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Estimating urban natural ventilation potential by noise mapping and building energy simulation

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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. In noisy urban areas this can conflict with the need to reduce the ingress of external noise. In this study the effect of building exposure to noise on natural ventilation potential is investigated. The occurrence of window openings on a building façade was adjusted according to road traffic noise levels. Road traffic noise levels at the building façade were modelled using a noise map of Manchester in CadnaA. Window openings were adjusted in representative DesignBuilder/EnergyPlus building energy models with calculated natural ventilation and opening schedulings. This enabled acoustic considerations to be quantified in terms of building ventilation and chiller energy use at the whole building level over a summer time period.

INTRODUCTION

Natural ventilation strategies are difficult to implement for buildings in urban areas due to a number of reasons, such as lower wind speeds, higher temperatures due to the urban heat island effect, pollution and noise (Ghiaus et al. 2006). In their work street canyon situations were adressed with measurements being taken outside the facade at different heights above street level. Relationships were then defined between street aspect ratio, height above street level and noise levels at which occupants might be motivated to close the windows. This demonstrated how the influence of noise on ventilation changes with position on the building facade.

The pressure differences that drive natural ventilation, wind and or buoyancy effects, are very weak, typically less than 10Pa. The easiest way to achieve the least restriction of a ventilation path is to open large areas of the facade. This can conflict with attempts to reduction noise ingress. External noise levels are often given as the reason for air-conditioning buildings (Wilson & Nicol 1994). Summer time over heating risk could be an increasing problem for the future. Future performance analysis of case study buildings (Jentsch & Bahaj 2008; Holmes & Hacker 2007) suggested that with expected future temperature rises providing a comfortable summer time indoor environment without a heavy reliance on mechanical cooling will be one of the major challenges.

Various systems exist that reduce noise ingress whilst minimising the restriction of the ventilation path. Some examples of these include passive system that stagger glazing, employ absorbing liners or louvres and active systems (Kang & Zhemin 2007; Oldham et al. 2005; Kang & Brocklesby 2005).

The acoustic insulation and ventilation requirements for a specific site and building are complex so it can be difficult to quantify the benefits of different approaches. Noise mapping has become a legal requirement in Europe (European Union 2002). In this paper the extent to which noise mapping could be a useful resource for quantifying natural ventilation potential is investigated. By extension this could enable noise reduction measures to be quantifying in terms of ventilation and energy.

The first question is: are there discernible differences detected in modelled ventilation rates and air-conditioning use in buildings from different noise positions? Does this present the possibility of using noise mapping to help evaluate natural ventilation potential for a building site? And could this method be used to quantify the benefits of noise reduction measures in terms of natural ventilation and air conditioning use?

In this study natural ventilation and acoustic insulation of buildings are linked by the size and position of openings in the facade. The level of calculated road noise ingress was changed for three representative buildings in two noise environments and compared with the corresponding change in effectiveness of natural ventilation. A combination of noise mapping and building energy simulation is used to achieve this

An overview of the method will be followed by a brief description of building energy simulation software and airflow network models. The representative building models used here are then introduced and a description of the method used to calculate sound insulation from simple window opening in a facade. The noise map of Manchester that was used to represent two contrasting positions of noise exposure is presented.

Some of the main limitations of the two modelling approaches combined here are also discussed through the paper.

This is important when considering what levels of accuracy is required for useful conclusions about site natural ventilation potential and noise control strategies to be drawn?

METHODOLOGY

The method employed here is to use the calculated noise levels at the facade of a building to determine how much the windows on that facade are opened. The noise level that each window is exposed too is available from building evaluation calculations done with noise mapping software. The opening area created by the opening of a window is treated as a simple aperture in the facade of the building. Effective sound insulation of the facade is then treated as a function of the percentage of window that is opened.

Between the maximum and minimum levels of noise ingress experienced when all windows are either opened to their maximum or fully closed, a number of tolerated noise levels are set. The window opening at all points on the facade are adjusted so that noise ingress is as close to these tolerated noise levels as possible. The intermediate tolerated noise levels correspond to levels where a mixture of different opening areas occurs over the facade of the building depending on its noise exposure. A separate building energy calculation is carried out for each tolerated noise level. These are run over a summer time period to quantify the effectiveness of natural ventilation cooling.

