams) are distracting, and which impairs verbal communication; it also results in low sound isolation between different work areas, allowing sound to propagate with little attenuation between them, causing noise problems;

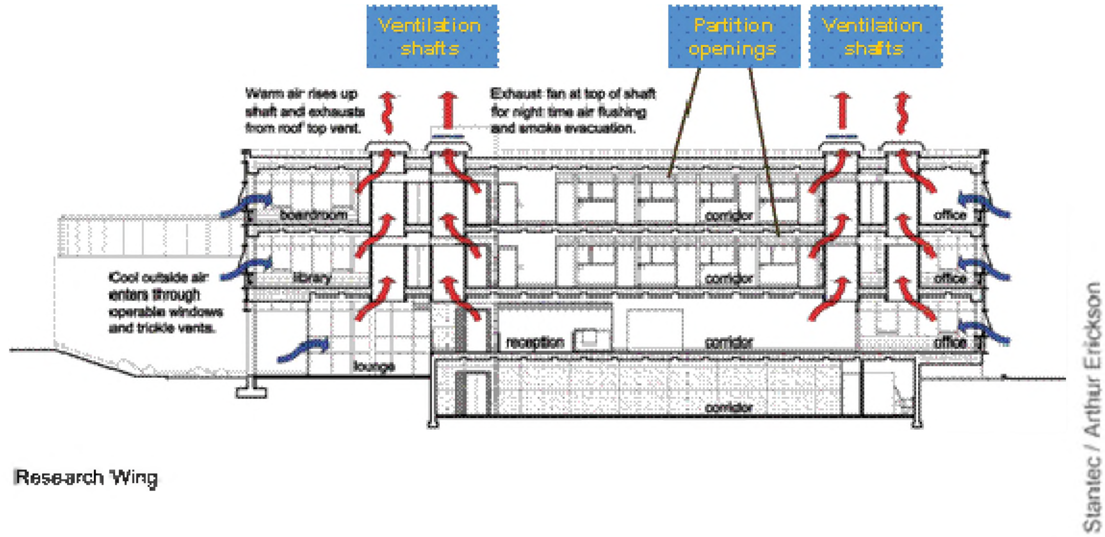

Figure 3: Elevation of the Liu building, showing components of its natural-ventilation system.

- one of the buildings housed an elementary school; school classrooms are acoustically critical spaces that require careful attention to the acoustical design—in particular, with respect to building, school and classroom layout, HVAC and equipment noise levels, noise isolation to adjacent spaces and reverberation times (consult ANSI Standard S12.60-2002 for more details).

'Green'-building design issues:

- since LEED® virtually ignores acoustics, a building designed to obtain LEED® certification is unlikely to have adequate attention paid to the acoustical environment;
- 'green' buildings often are designed to have natural/displacement ventilation systems. These can affect the acoustical environment beneficially or detrimentally, resulting in low background-noise levels and low noise isolation. However, forced-air ventilation *can* figure in 'green'-building design;
- many 'green' buildings have few sound-absorbing materials. This affects the acoustical environment detrimentally, resulting in excessive reverberation, low acoustical privacy and inadequate attenuation of sound propagating through the building. However, beneficial sound-absorbing materials *can* figure in 'green'-building design;
- since LEED® virtually ignores acoustics, a building designed to obtain LEED® certification is unlikely to have adequate attention paid to the acoustical environment;
- if a 'green' building, designed with a ventilation system relying on operable windows, is located next to significant noise source, noise problems are likely, especially if the windows open on the source side;
- a 'green' building designed to rely on a natural or displacement ventilation system, and with a transparent envelope for day-lighting, may overheat on hot, sunny days, forcing occupants to open windows and doors, causing excessive noise and low speech privacy;
- background-noise levels in a 'green' building with ful or partial natural-ventilation system may be lower thai as expected in a conventional building with a forced-ai system; these low levels may make it more difficult t achieve adequate speech privacy;
- a 'green' building designed to rely on a natural ventilation system usually involves air-transfe openings and/or ducts in partitions; these reduce nois isolation between areas, even when treated acoustically

3. ACOUSTICAL EVALUATION OF THI UBC LIU BUILDING

A detailed study was next made of one particular 'green office building—the naturally-ventilated, three-storey offic block of the Liu building on the UBC campus—no involved in the original study. Figure 3 is an elevatio drawing showing components of the natural-ventilatio system. Liu was again evaluated by occupant survey an acoustical measurement.

