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Combining noise mapping and ventilation performance for non-domestic buildings in an urban area

Michael Barclay [a], Jian Kang [a,*], Steve Sharples [b,1]

[a] School of Architecture, University of Sheffield, Western Bank, Sheffield S10 2TN, United Kingdom
[b] School of Architecture, University of Liverpool, Leverhulme Building, Liverpool L69 7ZN, United Kingdom

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ABSTRACT

Maximising the natural ventilation of a building can be beneficial in terms of comfort and reduced reliance on air-conditioning. However, in urban areas this can conflict with the need to reduce the ingress of external noise. In this paper a method is presented to quantify the interaction of building noise exposure with natural ventilation potential. Finite element models of ventilation aperture sound reduction index were used to determine façade sound insulation values for naturally ventilated buildings in two locations. Road traffic noise levels at the building façade were obtained from a calculated noise map of Manchester (UK). Window openings were adjusted in the thermal simulation package and modelled with mixed mode cooling ventilation strategies (both natural and mechanical). This enabled noise considerations to be quantified in terms of building ventilation and energy use for cooling at the whole building level. For a tolerated internal road noise ingress of 34 dB(A) cooling energy consumption for the example buildings in the quieter noise locations was found to decrease by 22%–45% compared to the noisier locations. Most importantly, the introduction of noise reduction measures equal to 10 dB(A) resulted in reductions in cooling energy consumption that varied from 28% to 45% of the original cooling energy consumption. This study illustrates the importance of an integrated approach to both noise exposure and ventilation performance in urban buildings.

1. Introduction

Natural ventilation strategies are difficult to implement for buildings in urban areas due to a number of factors, such as lower wind speeds, higher temperatures due to the urban heat island effect, pollution and noise. The pressure differences that drive natural ventilation, wind and or buoyancy effects, are very weak, typically less than 10 Pa. The easiest way to achieve the least restriction of a ventilation path is to open large areas of the façade. This can conflict with attempts to reduce noise ingress. Ghiaus et al. [1] made noise measurements outside the façades of street canyon buildings at different heights above street level. Relationships were defined between street aspect ratio, height above street level and the noise levels at which occupants might be motivated to close the windows. External noise levels are often given as the reason for air-conditioning buildings [2]. Summertime over heating risk could be an increasing problem for the future, and performance analysis of case study buildings [3,4] suggested that, with expected future temperature rises, providing a comfortable summertime indoor environment without a heavy reliance on mechanical cooling will be a major challenge.

Various systems exist that reduce noise ingress whilst minimising the restriction of the ventilation path. Some examples of these include passive systems that stagger glazing, employ absorbing liners or louvres and active systems [5–8]. The acoustic insulation and ventilation requirements for a specific site and building are complex and so it can be difficult to quantify the benefits of different approaches. Noise mapping has become a legal requirement in Europe [9] and is therefore an existing source of information about the noise environment. This information is represented spatially taking into account the complex distribution of noise and could be from either modelled or measured information about noise levels through an urban area. Noise mapping could be a useful resource for quantifying natural ventilation potential in urban areas and, by extension, enable noise reduction measures to be quantified in terms of ventilation and energy use. In an initial study [10] natural ventilation and acoustic insulation of buildings were linked by the size and position of openings on a building

* Corresponding author. Tel.: +44 114 2220325; fax: +44 114 2220315.
E-mail addresses: arp08mb@sheffield.ac.uk (M. Barclay), j.kang@sheffield.ac.uk (J. Kang), steve.sharples@liverpool.ac.uk (S. Sharples).
[1] Tel.: +44 151 794 2607; fax: +44 151 794 2605.

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façade; differences were detected between modelled ventilation rates and air-conditioning use in buildings with different façade noise level patterns.

In this investigation the linking of whole building noise exposure and whole building natural ventilation will be developed in more detail, with particular attention being paid to improving the description of the combined façade sound insulation. The acoustic insulation properties of a façade with ventilation apertures are dominated by the poor performance of these apertures. For this study the sound reduction index of apertures was calculated using finite element simulation. The benefit of this approach is that different aperture arrangements can be modelled in detail and then applied over whole buildings.

2. Method

Noise levels at windows in the façade of a building were calculated using noise mapping techniques (see Section 2.4 below). The opening created by an occupant's operation of a window was treated as an aperture in the façade of the building, affecting the combined sound insulation of the façade. Between the maximum and minimum levels of noise ingress, experienced when all windows are either fully opened or fully closed, a number of tolerated noise levels were sampled. Each individual window opening was adjusted in size so that noise ingress was as close to these tolerated noise levels as possible. This resulted in a range of ventilation opening sizes over the façade of the building depending on the uneven noise distribution. A separate building energy calculation was carried out for each tolerated noise level and opening regime. These calculations were run over a summer time period to establish the effectiveness of natural ventilation cooling. Cooling electricity used is presented as a graph curve against tolerated noise level.

2.1. Sound transmission of ventilation aperture

An open window represents an aperture in a building's façade. For circular apertures in a wall of finite thickness and for normal incidence of the sound source, an exact mathematical solution for sound transmission has been given [11]. This exact solution is complicated and so more practically useful approximate solutions have also been developed [12,13]. These approximate solutions show good agreement with the experimental results for circular apertures up to values of $ke < 1.5$, where k is the wave number and e is the radius of the aperture. There does not appear to be an exact solution for sound transmission through slit shaped apertures, although Gomperts does suggest an approximate solution that matches the experimental results with acceptable accuracy for some cases [12]. Oldham and Zhao found that this approximation fitted the experimental results to within 1.5 dB for $kd < 2$, where d is the width of the slit aperture [14].