Building Energy modelling

In the 50 years over which building energy simulation software has been developed many versions have been produced. (Crawley & Hand 2006) contrast the capabilities of twenty of the major simulation packages available. Two numerical simulation techniques which are widely used for calculating air movement within buildings are network air flow and Computational Fluid Dynamics CFD. Network airflow is well adapted to building energy analysis. For detailed simulation of airflow such as that required when looking at individual rooms or openings CFD is most appropriate. Network air flow models aim to represent whole building internal airflow over larger time periods. In a network airflow model the building is modelled as a collection of nodes representing rooms, parts of rooms, equipment connection points, ambient conditions etc. The paths between these nodes then represent the cracks, doors, and windows etc. (Clarke 2001). The mass flow rate between nodes is then given as a function of pressure difference. This and the conservation of mass at each node give the set of equations that can be solved at successive time steps. The flow rate through each opening is give by.

$$Q = C.(\Delta P)^n \qquad (1)$$

Where Q is the flow rate through the opening, C is the flow coefficient which is related to the opening size, ΔP is the pressure difference across the opening n is the flow exponent varying from between 0.5 fully turbulent flow and 1.0 for laminar flow.

For this work the whole building level air flow patterns and cooling energy use was modelled for an extended summer time period. DesignBuilder/EnergyPlus software (DesignBuilder Software Ltd 2009) 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 (Henninger & Witte 2009). It provides a heat balance based solution to the heating and cooling loads required to maintain a buildingôs thermal conditions. Various modules link into this core calculation to enable the representation of the building and its processes. This includes the airflow network module that is focused on in this work.

The approach used in this study was to use the cooling energy output from mixed mode buildings during a June to August time period. The June to August time period is represented by typical hourly weather data covering these months of the year. In mixed mode buildings internal comfort conditions are primarily maintained by natural ventilation. When this is inadequate active cooling is introduced (DesignBuilder Software Ltd 2009). The cooling energy used by the air handling unit will therefore be used to indicate the extent to which the acoustic environment has affected the natural ventilation potential.

Mechanical ventilation is also modelled to ensure that a minimum level of air exchanges occur for air freshness regardless of the acoustically driven window opening patterns. This ensures the same internal environment is modelled. The differences in cooling energy use are then only due to the different acoustic situation and its window opening patterns.

The window opening for these buildings follows an office operation schedule that is from Monday to Fridays 08:00 till 18:00. Window opening is controlled by this operation schedule and a temperature set point. When internal comfort requires it windows are opened. Another condition for opening is that external temperatures are lower than the internal temperature. This is illustrated by figure 1. Total fresh air which includes that supplied by natural ventilation, mechanical ventilation and infiltration is plotted alongside internal and external temperature throught a 24 hour period.

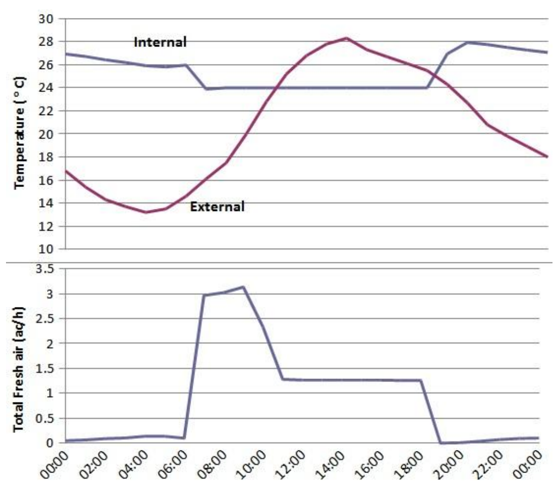


Figure 1. Total fresh air to a zone throughout a 24 hours period

In addition to this standard modelled window opening pattern the opening percentage is adjusted so that the acoustic insulation of the facade at each window is not reduced to a level where the noise ingress exceeds a set tolerated level. This is done until windows are at maximum opening percentage or fully closed.

The window openings in the building energy model correspond to horizontal sliding windows. So the opening orifice is a vertical slit the full hight of the window. The windows in the buildings modelled here have a standard hight of 1.5m and have a standard separation of 5m where the facade dimensions allow. The exact width of the window is then defined by the percentage glazing which is 40% for building 1 and 30% for buildings 2 and 3. Window opening is defined by percentage of the window that opens with each percentage corresponding to approximately 4cm increase in aperture width.

