Architectural Science Review

ISSN: 0003-8628 (Print) 1758-9622 (Online) Journal homepage: http://www.tandfonline.com/loi/tasr20

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To cite this article: Christina E. Mediastika, Luciana Kristanto, Juliana Anggono, Fefen Suhedi & Hariyati Purwaningsih (2018) Open windows for natural airflow and environmental noise reduction, Architectural Science Review, 61:5, 338-348, DOI: 10.1080/00038628.2018.1502151

To link to this article: https://doi.org/10.1080/00038628.2018.1502151

ARCHITECTURAL SCIENCE REVIEW
2018, VOL. 61, NO. 5, 338–348
https://doi.org/10.1080/00038628.2018.1502151

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Open windows for natural airflow and environmental noise reduction

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ABSTRACT
For buildings in tropical climates, the use of open windows for natural ventilation can not only provide low cost and low energy comfort but also provide thermal delight for occupants. However open windows let in environmental noise. The size and location of windows in walls are key but this study set out to determine whether there are any window forms that can effectively reduce the level of sound ingress into a building. A top-hung window was chosen for this study looking at the dimensions of the window opening and its orientation in relation to the environmental noise source. The top-hung form was selected for its potential to balance the functions of allowing airflow while potentially blocking and reducing noise levels with its window pane angle. The window pane was tested in a laboratory at three opening angles: 0° (closed), 5°, and 10° to let the outdoor air in. The angles were also tested in three different orientations in relation to the noise source position: perpendicular, sideways 60°, and sideways 90°. The test was conducted at 1/3 octave band frequency as specified by ASTM E90-09 to obtain the transmission loss, then ASTM E1332-90 was referred to calculate the outdoor-indoor transmission class (OITC) of the specimens. The study revealed that window orientation and extent of the openings and window pane angle have little effect on noise reduction. The paper concludes with a discussion of how higher levels of natural ventilation can be achieved, particularly in noisy urban areas. The top-hung window, once open, barely blocks environmental noise. However, when the window was closed, the perpendicular orientation offered more noise reduction when compared windows placed sideways to the noise source. The adjustable pane-angle of a top-hung window placed perpendicular to the airflow, and thus the noise source, seemed to have the most potential to balance the functions of allowing airflow when opened and reducing significant noise when closed. Nonetheless, an open window that through its design alone can significantly reduce the ingress of ambient noise into a building is still an issue.

ARTICLE HISTORY
Received 4 July 2018
Accepted 14 July 2018

KEYWORDS
Natural airflow; top-hung window; environmental noise reduction; outdoor-indoor transmission class

SUBJECT CLASSIFICATION CODES
Buildings

1. Introduction

The most dominant environmental noise source for buildings alongside streets and roads is traffic noise which is increasing in many places (Ali and Tamura 2003; Alberola, Flindell, and Bullmore 2005). In Indonesia, where this study was done, the mean traffic noise level beside built-up roads typically reaches up to 75 dB (Husti and Fujimoto 2012), with additional excessive noise levels from vehicular horns reaching over 90 dB (Husti and Ramli 2013). Nuisance from outdoor noise makes the use of opening windows less attractive and in some areas almost impossible. Building occupants, where they can afford to, tend to close windows and turn on air conditioning.

The noise issue aside there are many benefits in using an open window to provide natural airflow in the tropics needed for comfort and to prevent the build-up of mould arising from conditions where there are little air-movement and high levels of humidity, for instance behind and inside cupboards. Even small open window areas, such as provided by a single side-hung window stimulating low airflow was found to be capable of introducing useful levels of fresh air inside a building by Guohui (2000). An open window is a key building feature in terms of its ability to contribute to comfort cooling indoors (Rijal et al. 2007) and a range of studies have shown that air movement from windows also positively influences the health of building occupants (Mangkuto, Rohmah, and Asri 2016; Vincent et al. 1997; Jaakkola and Miettinen 1995; Anon 1995).

Buildings in tropical regions have a particular imperative for the use of natural ventilation for comfort cooling as the outdoor temperatures often correlate well with indoor comfort temperatures with the assistance of a little air movement. In terms of the development of low energy and low carbon buildings in tropical zones, the longer a building can be run over a day or year using just natural ventilation for comfort cooling over a year the less energy it will use. This is an increasingly critical issue with the rise in the cost of energy in many regions, the decreasing value of the salaries of many in flat lining global economies and the rise in levels of fuel poverty in both the developed and developing nations (Roaf and Nicol 2017).

An open window that allows natural airflow and conquers noise intrusion all at once is a complicated issue, involving not

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only sound and smells but also the ingress of pollution from the traffic itself (Mediastika 1999). Insertion of openings on a wall inevitably reduces the sound insulation properties of the wall (Lord and Templeton 1996; De Salis, Oldham, and Sharples 2002). The use of thin materials inserted into a wall, such as with a glass window decreases the sound insulation property of the masonry accordingly (Quirt 1981, 1982; Garg, Sharma, and Maji 2011). Opening the window in the envelope then exacerbates the level of the sound intrusion indoors (De Salis, Oldham, and Sharples 2002; Sharland 1979).

Research on different ways of controlling noise intrusion resulting from natural ventilation systems is limited, although some work on the subject has been done by Jorro (1990), Peliza (1994), Irvine (1993), Field and Fricke (1995, 1997), Mohajeri and Fricke (1995, 1996), Kwon and Park (2013), and Yu et al. (2017). None of these studies specifically investigate the effect of the actual design of the opening windows on environmental noise reduction as a positive passive strategy for encouraging natural air flows through buildings while reducing noise nuisance from them. Those studies concentrated largely on the use of active noise control for open windows, an example of which is shown in Figure 1, in which significant noise spectrum attenuation was gained using quarter wave resonators.

Other studies investigated the use of effective methods for achieving both airflow and noise reduction indoors by locating the building in an area of low noise concentration, by the application of noise screening using internal or external barriers (Alberola, Flindell, and Bullmore 2005; Twinn 1994), by using acoustic ceiling design to absorb outdoor noise intrusion (Buratti 2002, 2006) and by using partially open double layered windows (Ford and Kerry 1973) (Figure 2). The opening configurations of these previous studies were not of widely or fully adjustable open window types. Thus, none allowed sufficient outdoor air movement through them to compromise indoor comfort resulting from the high daily outdoor temperatures (Karyono 2000; Feriadi and Wong 2004). Two other studies suggested placing the open aperture on a wall facing away from direct noise paths (Twinn 1994; Bunn 1993), a strategy also discussed below in this paper. No previous studies have reported on the use of a fully opening window that through its design alone can significantly reduce the ingress of ambient noise into a building. Previous work demonstrates that a fully open window has little potential to reduce environmental noise. However, given the imperative for natural ventilation in the future of passive cooling in buildings in the tropics, it was felt that an attempt to produce an opening window able to significantly reduce noise ingress through the merits of its design alone was warranted and it is on this attempt that the paper below reports.