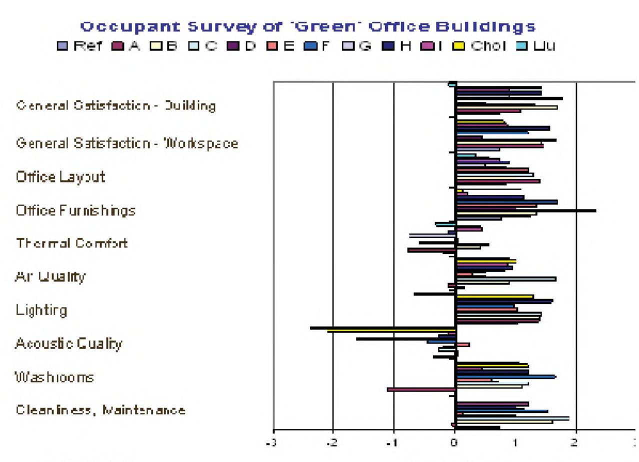

Figure 4: Occupant-satisfaction survey results for eleven 'green' office buildings, including Liu (and Choi).

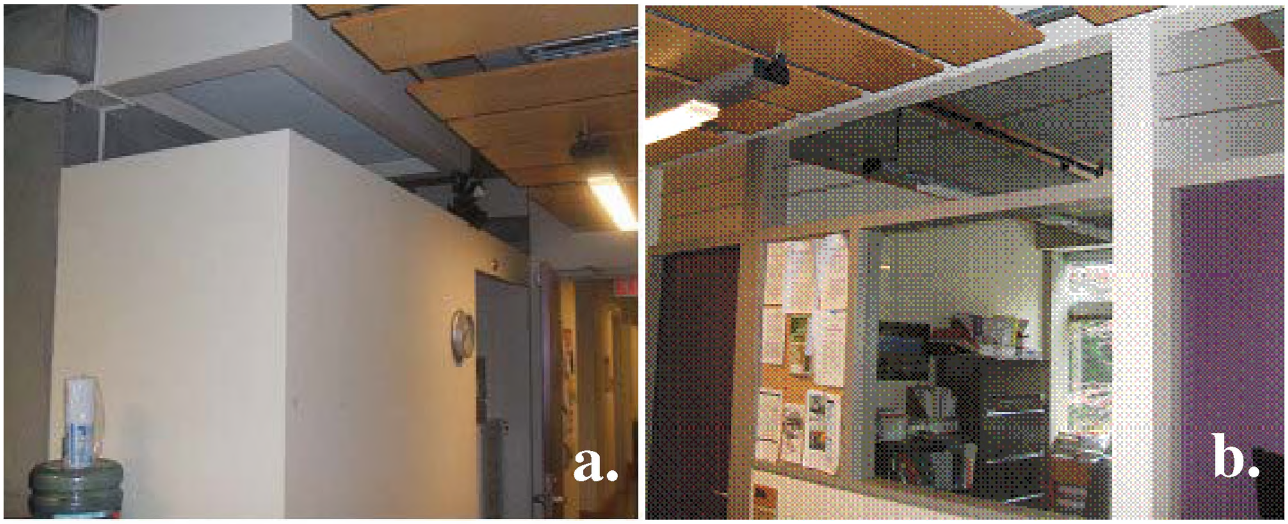

Figure 5: Liu building natural-ventilation system: (a) shafts and floor openings; (b) office/corridor openings.

3.1 Occupant-Satisfaction Survey

Figure 4 shows the occupant-satisfaction results of Figure 2, with those for the Liu building—and for the adjacent, similarly naturally-ventilated Choi building and several othr 'green' buildings—added. Of particular note is the extremely low satisfaction with acoustical quality in these two buildings.