Some of the range of opening widths and frequency ranges that are needed to describe the octave band sound reduction index lie outside this kd condition. Numerical techniques present the possibility of investigating apertures with geometries more like those found in practice. They also give the opportunity to incorporate the noise reduction impact of absorbing materials. Finite element models are used to give values of acoustic pressure at the mesh nodes by the numerical solution of the wave equations. In this way acoustic wave propagation through the aperture was simulated. The Sound Reduction Index (SRI_A) for an aperture can then be calculated by the numerical solution of acoustic pressure from:

$$\mathrm{SRI}_A = 10\log_{10}\left(\frac{1}{r}\right)\mathrm{dB} \tag{1}$$

$$r = \frac{W_0}{W_i} \tag{2}$$

where r is the transmission coefficient, which is the ratio between energy incident on the aperture W_0 and energy transmitted through the aperture W_i. These energies can be calculated as integrals of pressure over the relevant surface:

$$W_0 = \int_{\delta\Omega} \frac{p_0^2}{2\rho c_s} dA, \quad W_i = \int_{\delta\Omega} \frac{|p|^2}{2\rho c_s} dA \tag{3}$$

When r is equal to 1, SRI_A will equal 0, indicating that all the acoustic energy incident on the aperture passes through to the receiving side. Negative values of SRI_A represent the cases where more acoustic energy passes through the aperture than is directly incident on its opening area – this was observed in the experimental results of Oldham and Zhao [14]. The frequencies at which this occurs depend on the aperture width and depth and is due to a reflected wave issuing from the aperture entrance.

As a first step to validate this numerical approach of simulating acoustic wave transmission through apertures, a circular aperture was modelled using the acoustic module of COMSOL [15] and the results compared to those given in the literature [12–14]. A circular aperture was incorporated into a continuous wall and the sound reduction index calculated from the finite element results for acoustic pressure. This was compared to the approximate solution derived by Wilson and Soroka [13]. Fig. 1 shows the comparison and also illustrates the nature of aperture sound reduction index.

There was good agreement between the finite element model and the Wilson-Soroka [13] method and this gave confidence that the numerical model could be used to describe the sound reduction index of the ventilation apertures. As well as showing the good accuracy, Fig. 1 also demonstrates how the sound reduction index varies with frequency. In this study the sound reduction index of apertures corresponding to the sliding window ventilation openings of the example buildings (see Section 2.3 below) are calculated. This is important as the combined sound insulation of the façade is dominated by the poor performance of the ventilation openings [16].

The ventilation aperture models were set up to represent a normal incident plane wave on an infinite area of wall with finite thickness. A plane wave was introduced at one side of the model with its direction incident on the wall with the aperture. The wall and internal aperture surfaces were represented in this case as

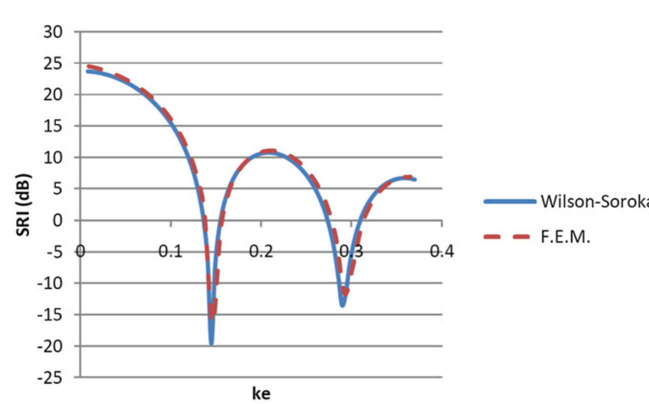

Fig. 1. Comparison of sound reduction index against ke for a circular aperture of radius 11 mm and depth 220 mm.

being fully acoustically hard. To minimise reflections from external boundaries, perfectly matched layers (PMLs) were used. Fig. 2 shows the model set up, PMLs on the source side and radiation conditions on the receiving side.

The assumption of a plane wave impacting on the aperture normally was considered appropriate given the needs of this investigation, particularly as the road traffic source would be at least several wavelengths away from the window in any case. This is also the boundary assumption used in the Wilson-Soroka method. The limits of aperture dimensions for the approximate solutions [12,13] should not apply to the numerical calculations, so wider and shallower apertures can be modelled. For numerical calculations the main concern is to ensure that the acoustic waves are sufficiently resolved with at least five elements per wavelength. For some configurations, and at high frequencies, this might require substantial computational resources. The apertures modelled with this technique corresponded to the ventilation openings of the building models. These were regular slits with a depth of 100 mm, corresponding to the window frame depth. For the example buildings used in this study an aperture width increase of 40 mm corresponds to each additional percentage that the window was opened.

2.2. Combined façade acoustic insulation

External noise levels are attenuated by the acoustically insulating properties of the façade which can be described as the SRI. The standard equation for the SRI of a composite panel ($SRI_{combined}$) is given in Equation (4), where it can be seen how the effective SRI of the façade can be dominated by the poor performance of a window opening [17].

$$SRI_{combined} = -10\log\left[\frac{A_{wall}10^{\left(\frac{-SRI_{wall}}{10}\right)} + A_{window}10^{\left(\frac{-SRI_{window}}{10}\right)} + A_A 10^{\left(\frac{-SRI_A}{10}\right)}}{(A_{wall}+A_{window}+A_A)}\right] \quad (4)$$

where the aperture has area A_A and sound reduction index of SRI_A, the wall has area A_{wall} and sound reduction index of SRI_{wall}, and the window has area A_{window} and sound reduction index of SRI_{window}.

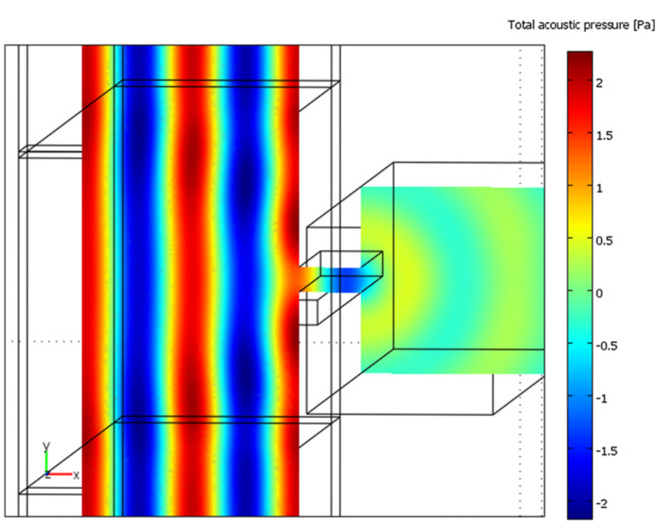

Fig. 2. Finite element model set up representing a plane wave incident on the ventilation aperture and sound transmission through it. Left hand side is source side and right hand side is receiving side.