This paper focuses on the investigation of a potentiality of using a specific window type that gives access to building occupants to open or close it to suit their needs of natural airflow. The openable window referred in this study is a fully openable window designed to enable natural airflow. The term 'fully' is used to distinguish it from a partially open double layered window as was by Ford and Kerry (1973) (Figure 2) or as typically used in Indonesia (Figure 3) or other fixed open window types which cannot be adjusted by the users to suit their need of fresh air. In a warm-humid tropical climate, an adequate passive cooling system using open windows is suggested to require an open area of at least 5% of the ventilated floor area (Mediastika 1999; SNI 2001). As an example, a 15 m^2 floor area will need 0.75 m^2 of

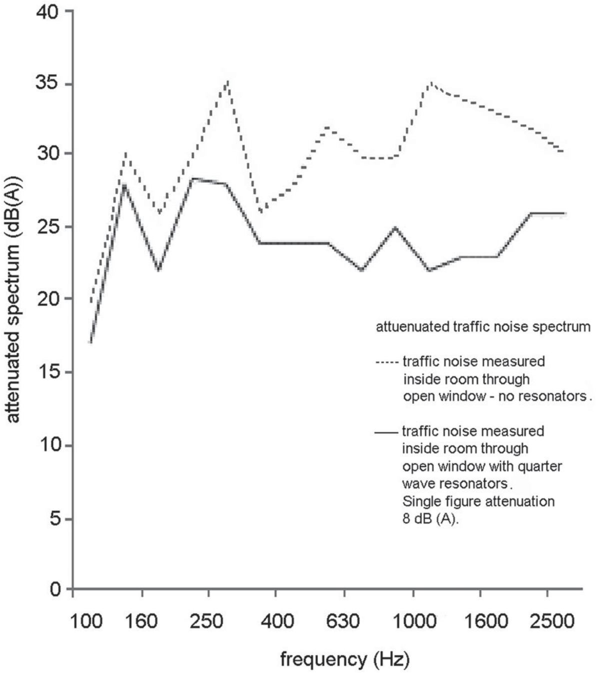


Figure 1. The calculated attenuation effect of the prototype set of quarter wave resonators around a test window exposed to the noise of a medium-sized passenger vehicle drive-by (Field and Fricke 1995, 1997).

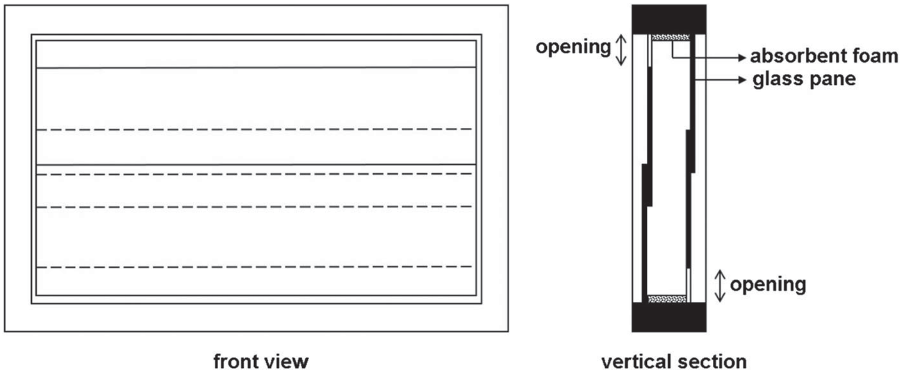
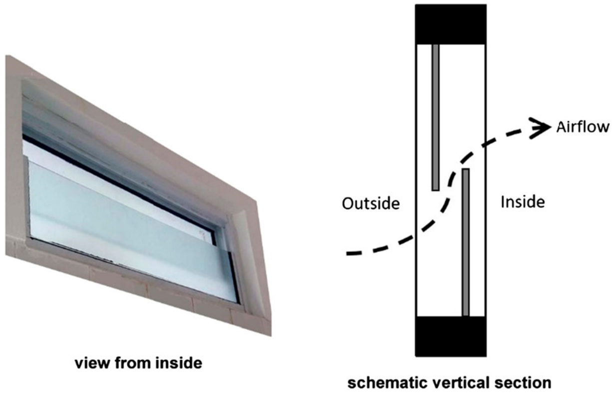


Figure 2. Schematic view of the 'non-fully adjustable opening window' constructed from double glass panes (reproduced after Ford and Kerry 1973).


view from inside

schematic vertical section

Figure 3. A typical fixed open glass window used in Indonesia, usually for bathrooms or other small rooms.

openable window. Using a partially open doubled glazed window with a maximum gap of 0.2 m as was posited by Ford and Kerry (1973) and Buratti (2002, 2006), the room needs a window as large as 3.75 m^2 minimum or 25% of the floor area. De Salis, Oldham, and Sharples (2002) found that 10% of a fully adjusted open window in such a wall area could only provide 10 dB of sound insulation. Fully adjusted open windows are currently deemed incapable of supplying both natural airflow and outdoor noise reduction at the same time. Figure 4 shows that until now no open window configuration exists in the chart that offers the possibility of noise reduction over all frequencies, so the challenge here was to construct a window capable of providing some noise reduction while the window was fully opened.

The placing of the aperture away from direct noise paths as explored by Twinn (1994) and Bunn (1993) is often impractical for buildings on small sites, the optimization of the orientation of an open aperture in the path of the noise was considered more practical. A top-hung style window was selected as possibly offering higher noise blocking potential due to the angle of its window pane position. Gao and Lee (2010) had determined that a top-hung window performed the worst in terms of natural ventilation compared to end-slider and side-hung window. The lower ventilation rate for the top-hung window was caused by the pane angle that directly faced and blocked the airflow. Nonetheless, despite its poor performance in terms of natural airflow, a top-hung window is capable of supplying more airflow (Moore 1993; Coley 2008). An open top-hung window gives access to the users to adjust the opening levels to suit their needs compared to a fixed open window (Figure 4) or a closed window with trickle ventilators. A top-hung window, as produced in Indonesia, has typical opening levels distances of 10 cm to 30 cm letting in airflows 75% of the incoming air that hits the pane, and the rest 25% is blocked by the pane and the frame (Moore 1993). This is less than the end-slider or side-hung that allow 90% airflow of the incoming air (Moore 1993). A bottom-hung window pane position was not tested because it is rarely used in Indonesia due to less accessible handle and latch locations.