The results of the occupant-satisfaction survey and preliminary acoustical measurements showed that two main acoustical problems in the Liu building, which are main sources of dissatisfaction with the acoustical quality, are:

- poor sound isolation between building floors due to sound transmission through ventilation shafts and natural-ventilation openings in the floor/ceiling slabs (see Figure 5a);
- poor sound isolation between offices and corridors on the 2nd and 3rd floors due to 45-cm-high natural-ventilation openings in the separating partitions (see Figure 5b).

Thus, more detailed acoustical measurements were made between floors in the vicinity of the north-end pair of ventilation shafts and floor/ceiling openings, and between a third-floor office and the adjacent corridor.

3.2 Acoustical-Parameter Measurements

The acoustical parameters described in Table 1 were again measured in various locations at the north end of the Liu building before treatment, and the results were compared with the same acceptability criteria. Table 2 shows the NIC and SII values measured between floors at the Liu north end. Table 3 shows the NIC and SII values measured between an office and the adjacent corridor (with door closed).

The noise isolation between offices on the first and second floors was an inadequate NIC 22-25; that between offices on the first and third floors was an adequate NIC 34-46. It was concluded, not surprisingly, that the ventilation shafts and floor/ceiling natural-ventilation openings have a significant effect on the transmission of sound energ between floors. The exact noise isolation obtained depend on the relative source and the receiver positions, and thos relative to the ventilation shafts.

Measured values of Speech Intelligibility Index ar presented in Table 2. Between adjacent floors, SII wa borderline acceptable with a normal voice, but unacceptabl with a raised voice. When the source and receiver wer separated by two floors, SII was quite acceptable.

Table 3 shows the analogous NIC and SII result between the office and the adjacent corridor. The nois isolation is a very inadequate NIC 10. Even with a casua voice, speech privacy is very low; in fact, with normal voic the SII corresponds to acceptable speech intelligibility!

In summary, the measured NIC and speech privac values for offices on the north end of the corridors wer lower than desirable in key cases and acceptable in others Those between the office and corridor were unacceptable.

4. DESIGN AND EVALUATION OF NOISE CONTROL MEASURES FOF NATURAL-VENTILATION OPENINGS IN THE LIU BUILDING

4.1 Objectives

Following the acoustical evaluation of the Liu building, project was initiated to find engineered noise-contro solutions to the identified problems. Given the NIC and SI results, and the available budget, it was decided to target th pair of north-end ventilation shafts, and one office partition The objective was to design and install noise-contro devices with adequate acoustical performance, subject t ventilation constraints, and then evaluate the performanc by acoustical measurement.

4.2 Noise-Control Concepts, Constraints, Criteria

Preliminary meetings held to discuss feasible design con

Table 2: NIC and SII measured between floors at the Liu north end, before treatment.

Source	Receiver	Noise Isolation Class, NIC (dB)	Speech Intelligibility Index (SII)		
			Casual voice	Normal voice	Raised voice
First-floor office	Office, second floor	25	0.03	0.20	0.42
	Office 1, third floor	37	0.00	0.08	0.30
	Office 2, third floor	41	0.00	0.07	0.29
	Corridor, third floor	27	0.01	0.14	0.36
Second-floor office	Office 1, first floor	22	0.04	0.20	0.42
	Office 2, first floor	25	0.06	0.22	0.43
	Office 1, third floor	34	0.00	0.07	0.28
	Office 2, third floor	46	0.00	0.03	0.24
	Corridor, third floor	23	0.01	0.12	0.33

Table 3: NIC and SII measured between Office 310 and the corridor, before treatment.