Three idealized office building types were chosen, as shown in figures 2, 3 and 4. Standard template discriptions of construction and HVAC equipment were used. Building 1 has a 40% glazed facade with 10% of this glazed area opening. Its footprint was 65.4m long by 13.4m wide at its widesest section.

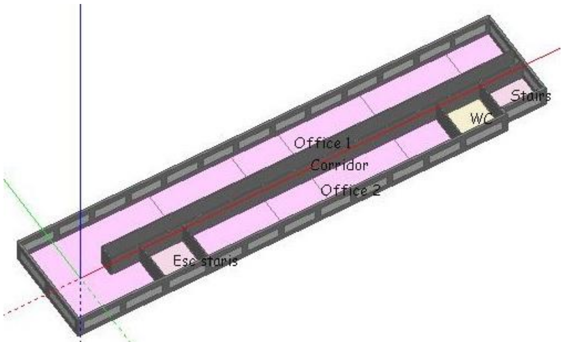


Figure 2. Floor plan of office building 1

Buildings 2 and 3 are two simple offices with square footprints of dimensions 20m by 20m and 13m by 13m respectively. The floor plans have contrasting room depth but other than that the layouts were kept the same as much as possible.

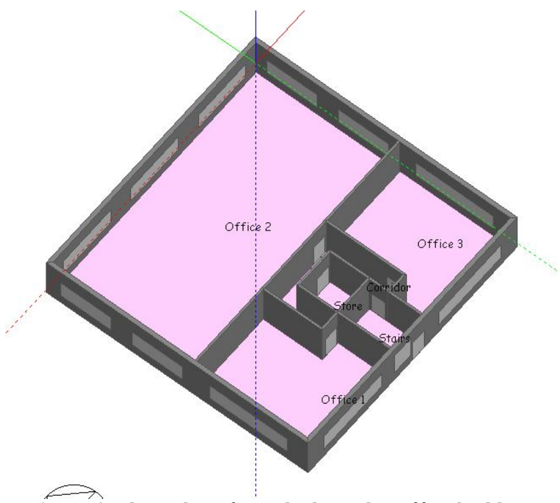


Figure 3. Floor plan of simple deep plan office building, (Building 2)

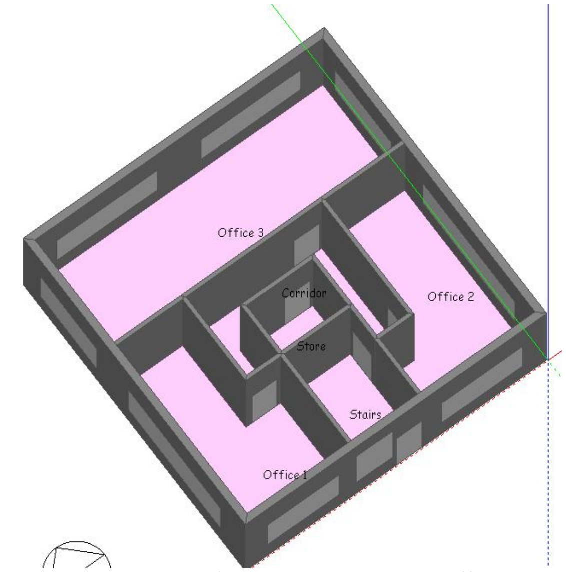


Figure 4. Floor plan of the simple shallow plan office building (building 3)

Wind pressure coefficients are one of the major sources of uncertainty when using airflow network models (de Wilt & Augenbroe 2002). For the models used in this work wind pressure coefficients are from AIVC Table (Liddament 1986). They are meant for buildings up to three stories and with a length to width ratio of 1:1. AIVC Table wind pressure data is thought to be a good initial approximation and were therefore considered acceptable for this initial comparative study. For more accurate wind pressure coefficients scale model testing or CFD simulation would be required.

The simple office buildings, buildings 2 and 3, fit the criteria for the use of the wind pressure coefficients from AIVC Table well. They have 1:1 ratio and are three stories high. This means there is more reason to be confident that the air flow patterns for these buildings are representative. For practical reasons it was was not possible to obtain wind pressure coefficients specifically for building 1. More caution is therefore required when considering the results for building 1, particularly the absolute values. It was thought that including the results for this real building could still give useful insights to the limitations and possibilities of this method for buildings with different shapes.

