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Effects of built environment morphology on wind turbine noise exposure at building façades

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Abstract

With wind farms installed in urban and suburban areas, the noise exposure of buildings is affected both by distance attenuation and the morphology of the built environment. With the aim of exploring the noise-resisting effects of built environment morphology, 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. Relationships between morphological indices and building façade exposures were examined through regression analyses. Noise reduction levels of five morphological indices were given in terms of resisting wind turbine noise with different source-receiver (S-R) distances, and at different frequencies. The results show that built environment morphology has considerable effects on resisting the noise exposure of buildings and can create a quiet façade with up to 13dBA difference to the most exposure façade. Among the five indices, building orientation is found to be most effective in resisting the noise exposure of building façades, followed by the length and shape of the building. The noise resistance effects vary by different S-R distances and differ by frequency. Four morphological indices are found to be effective in resisting noise at low frequencies, typically at 50Hz.

Keywords

wind turbine, noise, urban morphology, quiet façade

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Nomenclature

SPL	Sound Pressure Level [dB]
Source-receiver distance (D_{S-R})	Distance between the wind turbine and the receiver building [m]
Length (L)	The length of the longer façade of the building [m]
Shaped layout	Building with an L/U/H shaped, in-rectangular floor plan
Compactness index (D_{S-R} / D_1)	Ratio between source-receiver distance (D_{S-R}) and the distance from the nearest building at the front along the incidence wave (D_1)
Orientation (A)	The angle between the incidence wave and the longer façade [degree]

1. Introduction

Wind turbines are playing an increasing role in the global process of producing renewable energy. 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 sensitive landscapes and residential areas than ever before [1]. Nowadays there is a development towards integrating large-scale wind turbines within urban environment, especially in elevated or coastal locations [2]. In the UK, a number of large-scale wind turbines have been introduced into suburban and urban settings, some of these as close as 350m from densely populated residential areas, such as the wind turbines in the suburbs of Bristol, Dundee, and Nottingham. Although wind speeds are relatively lower in built-up areas than in remote rural areas [3,4], large-scale urban wind energy can be successfully implemented, as proposed by recent studies [2,5]. Since the properties of urban and residential areas with uniformed buildings and turbulent air are unsuitable for small turbines [6], large wind turbines that are installed higher can take advantage of optimum wind conditions [7,8]. More importantly, there are good reasons for developing wind turbines in an urban and suburban environment where electricity is consumed since it can reduce electricity loss in long-distance transmission [9] and can reduce network costs due to its proximity to population of high demand [10]. It is also documented that urban siting of wind turbines gains more support of the local community, unlike rural wind farms that are often opposed by residents on aesthetic rural grounds [11]. These advantages herald considerable potential of future wind energy projects to be fully developed in urban environments.

However, the urban environment has unique challenges in exploitation of large wind turbines: One of the main obstacles is the noise pollution to the surrounding residential areas. Noise from wind turbines in residential areas is dominated by aerodynamic sounds with large components at low-frequencies (below 200Hz) produced during the downward movement of the blade [12], which is less attenuated by buildings than mid- to high-frequency sound [13]. The potential adverse impacts of wind turbine noise on neighbouring residents have been attracting considerable interest. Large field studies have been conducted focusing on the noise impact of rural and suburban wind turbines, with dose-response relationships being elucidated between noise levels and annoyance [14–16]. Exposure to noise pollution may further cause environmental health concerns, and health risks such as dizziness, headache, feeling tense and irritable [17,18]. It is possible that locating wind energy in highly populated urban and suburban areas may exacerbate the noise impact. However, to date there is little research towards noise impact of large-scale wind turbines in urban environments with large coverage of residential buildings. In addition, a previous study has already indicated that in built-up areas, the sound levels at dwellings is probably overestimated using the existing calculation methods for flat, rural landscapes [19]. Therefore, there is a need to investigate the distribution of wind turbine noise in densely built residential areas with a focus on localised noise exposure on and around receptors' building façades, with the purpose of identifying the effects of built environment morphology on the noise exposure from urban turbines.

The morphology of the built environment has a large effect on the exploitation of urban wind energy. Despite the fact that several works have been done on the effect of built environment morphology on urban wind profile and energy yielding [4,20,21], no or very little work has been done on its effect on wind turbine noise resisting. It has been found that the resisting effects of built environment morphology of the residential areas create large variances among wind turbine noise exposures at different buildings [22]. This is due to the fact that noise propagation in a densely built residential area is affected by the acoustical effect of absorbing, reflecting, and shielding from buildings [23], which promotes the creation of protected areas or shadow areas in an urban context [24]. Morphological parameters – such as the height, shape, and orientation of the building, as well as the spacing between adjacent buildings – largely influence the above effects and hence may contribute to obtain reduced levels of noise pollution from wind turbines [25]. Some works have already demonstrated the effects of morphology in urban or residential areas on the distribution of traffic, bird, and aircraft sounds using noise mapping techniques. Most of the studies have put emphasis on meso-scale urban morphology such as road and building coverage ratio, building plan area fraction, building frontal area index, and have related these parameters to the average, maximum and minimum noise exposure within the studied urban grid [26–30]. Other studies focus on the noise resisting effects of urban layout and formation such as urban density, green space ratio, road length and intersections, at larger urban-scale [31,32]. For this reason, the results of previous studies cannot be directly applied in predicting wind turbine noise with a focus on localised noise exposure at receptors at the building-scale, i.e. the noise exposure on and around the façades of a receptor's dwelling. Given the fact that little work has assessed the possible effects of built environment morphology on wind turbine noise, there is a need to model and graphically show the distribution of wind turbine noise in typical residential layouts, and to examine how these sound levels might be resisted by different types of built environment morphologies, such as the shape of the building, and the spacing between adjacent structures.