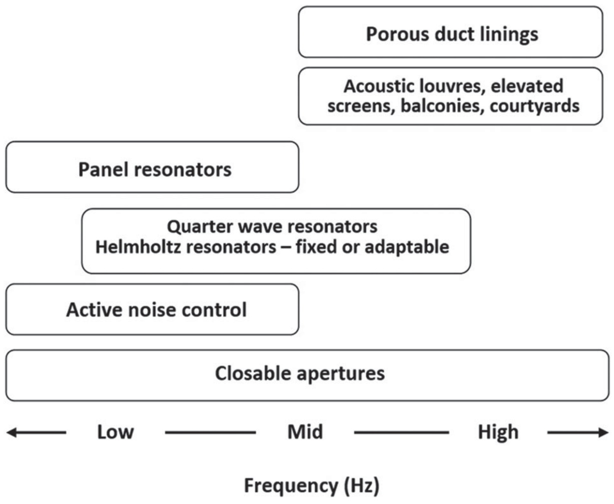


Figure 4. Frequency ranges of useful attenuation for noise control treatments of low flow resistance for use in inlets or outlets of natural ventilation systems (De Salis et al. 2002).

2. Previous work

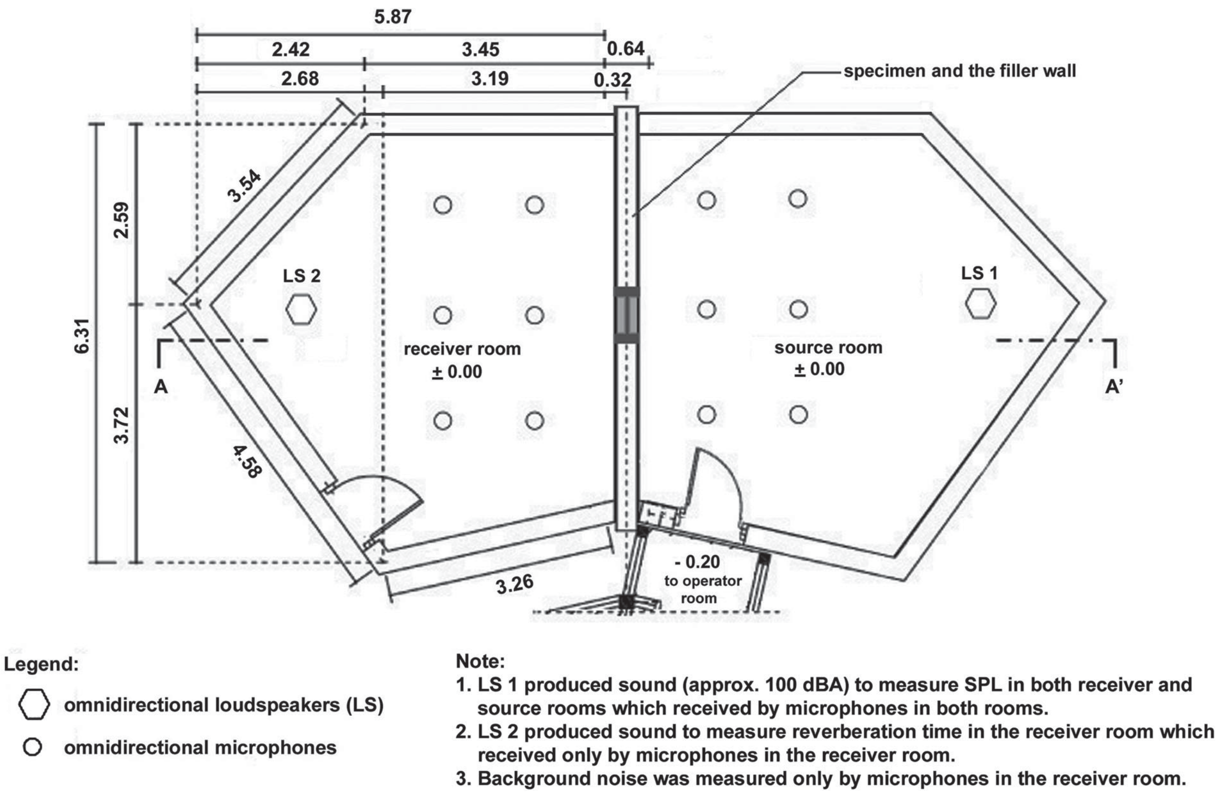
Previously the research team had looked at the possibility of using a bespoke glass window design within an optimized framing material for that glass for tropical climates to let airflow and conquer environmental noise using a particular warm temperature. This work was conducted in a laboratory to test models at a 1:1 scale consisting of three glass types commonly used in Indonesia i.e. monolithic, laminated and tempered in three different window framing materials, timber, aluminium and unplasticized polyvinyl chloride (uPVC).

All these tests were conducted twice at temperatures specified according to the ASTM E90-09 (ASTM 2009) standard, and at the warmer temperature of 32°C, being around the daily average temperature experienced in the tropics during the hot season. The glasses were tested for their sound transmission class (STC) and outdoor indoor transmission class (OITC). The test exhibited laminated glass resulted in the best transmission loss (TL) contour and STC, but not of the OITC due to a coincidence dip at 125 Hz (Mediastika et al. 2015, 2016). The OITC of laminated glass used at a warmer temperature was not as good as that of the laminated glass used at the standard temperature possibly because of sound travels faster in the warmer air (Zitzewitz 2011), which at frequency 125 Hz resonates with the frequency of the laminated glass to cause a dip.

The framing material tests showed that all tested frames performed similarly to outdoor noise intrusion when the window pane was opened. But with the pane closed, the most effective frame in conquering environmental noise was the uPVC frame as it is completed with rubber strips and sealant providing good sound breaks within its construction (Mediastika et al. 2017).

