# DETERMINING APPROPRIATE ACOUSTIC DESIGN CRITERIA FOR SUSTAINABLE OFFICE BUILDINGS

C Field Arup, Sydney, Australia

## 1 INTRODUCTION

Natural ventilation is widely accepted as a sustainable design strategy for buildings. The use of natural ventilation in buildings often conflicts, however, with the control of ingress of external noise via the façade because of the need to provide ventilation openings. In addition, national noise standards provide recommended guidelines for internal background noise limits for building use based on the assumption that the buildings can be sealed and air-conditioned, and therefore external noise ingress can be controlled by the façade construction.

In many projects, the use of natural ventilation is considered infeasible because of noise issues—either because the perceived high-noise environment cannot be controlled with practical measures to the noise level limits recommended in national standards, or that the capital cost of noise mitigation measures outweighs the benefits of natural ventilation.

The intent is to challenge the use noise level limits presented in national standards with respect to the need to provide a compromise to meet other non-acoustic sustainability goals.

## 2 ACOUSTIC DESIGN CHALLENGES POSED BY SUSTAINABLE BUILDING DESIGN INITIATIVES

Sustainable design considerations listed in green building rating systems can introduce the following acoustic design challenges.

Indoor Environmental Quality (IEQ) credits related to the use of natural ventilation in buildings conflict with the control of ingress of external noise through ventilation openings to meet internationally recognized background noise limits for building use.

The use of passive cooling systems such as radiant flooring and exposed thermal mass of ceilings may conflict with the use of acoustically absorptive floor and ceiling finishes to control reverberance and occupational noise levels (therefore controlling distraction and annoyance to nearby occupants). Acoustic finishes also assist in achieving adequate speech intelligibility within office buildings.

The use of daylighting is also an important sustainable design factor. Occupant productivity and well-being is enhanced with direct connection between indoor and outdoor spaces1. This is achieved with the use of lower partition heights, interior light shelves and interior glazing. The benefit is quantified by achieving a minimum percentage floor area illuminated by natural daylight.
The consequence of lower partition heights, light shelves and the use of interior glazing, however, is the increase in noise disturbance to workers seated at open plan workstations, and reduced acoustic privacy in meeting rooms using glazed walls. These effects are due to the use of lower partition and workstation heights, the acoustic barrier effect provided by these elements is lost, resulting in increased propagation of noise from occupants throughout open plan offices. Light shelves are often hard and reflective acoustically, resulting in the increase of discrete sound reflections within the building. For private offices and meeting rooms, glazed walls, used to allow daylight penetration, have lower sound insulation performance compared to conventional plasterboard and stud partitions.

To a lesser degree, the encouraged use of recycled content in materials poses difficulties for acoustic design due to the lack of choice of recycled materials that provide the required acoustic properties. In addition, non-fibrous alternatives are now being more widely considered as a replacement for traditional fiberglass. Examples include packless silencers which do not include any fibrous sound absorbing media and closed cell foam duct liners which are manufactured using more environmentally friendly processes. The acoustic performance of these alternative products, however, is generally lower or cost significantly more than the fibrous products.

# 3 CAN WE USE THE THERMAL COMFORT ASSESSMENT APPROACH USED IN GREEN BUILDING RATING SYSTEMS FOR ACOUSTIC DESIGN?

Green building rating systems[2,3,4] include credits for high levels of thermal comfort in office buildings. Different assessment criteria are specified depending on whether the building is naturally ventilated or mechanically ventilated. For example, Greenstar[3] stipulates that for naturally ventilated buildings, the 80% and 90% acceptability limits set out in ASHRAE Standard 55-2004[5] must be complied with to achieve one credit and two credits respectively. The acceptability limits are calculated using an adaptive thermal comfort model derived from a global database of over 21,000 measurements taken primarily in office buildings.