Source	Receiver	Noise Isolation Class, NIC (dB)	Speech Intelligibility Index (SII)		
			Casual voice	Normal voice	Raised voice
Office 310	Corridor	10	0.44	0.57	0.67

cepts, the constraints on the design, and design evaluation criteria, came to the following conclusions:

- Ventilation shafts—feasible acoustical treatments could involve lining the internal surfaces of the ventilation shafts, and/or suspending sound-absorbing baffles in them; of course, these treatments are reminiscent of ventilation-duct linings and acoustical louvers;
- Office partition—the noise-control concept that was chosen was to create an acoustically-lined,, Z-shaped silencer in the natural-ventilation opening; this is similar to the concept of the transfer silencer, already used in naturally-ventilated 'green' buildings;
- Constraints—it was, of course, not acceptable in this 'green' building to excessively compromise natural-ventilation airflows through the silencers; preliminary airflow modelling imposed the design constraint that the treatment of the ventilation shafts could not reduce their cross-sectional area by more than 25%; as for the partition opening and lined, Z-shaped silencer, a minimum airflow-path dimension of 125 mm had to be maintained;
- Acceptability/design criteria—the noise isolation design target was again NIC 30-35 for general offices and 35-40 for private office; as for speech privacy, SII < 0.2 was deemed acceptable.

4.3 Ray-Tracing Prediction

A ray-tracing room-prediction tool was used to create a virtual model of the three floors of the north end of the Liu building with its ventilation shafts and floor/ceiling ventilation openings (see Figure 6), and to predict the noise isolation between floors. Note that this was an energy-based model intended for rooms with dimensions much greater than the sound wavelength; in the case of sound propagation through shafts and openings with dimensions which are not large compared to the wavelength, high prediction accuracy is not guaranteed.

The building model was validated by comparing the predicted noise isolation with that measured in the untreated building. Figure 7 shows the results, which are generally within 5 dB, suggesting the model is reasonable.

Ray tracing was then used to predict the noise isolation between floors for various engineered noise-control measures involving acoustical lining of the ventilation shafts, or a combination of lining and various configurations of absorbent baffles suspended in the shafts. Figure 8 shows the results for various control measures and source and receiver positions.

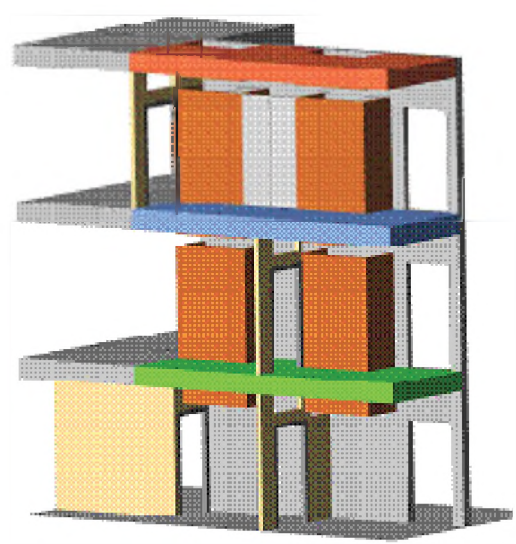

Figure 6: The ray-tracing virtual building model with (front and side walls removed).

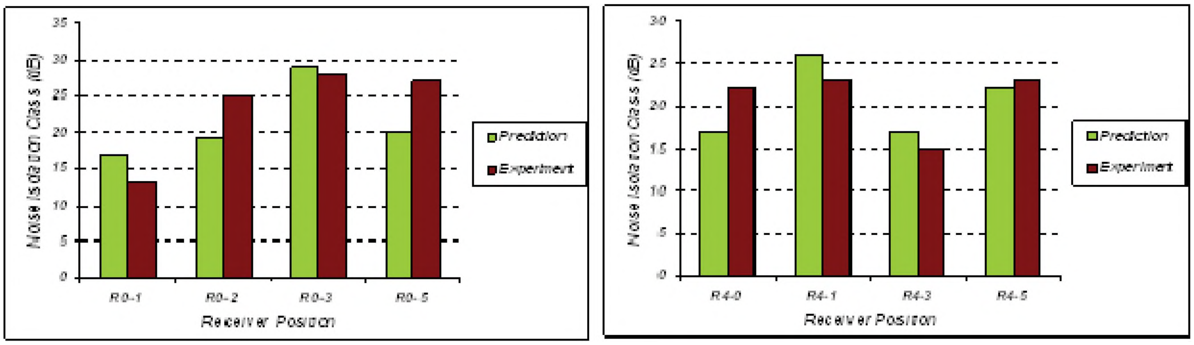

Figure 7: Measured and predicted noise isolation (NIC) between floors of the Liu building: (left) source on first floor, (right) source on second floor.