3. Methodology

The current work was also conducted in a laboratory with 1:1 scale models. The transmission losses of different window orientations were tested in the laboratory as shown in Figures 5 and 6. A laboratory test set up with a diffuse incident sound field was deemed adequate to represent the ambient environmental noise since environmental noise enters a building from many directions. The environmental noise around buildings is



Note:
1. LS 1 produced sound (approx. 100 dBA) to measure SPL in both receiver and source rooms which received by microphones in both rooms.
2. LS 2 produced sound to measure reverberation time in the receiver room which received only by microphones in the receiver room.
3. Background noise was measured only by microphones in the receiver room.

Figure 5. The plan of the testing rooms and the equipment layout.

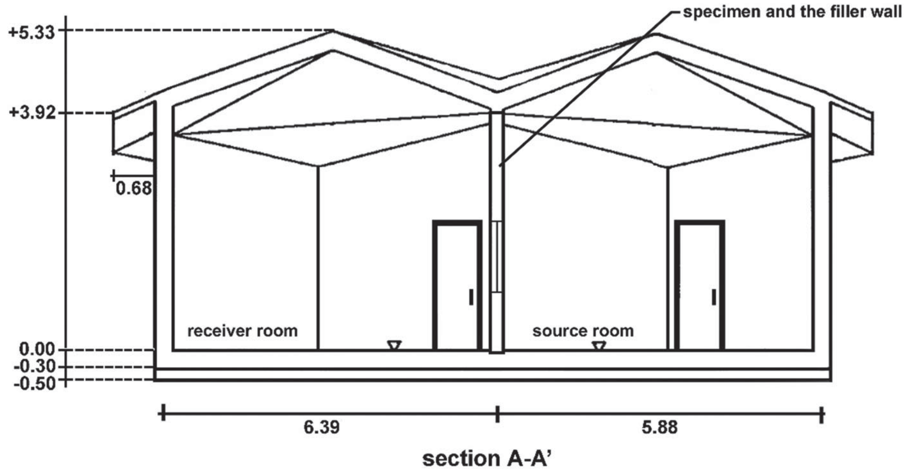


Figure 6. The A-A' section of the testing rooms.

produced by a mixture of outdoor noise sources that disperse directly mostly from traffic as the primary source and in turn are reflected on by outdoor objects, such as vegetation, fence, pillar, sculpture, etc. However, the indoor test unit was limited by the laboratory dimensions in its ability to accommodate long wavelength of low-frequency sound. With the linear dimension of 5.87 m × 6.31 m and volume of source room being 135,07 m^3 and the receiver room of 120,36 m^3 the laboratory is sufficient to conduct a sound test of frequency as low as 80 Hz, for which the wavelength is around 4.25 m. According to ASTM E90-09 (ASTM 2009), the minimum source room volume is 125 m^3. The frequency of 80 Hz was the lowest to be measured to calculate outdoor-indoor transmission class (OITC) used in this paper.

Six fixed microphones were used in each room as plotted in Figure 5. The sound pressure levels were measured in both directions of the flip source and receiver rooms to calculate transmission loss between the rooms due to the specimen insertion. The averaging time was 12 s with the background noise in the receiver room also being recorded (Table 1). The transmission loss of the masonry wall was recorded as the reference for the transmission loss of the specimen. This is plotted in Table 2. The sound absorption in the receiving room was measured with a Sabine formula based on the room reverberation time (RT). The RT was calculated with a pink-noise source in an interrupted noise method. It was measured in 3 positions; 10 times each. The Pulse Reflex Building Acoustic method by

Table 1. Transmission loss (TL) and outdoor-indoor transmission class (OITC) of the filler wall (full masonry wall before the openings insertion).

1/3 Octave band frequency (Hz)	Plain perpendicular wall	Sideways 60° wall	Sideways 90° wall
80	41	33	32
100	37	33	36
125	31	30	31
160	34	34	35
200	29	29	30
250	30	29	34
315	29	30	33
400	28	31	34
500	32	32	36
630	36	35	38
800	38	38	40
1000	41	42	43
1250	44	44	46
1600	47	46	48
2000	49	48	50
2500	51	50	50
3150	53	52	52
4000	55	53	54
OITC	34	34	37

Bruel & Kjaer Type 8780 was employed to correct and calculate the test.

The testing tool used was a Bruel & Kjaer 2- channel building acoustic system consisting of power amplifier type 2734 and 4292 omnidirectional loudspeakers as the sound source, 2 pieces of type 4189 omnidirectional microphones as the sound sensor, and 2-channel handheld analyzer type 2270 was included as the main instrument data processor. The microphones were calibrated using Bruel & Kjaer calibrator type 4231. The temperature and relative humidity during the testing stages were plotted at 25°-26°C and 80% - 90% to conform ASTM E90-09 (ASTM 2009).

The models were placed in 3 different orientations to the main noise source, being perpendicular, sideways 60° and sideways 90° (Figures 7–9). The terminology of perpendicular is used here to describe the position of the window pane directly faced the main or the primary noise source. Meanwhile, the terminology of sideways is used to describe the position of window pane not directly faced the main noise source, either oblique 60° or 90°. The top-hung window was selected and the glass type, dimensions and framing materials were all fixed variables using monolithic glass types, 10 mm thickness, 800 mm × 1200 mm dimension, inserted within a uPVC frame (Figures 10 and 11).

The models were tested at 3 opening angles i.e. 0° (closed), 5°, and 10° (Figure 10) for each orientation assigned. The closed window was tested to study the effect of slit alongside the pane and the frame on noise intrusion due to the window orientation. In tropical climates, a slit between the pane and the frame is assigned for ease of use due to material expansion and shrinkage during the dry and wet season. The 10° angle (approximately 0.2 m opening width, Figure 11) was selected as the maximum opening level for reasons of safety and ease of use.