In this work SRI values were adopted from the acoustic design of schools guidance [18]. Two sets of standard construction type were used. Construction 1 was 4/12/4 mm double glazing and two leaves of 102.5 mm brickwork with a 50 mm cavity, and Construction 2 was 6 mm single glazing and 200 mm of solid block wall. These construction materials had the sound insulation properties shown in Table 1.

Equation (4), plus the values provided for construction material sound insulation, and the percentage of the façade made up of wall, glazing and opening, means that a composite SRI value can be calculated. Road noise levels in the rooms were calculated according to:

$$L_R = L_0 - SRI_{combined} + 10\log(S/A) \quad (5)$$

where L_R is the sound level in the room, L_0 is the sound level at the façade, $SRI_{combined}$ is the combined sound reduction index of all elements of the façade, S is the surface area of the façade, for the example models used in this study there was a window for each 17.5 m^2 of façade area. A is the room absorption and is assumed to be a standard 10 m^2. The ratio of façade surface to absorption area will stay relatively constant, as will the last term of Equation (5). With the use of the values above, Equation (5) becomes

$$L_R = L_0 - SRI + 2.4 \quad (6)$$

2.3. Building energy modelling

Whole building level air flow patterns and cooling energy consumption were modelled for an extended summer time period. DesignBuilder/EnergyPlus software [21] was used for this. The DesignBuilder user interface uses EnergyPlus as its simulation engine. EnergyPlus is a building energy calculation tool that has been widely used and tested [22]. It provides a heat balance based solution to the heating and cooling loads required to maintain a building's thermal conditions. Various modules link into this core calculation to enable the representation of the building and its processes. This includes the calculation of solar heat gains and the airflow network module that was the focus of this work. The air flow rate through each opening is driven by the pressure differences that, in the case of natural ventilation, are caused by wind pressures and buoyancy.

For the example buildings used in this study a large degree of overheating was evident under free running conditions, i.e. where no heating or cooling systems are introduced into the model but heat gains from occupants and the external climate are

Table 1
Construction material sound insulation values (dB).

	Frequency (Hz)				
	125	250	500	1000	2000
Double glazing [18]	24	20	25	35	38
Single glazing [19]	20	24	28	29	26
Cavity brick wall [19]	41	45	48	56	58
Solid wall [20]	35	38	43	49	54

represented. The percentage of occupied hours above 28 °C for the example buildings are well above the Chartered Institution of Building Services Engineers (CIBSE) 1% guideline [23] to determine whether a building is said to be overheating. This was the case even with the window opening at its maximum level – in this work mixed mode buildings (part natural/part mechanical ventilation) were simulated. In mixed mode building's internal comfort conditions are primarily maintained by natural ventilation. When this is inadequate active cooling is introduced. The cooling energy consumption of the air handling unit will therefore be used to indicate the extent to which the acoustic environment has affected the natural ventilation potential. For all building models a natural ventilation set point of 24 °C was used as this is a central adaptive comfort temperature from ASHRAE 55 [24]; a 2 °C difference between cooling and natural ventilation set points is recommended [21] so a cooling set point of 26 °C was used. The simulations were run over a June to August time period (summer in the UK) with typical weather data covering these months. CIBSE weather data for Manchester was used. The same set of weather data and surrounding terrain roughness characteristics was used for all the results to ensure that the window opening was responsible for the different calculated ventilation rates and cooling energy consumption.

The window opening for these buildings followed an office operation schedule of Monday to Fridays 08:00 till 18:00. Window opening was controlled by this operation schedule and the fixed temperature set point. When internal temperatures exceeded this set point windows were opened as long as external temperatures were lower than the internal temperatures. In addition to these standard modelled window opening patterns the opening percentage was adjusted so that the noise ingress was as close to the tolerated level as possible. This was done so that a range of openings between maximum open to fully closed, could occur over the façade depending on the noise distribution.

For the building models used in this work wind pressure coefficients from an Air Infiltration and Ventilation Centre (AIVC) document [25] were used. They represented a good initial approximation and were therefore considered acceptable for this comparative study. For more accurate representations of specific buildings wind pressure coefficients from scale model testing or CFD simulation would be required. Standard template descriptions of construction and HVAC equipment were used including a fan coil cooling system and two types of construction. Construction 1 had cavity walls with coated double glazed windows and Construction 2 had solid block walls with single glazed windows. Three idealized office building types are shown in Figs. 3–5. The footprint of Building 1 was 65.4 m × 13.4 m and it has 5 floors. Buildings 2 and 3 are two simple 3 floor office blocks with square footprints of dimensions 20 m × 20 m and 13 m × 13 m respectively. The floor plans for these last two office buildings have contrasting room depths but otherwise the layouts were kept as similar as possible.

The window openings in the building energy model correspond to horizontal sliding windows, so the opening orifice is a vertical slit the full height of the window. The dimensioning of the windows was done using the design builder preferred height method [21], the windows had a standard height of 1.5 m and a standard separation of 5 m where the façade dimensions allowed. The exact

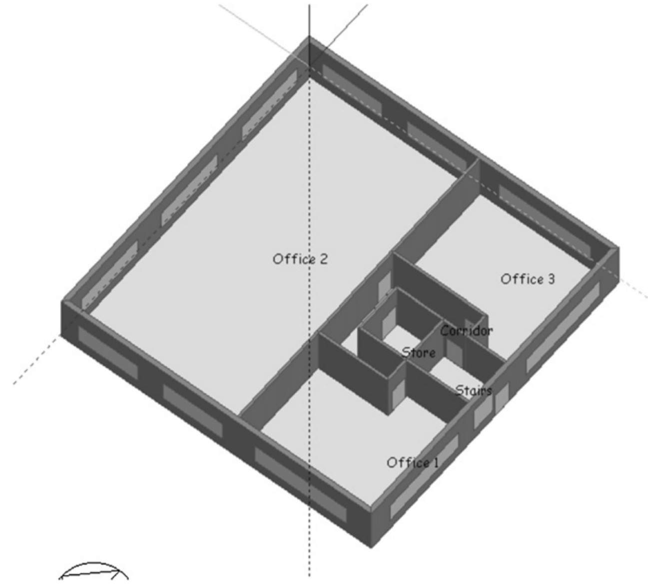

Fig. 4. Floor plan of simple deep plan office building (Building 2).