For mechanically ventilated buildings, the Predicted Mean Vote (PMV) levels calculated in accordance with ISO7730-2005[6] are used as the basis for compliance (ASHRAE Standard 55-2004 also proposes this PMV method for mechanically ventilated buildings).

The reason for using separate assessment criteria for natural ventilation and mechanical ventilation is explained in ASHRAE Standard 55-2004 by stating that occupants' in naturally ventilated spaces have "different thermal experiences, changes in clothing, availability of control, and shifts in occupant expectations".

ISO7730-2005, Section 10, also states "extended acceptable environments may be applied for occupant-controlled, naturally conditioned, spaces in warm climate regions or during warm periods, where the thermal conditions of the space are regulated primarily by the occupants through the opening and closing of windows. Field experiments have shown that occupants of such buildings could accept higher temperatures than those predicted by the PMV".

Therefore, taking the different assessment approaches to assessing thermal comfort in green building rating systems as an example, should separate acoustic design criteria be specified for naturally ventilated buildings and mechanically ventilated buildings and should acoustic criteria be further re-evaluated to more appropriately take account of the ability to control one's acoustic environment?

Re-evaluating acoustic criteria does not necessarily have the underlying aim of reducing noise levels in indoor environment in office buildings so that they are not noticeable. The preferred approach is to provide a "comfortable" acoustic environment while facilitating the other sustainable design elements of office buildings including:

- natural ventilation
- natural daylight
- reduced energy consumption
- increased use of recycled and renewable materials
- individual control of the working environment to enhance productivity.

The definition of "comfortable" must be carefully considered while facilitating these non-acoustic sustainable design elements. The discussion presented here focuses on a suitable acoustic environment to facilitate the use of natural ventilation in office buildings. As a compromise for the non-acoustic benefits natural ventilation provides, alternative approaches are offered to challenge noise level standards already set for sealed, air-conditioned buildings.

# 4 ACOUSTIC CRITERIA USED IN THE PAST

## 4.1 Standards and guidelines for mechanically ventilated buildings

As a point of reference for establishing design criteria for naturally ventilated buildings, recommended background noise levels for unoccupied office spaces provided by three nationally recognised guidelines are given in Table 1.

Table 1: Recommended background noise limits for unoccupied mechanically ventilated spaces

| Occupancy Type | BS8233[7] ($L_{Aeq}$, dB) | | AS2107[8] ($L_{Aeq}$, dB) | | ASHRAE[9] (NC)[1] | |
|---|---|---|---|---|---|---|
| | Satisfactory | Maximum | Satisfactory | Maximum | Satisfactory | Maximum |
| Private Office | 35 | 40 | 40 | 50 | 25 | 35 |
| Meeting Room | 30 | 40 | 35 | 40 | 25 | 35 |
| Open Plan Office | 40 | 45 | 45 | 50 | 30 | 40 |

1. For comparison purposes, the NC rating is typically 5 dB below the $L_{Aeq}$

In summary, for open plan offices, a typical background noise limit of 40 - 45 $dBL_{Aeq}$ is recommended and for private offices and meeting rooms, a typical background noise limit of 30 – 35 $dBL_{Aeq}$ is recommended.

## 4.2 Acoustic Criteria Currently Used in Green Building Rating Systems

Acoustic criteria used in green building rating systems generally reference national guidelines and standards intended for mechanically ventilated buildings. No specific acoustic criteria for naturally ventilated buildings are given.

The Green Building Council of Australia includes a credit in their rating system, Greenstar – Office Design and Office As Built[3], for meeting the recommended background noise levels given in AS2107-2000 (and reproduced in Table 1 above).

The US Green Building Council's rating system LEED®-NC[2] does not currently offer a credit for limiting background noise levels in offices.

The Building Research Establishment in the UK includes a credit in their rating system, BREEAM Offices[4] to "ensure the acoustic performance of the building meets the appropriate standards for its purpose". The acoustic criteria referred to generally follow the recommendations of BS8233-1999 and are reproduced in Table 1 above.

