6th International Meeting
on
Wind Turbine Noise
Glasgow 20-13 April 2015

Effects of built environment morphology in residential areas on resisting wind turbine noise on building façades

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Summary

In residential areas, the average noise exposure on buildings is affected both by distance attenuation and the morphology of the built environment. Aiming at exploring the noise-resistance of built environment morphology at specific distances, three kinds of typical suburban areas in the UK were sampled and noise maps were generated based upon an idealised modern wind turbine placed at various setback distances from each site. Relative importance of five morphological indices was examined on reducing the average façade exposure in terms of resisting wind turbine noise with different source-receiver distances, and at different frequencies. The results show that morphological parameters have considerable effect (up to 8.1dBA) on resisting the average noise exposure at buildings. Among the five indices, a compactly structured built environment is found to be most effective in resisting the average noise exposure on building façades, followed by using the long façade to face the wind turbine. The building orientation and the distance from the building in front are also found to be effective in resisting noise for low frequencies, typically at 50Hz. Having demonstrated to what extent changing a morphological index of the built environment would reduce the average noise level with different source-receiver distances, the findings could be applied to guide the design of residential layouts within different proximities from a wind turbine.

1. Introduction

As onshore wind farms are becoming a common feature of landscapes in many countries, there is an increasing likelihood that proposed projects would be closer to residential areas than ever before. There are good reasons, however, for developing wind turbines close to population centres. Locating turbines closer to where electricity is consumed reduces electricity loss in long-distance transmission (Archer et al., 2007) and there is some evidence that installing wind turbines in more urban contexts can reduce opposition to proposed development on aesthetic grounds (Knight, 2004). In the UK, a number of onshore wind turbines are introduced into suburban settings, some of these as close as 350m from highly populated residential areas, such as the wind turbine in the suburbs of Bristol, Dundee, and Nottingham. Therefore, there is a need to model the distribution of wind turbine noise in suburban built environment, with a focus on the localised noise exposure on and around receptors' dwellings, and the differences between types of suburban built environments.

The potential adverse impacts of wind turbine noise on neighbouring residents have been attracting great interest. Hence, the exposure indicator that best describes the level of wind

turbine noise received by the residents can be further explored. In previous studies, the noise exposures received by the residents were considered as A-weighted sound pressure levels (SPLs) outside their dwelling (i.e. Pedersen and Waye, 2007), calculated based on outdoor sound propagation models. However, it is important to note that in a residential area, noise exposure on buildings is affected both by outdoor propagation and the morphology of the built environment. The substantial differences between the maximum and minimum exposures at a building affected by the morphological indices have been modelled using noise mapping in a recent study (Qu and Kang, 2014). It has been found that morphological indices of the built environment have considerable effects on decreasing the minimum exposure at a building. Such effects are further examined in this paper in terms of resisting the "average façade exposure", which is a more conventional noise indicator that takes into account the noise exposures at all the façades around the building. The paper will examine whether the built morphology that reduces the minimum noise exposures can also decrease the average sound pressure levels (SPL) at the building. Various setback distances of the wind turbine are also considered in this research to represent the condition of residential areas in practice with different wind turbine proximities.

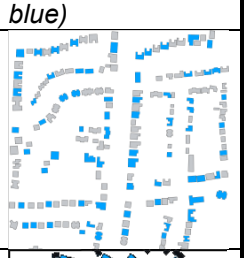
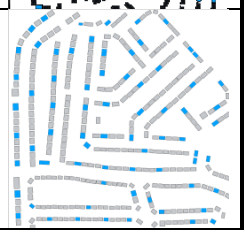
Therefore, the aim of this research is to explore the noise-resistance of building morphology at specific distances. Noise mapping techniques were applied for three typical suburban sites and the average façade exposure at sampled buildings were obtained, which were categorised by source distances and input in quantitative analyses with five morphological indices of the built environment. The noise resistance effects of the built environment morphology are examined in terms of both A-weighted SPL and SPL at different frequencies.