Acoustic insulation

In this section the method for calculation of acoustic insulation indices is covered. Road traffic noise is considered for this study and for this reason the sound reduction (SRI) values for the facade construction were adjusted for the low frequency components of road traffic noise. This is then presented as a single figure weighted value that corresponds to the noise mapping output. This was done according to BS EN ISO 717-1:1997.

The standard equation for the SRI of a composite panel (SRI_{W+A}) is given below, where it can be seen that effective SRI of the facade is dominated by the poor performance of the ventilation opening when the window is open (De Salis et al. 2002).

$$SRI_{W+A} = -10\log\left[\frac{A_W 10^{\left(\frac{-SRI_W}{10}\right)} + A_A 10^{\left(\frac{-SRI_A}{10}\right)}}{\left(A_W + A_A\right)}\right] \quad (2)$$

where the aperture has area A_A and sound reduction index of SRI_A and the wall has area A_W and sound reduction index of SRI_W

Different construction types attenuate traffic noise to different degrees. In (Oldham et al. 2004) values for walls of between 10 dB(A) and 40 dB(A) were used. Sealed single glazing gives SRI values of between 20 dB(A) and 25 dB(A) (Ford & Kerry 1973) and their double glazing arrangement between 35 dB(A) and 40 dB(A). In this work SRI values where adopted from the acoustic design of schools guidance (Hopkins et al. 2003). Two standard construction types where used 4/12/4 mm double glazing and Two leaves of 102.5mm brickwork with a 50mm cavity. These had adjusted SRI values of 27 dB(A) and 50 dB(A) respectively. Using equation (2) and considering the percentage of the facades made up of wall and glazing gives a compose SRI value.

Building 1 had 40% of the facade glazed so with windows fully closed this gives an effective SRI of 31 dB(A). Buildings 2 and 3 are 30% glazing which gives an effective SRI of 32 dB(A).

The opening of windows is assumed to create a simple aperture in the facade and as an initial approximated this is given an SRI value of 0 at all frequencies. This assumes that the opening arrangement is such as not to significantly effect the sound field (Oldham et al. 2005).

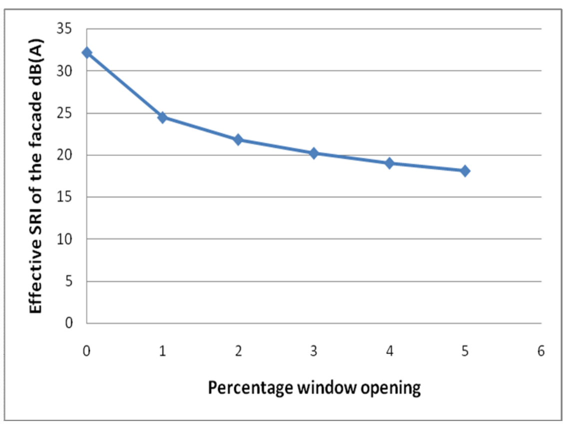


Figure 5. Effective SRI of the facade to traffic noise against percentage opening of the window for buildings 2 and 3.

Road noise levels in the rooms were calculated according to following equation.

$$L_R = L_0 - SRI + 10\log(S/A) \quad (3)$$

where L_R is the sound level in the room, L_0 is the sound level at the façade, SRI here is the combined sound reduction index of all elements of the facade, S is the surface area of the facade and A is the room absorption.

A is assumed to be a standard $10m^2$. The ratio of facade surface to absorption area will stay relatively constant and so, therefore, will the last term of equation (3). In this way the effect of window opening was focused on. Equation (3) becomes.