The morphology at building scale is also important. In previous studies on the impact of wind turbine noise in residential areas, noise levels that the residents were exposed to were normally calculated in terms of A-weighted sound pressure levels (SPLs) outside their dwelling, based on outdoor sound propagation formula [14,15], which mainly present the noise at the most exposed place but consider less the variance among all the façades of the building. Since buildings are three-dimensional objects, identifying the noise exposures at multiple sides can play an equally important role in determining indoor noise pollution at various rooms [33] hence influencing noise perceptions at home. In particular, it is indeed important to examine the presence of a quiet façade, which has been proved to have positive effects on noise perception in a number of studies [34–36]. A study on road traffic noise has demonstrated that a large difference in exposure (10-20 dB) between the most and least exposed side of a dwelling is associated with significantly lower noise annoyance and less prevalence of noise-induced health problems [34]. The recent studies have found that the actual exposure level at the least exposed façade itself has a direct effect on annoyance, independent of that at the most exposed façade, by showing that higher exposures at the least exposed façade may increase adverse noise impacts [35,36]. The EU Environmental Noise Directive [37] has put emphasis on the benefit of quiet façade and states that major EU cities should indicate how many persons live in dwellings with a quiet façade and protect quiet areas by means of noise action plans. However, an accurate method for calculating wind turbine noise levels at the quiet façade has found little presence in the literature particularly with reference to building and site parameters that influence the distribution of wind turbine noise at the quiet facades. Pilot studies have modelled the distribution of wind turbine noise around all façades of a dwelling using noise mapping techniques that take into account parameters of buildings and the ground surface on generic residential areas [22,38]. As found in pilot studies, the levels of wind turbine noise at the least exposed façade [22] and around all façades on average [38] are both highly related to built environment morphology, which also depend on the setback distance to the wind turbine. In a certain setback condition, a better designed residential area can resist wind turbine noise and substantially reduce the noise level at the quiet façade. The noise resisting effect of built environment morphology merits further investigation.

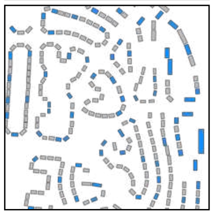
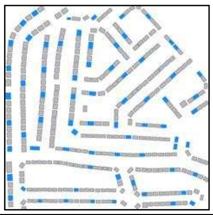
The aim of this research is therefore to explore the noise-resistance of built environment morphology of densely built residential layouts, in terms of creating shielded areas and quiet façades with relatively less noise exposure from urban or suburban wind turbines. More specifically, by defining five morphological indices, this paper demonstrates how the changing of a morphological index may reduce the noise level at the least exposed façade and at all façades on average. This paper, based on noise mapping techniques, examines the sound level distribution of wind turbine noise at dwelling façades in generic residential areas, with more focus on the quiet façade that needs to be well protected. The relative importance of various morphological indices is examined on different levels of wind turbine proximity and at different sound frequencies.

2. Methods

2.1 Studied residential areas

In order to model the distribution of wind turbine noise on typical residential areas representing the main categories of residential areas in the UK, a categorisation of residential areas was developed for site selection. Since large scale wind turbines were more likely to be located in the periphery of the urban areas [2], the focus of the categorisation was on the suburban residential areas characterised by medium density development, with detached or semi-detached houses. Referring to the typology based on built form and neighbourhood setting that was widely cited in British suburban studies [39], three types of residential areas were considered, including historic, garden and interwar period types. A 500*500m grid of generic residential area was created for each category based on real sample location as shown in Table 1, representing the main categories of residential areas in the UK. Furthermore, from each of the three residential areas, 72 buildings, representing around 30% of the total building numbers, were randomly sampled to calculate their noise exposures from the wind turbine.

Table 1. Studied categories of residential areas and sampled buildings for analyses, where the sampled buildings are indicated in darker (blue) colour.

Type	Characteristics	Period	Location of studied sample area	Plan of buildings (Sampled buildings shown in blue)
1. Historic type	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 type	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, Rotherham	
3. Interwar Period type	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

To simulate the spatial distribution of wind turbine noise levels in studied residential areas, sound maps were calculated using a software package of CadnaA [40]. The calculation in the software was based on the ISO 9613 [41] sound propagation standard. The accuracy of this standard for wind turbine noise calculation has been stated in several studies, by investigating the agreement between calculated and measured sound pressure level (SPL) at distances up to 2km downwind of the turbines [42,43]. It has been found that the calculation accurately determined the noise levels at 400m source-receiver distance and underestimated the measured level by 3 dB at distances of 1-2 km [42]. However, its accuracy for wind turbine noise across built up environments has not been specified.

Noise emission from the wind turbine was simulated with generic settings in CadnaA to estimate noise exposures in favourable downwind conditions. According to the IEC 61400-11 standard [44], the wind turbine was simulated as a point source at 100m hub height to represent large modern wind turbines. The spectrum of the point source was set based on an averaged spectrum of 37 wind turbines shown in a previous study [45], where the sound pressure levels are higher at low-frequencies and attenuate by 4dB per octave, with an equivalent sound power level of 96.4dBA. The ground absorption was set as 0.5 in accordance with the Good Practice Guide in the UK [46]. Temperature was set to 10 ℃, relative humidity to 70% for atmospheric absorption, consistent with common practice [43]. The reflection order by buildings was set as 3, based on a previous study [47]. The height of the building was set as 8m representing for typical 2-storey dwellings and the façade-receiver distance was set to 0.05m. The calculations using above method have been verified by on-field measurements with focus on noise attenuation around the building [48].