2. Methodology

2.1 Studied suburban areas

Based on the typology identified by Gwilliam et al. (1998) and refined by the SNACC (Williams et al., 2012), three categories of suburban areas were built based on real sample location as shown in *Table I*, representing the main categories of residential areas in the UK. A 500*500m plan was generated for each area.

Table I. Studied suburban categories and sampled dwellings for analyses

Type	*Characteristics*	*Period*	*Location of studied sample area*	*Plan of buildings (Sampled buildings shown in blue)*
1. Historic Suburb	Established terraced or semi-detached developments. The site includes a number of dwellings with H-shaped and L-shaped designs.	Victorian / Edwardian - up to 1919	*North Oxford*	
2. Pre-War Garden Suburb	Medium-large semi and detached homes with large gardens. It features curve streets with buildings of changing orientations and large openness within the suburban fabric.	1900s - 1930s	*East Dene, Ratherham*	
3. Interwar Period Suburb	Medium density, homogeneous speculative suburbs, usually semi-detached, in a closely structured urban fabric	1920s - 1930s	*Welling, Greater London*	

2.2 Wind turbine noise simulation

Noise mapping calculations were carried out using [CadnaA] (DataKustik, 2006) for the sampled sites as shown in *Figure 1*, to examine the noise distribution across suburban layouts with different wind turbine proximities. A wind turbine was placed at the corner of each site (50m from the nearest building), then at 300, 500, and 1000m setbacks from the studied area along the southwest diagonal of the plan.

For the sake of convenience, the wind turbine was simulated as a point source at 100m height with an equivalent sound power level of 96.4dBA, and the spectrum of the point source was set to represent typical modern wind turbines referring to the measurements of 37 wind turbines (Verheijen et al., 2011), where the levels are higher at low-frequencies and attenuate by 4dB per octave.

It can be seen from *Figure 1* that in the residential areas, the noise exposure on buildings is affected both by distance attenuation and the morphology of built environment. When the wind turbine is close to the residential area, the distribution of wind turbine noise is more localised (Standard Deviation=2.2dBA), with shadow zones of lower noise levels created around each building, by up to 17dBA lower than the maximum levels, which implies the noise resisting effect of that building. When the wind turbine is installed farther away from the residential area, with longer shadow zones of the front built environment, protected areas with evenly distributed noise levels (Standard Deviation=1.6dBA) can be seen at the rear of the sites away from the wind turbine, in which case the noise exposure at a building is also influenced by its interaction with the neighbourhood built environment. Therefore, the effects of built environment morphology will be examined in specific setback conditions and taking into account morphological factors at source, neighbourhood, and building scales.

Furthermore, from each of the three suburban areas, 72 dwellings were randomly sampled to calculate their noise exposures from the wind turbine. The sampled houses are indicated in blue in the table above. The noise exposure at the building level is captured using the "average façade exposure", which is obtained by calculating the average of SPL on all the building façades longer than 1m.