These green building rating systems have adopted internal acoustic criteria usually applied to mechanically ventilated buildings without consideration given to natural ventilation strategies usually employed in these buildings. Obtaining the acoustic credits in the respective green building rating systems are therefore unachievable in most practical building locations due to noise ingress via the large areas of façade open areas required to achieve the natural ventilation credits.

# 5 ESTABLISHING ALTERNATIVE CRITERIA USING SUBJECTIVE ASSESSMENTS

As a starting point for establishing more suitable design criteria for naturally ventilated buildings, subjective assessments were carried out. Two separate subjective assessments were carried out in a controlled acoustic environment to determine the effect of traffic noise ingress via naturally ventilated facades on speech intelligibility and task distraction. The goal was to determine the traffic noise level at which speech intelligibility in offices was impaired and occupants are distracted from their usual tasks.

The key points and conclusions from the subjective assessments are presented below. Details regarding assessment methodology and experimental set-up have not been included, but are available on request.

## 5.1 Assessment Assumptions

Some assumptions were made during the assessments in the interest of achieving some meaningful conclusions. The assumptions were follows:

- 5 min noise source recordings taken were representative of typical street activities in Manhattan, New York, with no preference given to particular intermittent noise events or absence thereof.
- The assessments were carried out for a one-off configuration of open window area, distance from the window and elevation of the window above the principal noise sources.
- The window was sufficiently open so that the principal transmission path for external noise was via the opening.
- Assessments were carried out in the Arup SoundLabs in New York and San Francisco. This is a controlled acoustic environment with low background noise level and reverberation time.

For the assessment of speech intelligibility:

- The goal for the assessment was restricted to assessing speech intelligibility levels in offices affected by external noise sources, and does not account for internal office activity noise sources.
- The speech level used in presenting word score lists for subjective testing was calibrated and normalized to 68 $dBL_{Aeq}$ at 1 m on axis.
- Speech intelligibility has been assessed in terms of the Articulation Index (AI).

For the assessment of task distraction:

- Subjects were instructed to perform both written and arithmetic tasks using a computer workstation situated in the middle of the SoundLab.
- Participant data was collected to document fluctuations in both the accuracy of completed written and arithmetic tasks and the time taken to complete it. The data was analyzed in such a way that trends in these fluctuations could be discovered as a function of background noise level.

## 5.2 Speech Intelligibility Assessment

### 5.2.1 Outline Methodology

The aim of the assessment was to use subjective word tests to ascertain the level of impairment of speech intelligibility in the presence of external background noise entering office buildings via natural ventilation openings. Traffic noise recordings measured internally were varied in 3 dB increments to determine the sound pressure level at which the level of speech intelligibility in offices would be unsatisfactory.

### 5.2.2 Testing Procedure

1) A series of 5 min recordings were carried out using a Soundfield microphone in downtown New York. The measurement position was 1 m from the open window inside a private office.

2) Stimulus word lists were generated by a trained female speaker, at a calibrated level in the Arup Acoustics NY SoundLab. Modified Rhyme Tests (MRT) were carried out in accordance with ANSI S3.2-1989[10]. The word lists were played back to 15 test participants using a single loudspeaker (mono) located directly in front of the listener at a distance of 2 m. The level of reproduced speech at the listening position was 59 $dBL_{Aeq}$, measured during playback of the entire MRT set of 500 words.

3) A randomized playback system for the word lists was developed with a MATLAB script and a graphical user interface was used to facilitate the tests.

4) The calibrated noise recordings were played back during the balanced word score tests via a 12 loudspeaker ambisonic set-up in the Arup Acoustics NY SoundLab.

5) A 20 word MRT was carried out for 9 randomized increments of recorded background traffic noise level to ascertain the impairment of speech intelligibility as the level of traffic noise changes.

6) The level of speech intelligibility (SI) was quantified by the % of correct words, in accordance with ANSI 3.2-1989[10]. The SI values were then converted to equivalent values of Articulation Index (AI) using the method given by AS 2822-1985[11].