Noise maps for the sampled sites are shown in Fig. 1, which illustrate the graphical distribution of wind turbine noise coloured by SPL levels. Four scenarios were created for each type of residential area 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 southeast diagonal of the plan. Consequently, the number of sampled buildings was increased by four times to a total of 864, at distances ranging from 50-1700m from the wind turbine, consistent with the distance range attracting most attention in previous socio-acoustic studies [15,16,49].

It can be seen from Fig. 1 that in the residential areas, the noise exposure of buildings is affected both by distance attenuation and the morphology of the built environment. The shadow zones of lower noise levels created around each building indicate the noise resistance effect of that building. With increasing setback distance, the longer shadow zones of the front built environment also “protect” the buildings at the rear of the sites away from direct noise exposures. In this case the noise exposure at a building is influenced by its interaction with the neighbourhood built environment. Therefore, in this study, the effects of built environment morphology were examined in given setback conditions and took into account morphological indices at building, neighbourhood, source, and site scales.

Noise levels on the façade of 864 buildings were calculated based on building noise maps, as can be seen in Fig. 1 [40]. Two exposure indicators of a dwelling that described the level of wind turbine noise received by the residents were explored, the “minimum façade exposure” and the “average façade exposure”. The former represented the quiet façade effect that calculated the level of exposure at the least exposed façades, following the approaches in previous studies on road traffic noise [32,35,36]. These were usually at the shielded side where the wind turbine noise was most obstructed by the building, hence also representing the noise-resistance effects of the building. However, such effects need to be further examined in terms of resisting the noise exposure at other façades. For instance, morphological layout that benefits the quiet façade may at the same time increase the noise at the front façade due to amplification of the noise levels by reflections [36]. Therefore, “average façade exposure” was also examined, which was a more conventional noise indicator obtained by calculating the arithmetic average of SPL on all the building façades longer than 1m. This indicator represented the overall exposure level on the building. The “maximum façade exposure” was not examined in this study, due to the fact that maximum exposure at a dwelling would rather depend on source-receiver distance and is less related to the local effect of the building, except in very rare cases that the building is fully obstructed by large object nearby, as proposed in pilot studies [22]. Sound from the wind turbine was also simulated as a single-band source at 50Hz, to investigate the effects of built environment morphology on resisting the low frequency component of the sound.

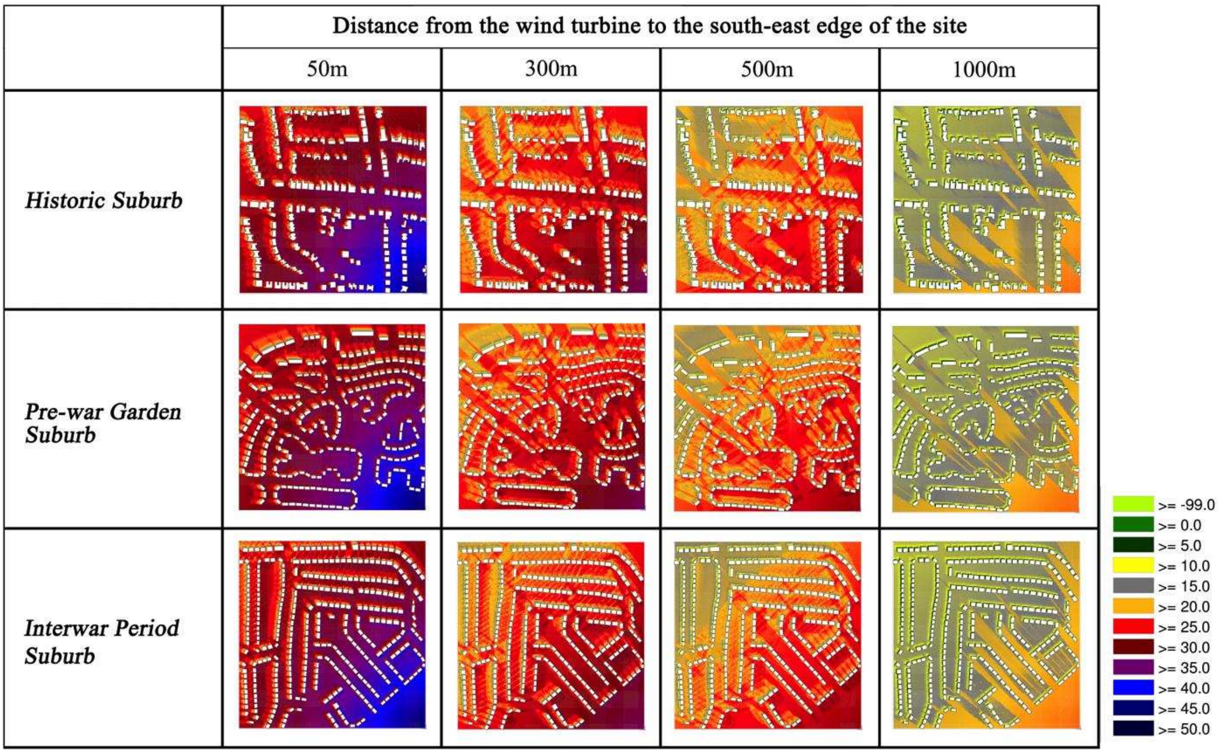


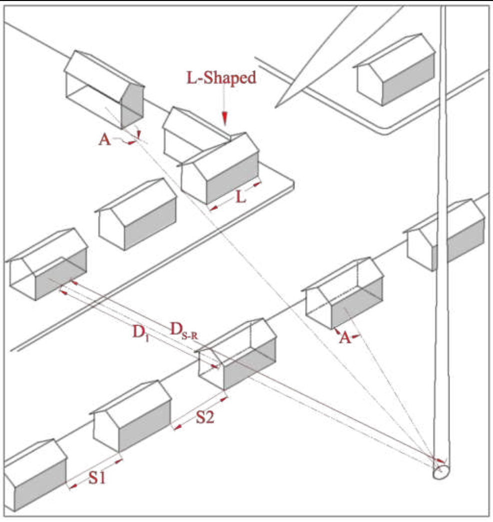
Fig. 1. Distribution of wind turbine noise on studied suburban layouts with different setback distances of the wind turbine