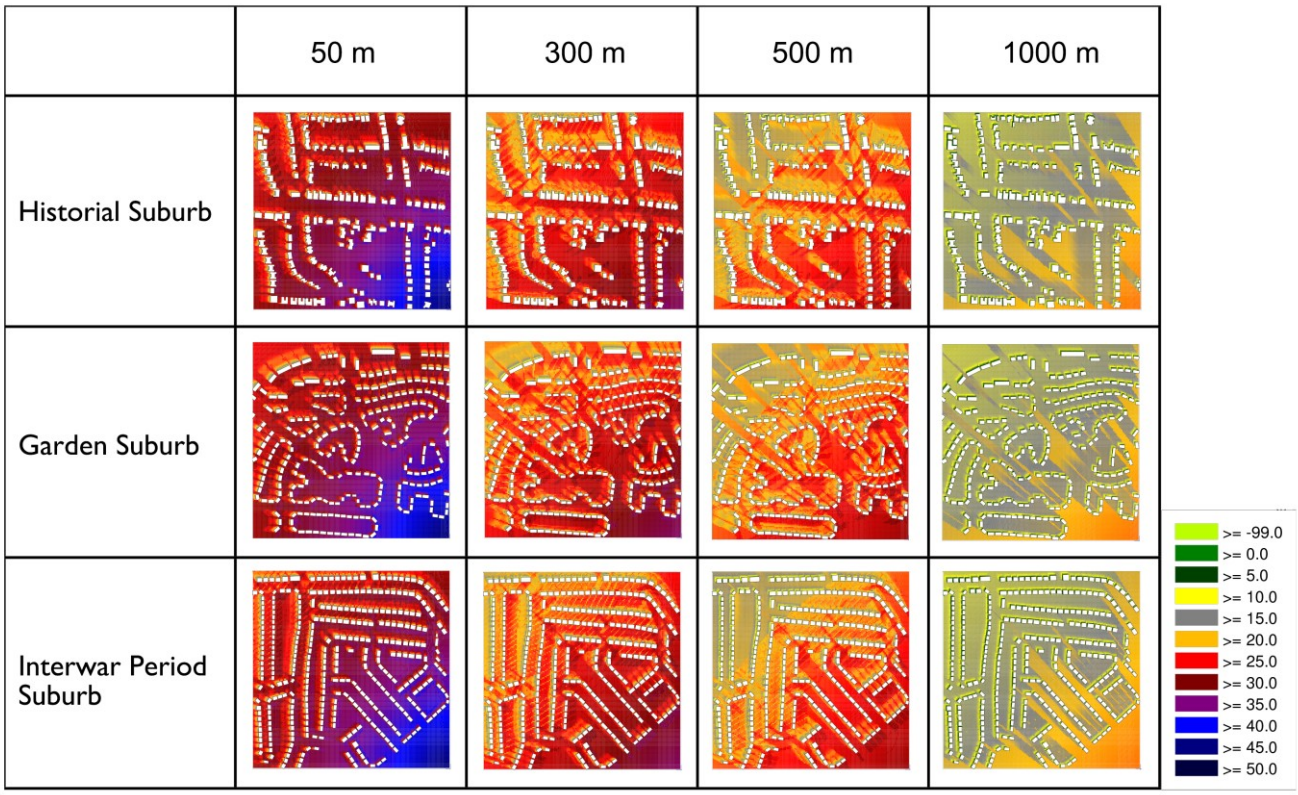
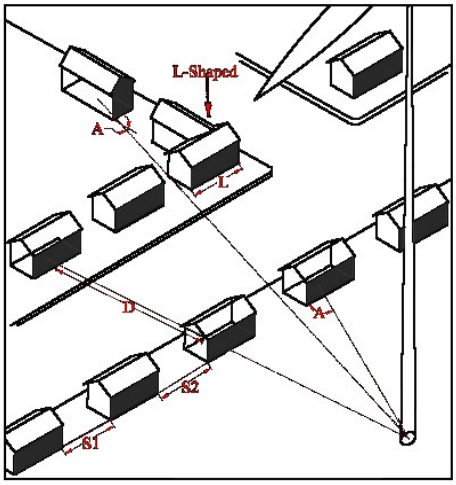


Figure 1. Distribution of wind turbine noise on studied suburban layouts with different setback distances of the wind turbine

2.3 Morphological indices

To build multivariate models that relate exposure levels to morphological indices, a series of morphological indices are taken into account to represent the morphological characteristics of the site. Based on a previous study (Qu and Kang, 2013) five indices have been identified, as listed in *Table II*, which describe the built environment morphology at three scales, including source-building, neighbourhood buildings, and individual building scales. To make the analysis more generic, the building height was set as 8m for all the sampling buildings.

Table II. Morphological indices

Key Indices		*Definition*	*Illustration*
Source-building scale:	***Orientation*** *(A)*	The angle between the incidence wave and the longer façade	
Neighbourhood scale:	***Spacing Index*** *(S)*	The average spacing from the target house to the adjacent house units on both sides	
	Compactness index *(D)*	The distance from the nearest building at the front along the incidence wave	
Individual building scale:	***Length*** *(L)*	The length of the building	
	Shaped layout	The value=1 represents an L/U/H-shaped floor plan; the value=0 represents a normal rectangular plan.	