7) The % of correct words was correlated with a "good" standard of speech intelligibility (AI > 0.45) expected for satisfactory office communication[11].

8) The internal break-in noise level limit ($L_{Aeq}$) appropriate for speech intelligibility in naturally ventilated office spaces was then determined.

### 5.2.3 Results and Discussion

The results of the subjective testing are given in Figure 1 below.

The results in Figure 1 indicate an AI > 0.45 is achieved for an internal noise level of 59 $dBL_{Aeq}$ or a signal to noise ratio of 0.6.

The results demonstrate that the allowable level of external noise break-in to naturally ventilated buildings could be set higher than for sealed and mechanically ventilated buildings, whilst still maintaining a good level of speech intelligibility within office spaces. This provides opportunities for introducing practical and less stringent noise mitigation measures, if necessary, for naturally ventilated buildings at a reasonable cost in the context of the building construction budget.

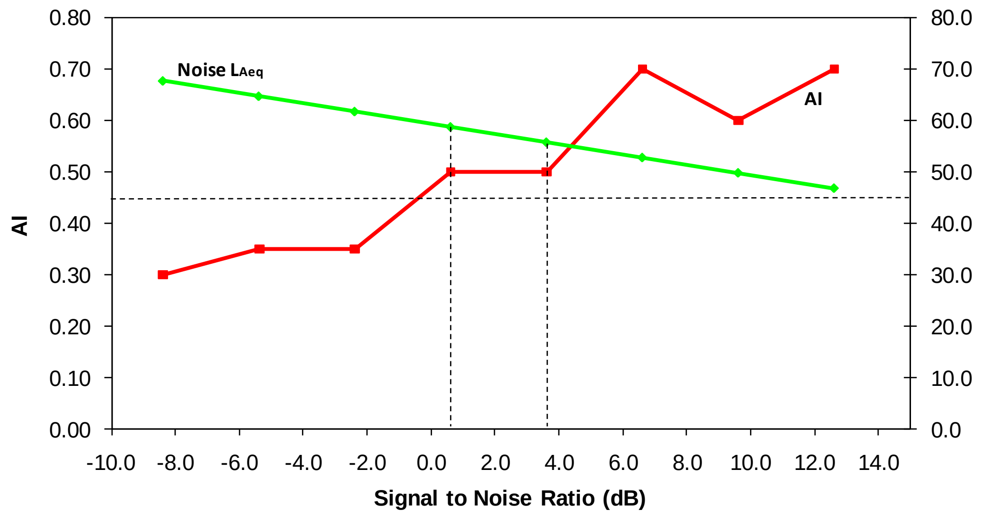


Figure 1: Results of articulation index (AI) for various background noise levels

## 5.3 Task Distraction Assessment

### 5.3.1 Outline Methodology

Participants were exposed to calibrated levels of pre-recorded traffic noise through a naturally-ventilated façade. Subjects were instructed to perform both written and arithmetic tasks using a computer workstation situated in the middle of the SoundLab.

Data was collected to document fluctuations in both the accuracy of the completed task and the time taken to complete it. The data was analyzed in such a way that trends in these fluctuations could be discovered as a function of background noise level.

### 5.3.2 Testing Procedure

1) Thirty-three people (all Arup employees) participated in the subjective test.

2) The calibrated noise recordings were played back during the tests via a 12 loudspeaker ambisonic set-up in the Arup Acoustics San Francisco SoundLab.

3) Each written and arithmetic test was carried out for 9 randomized increments of recorded traffic noise level to ascertain the level of distraction from completing the task as the level of traffic noise changes.

4) The following data were collected from each participant:

- Gender.
- Approximate age.
- Hearing difficulties (if any).
- Levels of presented background noise.
- For the written task:
    a. ASCII keystrokes involved in copying printed paragraphs into a text box, including backspace/delete keys and arrow/navigation keys.
    b. Time between keystrokes, in milliseconds.
- For the arithmetic task, consisting of self-paced progress through a list of summation operations:
    a. Time taken between each presented sum.

b. Final answer at the end of each sequence.
c. Presented order of summation sequences.