Window orientations of 0°, 60°, and 90° were selected based on a possible orientation used by architects and developers. The sideways orientation is usually selected to avoid direct solar radiation (Capeluto 2003). Angles of orientation smaller than 60° and

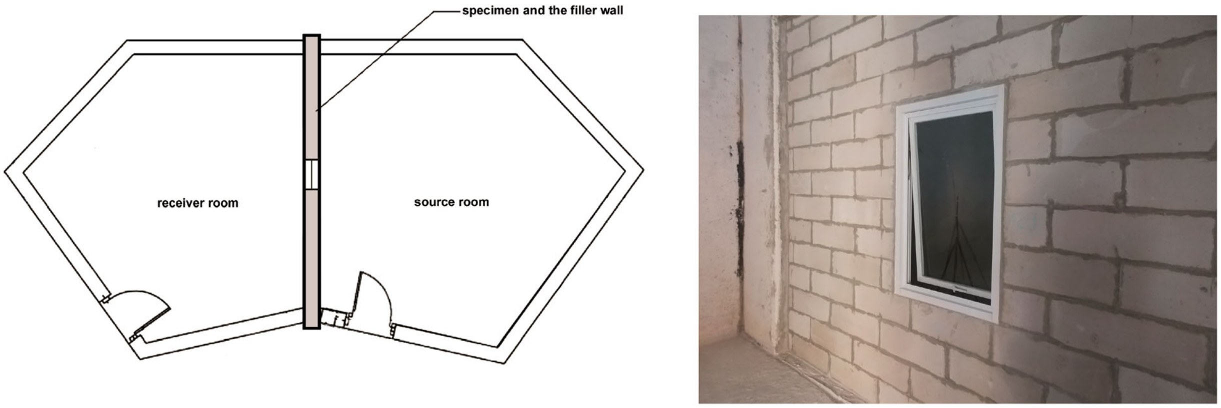


Figure 7. Specimen layout of the perpendicular orientation and view from the receiver room.

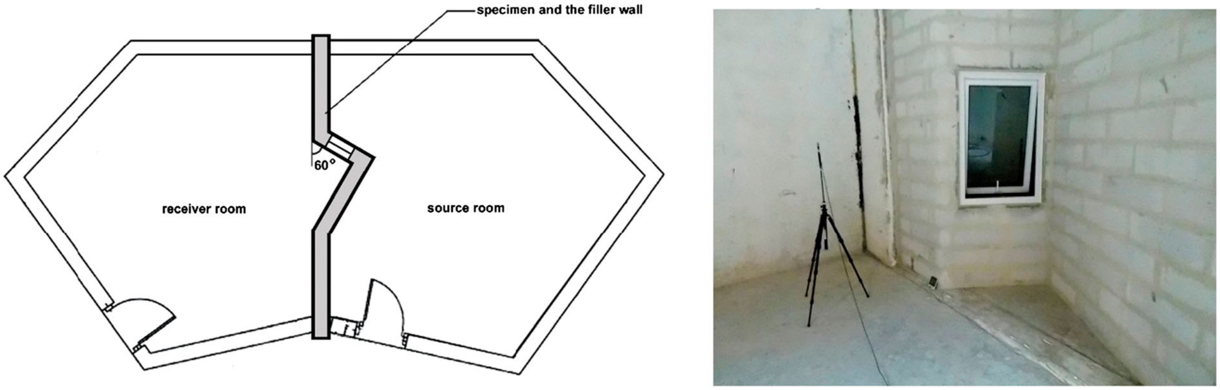


Figure 8. Specimen layout of the sideways 60° orientation and view from the receiver room.

Table 2. Background noises (BN) and sound pressure levels (SPL) in the receiving room*.

1/3 Octave band frequency (Hz)	BN Plain perpendicular wall	SPL perpendicular	BN Sideways 60° wall	SPL sideways 60°	BN Sideways 90° wall	SPL sideways 90°
80	29.2	61.7	32.4	69.8	30.3	74.5
100	36.2	73.8	28.3	77.1	29.4	74.9
125	31.4	83.1	30.7	84.9	27.3	82.8
160	28.5	81.0	27.3	83.8	25.9	82.1
200	21.6	86.8	29.4	88.9	25.5	86.3
250	23.5	84.7	24.5	85.8	24.5	82.6
315	21.9	84.3	19.5	84.4	23.7	82.1
400	20.4	83.6	17.4	82.4	21.4	80.1
500	18.6	77.9	16.6	78.9	19.7	76.0
630	18.5	72.5	16.0	73.9	22.1	72.5
800	16.6	68.3	13.4	69.2	17.6	68.3
1000	14.5	63.4	11.5	64.4	16.7	63.3
1250	13.5	59.4	12.2	61.0	16.3	59.7
1600	9.9	57.5	8.9	59.2	13,9	57.5
2000	8.4	55.4	7.9	57.2	10.7	55.5
2500	15.5	51.7	10.7	54.1	12.8	53.8
3150	20.8	50.4	13.0	52.8	13.0	53.0
4000	21.9	47.1	12.9	49.9	11.7	49.4

*The measured SPL were all 10 dB above the background noise (BN) as specified by ASTM E90-09 (ASTM 2009).

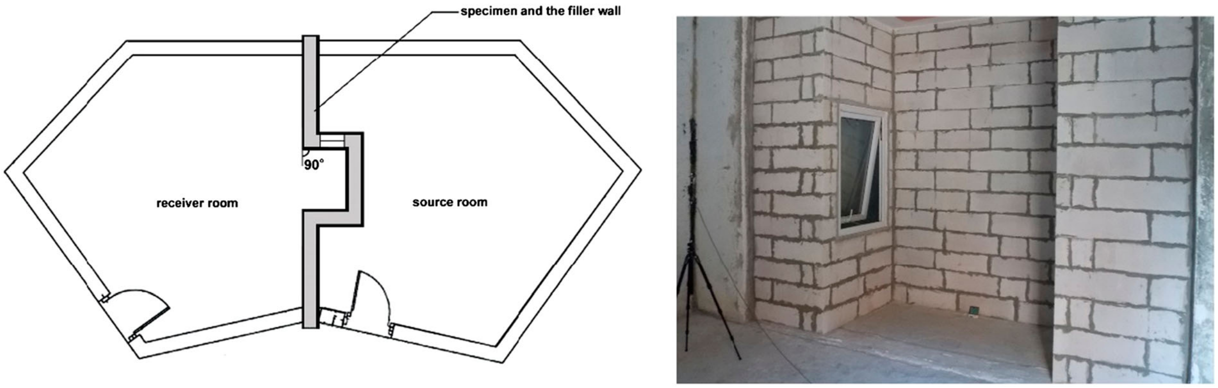


Figure 9. Specimen layout of the sideways 90° orientation and view from the receiver room.

also between 60° and 90° were not tested due to its uncommon use resulting from its complicated construction.