3.0 Results

3.1 Distance attenuation of building façade exposures within different wind turbine proximities

To examine the distribution of wind turbine noise on building façades, *Figure 2* shows the average façade exposure, corresponding to the source-receiver distance of each building, colour coded by four setback distances. Overall, a curve shaped relationship with a negative trend is generated through out the scatter diagram, where the wind turbine noise attenuation with increasing distance can be determined. However, the deviation of the noise exposures at any given distance demonstrates the potential of wind turbine noise control by morphological design at each distance.

Comparing the noise exposures at different distances, it is found that within source-receiver distances of 400-1000m, the noise level deviation is greater, by as much as 9dBA. Higher deviations are also found for setback distances of 300m and 500m, than that with the other two distances. A possible reason for the different clustering strengths is that when the wind turbine is as close to the built environment as 50m, the average exposure at a building façade is determined mostly by the source-receiver distance, and the building is hardly shielded by the building in front (also shown in *Figure1*). On the contrary, when the distance is increased to more than 1000m, the distance attenuation is weaker. Due to the longer sound shadows of the buildings in front, more buildings at the rear of the residential area are shielded and the variation between façade exposures are small (see *Figure1*). In the case above, either too close or too far from the wind turbine, the differences created by building morphology on the façade exposures are expected to be small, while at distances in between, the dispersion in the diagram imply that factors other than the source-receiver distance might affect the average exposure at the building façade, such as the length of the build that influences the screen effects and the spacing between adjacent buildings that influence the diffraction effects. These are examined in Section 3.2 and 3.3.