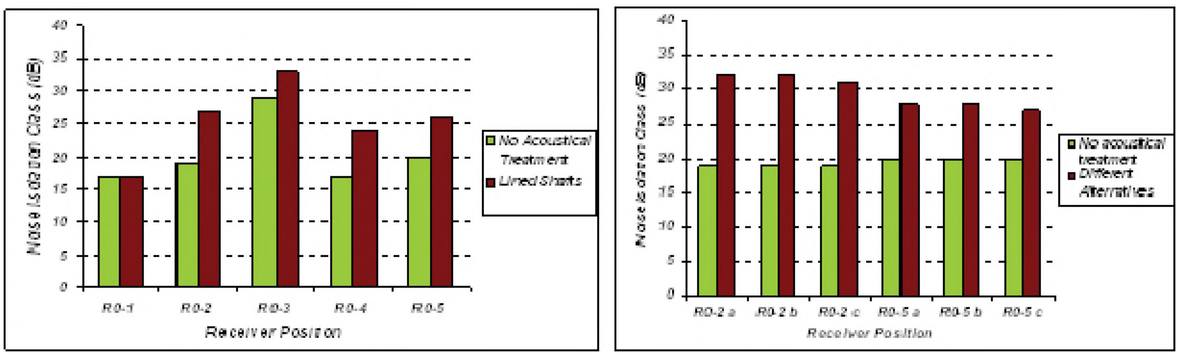

Figure 8: Ray-tracing predicted noise isolation (NIC) between floors of the Liu building without and with engineering-control measures: (left) ventilation shaft absorbent lining; (right) lining plus suspended baffles; a. 32 baffles (high α) in the opening between floors; b. 32 baffles (high α) located at the top of the ventilation shafts; c. 32 baffles (typical α) located at the top of the ventilation boxes).

Prediction modelling was also used by Stantec to optimize the design of the office-partition lined, Z-shaped silencer; the results are presented elsewhere [31].

4.4 Control Measures Implemented

Considering the results of the predictions, the final design of the noise-isolation system for ventilation shafts chosen for implementation was as follows:

1- Lining the inner surfaces of the lower boxes on the second and third floor shafts with 50-mm-thick acoustical liner;
2- Lining the inner surface of the upper boxes on the first and second floor shafts with 25-mm-thick acoustical liner;

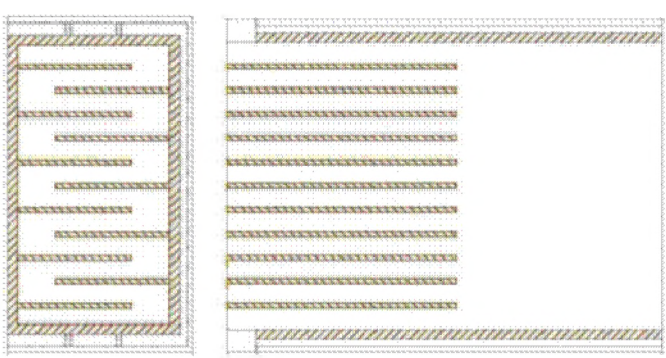

Figure 9: Drawing of the lining and baffle configurations that were installed in two pairs of ventilation shafts in the Liu building.

3- Locating baffles in the second and third floor ventilation shafts as follows: number of baffles: 11; baffle dimensions: 25 x 400 x800 mm^3.

Figure 9 shows a drawing of the linings and baffles that were installed in the two pairs of north-end ventilation shafts on the second and third floors. Lining alone was installed in one of each pair, and lining and baffles in the other (to allow their independent evaluation). Figure 10 is a drawing and photographs of the lined, Z-shaped silencer installed in the Liu office-partition opening.

4.5 Results

The noise isolation and Speech Intelligibility Index were re-measured after treatment. The results are shown in Tables 4 and 5, along with the changes due to the treatments. The ventilation-shaft lining and baffles increased the noise isolation to NIC 39-56 (increase of NIC 15-23). The lined, Z-shaped silencer in the partition opening increased the noise isolation to about NIC 25 (increase of NIC 15).