In general, the transmission loss generated by the specimen is calculated as follows,

$$TL = L_S - L_R + 10 \log S/A_R \tag{1}$$

where: TL is transmission loss (dB), L_S is average sound pressure level in the source room (dB), L_R is average sound pressure level in the receiving room (dB), S is area of the test specimen that is exposed in the receiving room (m^2), and A_R is sound absorption of the receiving room with the test specimen in place (m^2). Nonetheless, since a composite wall system was used, a particular formula to develop transmission loss of each 1/3 octave band frequency was applied as follows,

$$t_cS_c = t_sS_s + t_fS_f \text{or } t_s = (t_cS_c - t_fS_f)/S_s \tag{2}$$

where S_c is area of the composite construction ($S_c = S_f + S_s$) (m^2), S_f is area of the filler element (m^2), S_s is area of the test specimen (m^2), τ_c is transmission coefficient of the composite construction, τ_f is transmission coefficient of the filler element, and τ_s is transmission coefficient of the test specimen.

The composition between the filler wall and the inserted window is as Figure 10.

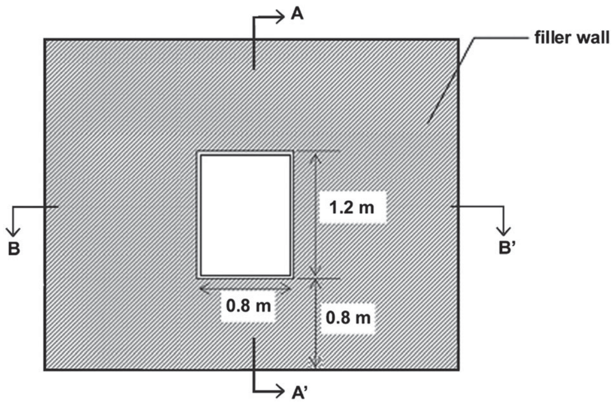


Figure 10. Front view and schematic dimension of the perpendicular orientation. A similar composition was applied to the sideways orientation.

Later, the outdoor-indoor transmission classes (OITCs) were calculated from the transmission loss (TL) of the 1/3 octave band frequency recorded during the test according to ASTM E1332-90 (ASTM 1998). Measurement of the 1/3 octave band frequency was considered appropriate to simulate spectrum to replicate typical street noise on city streets (Stewart 2008). OITC is a single number representing TL$_s$ of the 1/3 octave band frequency from 80 Hz to 4000 Hz inclusive. It was calculated using formula

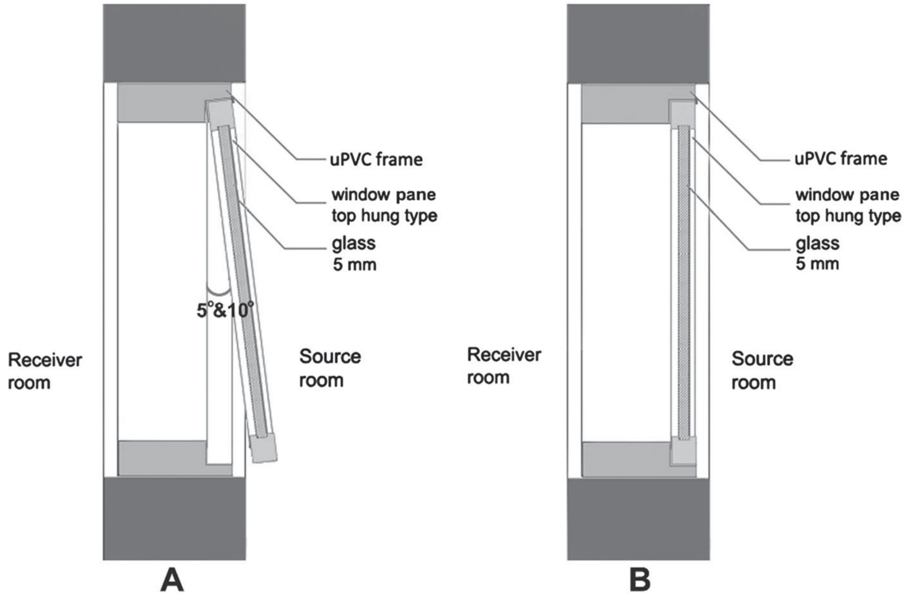


Figure 11. Sections A-A' of the top-hung windows showing the level of the openings of the window pane: 5° (the bottom part of the pane swings out approximately 0.1 m) and 10° (the bottom part of the pane swings out approximately 0.2 m) (A) and 0° or when the pane was closed (B).

as follows,

$$OITC = 100.13 - 10 \cdot \log \left\{ \sum_{i=80Hz}^{4000Hz} 10^{\frac{(AWRS_i - TL_i)}{10}} \right\} \tag{3}$$

where 100.13 is the logarithmic sum factor integrated to correct the formula to a frequency related energetic distribution. This value is the to 2 decimals rounded logarithmic sum of the A-weighted reference spectrum,

AWRSi is the A - weighted reference sound spectrum (1/3 octave band), and.

$TL_i$is the sound transmission loss for the 1/3 octave band, i, respectively.

4. Findings and discussions

A series of laboratory tests were carried out to study the potential of a top-hung window to provide natural airflow indoors while blocking environmental noise ingress from outside. Table 3 shows the TLs recorded during the tests, and the TL fluctuation is shown in Figure 12.

Legend: P is perpendicular orientation, 60 is sideways 60°, 90 is sideways 90°, 10, 5 and 0 is the level of openings. The 60–0 and 90–0 curves are identical. The 60–5 and 90–5 curves are identical. Meanwhile the 60–10 curve is identical to some curves as Table 3 indicates.

The results show that the transmission losses (TLs) of the open windows were all almost identical regardless orientation and level of openings. At the low frequency of 80 and 100 Hz, the TLs of the open windows, either open at 5° or 10°, are substantially higher then descend when the frequencies ascend. A

Table 3. Transmission loss (TL) and outdoor-indoor transmission class (OITC) of the perpendicular, sideways 60°, and sideways 90° orientation.