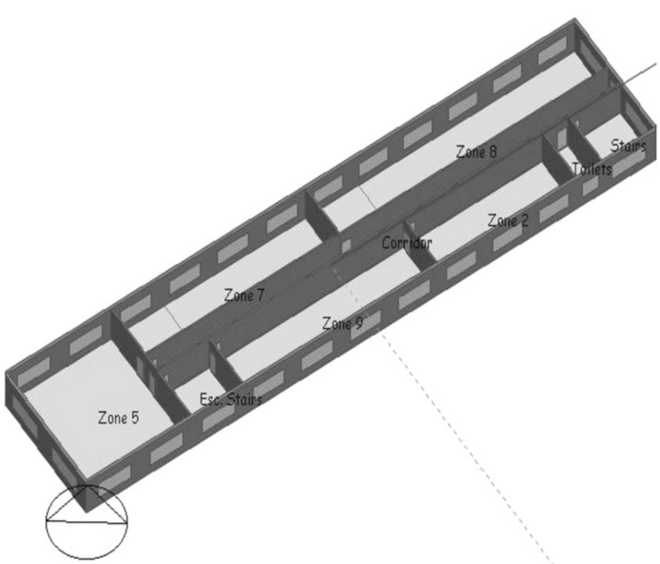

Fig. 3. Floor plan of office Building 1.

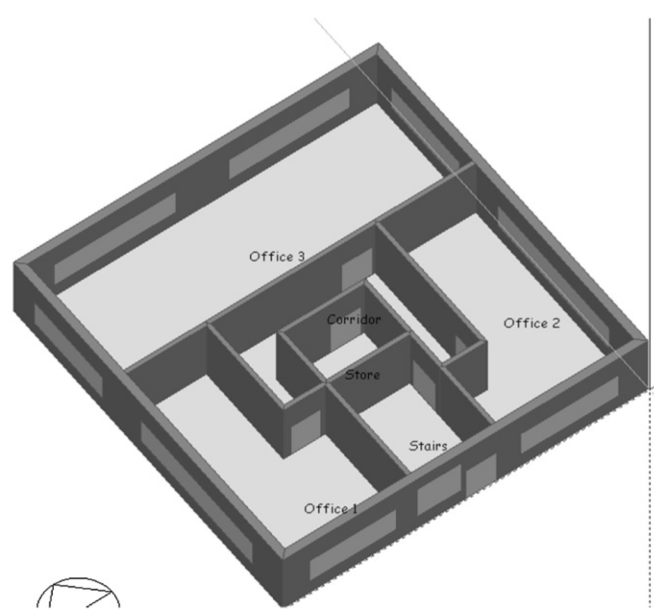

Fig. 5. Floor plan of the simple shallow plan office building (Building 3).

width of the window is then defined by the percentage glazing, which was 30% for all the buildings. Also, the maximum proportion of the window area that could be opened for the purposes of natural ventilation was 5% for all the buildings.

2.4. Noise mapping

The noise mapping from this study was completed using the software CadnaA [26]. The Calculation of Road Traffic Noise (CRTN) [27] method was chosen for the calculations as this has been shown to produce results that fitted well with measured noise levels at different building floor levels [28]. The noise map of Manchester was one previously used for a study of urban morphology [29]. The area mapped is shown in Fig. 6, [31]. The road and building layout for the typical 500 m $\times$ 500 m urban area were taken from a digital mapping service. Traffic flow was measured and characterised in accordance with the best practice guidance [30]. The noise level measurements were compared with modelled values. The two sites chosen for the location of the example buildings are marked A and B. The building location A next to a motorway was compared to the less noisy location B. The locations chosen have different noise exposures to enable clear comparison but are still considered representative of a normal urban environment. Positions were chosen where direct sound was dominant, avoiding situations with diffraction (i.e. behind buildings), where noise mapping could be less accurate.

Noise mapping has become a legal requirement in Europe [9], but there are some concerns about its accuracy which is highly dependent on the importance of reflected noise to a specific noise map [32–37]. Noise mapping does though present an easily available source of information about noise levels at a particular site and has been validated for a number of cases [38,39]. Road noise is not the only possible noise source that could affect buildings. Other noise sources are, for example, aircraft, industry and energy generation, such as wind turbines or micro hydro systems. These other noise sources could also be mapped and the results integrated into the method presented here.

2.5. Combining noise mapping and buildings energy modelling

There are a number of steps in the integration of the previously introduced concepts. The varying road traffic noise levels at each window position on the building façade were obtained from CadnaA as single figure A weighted values. The normalized road traffic noise spectrum given in BS EN ISO 717-1:1997 [40] was adjusting so that it represented the octave band road noise level at each window. Attenuation from the composite façade was taken into account through Equation (6) giving the internal octave band noise levels. This was reduced to a single figure value by the standard A weighting network, for all degrees of window opening at all the windows. The concept of a tolerated internal noise level was then used in the following way. The degree of opening for each window was chosen so that the internal noise levels, calculated previously, were as close to the tolerated level as possible. A separate building energy model corresponded to each tolerated noise level. A range of tolerated levels were chosen that described opening patterns between a maximum open and fully closed façade. The building energy model results could then be plotted as a curve against tolerated noise levels quantifying the relationship between acoustic considerations and natural ventilation potential for the