2.3 Morphological indices

To build multivariate models that relate exposure levels to morphological indices, a range of morphological parameters that quantitatively describe the layout of residential areas were explored. Parameters that developed in previous studies, such as aspect ratio, height-to-width ratio, building surface area to plan area ratio [26,27], have been employed in pilot studies to examine their effect on wind turbine noise levels at the façade. These parameters were being filtered with a purpose to choose the least number of indices in this study which were simple and adjustable for design and construction practice.

Finally, five indices have been identified, as listed in Table 2, which describe the built environment morphology across three scales, each covering: the individual building, the neighbouring buildings, and the source-building. They were chosen due to observed effects on wind turbine noise exposure in generic noise mapping experiments and pilot studies[22,25,38], as well as stated effects on the distribution of other environmental noise [29,30,47]. For example, the length of the building was observed to influence the screening effects hence protect the quiet façade and the spacing between adjacent buildings was observed to influence the diffraction effects. The non-rectangular shaped layout was hypothesised to reduce environmental noise levels on the least exposed façade by keeping the inner façade away from diffraction and reflections from outside. The compactness index, calculated as the ratio between the S-R distance and the distance to the front building, predict the possibility of noise obstruction by the building in front. The orientation of the building was defined as the angle between the incidence sound and the longer façade from 0 to 90 degrees, which presents the extent to which the building's longer façade resists the wind turbine noise. To make the analysis more generic, the building heights were set as 8m for all the buildings hence no height-related index was included in this research.

Table 2. Morphological indices

Key Indices		Definition	Illustration
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.	
Neighbourhood scale	Spacing index (S)	The averaged spacing from the target house to the adjacent house units on both sides. S=(S1+S2)/2	
	Compactness index (D_{S-R} / D_1)	Ratio between source-receiver distance (D_{S-R}) and the distance from the nearest building at the front along the incidence wave (D_1)	
Source-building scale	Orientation (A)	The angle between the incidence wave and the longer façade	

3. Results

3.1 Effects of built environment morphology depending on source-receiver distance

Fig. 2 shows the minimum façade exposure of 864 buildings, plotted along its distance from the wind turbine, colour coded by four setback distances. In the same way, Fig. 3 shows the distribution of average façade exposures. The curve in each figure indicates the theoretical noise attenuation of the same wind turbine in a free-field. Comparing with a free-field, the areas with buildings have much lower noise levels, suggesting that built-up areas have a considerable resistance effect on wind turbine noise. It is worth noting that buildings create up to 13dBA difference between the minimum and maximum façade exposures at distances within 800m from the wind turbine. Moreover, from Figs. 2 and 3 it can be seen that the sound attenuation in built-up environments, in terms of the minimum and average façade levels, is greater than that in a free field. Furthermore, unlike in a free field, the minimum and average exposures on building façades have considerable variations at a given distance, especially in the distance range of 600-1000 m, and such variations caused by suburban morphology can be as much as 10dBA, equivalent to the sound attenuation from 600m to 1600m in a free-field, for example. In other words, there is a great potential of resisting noise by strategically planned suburban morphology.

Comparing the noise exposures at different distances, it can be seen in Figs. 2 and 3 that within S-R distances of 400-1000m, the noise level variation is greater for both minimum and average façade exposures, by up to 10dBA. Lower variations are found for setback distances of 50m and 1000m than 300m and 500m. A possible reason is that when the wind turbine is very close to the edge of the site as 50m, the exposure at a building façade is hardly shielded by buildings in front, so that the exposure level is more likely to depend on S-R distance alone. This is also shown in Figure 1, when the wind turbine is close to the residential area (e.g. 50m, 300m), the shadow zones created around each building are rather small. When the wind turbine is installed farther away from the residential area such as over 1000m, longer shadow zones of the front built environment appear, which to some extent “protect” the buildings at the rear of the sites away from direct noise exposures. Although more buildings are shielded by buildings to the front and the noise on building façades are much lower than free-field exposures, the variation of façade exposures at a given distance are very small, about 1dBA in terms of minimum exposure and within 5dBA in terms of average exposure (see Figs. 2 and 3). Therefore, the variation in façade exposure also depends on S-R distance, which is affected by the built environment morphology more in the distance range around 300-500m. In Section 3.2, the effects of the morphological indices will be examined by different S-R distance groups, which are 300-600m, 601-1000m, and over 1000m.