$$L_R = L_0 - SRI + 2.4 \quad (4)$$

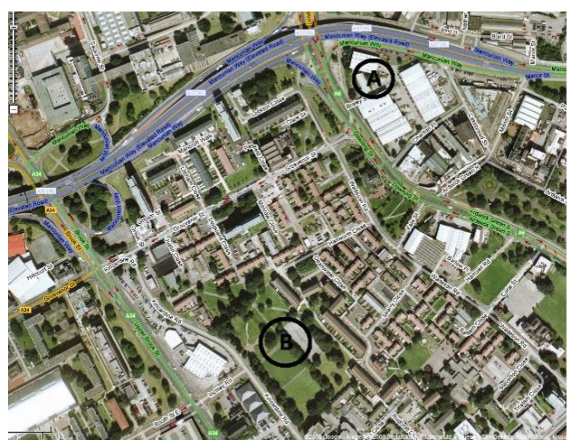
The concept of a tolerated internal noise level is used so that the output from a noise-mapping simulation can be used to describe site specific noise exposure. The noise-mapping output will give a range of noise levels for different positions on a building facade. The window opening percentage for each position on the facade will be adjusted in the buildings energy model so that the calculated sound level from equation (3) is kept as close to the tolerated level as possible. The simulations are repeated with a range of tolerated noise levels that describe opening patterns between maximum opening and fully closed over the whole facade.

The building energy model results from different tolerated noise levels aim to illustrate the relationship between acoustic considerations and natural ventilation potential for the specific building and site, and to quantify where noise reduction measures can have the greatest impact on the natural ventilation potential.

Noise mapping

The noise mapping from this study was completed using the software CadnaA (DataKustik GmbH 2004). The road and building layout for the 500m x 500m area was taken from a digital mapping service. Traffic flow was measured and characterised and noise level measurements taken to compare with modelled values.

Figure 6 shows the mapped area that was used in this study. The two sites chosen for the position of the example buildings are marked A and B. The building position A next to the motor way was compared to a less noisy position B. The positions chosen have relatively different noise exposure for this initially test of the method. The positions were also chosen to minimise the inaccuracies due to significant reflections.



Source: (Google maps, 2006)

Figure 6. Area of Manchester used for noise mapping

Direct sound is thought to be dominant for the building evaluation done in this study. While noise mapping has become a legal requirement in Europe (European Union 2002), there are some concerns about its accuracy. (Kang & Huang 2005) found that the accuracy of a noise map was highly dependant on the importance of reflected noise to the mapped area. Although the absolute accuracy of using this technique is often limited it does presents an easily available source of information about noise levels at a particular site and under ideal conditions about the noise levels at the facade of buildings or proposed buildings.

Figure 7 illustrates the facade exposure of building 1 to road noise in position A. In this position the average level at a window was 74 dB(A).

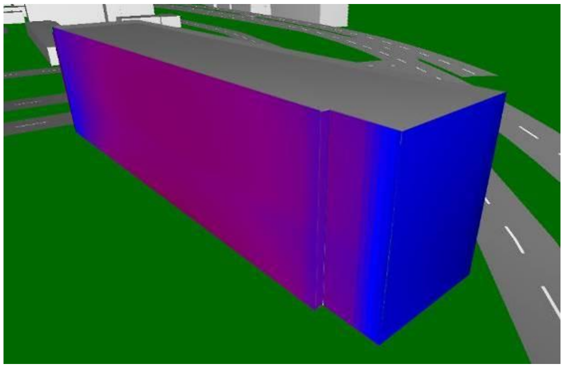


Figure 7. Contours of noise levels at the facade of building 1 in position A. Contours represent levels from 69 dB(A) in the purple zone to 79 dB(A) in the blue zone.

Buildings 1 in position B had an average exposure of 65 dB(A) but with a far greater range than for any other situations investigated in this study. As can be seen in figure 8, noise levels varied progrssively from 54 dB(A) to 75 dB(A) along the length of the building. Figures 9 and 10 show the exposure of building 2. The average levels at the windows were 74 dB(A) for position A and 62 dB(A) for position B. Noise exposure patterns for building 3 were similar to that for building 2.

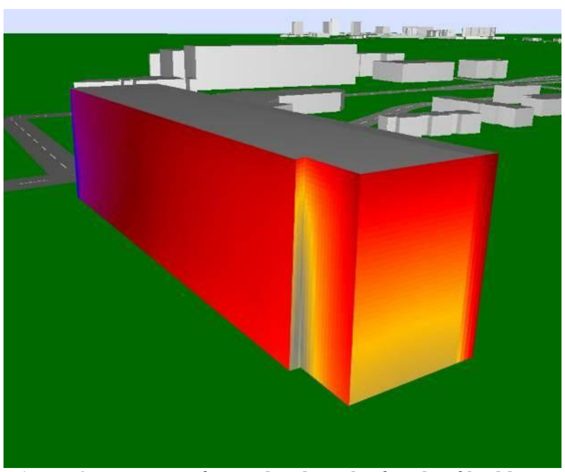


Figure 8. Contours of noise levels at the facade of building 1 in position A. Contours representing change in levels from 54 dB(A) in the yellow zone to 75 dB(A) in the blue zone.