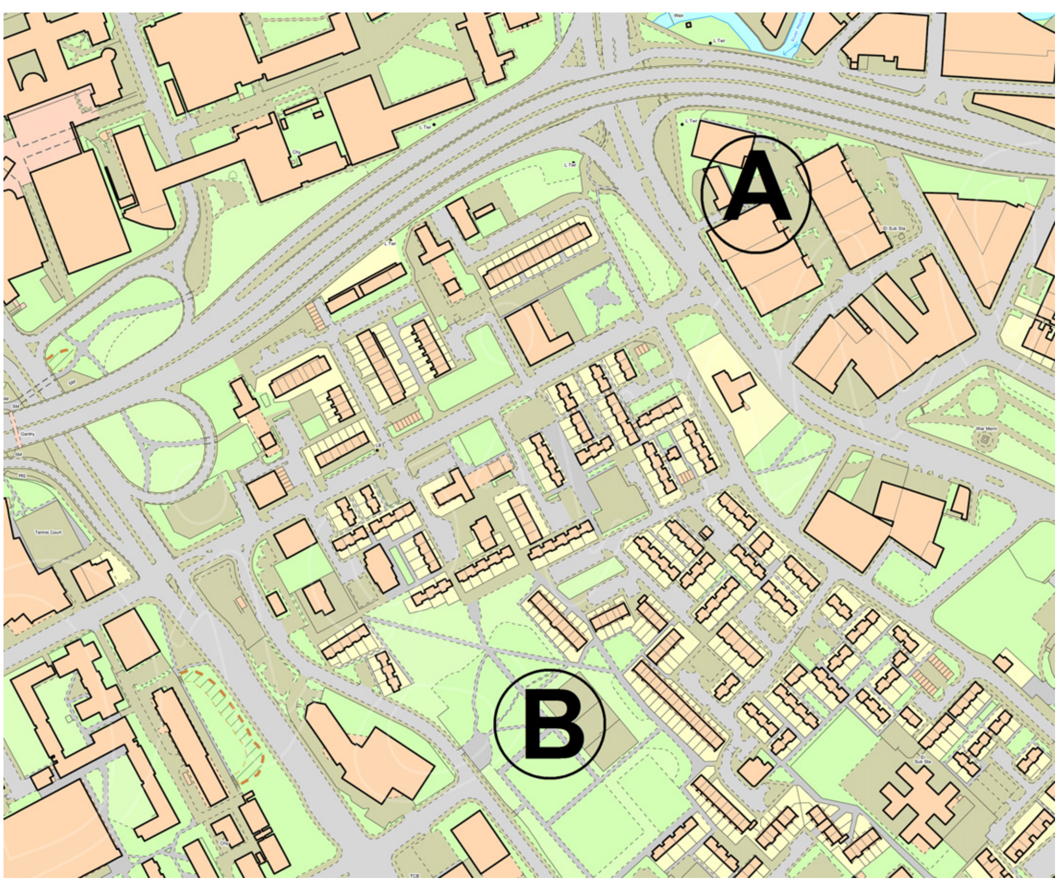

Fig. 6. Area of Manchester used for noise mapping [31]. The example locations A and B are marked on the figure.

specific building and site. The results also identify where noise reduction measures can have the greatest impact.

3. Results and discussion

3.1. Sound reduction index of ventilation aperture

Fig. 7 shows the calculated sound reduction index obtained from finite element analysis of an aperture of width 40 mm. This represents a 1% opening of one of the example building's windows which is the increment of opening of the building energy model's windows. As well as the series representing the acoustic spectrum with small frequency intervals, octave band average sound reduction index is also plotted.

The variation of sound reduction index with frequency is evident from Fig. 7. As mentioned previously, the negative sound reduction index values are due to reflected waves from the aperture and can be observed in experimental results [14]. Fig. 8 shows the octave band averages of apertures of widths from 40 mm to 200 mm – this represents the 1%–5% opening of the example building model's window area.

Due to computational expense the apertures were not modelled beyond 2000 Hz. This was seen as an acceptable simplification of the last octave band of interest, as fluctuations of sound reduction index with these higher frequencies were well within 1.5 dB of no sound reduction. It is assumed that any change due to extending the calculation into the higher frequencies would not affect the results significantly. Published results [12,14] show that the difference between sound reduction index at the resonances and anti-resonances tends to decrease as the frequency is increased. The crossing of the lines in Fig. 8 is due to the size of the aperture influencing the frequency at which resonances and anti-resonances occur. The largest differences between maximum and minimum aperture sound reduction index occur with the smaller apertures. For the 40 mm aperture this is from 6.5 to −1.6 dB. By the use of Equation (4), the construction material properties given in Table 1 and the aperture sound reduction index results in Fig. 7, the combined SRI values of the façade were calculated and these are presented in Fig. 9

3.2. Building noise exposure

Fig. 10 illustrates the façade exposure of the example buildings to road noise in location A. For Building 1 in location A the average noise level at a window was 74 dB(A). In location B the average exposure was less, at 65 dB(A), there was also a far greater range than for any other situation investigated in this study. Noise levels varied progressively from 54 to 75 dB(A) along the length of this building.

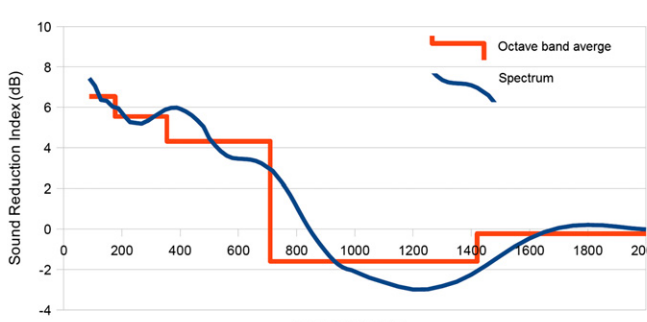

Fig. 7. Sound reduction index for a slit aperture representing 40 mm window opening, spectrum values and octave band averages.

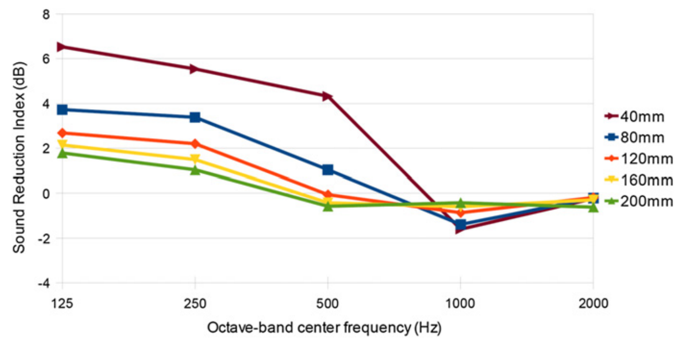

Fig. 8. Sound reduction index averaged over the octave bands for different sized ventilation apertures (aperture width indicated in the legend).

The exposure of Building 2 was similar to that of Building 3. The average levels at the windows were 74 dB(A) for location A and 62 dB(A) for location B and due to the smaller perimeter length of these two buildings compared to Building 1, noise level across façades was more uniform.

3.3. Cooling energy variation with noise tolerance

The results presented in Figs. 11–13 show average chiller electricity use during occupied hours of the summer period against tolerated internal noise level. The results are displayed from minimum chiller use, corresponding to the situation where all windows were open, to maximum chiller use, corresponding to the situation where windows were sealed. These end points represent the limits of this investigation. The shapes of the curves in Figs. 11–13 are the product of the noise exposure patterns and the window positions for the buildings. For these results Construction 1 was used.