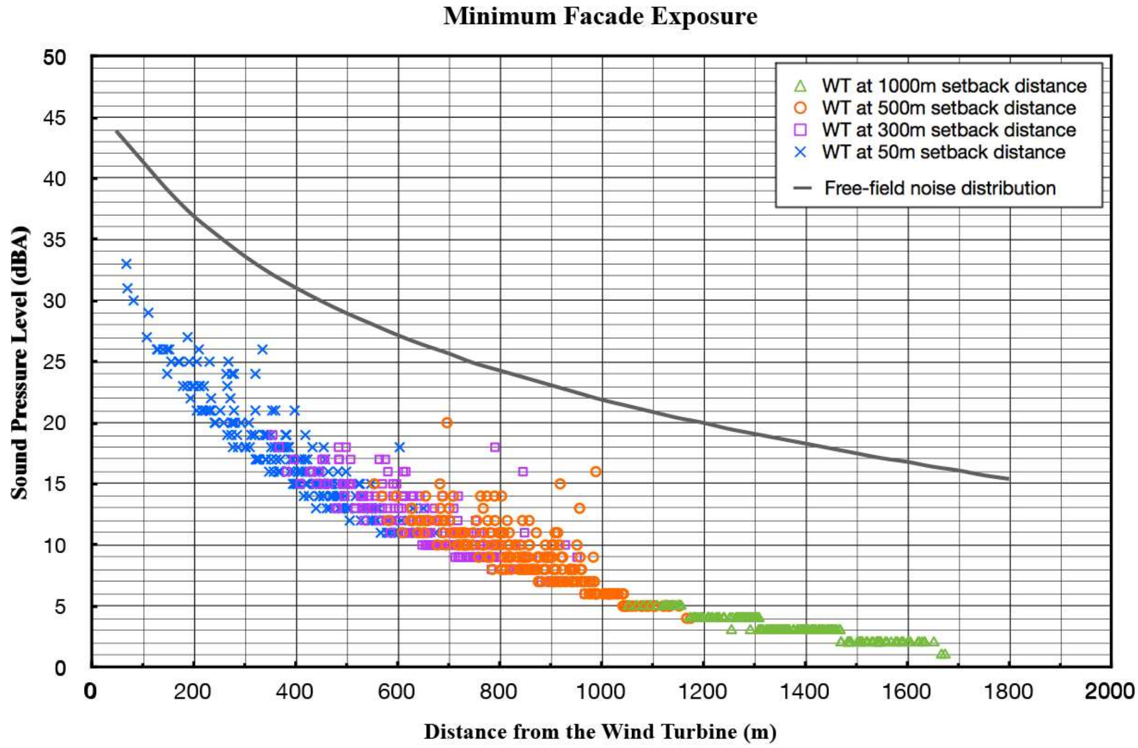


Fig. 2. Distance attenuation of the minimum exposure on building façades, where each sampled building has four values based on four setback distances of the wind turbine, which are colour-coded in the figure. N=864.

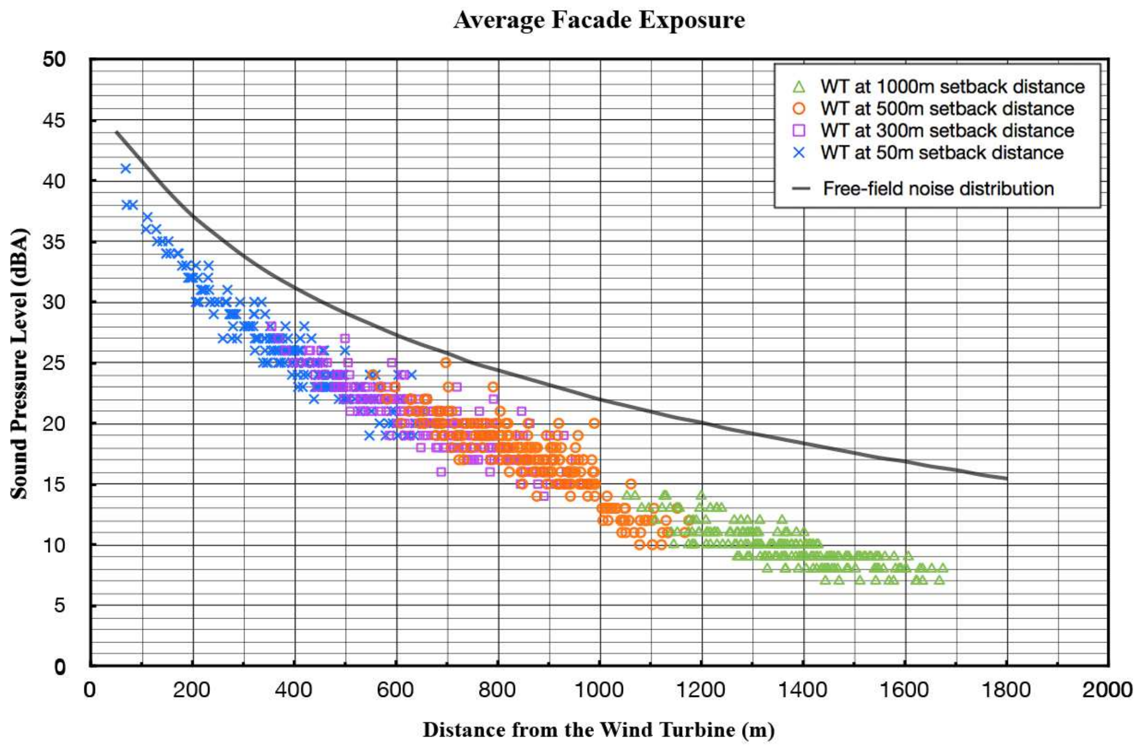


Fig. 3. Distance attenuation of the average exposure on building façades, where each sampled building has four values based on four setback distances of the wind turbine, which are colour-coded in the figure. N=864.

3.2 Relationship between morphological indices and building façade exposures

Before examining the effects of morphological indices at specific wind turbine proximities, the 864 buildings studied are grouped by their S-R distances as 300-600m, 601-1000m, and over 1000m. Ordinary Least Squares (OLS) regression analyses at the individual building level are applied for each distance group with façade noise exposure as the dependent variable and the S-R distance and the five morphological indices (see Table 2) as independent variables. Squared terms are included to examine non-linear relationships. Site dummies are also included to compare the site scale differences between historical and garden suburb to the reference group of interwar suburb. The results of the regression analyses on minimum façade exposure and average façade exposure are reported in Table 3 and Table 4, respectively.