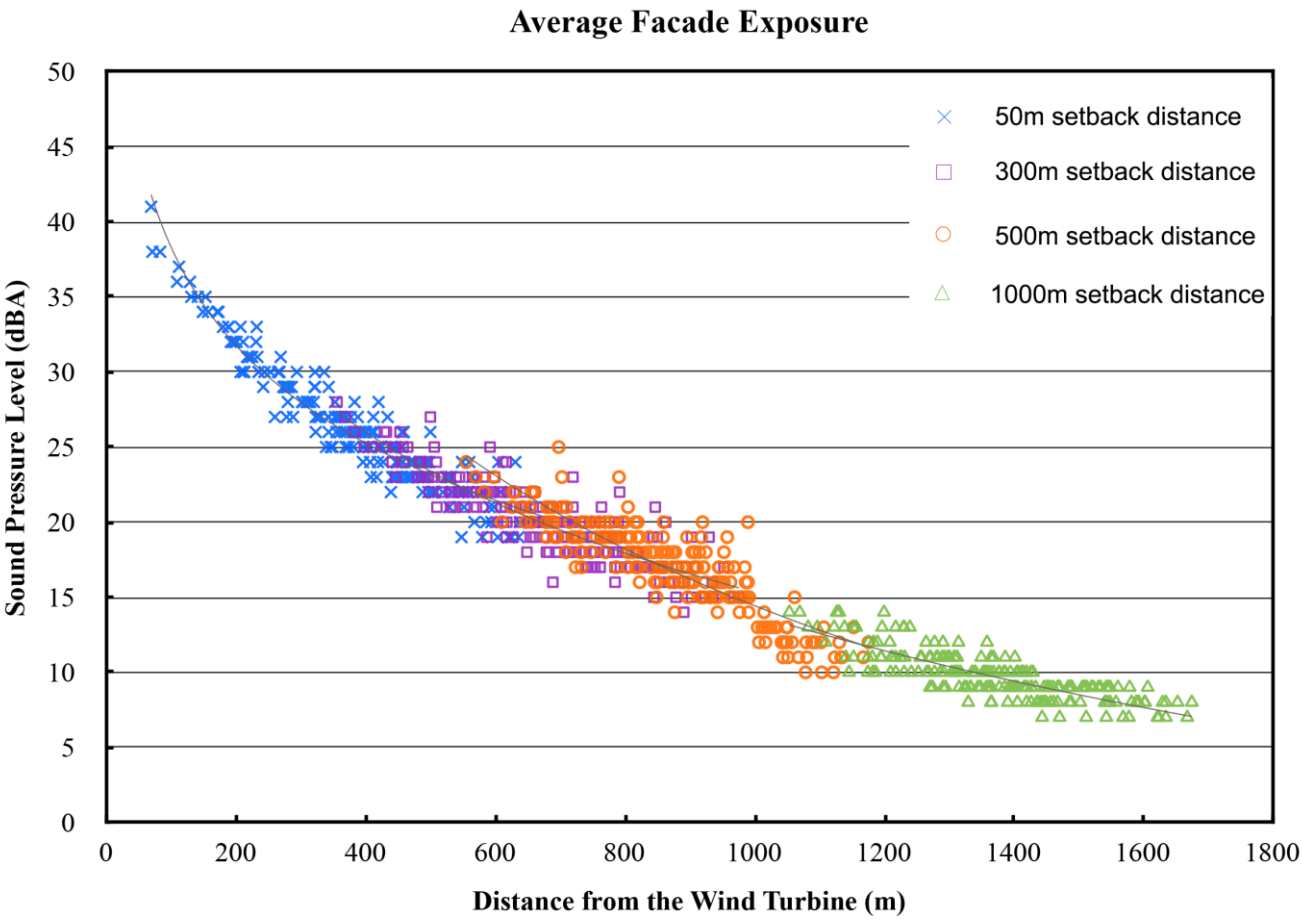


Figure 2. Distance attenuation of the average exposure on building façades, where each sampled building has four values of average façade exposures based on four setback distances of the wind turbine, which are colour-coded in the figure. N=864.

3.2 Effects of morphological indices on building façade exposures at various source distances

Before examining the effects of morphological indices at specific wind turbine proximities, the 684 buildings studied are grouped by their source-receiver distances. Ordinary Least Squares (OLS) regression analyses at the individual house level are applied for each distance group with average noise exposure as the dependent variable and the source-receiver distance and the five morphological indices (see *Table II*) as independent variables. Squared terms are included to examine non-linear relationships. The results of the regression analyses are listed in *Table III*. Since the differences between three suburban areas are found to be small, the regressions are conducted pooling across the three areas.

Generally speaking, S-R distance has negative effects on the noise exposure, which are significant for all distance groups studied, at a diminishing rate by distance group. The effects of each morphological index on the average noise exposure vary by source-receiver distance. The *"**length**"* of the building is not significant on resisting the average noise exposures. The ***"shaped layout"***, which enables the inner façade to be kept away from diffraction and reflections from outside, is significant on decreasing the average façade exposures at all source distances.

As shown in *Table III*, non-linear relationships are found between average façade exposure and three morphological indices. The *"**orientation**"*, describing the angle between the incidence sound and the longer façade from 0 to 90 degrees, is found to first decrease the average exposure at a building, but when it reaches a certain degree, it increases the noise exposure. Likewise, the "***spacing index***" and "***compactness index***", showing the spacing from neighbourhood buildings at two directions, also have hump-shaped relationships. Enlarging the spacing from neighbourhood buildings, keeping other factors constant, will increase the

average noise exposure at the building, but not beyond a certain point. These hump-shapd relationships might be due to the interaction between reflection, screening and diffraction effects at the buildings. For example, changing the morphology to enhance the screening effects might to certain extent increase strong reflection effects at the other side of the building. It is important to know these increasing and decreasing patterns to work out how much noise a morphological factor can control. These are examined in Section 3.3.