The differences in noise exposure between the two sites are quantified in the results by the separation of the curves. A greater tolerance of noise is needed in location A for the same level of air-conditioning used as in location B. The distance between the curves for the buildings is related to the range of noise exposure for the buildings in each location. Maximum exposure for Building 1 is relatively uniform between locations A and B, changing from 75 to 79 dB(A). The minimum values for building noise exposure vary much more, from 54 to 69 dB(A), this being due to the length of the building and the main noise source for location B being concentrated on one side.

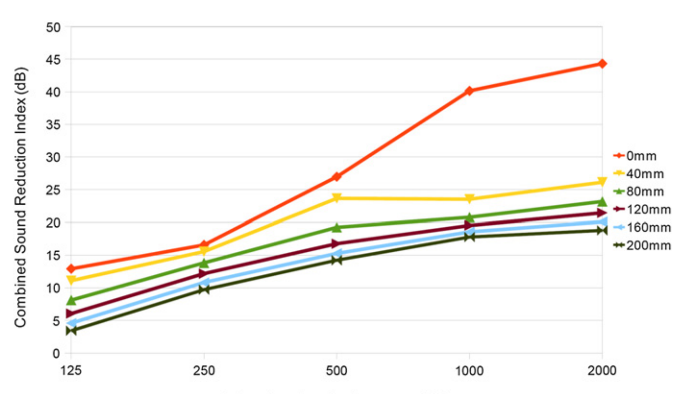

Fig. 9. Combined sound reduction index variation with frequency and ventilation opening size indicated in the legend.

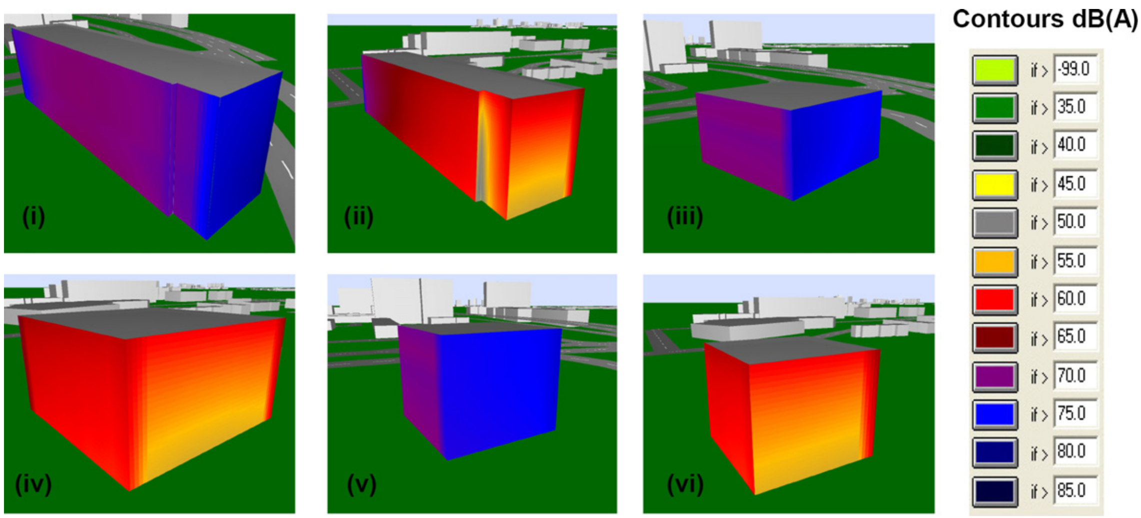

Fig. 10. Contours of noise levels at building façade – (i) Building 1 in location A. (ii) Building 1 in location B. (iii) Building 2 in location A. (iv) Building 2 in location B. (v) Building 3 in location A. (vi) Building 3 in location B.

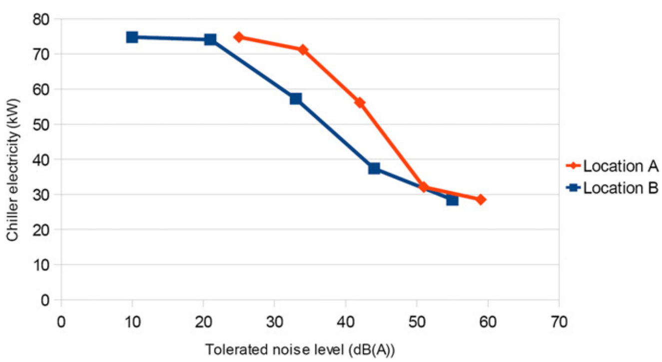

Fig. 11. Comparison of Building 1 in different noise locations.

There is a wide range of guidance on what level of external noise ingress is acceptable depending on the different national codes or guidelines, room use, time of day etc. For England and Wales the requirements for the acoustic design of schools are mandatory but there are no similar mandatory requirements for office buildings. To illustrate the potential use of this new method an assumed tolerated noise level was used to compare cooling energy consumption between buildings and locations. The suggested maximum noise rating of NR 35 for open plan offices [41], which for a broad band traffic noise spectrum from BS EN ISO 717-1:1997 [40] equates to 34 dB(A), was used. This represents an external noise ingress of a similar order to that, which is suggested as the maximum background noise levels generated by building services installations. Using this as the tolerated noise level, the cooling energy consumption for each building and noise location can be estimated from Figs. 11 to 13.

For Building 1 the reduction in average cooling energy consumption between location A and B is 22%. The change between locations for Building 2 is 39% and a 45% change is calculated for Building 3. Such information would be useful to inform decisions about which cooling strategy to implement depending on the noise exposure of a particular location. A rule of thumb for the change in noise exposure due to a change in traffic flow gives an even 3 dB decrease for a halving of the traffic flow. Using the gradient of the curves in Fig. 11 the change in cooling energy due to a halving of traffic around Building 1 can be estimated. For Location A this gives a 1.7% decrease and for Location B a 8.3% decrease is calculated. A similar method can be used to estimate the potential benefit of introducing noise mitigation measures over the whole building. Table 2 shows the reductions of cooling energy consumption if the 34 dB(A) level is again used as the tolerated noise level and it is assumed that through the application of acoustic treatments an improvement of 10 dB(A) can be made to noise levels experienced by the occupants.