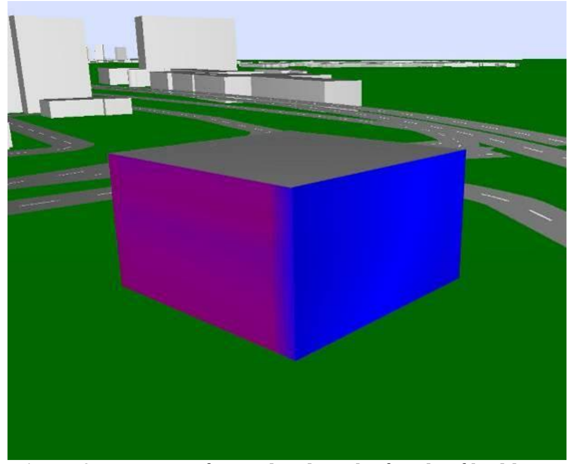


Figure 9. Contours of noise levels at the facade of building 2 in position A. Contours represent levels from 70 dB(A) in the purple zone to 77 dB(A) in the blue zone.

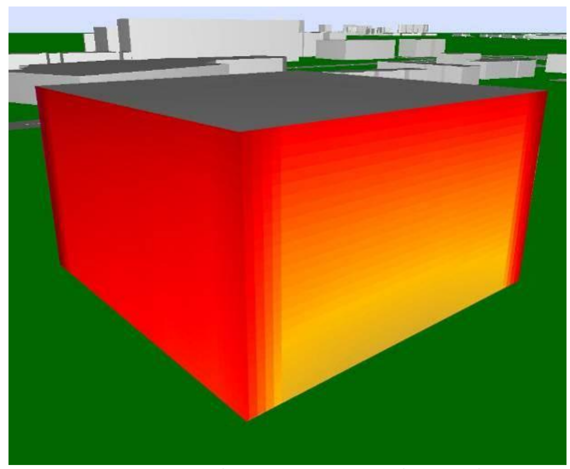


Figure 10. Contours of noise levels at the facade of building 2 in position A. Contours represent levels from 55 dB(A) in the purple zone to 67 dB(A) in the blue zone.

The facade noise levels were mapped onto the corresponding surface of the design builder model and window opening percentage adjusted so that combined acoustic insulation kept internal levels as close to a set tolerated level as possible.

RESULTS

The results for air conditioning use during the summer period are presented in figures 11, 12 and 13. These show average chiller electricity use by the air handling unit during occupied hours against tolerated internal noise level. Tolerated noise level is a level where the occupance do not want to close the window any more. The results are displayed from minimum chiller used corresponding to the situation where all windows are opened and maximum chiller use corresponding to the situation where windows are sealed. These end points represent the limits of this investigation. The points in between sample the possible tolerated internal noise levels that represent partial opening of the facade. The Legend A and B indicate positions A and B in the noise map which are shown in figure 6.