Table III. Results of three regression models with slope coefficients and significant levels

	Regression Model	*Average facade exposure*		
		300-600m (N=215)	*601-1000m (N=337)*	*over 1000m (N=257)*
	(Constant)	34.686	30.266	21.524
	S-R distance	**-.022*** **	**-.014*** **	**-.009*** **
Source-building scale:	**Orientation (A)**	**-.046*** **	**-.062*** **	**-.028*** **
	Orientation squared (A^2/100)	**.055*** **	**.068*** **	**.040*** **
Neighbourhood scale:	**Spacing index (S)**	**.080** **	**.082** **	**.081*** **
	Spacing index squared (S^2/100)	**-.249** **	**-.225** **	**-.176** **
	Compactness index (D)	**.009*** **	**.014*** **	**.008*** **
	Compactness index squared (D^2/100)	**-.002** **	**-.003*** **	**-.001** **
Individual building scale:	**Length (L)**	-.013	-.038	.032
	Length squared (L^2/100)	-.037	.003	-.061
	Shaped layout (1=has U/L/H shaped layout)	**-.827*** **	**-.710*** **	**-.575*** **
	** R square of the regression*	.782	.703	.822

*** p<0.01; ** p<0.05; * p<0.1

3.3 Noise control of morphological indices at different wind turbine proximities

The effect of each morphological factor on noise level can be estimated by the maximum range in noise level it can theoretically make on the studied buildings, which can also be used to compare the relative importance of morphological factors at different wind turbine proximities. To achieve this, the coefficients from each regression model (shown in *Table III*) are used to predict the variation in the noise exposure variable based on the observed unit of change in each morphological variable while holding other variables in the model constant. Such estimated noise reductions are shown in *Table IV.* For the factors with non-linear (hump-shaped) relationships, their minima are calculated with the noise control levels below and above the minima (shown in *Table IV*).

Table IV. Estimated noise control of morphological indices at different source-receiver distances, where if the effects are not linear, the control levels below and above the minima are given.

Studied morphological indices		*Estimated noise control range (dBA)*					
		300-600m		*601-1000m*		*over 1000m*	
Source-building scale:	**Orientation (A)**	**-1.9** (0-42 degrees)	**+1.3** (43-90 degrees)	**-2.8** (0-45 degrees)	**+1.4** (46-90 degrees)	**-0.9** (0-35 degrees)	**+1.2** (36-90 degrees)
Neighbourhood scale:	**Spacing index (S)**	**+1.2** (1.5-16.1m)	**-0.6** (16.2-30m)	**+1.4** (1.5-18.2m)	**-0.4** (18.3-30m)	**+1.7** (1.5-23.0m)	**-0.1** (23.1-30m)
	Compactness index (D)	**+2.0** (1.2-225m)	**-0.9** (225-432m)	**+3.2** (1.2-233m)	**-1.2** (233-432m)	**+3.2** (1.2-400m)	**0** (400-432m)
Individual building scale:	**Length (L)**	*(not significant)*		*(not significant)*		*(not significant)*	
	Shaped layout	**-0.8**		**-0.7**		**-0.6**	
Overall estimated range of noise control by above morphological indices:		**5.9** (53.6% of observed noise variance of 11)		**8.1** (73.6% of observed noise variance of 11)		**6.7** (83.8% of observed noise variance of 8)	

Comparing the noise control range of all the morphological factors, the neighbourhood scale "***compactness index***" makes the largest differences on average noise exposure at the buildings by up to 3.2dBA at source distances over 600m, followed by building "***orientation***" which reduces the average noise by up to 2.8dBA at wind turbine proximity within 600-1000m. The noise reductions due to the "***spacing index***" and "***shaped layout***" are relatively small, by up to 1.7dBA and 0.8dBA respectively.