Table 2 shows the large difference in the effectiveness of the noise reduction measure with regard to the mixed mode cooling

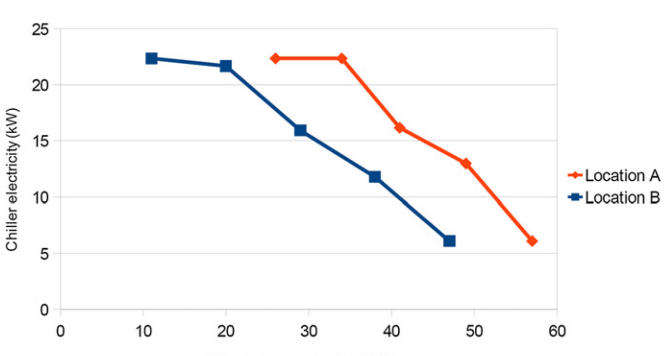

Fig. 12. Comparison of Building 2 in different noise locations.

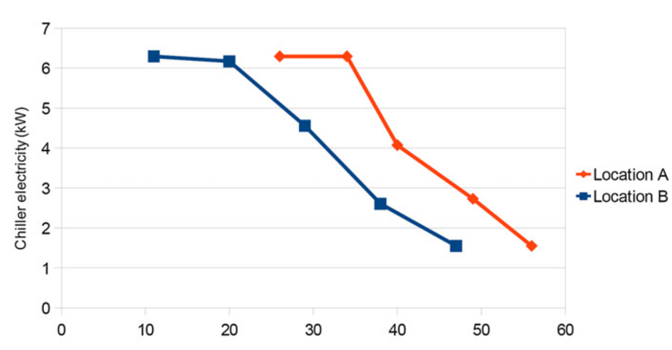

Fig. 13. Comparison of Building 3 in different noise locations.

Table 2
Influence of a 10 dB(A) acoustic treatment on mixed mode cooling energy consumption. Percentage change relative to cooling energy consumption before the implementation of 10 dB(A) treatment and a corresponding increase in ventilation opening to maintain noise ingress at 34 dB(A).

	Difference (kW)		% Change	
	Location A	Location B	Location A	Location B
Building 1	20.4	18.0	28.7	32.6
Building 2	7.4	5.6	33.0	41.4
Building 3	2.8	1.6	44.8	45.2

energy consumption, depending on the location and the building. Building 3 in Location B benefited most from the acoustic treatment, with a 45.2% reduction in its cooling energy consumption. A combination of acoustic treatments and passive cooling strategies could remove the need for mechanical cooling for this example. The noise exposure patterns of Buildings 2 and 3 were very similar, and so the differences between these buildings were largely due to the difference in the depth of the office space. This is a key influence on the effectiveness of natural ventilation and illustrates that a natural ventilation strategy, in general, is easier to implement for buildings with shallow floor plans. For Building 1 the influence of the noise reduction measure was a smaller percentage of the total cooling requirements but there was consistent improvement across the two locations. Building 1 had the largest variation of noise exposures at the different window positions and so applying an acoustic treatment over the whole building would not be the most effective strategy. Careful positioning of individual noise reduction measures, such as openings with higher sound insulation, would be a more effective way to maximise ventilation. For example, open areas with matching openings on either side of corners or opposite walls would develop cross ventilation. Openings concentrated on just one single wall would not encourage as much air flow. The model would have to be adjusted to represent this, but a similar method could be adopted iteratively for design optimisation. The influences of blinds, shading devices and green roofs [42] are interesting subject of future work as both the building's cooling performance and noise ingress would be affected.

A comparison of results for Construction 1 and Construction 2 is given in Fig. 14. With the open façade, corresponding to the lower chiller energy use, the noise ingress is similar for both constructions. This indicates how the acoustic insulations of the façades converge when opened, due to the dominant influence of the ventilation openings. With a more closed façade the variation in ingress due to the different sound insulation properties of the construction materials is apparent.

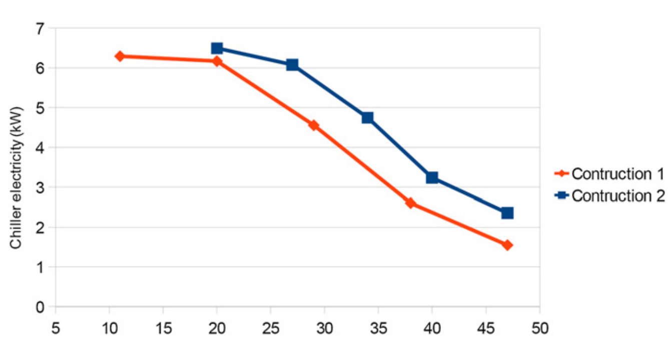

Fig. 14. Comparison of construction materials for Building 3 in location B.

4. Conclusions

In this paper a method has been presented that integrates noise mapping techniques with building energy modelling. Finite element models were used to define the ventilation aperture sound reduction index. It was found that sound reduction index values varied by up to 8 dB across the frequencies considered. The usefulness of this method was demonstrated for the consideration of ventilation potential for different locations, cooling energy consumption for the example buildings in the quieter noise locations were found to decrease by between 22% and 45%. A key potential use of the gradients of the results curves (Figs. 11–14) is to predict the appropriateness of adopting noise reduction methods. This quantifies how the acoustic requirements of a building can interact with the natural ventilation of a building and, in the case of mixed mode buildings, impact directly on the cooling load. The size of this effect varied with up to a 45% decrease of summer chiller energy use if a 10 dB(A) treatment is assumed.

This integrated approach could be automated within building energy calculation tools. The variation in these results demonstrated the importance of this approach when deciding where to adopt natural and mixed mode ventilation strategies and whether noise mitigation methods are worth adopting in specific cases. This is a particular issue where fixed acoustic criteria have been prescribed, as is the case for schools in the UK [18], where a background noise level of 35 dB(A) should not be exceeded. This can conflict in certain areas with the goal of reducing energy consumption and maintaining indoor air quality.