Generally speaking, the negative effects of S-R distance on noise exposure are significant in all distance groups. The effects of each morphological index on minimum and average noise exposures vary by distance groups. It is found in Table 3 that the morphological indices studied have no significant effect on the minimum exposures at S-R distance over 1000m. The *"length"* of the building is the only significant factor on noise resistance at distances within 1000m for both minimum and average façade exposures. *"*S*haped layout"* is significant in decreasing both minimum and average façade exposures. The *"spacing index"* and *"compactness index"* are not significant in controlling the minimum façade exposure but are both significant for average façade exposures. The *"orientation"* is found to be effective in resisting both minimum and average exposures at wide distance ranges.

Non-linear relationships are found between façade exposures and two morphological indices, as can be seen in Tables 3 and 4. The *"compactness index"*, predicting the obstruction of front buildings, has a double-edged effect on average façade exposure. Increasing the compactness index will firstly decrease average exposure, because a large ratio means the building is more likely to be in the shadow of the front building, but when the value is beyond a certain point, the average façade exposure increases. This hump-shaped relationship also applies to *"orientation"*. Increasing the angle between the line of incidence sound and the longer façade from 0 degree will first decrease the façade exposure at a building, but when it reaches a certain degree, it increases the noise exposure. These hump-shaped relationships represent the interaction between reflection, screening and diffraction effects, and deserve attention in morphological design.

Besides the indices above, site difference is also found to be significant, with the buildings in the "garden suburb" having higher minimum exposures than those in the "interwar suburb" at the distance of 601-1000m; and higher average exposures at distance over 1000m. This might be because dispersion in the curvy layout of the "garden suburb" enables more noise diffraction which is not controlled by the studied five indices.

3.3 Noise reduction caused by built environment morphologies

To compare the relative importance of morphological indices, the regression results are used to predict the maximum noise reduction they can bring, in terms of both minimum and average façade exposures, as shown in Table 5 and Table 6, respectively. These are calculated through multiplying the coefficient of each index (shown in Tables 3 and 4) by the observed unit of change in that variable, while holding other variables in the regression model constant. For the indices with non-linear (hump-shaped) relationships, their minima are calculated with the noise reduction levels calculated below and above the minima.

As can be seen in Tables 5 and 6, building *"length"*, *"compactness index"* and *"orientation"* have relatively high noise resistance values, while the differences made by *"shaped layout", "spacing index"* and the site are less. Among the five indices, *"orientation"*, *"length"*, and *"shaped layout"*

Table 3. Results of three regression models explaining minimum façade exposure with slope coefficients and significant levels

	Regression Model	Minimum Façade Exposure		
		300-600m (N=215)	601-1000m (N=337)	over 1000m (N=257)
	(Constant)	28.137	22.804	12.136
	S-R Distance	-.022***	-.013***	-.007***
Individual building scale:	Length (L)	-.046***	-.053***	.002
	Shaped layout	-.859***	-.504*	.056
Neighbourhood scale:	Spacing index (S)	.013	.008	.000
	Compactness index (D)	.002	-.003	.000
	- Compactness index squared (D^2/100)	-.001	.000	.000
Source-building scale:	Orientation (A)	-.094***	-.092***	.006
	- Orientation squared (A^2/100)	.084***	.091***	-.004
Site scale:	Historical suburb	.281	-.005	-.066
	Garden Suburb	.334	.541***	-.018
	* R square of the regression	.746	.580	.925

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

Table 4. Results of three regression models explaining average façade exposure with slope coefficients and significant levels

	Regression Model	Average Façade Exposure		
		300-600m (N=215)	601-1000m (N=337)	over 1000m (N=257)
	(Constant)	36.092	31.616	21.703
	S-R Distance	-.022***	-.014***	-.009***
Individual building scale:	Length (L)	-.030**	-.031**	.003
	Shaped layout	-.730***	-.627**	-.582***
Neighbourhood scale:	Spacing index (S)	-.007	.007	.019***
	Compactness index (D)	-.011***	-.006***	-.002***
	- Compactness index squared (D2/100)	.002**	.001***	.000**
Source-building scale:	Orientation (A)	-.053***	-.070***	-.037***
	- Orientation squared (A2/100)	.057***	.075***	.050***
Site scale:	Historical suburb	.187	.106	.273
	Garden Suburb	.279	.156	.213*
	* R square of the regression	.775	.672	.808

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

have resistance effects on both minimum and average façade exposures. *"Orientation"* is estimated to change the minimum façade exposure by up to 2.6dBA (at 300-600m) and change the average façade exposure by up to 2.2dBA (at over 1000m). The calculated minima show that to be set diagonally opposite (i.e. keeping a degree rather than 90 degree) to the wind turbine leads to the lowest exposure on building façades. Increasing the *"length"* of the building could decrease both minimum and average façade exposures within a distance of 1000m, by up to 2.7dBA and 1.6dBA respectively. A *"shaped layout"* has a relatively small noise control effect, making an up to 0.9dBA decrease on minimum façade exposures and 0.7dBA on average façade exposures. The *"spacing index"* and *"compactness index"* only affect average façade exposures, by up to 0.5dBA and 2.4dBA, respectively.

It is noted that the effects of various morphological indices on the minimum and average exposures are different. Taking *"orientation"* as an example, the above results predict that with the S-R distance of 300-600m, rotating the building from 46 degree to 56 degree will result in a reduction in the minimum façade exposure due to enhanced screening effects of the building, but will also result in an increase in the average noise exposure due to large areas of direct exposure and strengthened reflections. Hence the noise-resistance design of using long façades to face the wind turbine should be considered carefully in case it also increases the average façade exposure.