The effects of morphological factors vary at source distances. Taking *"**orientation**"* as an example, when the wind turbine is 601-1000m away, rotating the building on the spot from 0 degree (the longer façade aligned with the incidence wave) to 45 degrees (half-facing the wind turbine) will result in a reduction in the average façade exposure by up to 2.8dBA due to enhanced screening effects of the building. A further rotation to 90 degrees (directly facing the wind turbine) will result in an increase in the averaged noise exposure by 1.4dBA, probably due to large areas of direct exposure and strengthened reflections. A similar asymmetry is observed when the wind turbine is farther than 1000m away, where the minimum falls at 35 degrees, above which noise exposure increases at 1.2dBA, at a higher rate than the decrease of 0.9dBA below the minimum. This can be explained by the fact that at distances over 1000m, the reflection effects are more prominent than the screening effects of the building. Hence the previously proposed design of orientation in the way of using long façade to face the wind turbine (Qu and Kang, 2014) should be reconsidered in term of resisting the average façade exposure.

The bottom row in *Table IV* indicates the possible maximum range of noise reduction that the studied factors can result in if every index was varied from the nosiest layout observed to the quietest layout identified in the study. Higher level of overall noise control is achieved at distances between 600-1000m, which accounts for 73.6% of the maximum observed variance in this study by all related factors. When the wind turbine is more than 1000m away, the predicted level of noise control made by morphological factors is 6.7dBA, accounting for 83.8% of the overall observed variance in this proximity. Overall, the results confirm the great potential of wind turbine noise control by changing the morphology of the built environment.

3.4 Effects of morphological factors at different frequencies

Since wind turbine noise is dominated by low frequencies and there are much stronger diffraction effects at low frequencies, this section further examines the effects of the above morphological factors on the distribution of average façade exposure at 50, 250 and 1000Hz for three suburban areas with the wind turbine at 300m away. The results of the OLS regressions are shown in *Table V*. Using the same method above, the estimated noise control of the factors are calculated and shown in *Table VI*.

Table V. Results of four regression models at different frequencies with slope coefficients and significant levels

	Regression Model (N=216)	*Average facade exposure*		
		50Hz	*250Hz*	*1000Hz*
	(Constant)	51.853	33.779	24.169
	S-R distance	**-.019*****	**-.016*****	**-.018*****
Source-building scale:	**Orientation (A)**	**-.084*****	**-.060*****	**-.053****
	Orientation squared (A^2/100)	**.083*****	**.065*****	**.072*****
Neighbourhood scale:	**Spacing index (S)**	.027	.042	.109
	Spacing index squared (S^2/100)	-.055	-.119	-.309
	Compactness index (D)	**.010*****	**.011*****	**.022*****
	Compactness index squared (D^2/100)	**-.002*****	**-.002*****	**-.005*****
Individual building scale:	**Length (L)**	-.037	-.042	-.016
	Length squared (L^2/100)	.003	.040	-.038
	Shaped layout (1=has U/L/H shaped layout)	-.266	**-.439****	**-1.411*****
	** R square of the regression*	.895	.858	.741

*** p<0.01; ** p<0.05; * p<0.1

The associations between morphological indices and the noise are different by frequency. The "***orientation***" index is found to resist more noise at 50Hz than higher frequencies, whilst the "***compactness***" representing a compact constructed neighbourhood and a "***shaped layout***" of the building are found to be more effective at higher frequencies.

In terms of noise resistance at low frequencies, as shown in *Table VI*, the "***orientation***" and "***compactness index***" are found to be effective in resisting noise at low frequencies as 50Hz, by up to 4.2dB and 2.5dB respectively. The factor at the individual building scale such as the "***shaped layout***" is not significant in resisting noise exposure at 50Hz.This is possibly because the radius of the inner corner created by shaped layout is smaller than the wavelength of 50Hz noise transmission, and hence the noise is distributed overcoming the screening effects of the morphology. Nevertheless, the overall estimated range of noise control by the studied morphological factors is as much as 6.7dB at 50Hz, account for 47.9% of the overall observed noise variance at 50Hz in this study, within the wind turbine distances of 300-1000m.

Table VI. Estimated noise control of morphological indices at different frequencies, where if the effects are not linear, the control levels below and above the minima are given.