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References

[1] Ghiaus C, Allard F, Santamouris M, Georgakis C, Nicol F. Urban environment influence on natural ventilation potential. Build Environ 2006;41(4):395–406.
[2] Wilson M, Nicol JF. Tolerated noise levels in the U.K. and Pakistan and simultaneous thermal comfort. Renew Energ 1994;5(5–8):1006–8.
[3] Jentsch MF, Bahaj AS. Climate change future proofing of buildings – Generation and assessment of building simulation weather files. Energ Build 2008; 40(12):2148–68.
[4] Holmes MJ, Hacker JN. Climate change, thermal comfort and energy: meeting the design challenges of the 21st century. Energ Build 2007;39(7):802–14.
[5] Kang J, Li Z. Numerical simulation of an acoustic window system using finite element method. Acta Acust United Ac 2007;93(1):152–63.
[6] Oldham DJ, Kang J, Brocklesby MW. Modelling the acoustical and airflow performance of simple lined ventilation apertures. Build Acoust 2005;12(4): 277–92.
[7] Kang J, Brocklesby MW. Feasibility of applying micro-perforated absorbers in acoustic window systems. Appl Acoust 2005;66(6):669–89.
[8] Yu C-J, Kang J. Environmental impact of acoustic materials in residential buildings. Build Environ 2009 Oct;44(10):2166–75.
[9] European Union. European Union, directive 2002/49/EC. Relating to the assessment and management of environmental noise. Official J Eur Commun; 2002. No. L 189.
[10] Barclay M, Kang J, Sharples S, Wang B, Du H. Estimating urban natural ventilation potential by noise mapping and building energy simulation. In: Proceedings of 20th International Congress on Acoustics. Sydney, Australia: 2010.
[11] Nomura Y, Inawashiro S. On the transmission of acoustic waves through a circular channel of a thick wall, vol. 12 (B). Science Report of Tohoku University; 1960.
[12] Gomperts MC. The "sound insulation" of circular and slit-shaped aperture. Acustica 1964;14(1):1–16.
[13] Wilson GP, Soroka WW. Approximation to the diffraction of sound by a circular aperture in a rigid wall of finite thickness. J Acoust Soc Am 1965; 37(2):286–97.

[14] Oldham DJ, Zhao X. Measurement of the sound transmission loss of circular and slit-shaped apertures in rigid walls of finite thickness by intensimetry. J Sound Vib 1993;161(1):119–35.
[15] Comsol Multiphysics. Acoustics module, user's guide. 2008, http://www.eecs.berkeley.edu/~omiller/; 2011.
[16] De Salis MHF, Oldham DJ, Sharples S. Noise control strategies for naturally ventilated buildings. Build Environ 2002;37(5):471–84.
[17] Oldham DJ, De Salis MHF, Sharples S. Reducing the ingress of urban noise through natural ventilation openings. Indoor Air 2004;14:118–26.
[18] Hopkins C, Hall R, James A, Orlowski R, Wise S, Canning D. Building bulletin 93 (BB93): acoustic design of schools. 2003, www.teachernet.gov.uk/acoustics/; 2010.
[19] DfEE. Acoustics in educational buildings. Build Bull 1975;51. Department for Education and Employment, London, UK.
[20] Templeton D. Acoustics in the built environment. Butterworth Ar; 1993.
[21] Design Builder Software Ltd. Design Builder 2.1 User's Manual. 2009; http://www.designbuilder.co.uk/component/option, com_docman/task, cat_view/gid,20/Itemid,30/ [accessed 17.05.10].
[22] Henninger RH, Witte MJ. EnergyPlus testing with building thermal envelope and fabric load tests from ANSI/ASHRAE standard 140-2007. Washington, D.C.: Office of Building and Technologies, U.S. Department of Energy; 2009.
[23] Chartered Institution of Building Services Engineers. CIBSE Guide A: environmental design; 2007.
[24] ASHRAE. American Society of Heating, Refrigerating and air-conditioning engineers. ANSI/ASHRAE standard 55–2004. In: Thermal Environmental Conditions for Human Occupancy; 2004. Atlanta.
[25] Liddament MW. Air infiltration calculation techniques – an applications guide. AIVC; 1986.
[26] DataKustik GmHb. Cadna/A for windows – User manual. Greifenberg; 2006.
[27] Department for Transport (DfT) UK. Calculation of road traffic noise. The Stationery Office Ltd; 1988.
[28] Mak C, Leung W, Jiang G. Measurement and prediction of road traffic noise at different building floor levels in Hong Kong. Build Serv Eng Res T 2010;31(2):131–9.
[29] Wang B, Kang J. Effects of urban morphology on the traffic noise distribution through noise mapping: a comparative study between UK and China. Appl Acoust 2011;72(8):556–68.
[30] European Commission. Working Group assessment of exposure to noise (WG-AEN). Position paper – good practice guide for Strategic Noise Mapping and Theproduction of Associated Data on Noise Exposure, Version 2. 2006; http://ec.europa.eu/environment/noise/pdf/best_practice_guide.pdf.
[31] Ordnance Survey. Roam Digimap image. 2012; http://edina.ac.uk/digimap/index.shtml [accessed 09.01.12].
[32] Kang J, Huang J. Noise-mapping: accuracy and strategic application. In: Proceedings of inter noise. Rio de Janeiro, Brazil; 2005.
[33] Kang J. Acoustics of long spaces: theory and design practice. London: Thomas Telford Ltd; 2002.
[34] Kang J. Numerical modelling of the sound fields in urban squares. J Acoust Soc Am 2005;117(6):3695–706.
[35] Kang J. Numerical modelling of the sound field in urban streets with diffusely reflecting boundaries. J Sound Vib 2002;258(5):793–813.
[36] Kang J. Sound propagation in interconnected urban streets: a parametric study. Environ Plann B 2001;28(2):281–94.
[37] Kang J. Sound propagation in street canyons: comparison between diffusely and geometrically reflecting boundaries. J Acoust Soc Am 2000 Mar;107(3):1394–404.
[38] Kang J. Urban sound environment. Taylor & Francis; 2007.
[39] Xie H, Kang J. On the relationships between Environmental noise and socio-economic factors in greater London. Acta Acust United Ac 2010;96(3):472–81.
[40] BSI. BS EN ISO 717-1:1997–Acoustics – Rating of sound insulation in buildings and of building elements. part 1. Airborne sound insulation. London: BSI: (British Standards Institute); 1997.
[41] BSI. BS 8233:1999. Sound insulation and noise reduction for buildings – Code of practice. London: BSI: (British standards Institution); 1999.
[42] Yang HS, Kang J, Choi MS. Acoustic effects of green roof systems on a low-profiled structure at street level. Build Environ 2012 Apr;50(0):44–55.