4.6 Airflow and Air-Quality Measurement

To investigate the effect of the office-partition silencer on airflows and air quality, the following quantities were measured (by Dr. Karen Bartlett, UBC) before and after treatment:

- room volume, temperature and relative humidity;
- air changes (ACH)/hour, windows closed/open => calculate air flow (cfm)/person;

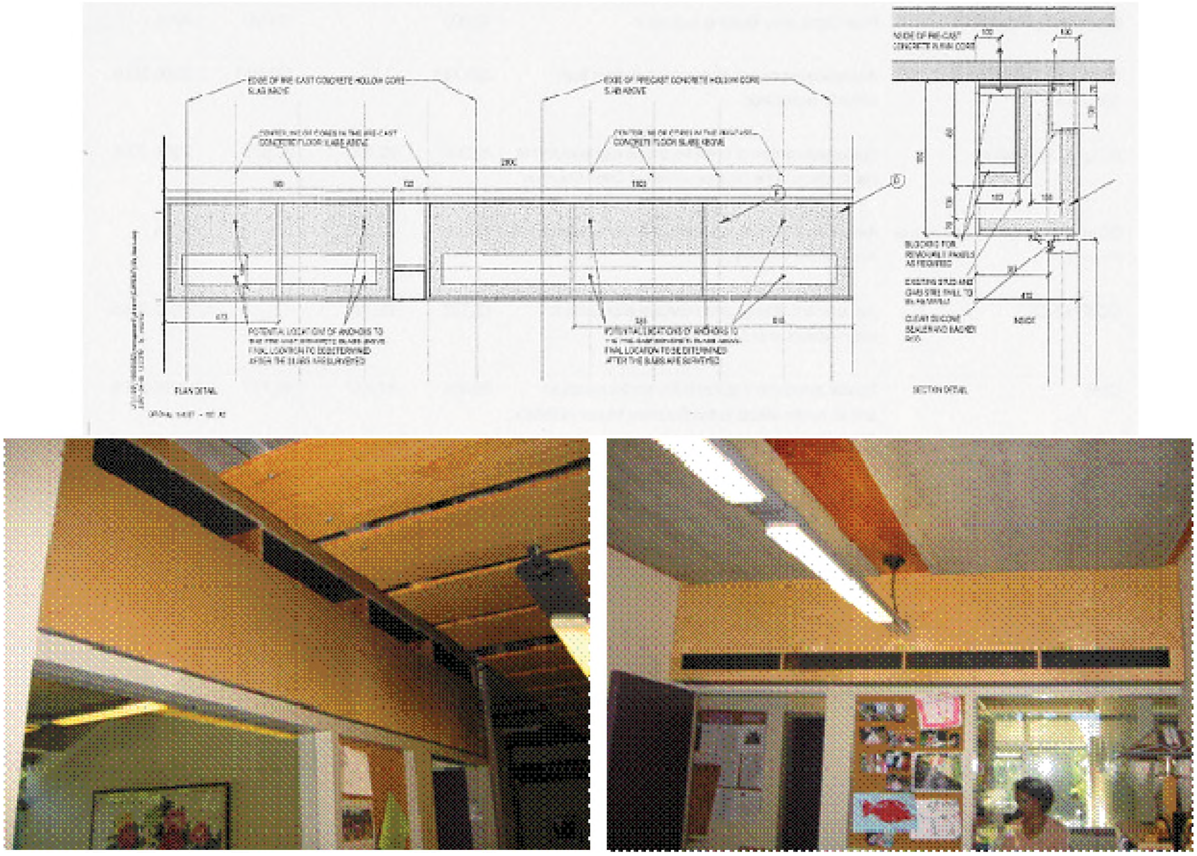

Figure 10: Drawing and photographs of the lined, Z-shaped silencer installed in the Liu office-partition opening.

- fibre concentration (fibres/ml);
- ratio of indoor-to-outdoor fungal-spore concentration (CFU/m^3).