It is also noted that the noise resistance effects of morphological indices vary by distance ranges. In terms of both minimum and average façade exposures, the *"length"* of the building has the highest level of resistance effect with S-R of 601-1000m, while the *"shaped layout"* is most effective at the distance of 300-600m in this study. In terms of the effects of *"orientation"*, with the increase of S-R distance, the turning point (minima) between noise reduction and increase falls down by up to 9 degrees, and the increasing effects are take more weight. This can be explained by the fact that at long distances, the reflection effects are more prominent than the screening effects of the building. This hump-shaped relationship also applies to the *"compactness index"*. When the distance to the building at the front is deceased from S-R distance (compactness=1.00) to 1/275 S-R distance (compactness=275), the averaged noise on a building façade decreases by up to 1.5dBA with the S-R distance of 300-600m. This resistance effect is limited to 0.8dBA with the S-R of 601-1000m, and reaches the maximum level of 2.4dBA with the S-R of over 1000m. In other words, a highly compact layout is only effective in noise reduction for certain S-R distances.

Table 5. Estimated noise reduction of minimum façade exposure by observed change in morphological indices at different S-R distances, whereif the effects are not linear, the control levels below and above the minima are given.

Studied morphological indices		Estimated Noise Control Scopes (dBA) - Minimum				
		300-600m		601-1000m		over 1000m
Individual building scale:	Length (L)	-2.3 (8.7-58.7m)		-2.7 (8.7-58.7m)		(N/S)
	Shaped layout	-0.9		-0.5		(N/S)
Neighbourhood scale:	Spacing index (S)	(N/S)		(N/S)		(N/S)
	Compactness index (D)	(N/S)		(N/S)		(N/S)
Source-building scale:	Orientation (A)	-2.6 (0-56 degrees)	+0.9 (56-89 degrees)	-2.3 (0-50 degrees)	+1.4 (50-89 degrees)	(N/S)
Site scale:	Historical suburb	(N/S)		(N/S)		(N/S)
	Garden Suburb	(N/S)		+0.5		(N/S)

"-": Noise decrease; "+": Noise increase; N/S: Not significant

Table 6. Estimated noise reduction of average façade exposure by observed change in morphological indices at different S-R distances, whereif the effects are not linear, the control levels below and above the minima are given.

Studied morphological indices		Estimated Noise Control Scopes (dBA) - Average					
		300-600m		601-1000m		over 1000m	
Individual building scale:	Length (L)	-1.5 (8.7-58.7m)		-1.6 (8.7-58.7m)		(N/S)	
	Shaped layout	-0.7		-0.6		-0.6	
Neighbourhood scale:	Spacing index (S)	(N/S)		(N/S)		0.5 (1.5-30m)	
	Compactness index (D)	-1.5 (1.0-275)	(N/A) (275-423.3)	-0.8 (1.7-300)	(N/A) (300-815.8)	-2.4 (3.3-1225)	
Source-building scale:	Orientation (A)	-1.2 (0-46 degrees)	+1.0 (46-89 degrees)	-1.6 (0-46 degrees)	+1.3 (46-89 degrees)	-0.7 (0-37 degrees)	+2.2 (37-90 degrees)
Site scale:	Historical suburb	(N/S)		(N/S)		(N/S)	
	Garden Suburb	(N/S)		(N/S)		+0.2	

"-": Noise decrease; "+": Noise increase; N/S: Not significant; N/A: Not applicable in design

3.4 Effects at different frequencies

Since wind turbine noise is dominated by low frequencies where there are strong diffraction effects, the effects of the above morphological indices on the distribution of minimum and average façade exposures are compared among50, 250 and 1000Hz for the three suburban areas, with a S-R distance of 300m. The results of the OLS regressions of minimum and average exposures are shown in Tables 7 and 8, respectively, where estimated noise reduction is also shown, using the methods in Section 3.3.

It can be seen that the associations between morphological indices and the noise are different by frequency. The *"length"* and *"orientation"* factors are found to resist more noise at 50Hz than higher frequencies, for both minimum and average façade exposures. The site differences are also significant at 50Hz. The *"spacing index"* is significant on minimum façade exposures at 50Hz only, while the *"compactness index"* is more effective on average exposures at higher frequencies. A *"shaped layout"* of the building is only effective on minimum façade exposures at 50Hz and is found to be more effective at higher frequencies for average façade exposures.

In terms of minimum façade exposures, as can be seen in Table VII, the morphological indices, except for *"compactness index"*, are all found to be most effective in resisting noise at low frequencies as 50Hz. Among them, the *"length"* and *"orientation"* of buildings make the largest reductions, by up to 3.3dB and 2.8dB respectively.

4. Discussions and Conclusions

The study uses noise mapping to examine the effects of built environment morphology on resisting wind turbine noise on building façades, in response to the advances in developing wind energy resource in urban environments. The study puts emphasis on the noise exposure at the least exposed façade (minimum façade exposure), which has been found to be largely governed by built

Table 7. Effects of morphological indices on minimum façade exposure at different frequencies with slope coefficients of the regression model and levels of estimated noise reduction

	Variables in regression (N=216)	Minimum Façade Exposure		
		50Hz	250Hz	1000Hz
	S-R Distance	-.017***	-.015***	-.012***
Individual building scale:	Length (L)	-.066*** (-3.3dB)	-.024* (-1.2dB)	-.020
	Shaped layout	-.777** (-0.8dB)	-.236	-.419
Neighbourhood scale:	Spacing index (S)	.034*** (+1.0dB)	.005	-.001
	Compactness index (D) -Compactness squared (D2/100)	.001 .000	.001 .000	-.002 .000
Source-building scale:	Orientation (A) -Orientation squared (A2/100)	-.096*** .083*** (-2.8/+0.8dB)	-.071*** .066*** (-1.9/+0.8dB)	-.089*** .092*** (-2.2/+1.5dB)
Site scale:	Historical suburb	.385	-.084	.234
	Garden Suburb	.679*** (+0.7dB)	-.156	.016
	* R square of the regression	.823	.872	.690