1/3 Octave band frequency (Hz)	Perpendicular (dB)			Sideways 60° (dB)			Sideways 90° (dB)		
	Open 10^{o}	Open 5^{o}	Open 0$^{o(closed)}$	Open 10^{o}	Open 5^{o}	Open 0$^{o(closed)}$	Open 10^{o}	Open 5^{o}	Open 0$^{o(closed)}$
80	18	19	31	18	19	14	18	19	14
100	16	18	29	16	18	24	16	18	24
125	9	9	21	5	6	17	5	6	17
160	4	6	21	7	9	20	7	9	20
200	4	7	20	4	5	18	4	5	18
250	5	8	21	6	8	20	6	8	20
315	6	9	22	7	8	21	7	8	21
400	3	7	22	4	7	22	4	7	22
500	3	6	23	3	7	23	3	7	23
630	4	6	27	4	6	24	4	6	24
800	4	5	29	5	6	25	5	6	25
1000	4	5	31	5	6	27	5	6	27
1250	4	6	34	5	6	30	5	6	30
1600	4	6	35	5	6	32	5	6	32
2000	5	6	33	5	7	33	5	7	33
2500	6	8	31	7	8	30	7	8	30
3150	7	10	31	7	11	31	7	11	31
4000	6	11	33	7	11	33	7	11	33
OITC	5	7	25	5	7	23	5	7	23

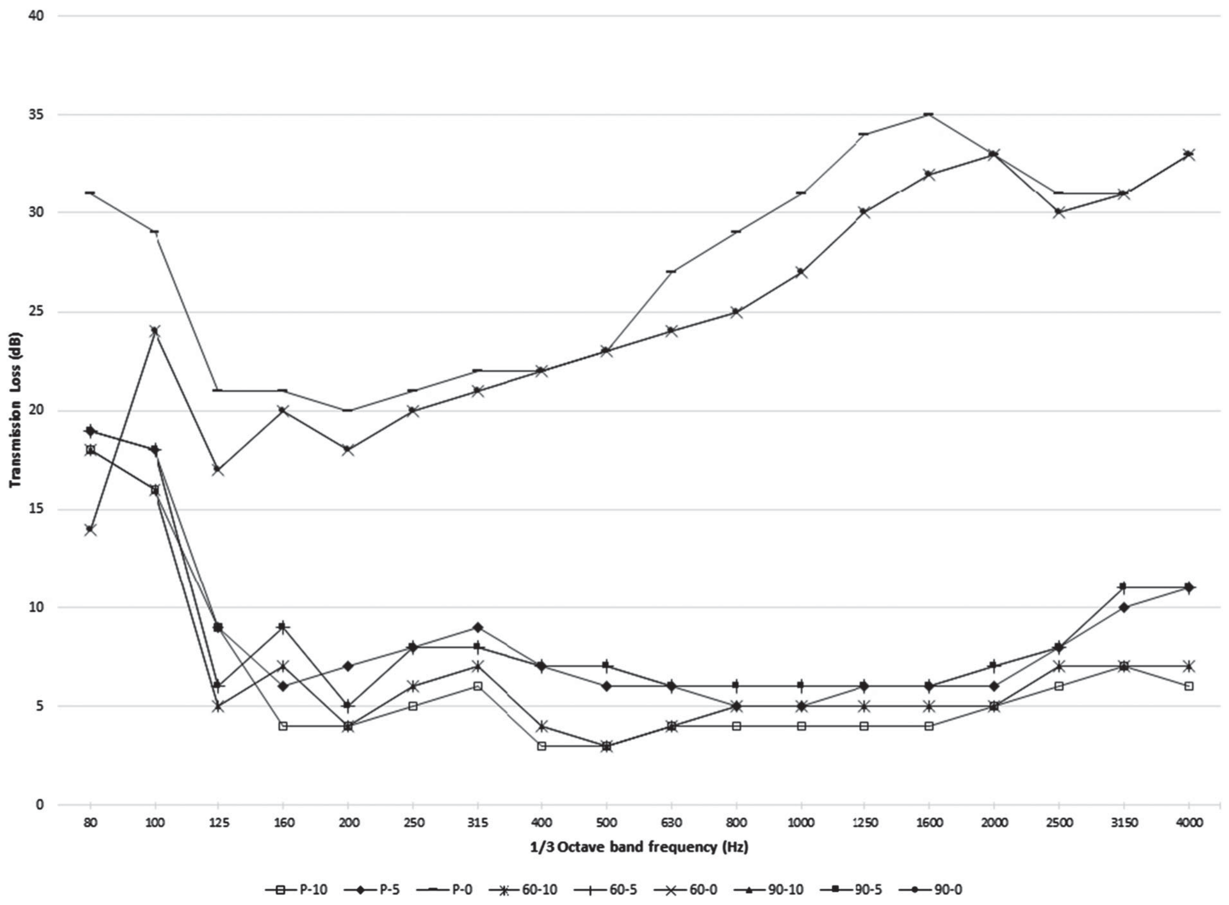


Figure 12. Transmission loss (TL) contours of the tested specimen.Legend: P is perpendicular orientation, 60 is sideways 60°, 90 is sideways 90°, 10, 5 and 0 is the level of openings. The 60–0 and 90–0 curves are identical. The 60–5 and 90–5 curves are identical. Meanwhile the 60–10 curve is identical to some curves as Table 3 indicates.

low-frequency sound is a long wavelength (Kinsler et al. 2009) that is readily blocked by a large window pane. Meanwhile, a high-frequency sound is a short wavelength which intrudes through a small opening more easily. Theoretically, when the primary environmental noise source hits the front wall with the open top-hung window placed perpendicularly, the open areas are at the bottom and alongside the pane (Figure 13). On the opposite wall, when a top-hung window placed sideways, the open area readily faces the noise source (Figure 14). Nonetheless, when the environmental noise enters the open area from many directions as happens in reality; similar to the diffuse sound field in the source room of the laboratory; the primary sound source has a little effect on the different open area positions and thus to the transmission loss obtained.

In Figure 12, the transmission losses (TLs) of closed top-hung sideways windows were identical regardless of the degree of obliqueness. Sharp coincidence dips were found in both closed top-hung sideways windows of 60°or 90° but not of the perpendicular ones. In an enclosure, wall angle near the boundary wall might cause TL drops. The occurrence of the coincidence dip

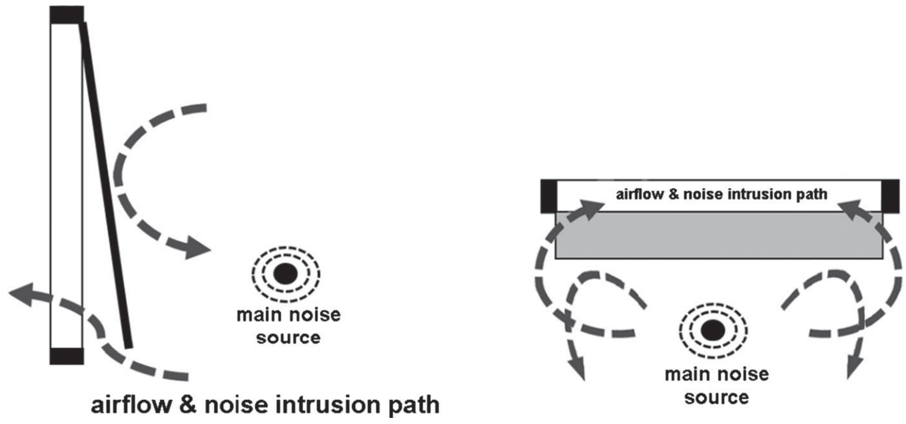


Figure 13. The vertical and horizontal sections of a top-hung window placed perpendicularly to the noise source, and the possible noise rebound by the pane and the intrusion path through alongside and the bottom of the pane.