### 5.3.3 Results

The results of the task distraction assessment indicated trends of participant resilience to noise ingress given office-related tasks. Due to the complexity of the current investigation conclusions regarding specific noise level recommendations/criteria were not possible.

While the experimental setup and methodology of the speech intelligibility assessment were dictated by an ANSI standard[9], the task distraction assessment methodology could not follow the guidance of a particular standard. In the absence of such a predetermined and codified method of quantifying performance in office-related tasks, in the presence of noise through openings in a façade, this assessment was developed based on references to previous research investigating similar subjects. Because of this, while possibly significant trends do emerge in the statistical analysis of the data collected here, some adjustment of the experimental setup is necessary to reach definitive conclusions. We have determined that our research method requires this type of adjustment due to its multi-modality, complexity, and multiple influencing factors inherent in this topic.

### 5.3.4 Discussion

Based solely on noise level, data suggests that people can perform tasks to a modest (though statistically erratic) degree of accuracy at higher levels of noise ingress than previously thought, but not enough data exists regarding other factors (acoustic comfort, resilience of experimental setup, non-acoustic environmental influence) to make absolute level recommendations.

While reliable trends begin to appear as a result of this phase of research, we believe that there are not enough data points to make conclusions about specific noise criteria and their effect on productivity and accuracy of task completion. With some revision of our experimental setup and further research, however, we believe these conclusions are feasible.

# 6 REVISED NOISE CRITERION (NC) CURVES FOR NATURALLY VENTILATED BUILDINGS

The results of the subjective assessments presented above demonstrate the complexity of assessing distraction to office tasks by ingress of traffic noise via the facade. An alternative approach would be to follow the empirical methodology adopted to develop the Noise Criterion (NC) curves, still in use today 50 years after first being published.

## 6.1 Original NC Curve Derivation

Noise Criterion (NC) curves are widely used to evaluate noise conditions in occupied spaces and are based on achieving satisfactory speech intelligibility or acoustic comfort in occupied office spaces with mechanical ventilation. The curves were derived by Beranek from personnel surveys and noise surveys in occupied office spaces of a US aircraft base in 1956[12]. The survey included 190 participants, working in 17 difference spaces with various background noise environments. A follow-up study in 1957[13] provided further data from other occupied office buildings to substantiate the results from the initial study and provide a revision to the initially proposed criteria. A total of 300 participants took part in the combined study. The same questionnaire was used for both studies, and focused on interference to speech and ability to accomplish tasks without loss of performance. Analysis of the subjective assessment with the background noise measurements carried out led to the derivation of the NC curves still used as the basis for mechanical noise control specifications today.

It would therefore be a reasonable approach to undertake a similar study in existing naturally ventilated buildings to derive suitable background noise criteria in occupied office spaces. The end goal would be a modified set of NC curves ("NV-NC" curves) suitable for applying to the design of naturally ventilated office spaces.

## 6.2 Approach for Naturally Ventilated Buildings

Undertaking such a study in real office environments has the advantage of removing some of the complexities encountered in a controlled and simulated laboratory assessment. The challenge, however, is that it relies on cooperation with office building owners/managers and building occupants to obtain meaningful results.

The intent is to partner with building owners to enable access to a range of naturally ventilated office buildings to carry out the assessment. Post occupancy surveys are regularly carried out on new office buildings (whether they have a green rating or not), and include general questions regarding satisfaction with the acoustic environment. It would be difficult to incorporate a thorough enough assessment into these current surveys. Arup currently has acoustic offices in 14 cities around the world, which will provide a good starting point to for indentifying appropriate office buildings for the study. It would be beneficial, however, to partner with other firms and academic institutions to increase the sample size of the study.

# 7 ACKNOWLEDGEMENTS

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