*** $p<0.01$; ** $p<0.05$; * $p<0.1$; "-": Noise decrease; "+": Noise increase;

Table 8. Effects of morphological indices on average façade exposure at different frequencies with slope coefficients of the regression model and levels of estimated noise reduction

	Variables in regression (N=216)	Average Façade Exposure		
		50Hz	250Hz	1000Hz
	S-R Distance	-.019***	-.016***	-.019***
Individual building scale:	Length (L)	-.037*** (-1.9dB)	-.013	-.023
	Shaped layout (1=has U/L/H shaped layout)	-.447* (-0.5dB)	-.671*** (-0.7dB)	-.988** (-1.0dB)
Neighbourhood scale:	Spacing index (S)	.008	-.001	.001
	Compactness index (D) -Compactness squared (D2/100)	-.001 .000	.008*** -.001*** (+1.6/-0.6dB)	-.016*** .002*** (-3.2/+1.3dB)
Source-building scale:	Orientation (A) -Orientation squared (A2/100)	-.087*** .088*** (-2.2/+1.4dB)	-.077*** .079*** (-1.9/+1.3dB)	-.072*** .084*** (-1.5/+1.8dB)
Site scale:	Historical suburb	.546** (+0.5dB)	.353	-.163
	Garden Suburb	.270	-.029	.212
	* R square of the regression	.888	.852	.727

*** $p<0.01$; ** $p<0.05$; * $p<0.1$; "-": Noise decrease; "+": Noise increase;

environmental morphology. Noise resistance effects of key morphological indices have been revealed and compared using statistical analysis. The conclusions can be summarised as follows:

4.1 General noise-resistance of built environment for wind turbine noise at quiet façade

It has been demonstrated that built environment morphology creates large variations of noise levels (up to 10dBA) around dwellings at building scale in the distant range of 400-1000m, equivalent to the sound attenuation from 600m to 1600m in a free-field in favourable conditions. It is worth noting that in practice, the effect of built environment could be even larger than stated in this paper, given a lower hub height (i.e. 80m [48]) and larger variation of building heights. This study proves that the noise resistance of buildings can create a quiet façade with up to 13dBA difference to the most exposure façade, which can offer the inhabitants an escape from the wind turbine noise.

Compared to other studies on quiet façade effects, wind turbine noise has relatively less difference around façades with respect to road traffic noise, which could be approximately 10-20dBA lower at the quieter side [34]. However, having a difference more than 10dBA between the most and least exposed façades can play an important role in reducing adverse impacts, based on previous studies, corresponding to a reduction of about 5dBA at the most-exposed side [35] and leads to lower annoyance [36]. Therefore, it is suggested that exposures at the quiet façade should be taken into account in future studies on the noise impact of wind turbine noise in residential areas.

4.2 Noise-resisting effect of morphological indices

Among the studied morphological indices, the building length, shape and orientation have considerable effects, both in terms of minimum and average façade exposures, while the spacing between neighbouring buildings only makes differences on average façade exposures. Using a long façade to face the wind turbine (orientation factor) makes the largest variation, with a noise reduction of up to 2.6dBA on minimum and 2.2dBA on average façade exposures. Increasing the length of the building also makes a large SPL variation, although it is found to be more effective in decreasing the minimum façade exposure, by up to 2.7dBA.

The effects are in consistent with those found in other studies on relationships between urban morphology and environmental noise. The index of shaped layout, corresponding to the irregularity of urban form, has been stated to allow the creation of protected areas or shadow zones [30]. The effect of orientation with respect to the source direction, is in accordance with previous findings from aircraft noise and birdsongs, which indicated that the area of the frontal façade facing the source direction was important for noise resistance [26,27].

The noise resistance effects of morphological indices vary by different S-R distance ranges. In this study, the resistance effects of a shaped layout and orientation are more prominent at S-R of 300-600m. The building length has the highest level of resistance with S-R of 601-1000m, but adjacent buildings (spacing and compactness index) are more effective with S-R over 1000m.

The effects of morphological indices differ by frequency. The studied morphological indices, except the compactness index, are effective at low frequencies as 50Hz, especially in terms of minimum exposure. Among them, the length and orientation of the building make the largest reduction, by up to 3.3dB and 2.8dB, respectively. However, the compactness index and shaped layout are estimated to reduce more average noise exposure at higher frequencies than 50Hz.

4.3 Practical tips and future investigation

The results of this paper allow the prediction of potential effects of new wind turbines in an existing built-up environment and will be useful for researchers and urban planners in the wind energy field to define in advance the formation of residential areas that can better resist the noise from wind turbines. More specifically, in practical design, to consider the above suburban morphological indices in an integrated way, it is suggested that, buildings with long façade that are diagonally opposite to the wind turbine leads to the lowest exposure of building façades. A shaped layout of the floor plan is also recommended especially for the residential areas that are very close to the wind turbine. In addition, a highly compact layout is only advised for certain S-R distances in design, such as over 1000m.

While urban environment has unique challenges in the energy-noise trade-off, future investigations can consider the effect of built-environment morphology on both noise resistance and energy generation. Studies have found that urban morphology and street geometry, such as building shape, height, aspect ratio and street length-to-depth ratios, greatly influence the wind flow and hence the extractable power of a wind turbine [2,4,50]. This gives opportunity for an interdisciplinary study that investigate how urban morphology responses to the challenge in the energy-noise trade-off, in order to take maximum advantage of the wind energy in the urban environment.

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