Studied morphological indices		*Estimated noise control range (dB)*					
		50Hz		*250Hz*		*1000Hz*	
Source-building scale:	**Orientation (A)**	**-4.2** (0-50 degrees)	**+1.3** (51-90 degrees)	**-2.8** (0-46 degrees)	**+1.3** (47-90 degrees)	**-2.0** (0-36 degrees)	**+2.2** (37-90 degrees)
Neighbour hood scale:	**Spacing index (S)**	*(not significant)*		*(not significant)*		*(not significant)*	
	Compactness index (D)	**+2.5** (1.2-250m)	**-0.7** (250-432m)	**+3.0** (1.2-275m)	**-0.5** (275-432m)	**+4.8** (1.2-220m)	**-2.3** (220-432m)
Individual building scale:	**Length (L)**	*(not significant)*		*(not significant)*		*(not significant)*	
	Shaped layout	*(not significant)*		**-0.4**		**-1.411**	
Overall estimated range of noise control by above morphological indices:		**6.7** (47.9% of observed noise variance of 14)		**5.8** (48.3% of observed noise variance of 12)		**7.0** (41.2% of observed noise variance of 17)	

8

4.0 Conclusions

The study uses noise mapping and quantitative analyses to examine the effects of built environment morphology on resisting wind turbine noise on building façades at specific wind turbine proximities. It has demonstrated that morphological factors have considerable effects, of up to 8.1dBA, in resisting noise exposure at buildings when the wind turbine is 600-1000m away.

Among the five factors, a compactly structured built environment (compactness index) is found to be the most effective in resisting average noise exposure on building façades throughout the source distances of 300-1700m, with a noise reduction of up to 3.2dBA in this study, followed by using the long façade to face the wind turbine (orientation index), by up to 2.8dBA when the source distances are within 600-1000m. Effects of the adjacent buildings (spacing index) and the building shape (shaped layout) are found to be small, by up to 1.7dBA and 0.8dBA respectively.

The building orientation and the distance from the front building (compactness index) are also found to be effective in resisting noise at low frequencies, by up to 4.2dB and 2.5dB respectively at 50Hz. However, the compactness index and shaped layout are estimated to reduce more noise at higher frequencies than 50Hz.

Overall, while the interaction between reflection and screening effects at different façades of the building make the estimation of average façade exposure a major challenge, this research has demonstrated to what extent changing the morphological factors of the built environment could reduce the average noise level and has generated the relative importance of the morphological factors in terms of resisting wind turbine noise at different frequencies, and with different

source-receiver distances. The findings could be applied to guide the design of residential layouts within different proximities from the wind turbine, rendering them less susceptible to the noise pollution caused by existing and future wind power projects.

Acknowledgements

This research has been funded by the University of Sheffield CCDRI network scholarship.

References

Archer C L, Jacobson M Z (2007) Supplying baseload power and reducing transmission requirements by interconnecting wind farms. *J Appl Meteorol Clim* 46: 1701-1717.

DataKustik GmbH (2006) Cadna/A for windows - user manual. Greifenberg.

Gwilliam , Bourne C, Swain C, Pratt A (2012) Sustainable renewal of suburban areas. Joseph Rowntree Foundation, 1998.

Knight J (2004) Urban wind power: breezing into town. *Nature* 430: 12-13.

Pedersen E, Waye K P (2007) Wind turbine noise, annoyance and self-reported health and well-being in different living environments. *Occupational and environmental medicine* 64(7): 480-486.

Qu F, Kang J (2014) Effects of spatial configuration on the wind turbine noise distribution in residential areas. *Proc Forum Acusticum 2014.*

Qu F, Kang J (2013) Modelling spatial distribution of wind turbine noise in sub-urban environments. *Proc 2013 AIA-DAGA Conf on Acoustics*.

Verheijen E, Jabben J, Schreurs E, & Smith K B (2011) Impact of wind turbine noise in The Netherlands. *Noise and Health* 13(55): 459.

Williams K, Joynt J L, Payne C, Hopkins D, Smith I (2012) The conditions for, and challenges of, adapting England's suburbs for climate change. *Building and Environment* 55: 131-140.