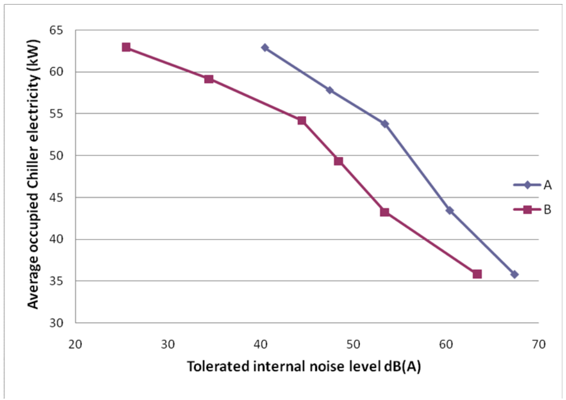


Figure 11. Results for building 1

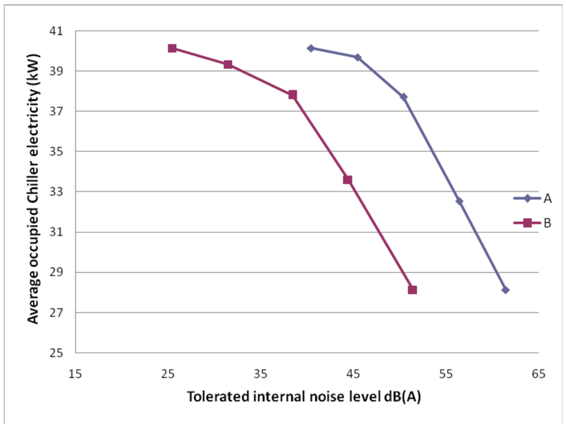


Figure 12. Results for building 2

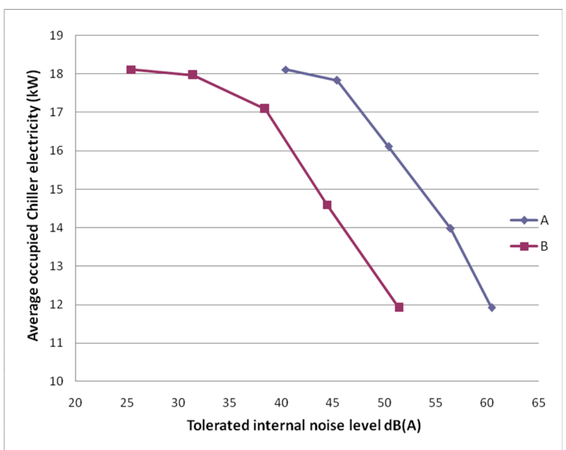


Figure 13. Results for building 3

The differences in noise exposure between the two sites are represented in the results by the separation of the curves. A greater tolerance of noise is needed in position A for the same level of air conditioning use in position B. This is what would be expected from the differences in average exposure level. The distance between the curves for buildings 2 and 3 are more constant than for building 1. This is a product of the larger range of noise exposure for building 1 in position B. Maximum exposure for building 1 relatively similar in position A and B, 79 and 75 dB(A) respectively. The Minimum values vary much more, from 69 to 54 dB(A).

The shape of the curves in figures 11, 12 and 13 appear to be a product of the buildings shape Buildings 2 and 3 which have the same aspect ratio have very similar curves. At the lower tolerated noise levels for these buildings there is a distinct change in gradient. This part of the results corresponds to the situation were there are small percentage openings being made in areas of the facade with lower noise exposure. Two factors that could be responsible for this characteristic are firstly that the initial small percentage openings have a greater influence on acoustic insulation than ventilation opening. This is illustrated by figure 5. This sharp gradient change in the results is not evident for building 1, though some less dramtic change does occur. The pattern of exposure for a specific building is important to the ventilation here as it effects the position of openings. For example open areas with matching openings on the other sides of corners or opposite walls would encourage cross ventilation. Openings concentated on just one single wall would not encourage as much air flow.

The benefit of introducing noise mitigation measures over the whole building might be estimated by considering the natural ventilation rates equivalent to a higher noise tolerance. Careful positioning of individual noise reduction measures such as openings with higher sound insulation would be a more effective way to maximise ventilation. The models would have to be adjusted to represent but a similar method could be useful for optimisation.

DISCUSSION

Linking noise mapping and building energy simulation has enabled acoustic considerations to be quantified in terms of ventilation rates and cooling energy use for specific noise sites and buildings. It was found that this method could detect discernible differences in air conditioning use when the acoustic environment was considered with noise mapping. The relationships between tolerated noise level and air conditioning use appeared to show characteristics specific to the site and the building. This is encouraging as this method of linking facade noise level to the builing energy simulation could be readily automated given matching facade surfaces.

These results need to be interpreted carefully, particular the absolute values. As has been mentioned there are various simplifying assumptions made throughout and both noise mapping techniques used and building energy simulation methods have their limitations. The two generic office buildings, building 2 and building 3 are thought to give more accurate results. This is because the wind pressure coefficients used are more valid for these buildings.

Future work

More accurate modelling of exposure to noise could be introduced. This could lead to a similar method beings adopted for buildings in a street canyon. This would also require careful consideration of the buildings exposure to wind in such a situation.

The introduction of specific ventilation device properties could enable the optimisation of their position on the facade. The method could be developed as a cost benefit tool for implementation of these noise reduction measures.

Climate change predictions could be introduced into the building energy simulation weather data to give an insight into the extent to which climate change could affect the results.

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