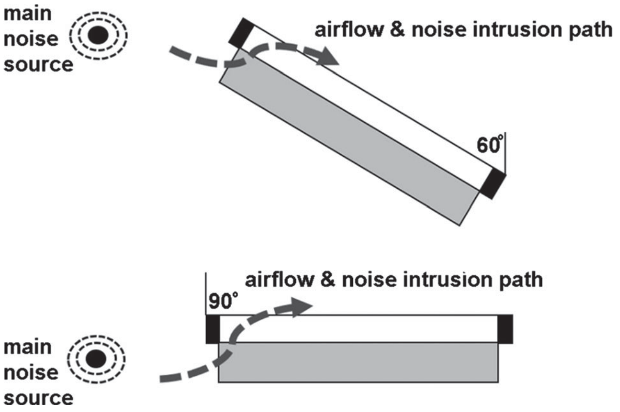


Figure 14. The horizontal section of a top-hung window placed sideways 60° and 90° to the noise source and the possible noise intrusion path through the open areas. Noise rebound is unlikely as the panes do not readily face the main noise source.

needs further validation to ensure the cause, whether due to the wall angle or due to the orientation of the window, or in particular due to the slit that exists between the frame and the pane. Overall, the closed perpendicular window obtained the highest TL compared to the sideways ones.

Table 3 demonstrates that when the window was closed (open 0°), the outdoor-indoor transmission class (OITC) of the perpendicular orientation was higher than the sideways ones. But when it was opened, the OITC was similar regardless of orientations and degrees of obliqueness. These findings strengthen earlier studies that larger openings permit noise intrusion more easily (De Salis, Oldham, and Sharples 2002). Both sideways and perpendicular open top-hung windows obtained similar OITC. The identical transmission loss (TL) in some frequencies of different levels of openings and orientations indicated that the sound transmission in a diffuse field from outdoor to the indoor area was mostly affected by the dimension of the available open area rather than by its orientations.

5. Conclusion

This study was undertaken to explore how feasible it is to use the configuration of different window designs to usefully reduce the ingress of outdoor noise into buildings with a view to helping to enable and encourage the use of natural ventilation in buildings.

The tests undertaken showed that an open top-hung window offered outdoor-indoor transmission class (OITC) as low as 5 when it was opened 10° regardless orientation of the window. The window obtained OITC 7 when it was less opened with a window pane angled 5° regardless window orientation. Both OITC of 5 and 7 are considered too small to reduce environmental noise in a building with natural airflow. Even if the 10° of opening area may be preferable to let more airflow, the users should pay attention to OITC.

Nevertheless, when the window was closed, a window orientated in a perpendicular plane to the main source of the external noise generated higher OITC of 2 points higher compared to the window placed in an oblique. This means that a closed perpendicular window reduce more noise ingress. It may correct a commonly held assumption that a window placed sideways to the noise source will reduce its ingress into a building via the closed pane caused by its indirect orientation to the assumed main noise source. Previous studies have shown that window orientation can have a significant effect on indoor daylight levels (Yoon, Manandhar, and Lee 2014; Mangkuto, Rohmah, and Asri 2016), which is shown here not to be the case for environmental noise. This study has usefully demonstrated that the tested openable window did not usefully reduce environmental noise ingress and more work with other configurations may prove more successful, but the general conclusion is that if the window in the direct path of an outdoor noise source is opened a significant amount of the noise will be transmitted indoors with top-hung windows.

The finding of this study may be referred by architects that to date an adjusted open window cannot satisfy environmental noise reduction. Since openings are important for buildings in tropical climates, installation of top-hung style windows may beneficial to users as they can adjust the pane. Whenever natural airflow is on demand, they may open it with a consequence that the outdoor-indoor trnsmission class (OITC) drops to 5 only. Once they need quietness, the pane should be slightly closed in to gain better OITC and be fully closed to gain much better OITC. The identical transmission loss (TL) in some frequencies of different levels of openings and orientations indicated that the sound transmission in a diffuse field from outdoor to the indoor area was mostly affected by the dimension of the available open area rather than by its orientations.

Nonetheless, the window style investigated in this study offered lesser environmental noise abatement compared to open-20 cm gap-double layered window by Ford and Kerry (1973) with averaged sound reduction index (SRI) of 14. SRI does not readily represent transmission loss of an object to environmental noise intrusion containing the sound frequency of 80 Hz which was not included by Ford and Kerry (1973). Outdoor-indoor transmission class (OITC) as was calculated here is more appropriate and handy.

The larger picture here is that the natural ventilation of buildings is a multiply challenging design venture that must take into account issues not only of noise but also key design impacts of levels of pollution and daylight indoors. To ensure that buildings can increasingly rely on the no cost, effective cooling and health benefits of good levels of natural ventilation indoors not only will more research of this type have to be done to gradually refine and optimize window design but architects will have to become more imaginative in their design of air flow paths through buildings to reduce noise and pollution impacts. Finally there is a hugely important role for political decision makers and planners to play in rethinking the way that cities and settlements are planned, developed and serviced to reduce the ambient levels of noise and pollution in them because in the future we will inevitable have to increasingly rely on natural ventilation to maintain comfort conditions in a warming world.

Acknowledgment

This study was fully funded by the Ministry of Research Technology and Higher Education of the Republic of Indonesia under the scheme of Penelitian Kompetensi under the project ‘Acoustical Characteristic of Architectural Glass in Warm Humid Climate’ with contract number 023.04.1.673453/2015 and 002/SP2H/P/K7/KM/2016 (made through Kopertis Wilayah VII Indonesia).

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This study was fully funded by the Ministry of Research Technology and Higher Education of the Republic of Indonesia under the scheme of Penelitian Kompetensi under the project 'Acoustical Characteristic of Architectural Glass in Warm Humid Climate' with contract number 023.04.1.673453/2015 and 002/SP2H/P/K7/KM/2016 (made through Kopertis Wilayah VII Indonesia).

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