The results are shown in Table 6. To determine the acceptability of the results, they were compared with the following values recommended by ASHRAE: ACH > 10–15 (depending on situation); cfm/person > 17.

It was concluded that no deterioration of air flows or air quality due to the acoustical treatment was measured. However, this may be explained at least in part by the fact that airflows in the untreated building were very low and could not be reduced much by treatment.

4.7 Summary

Following is a summary of the main conclusions of the study of the effectiveness of the engineering-control measures:

- Ventilation-shaft lining and baffles—the noise isolation increased to NIC 39-56 (increase of NIC 15-23); lining

Table 4: NIC and SII measured between floors at the Liu north end, after treatment, and changes.

Source	Receiver	Noise Isolation Class, NIC (dB)	ΔNIC (dB)	Speech Intelligibility Index (SII)					
				Casual voice	ΔSII	Normal voice	ΔSII	Raised voice	ΔSII
First-floor office	Office, second floor	40	+15	0.00	-0.03	0.05	-0.15	0.12	-0.30
	Office 1, third floor	56	+19	0.00	0.00	0.02	-0.06	0.05	-0.25
	Office 2, third floor	56	+15	0.00	0.00	0.01	-0.08	0.02	-0.27
	Corridor, third floor	50	+23	0.00	-0.01	0.01	-0.13	0.05	-0.31
Second-floor office	Office 1, first floor	39	+17	0.00	-0.04	0.02	-0.18	0.05	-0.37
	Office 2, first floor	45	+20	0.00	-0.06	0.02	-0.20	0.06	-0.37
	Office 1, third floor	46	+12	0.00	0.00	0.01	-0.06	0.04	-0.24
	Office 2, third floor	52	+ 6	0.00	0.00	0.01	-0.02	0.05	-0.19
	Corridor, third floor	43	+20	0.00	-0.01	0.01	-0.11	0.15	-0.28

Table 5: NIC and SII measured between Office 310 and the corridor, after treatment, and changes (Δ).

Source	Receiver	Noise Isolation Class, NIC (dB)	Δ NIC (dB)	Speech Intelligibility Index (SII)					
				Casual voice	ΔSII	Normal voice	Δ SII	Raised voice	Δ SII
Office 310	Corridor	24	+14	0.04	-0.40	0.18	-0.39	0.38	-0.29

Table 6: Results of air-flow and air-quality measurements in the Liu building before and after treatment (K. Bartlett).

Case	Room	Volume (ft^3)	Temp (deg C)	RH (%)	ACH closed	ACH open	cfm/person (closed)	fibres/ ml	CFU/m^3 (in/out)
Before treatment	302	1683.8	22.4	46.2	0.55	0.92	15.6	0.004	0.85
	309	1288.9	36.5	36.5	0.63	7.20	13.5	0.009	1.09
	312	864.3	41.1	41.1	0.88	3.20	11.6	0.007	1.04
After treatment	302	1683.8	22.0	57.0	0.16	1.43	4.5	0.007	0.65
	309	1288.9	22.6	57.1	0.99	5.00	21.3	0.005	0.46
	310	1149.0	23.4	56.5	0.47	6.90	9.0	0.008	0.61

and baffles together are too effective; further invest-tigations suggest that baffles alone might be the most cost-effective treatment;

- Partition-opening lined, Z-shaped silencers—the noise isolation increased to about NIC 25 (increase of NIC 15); the design criteria was not met; the Z-shaped silencer is apparently too short (due to space limitations?);
- Air flow, quality—no significant effect was measured (due to inadequate ventilation before treatment?).

5. DISCUSSION

The acoustical evaluation of 'green' office buildings has shown that occupants are often highly dissatisfied with the acoustical environment—in particular, with low speech privacy resulting from inadequate sound isolation between work areas. This results, for example, from the open-office design, inadequate sound absorption, and natural-ventilation openings in walls, floors and ceilings. Prioritizing obtaining 'green'-building ratings (e.g., LEED® ratings), and inadequate budget allocations for acoustical treatment, exacerbate the problems.

Detailed study showed that low sound isolation because of natural-ventilation openings is the main source of acoustical problems in the UBC Liu building (and Choi next door), leading to very low occupant satisfaction with the acoustical quality. Devices—essentially specially designed silencers with linings and/or baffles—were designed, installed and evaluated, and found to be effective, but not optimal. This demonstrates that engineered noise-control solutions can resolve acoustical problems in 'green' buildings. However, the desire, expertise and financial resources must be available for the benefits of these solutions to be realized.

'Green' buildings have other acoustical issues that were not specifically involved in the buildings discussed here. One is inadequate sound absorption due to thermal ceiling slabs (which cannot be obstructed by suspended acoustical ceilings) [32]. This problem also occurs because of the perception that many sound-absorbing materials are not 'green'. There is a great need to develop 'green' sound-absorbing materials, and work to do so is already underway [6, 12, 18, 21]. Life-cycle analysis can be used to determine the sustainability of building designs, and of their construction materials, including sound absorption [33].

Designers must remember that the various components of a building—thermal, ventilation, structural, acoustical, lighting, etc.—affect one another. Using extensive glazing in the envelope enhances natural day-lighting, but may cause glare, can negatively affect the thermal environment, and can reduce sound isolation and cause noise problems, especially if operable windows, or enclosed-office doors, are opened for ventilation. A recent pilot study [20] investigated the relationship between ventilation, air and acoustical qualities in 'green' and non-'green' buildings, finding that forced-air ventilation gives better indoor-air quality (IAQ), but higher ventilation-system noise levels, that IAQ and noise level are directly related, that in naturally-ventilated spaces with radiant ceiling slabs, lack of acoustical treatment gives lower fibre concentrations, but worse acoustical conditions, that naturally-ventilated spaces have unsatisfactory ventilation quality but acceptable noise levels with the windows closed, and satisfactory ventilation quality but excessive noise levels with the windows open (even without significant external noise sources), that naturally-ventilated spaces with few furnishings or sound-absorbing materials have higher IAQ, and that acoustical treatment can enhance acoustical quality, but worsens IAQ. 'Green'-building design must take an integrated, holistic approach.

As acousticians, we have a responsibility to help designers create buildings with acoustical environments which satisfy the occupants, and promote their health, well-being and productivity. Unfortunately, our advice is not always requested or followed due to ignorance, other priorities and financial constraints. So, what more can we do to achieve occupant satisfaction with acoustical quality in 'green' buildings? Here are a few ideas:

- make acoustics a mandatory component of the education of students who may become building designers;
- raise awareness of acoustical issues in 'green' buildings;
- educate 'green'-building designers in acoustical issues;
- ensure good acoustics is a priority in 'green'-building design;
- ensure that acoustical quality is valued in LEED® and similar 'green'-building rating schemes [9, 17, 22];
- include acoustical expertise at the design stage of all 'green' buildings;
- do research to investigate and resolve acoustical issues (e.g. perform more occupant-satisfaction surveys, develop better prediction tools, better design criteria, optimal noise-control measures);
- start focused programs on 'green'-building design for engineers, architects, teachers, policy-makers and others.

6. CONCLUSION

The aim of sustainable ('green') building is to create buildings that preserve the environ-ment and conserve natural resources, as well as to provide a 'healthy' environment for its occupants. Designing a building to preserve the environment and conserve resources is admirable and essential, but it must not be done to the detriment of the occupants, who will live and work in the building.

The acoustical environment is often judged the least satisfactory aspect of 'green' office buildings by the occupants. They are dissatisfied with excessive noise and poor speech privacy, and consider that the acoustical environment does not enhance their ability to work (i.e. productivity). Speech privacy is often the biggest concern.

The results of this work suggest that improving acoustical environments in 'green' buildings fundamentally requires good acoustical design—that is, the application in design of existing knowledge, with input from an acoustical specialist from the beginning of the design process. This knowledge relates to site selection and building orientation, to the design of the external envelope and penetrations in it, to the building layout and internal partitions, to the design of the HVAC system, to the appropriate dimensioning of spaces, and to the amount and location of sound-absorbing treatments. For a satisfactory acoustical environment, the advice of the acoustical specialist must be followed, and the budgetary resources made available for it to be realized.

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