Impacts of wind turbine noise on health and well-being from the perspective of urban morphology

A Thesis Submitted for the Degree of Doctor of Philosophy

by

Fei Qu

The University of Sheffield

School of Architecture

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Abstract

Wind turbines are playing an increasing role in the global process of producing renewable energy. There is a development towards integrating large-scale onshore wind turbines within urban environment, and some of these are close to residential areas. The potential adverse impacts of wind turbine noise on health and well-being have attracted substantial attention.

The aim of this thesis was to model the distribution of wind turbine noise in suburban-urban residential areas and to investigate the relationships between exposure to wind turbine noise, resident's response to the noise, and their health and well-being. Questionnaire responses on health and well-being were linked to the noise mapping of respondent's façade exposures, using statistical tests.

The overall results can be highlighted as follows: Firstly, urban morphology – such as the orientation, shape, and length of the building, as well as the spacing between adjacent buildings – could largely influence localised noise exposure especially the noise on receptors' quiet façades. Noise reduction levels of five morphological indices were identified to guide architects and urban planners in residential design. Secondly, wind turbine noise levels were positively associated with self-reported noticeability and annoyance due to the noise, as well as self-reported prevalence of ear-discomfort, dizziness and nausea. Wind turbine noise levels did not directly influence sleep and subjective well-being, although self-reported health and happiness of the study sample were poorer than the sample of national health survey. Non-acoustic factors – such as age, education, visibility of the turbine, and housing type – could affect self-reported noise evaluation and health. Thirdly, respondent's knowledge of the research purpose leaded to under-reported health symptoms, which was an important finding on research methodology that suggested the use of a control group with research purpose masked to minimise the focusing bias in health impact assessments. Finally, planning and design suggestions were provided towards wind turbine noise management in urban areas, such as siting urban wind turbines beside busy roads, designing long terraced houses, and engaging public participation.

Acknowledgements

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I would like to express a sense of gratitude and love to my beloved partner and parents for their support, encouragement, and unconditional love, without whom I would not be who I am today.

Dedicated to my son Junyi

Contents

Lists of Abbreviations

AM	Amplitude Modulation
ANOVA	Analysis of Variance
BHPS	British Household Panel Survey
dB	Decibel (unweighted)
dBA	Decibel (A-weighted)
CI	Confidence Interval
EEG	Electroencephalograph
EIA	Environmental Impact Assessment
END	Environmental Noise Directive
EU	European Union
HRQOL	Health Related Quality of Life
HSE	Health Survey of England
GHG	Greenhouse Gas
GHQ	General Health Questionnaire
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
L90	Sound pressure level exceeded 90% of the time
Lmin	Minimum sound pressure level over a time
Ld	Day-time averaged noise level
Ln	Night-time averaged noise level
LSID	Long-standing Illness and Disability
OLS	Ordinary Least Squares
OR	Odds Ratio
PSQI	Pittsburg Sleep Quality Index
H-L	Hosmer-Lemesow goodness-of-fit
REM	Rapid Eye Movement
RTN	Road Traffic Noise
SEMs	Structural Equation Models
SF-36	Short Form 36 (questionnaire)
SPL	Sound Pressure Level
SWB	Subjective Well-being
US	Understanding Society
VAD	Vibroacoustic disease
WHO	World Health Organization
WTN	Wind Turbine Noise

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Chapter 1

Introduction

Wind turbines are playing an important role in producing renewable energy. As onshore wind turbines are becoming common in many countries, a number of them have been introduced into suburban or urban settings, which can bring noise pollution to surrounding residents.
The aim of this thesis is to model the distribution of wind turbine noise in suburban-urban residential areas and to investigate the relationships between exposure to wind turbine noise, respondents' noise evaluations, and their health and well-being. The work also explores if noise exposures at relatively quiet façades and higher traffic noise in urban contexts have effects on the resident's noise evaluation and well-being.

1.1 Wind Energy

Over the last few decades, mitigation of greenhouse gas (GHG) emissions and climate change has been an important and long-term mission for the whole world. It takes enormous human effort and investment, particularly in the deployment of renewable energy technologies. Wind turbines are playing an increasing role in the global process of producing renewable energy, with many positive effects. The wind turbine emits no greenhouse gases, no air pollutions, and no micro-particles (WindEurope). As shown in Figure 1, the global cumulative wind turbine generating capacity continues to grow every year, bringing the total global installed capacity to nearly 487 GW by the end of 2016 (GWEC). In the UK, the government targeted the installation of 13GW of onshore wind power by 2020, which equates to an annual growth rate of 13% (DECC, 2011). The number of onshore wind farms has nearly tripled during the past four years, consisting of 1,217 operational sites across the country in 2017 (RenewableUK).

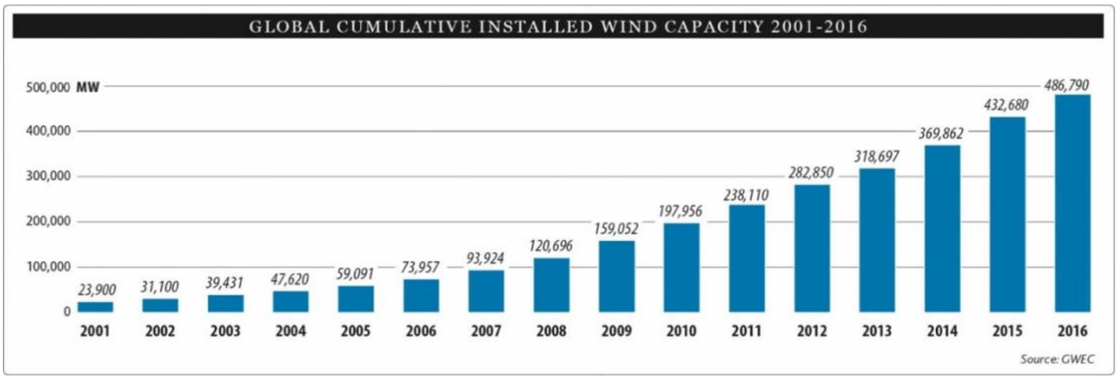


Figure 1. 1 Global cumulative installed wind capacity 2001-2016; Source: Global Wind Energy Council (GWEC).

1.2 Large Wind Turbines in Urban Settings

As onshore wind farms are becoming a common feature of landscapes in many countries, there is a development towards integrating large-scale wind turbines within urban environment (Ishugah, Li, Wang, & Kiplagat, 2014). Studies have confirmed that large-scale urban wind energy can be successfully implemented in urban areas (Cooney, Byrne, Lyons, & O'Rourke, 2017; Ishugah et al., 2014; Ledo, Kosasih, & Cooper, 2011; Murakami & Mochida, 1988) and can reduce electricity loss and network costs due to its proximity to the users (Archer & Jacobson, 2007; Hoppock & Patiño-Echeverri, 2010). It is also documented that urban siting of wind turbines gains more support of the local community compared to wind farms on aesthetic rural grounds (Knight, 2004). These advantages herald considerable potential of future wind energy projects to be fully developed in urban environments.

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. Figure 1.2 shows the photos of wind turbines near residential areas in urbanised settings.

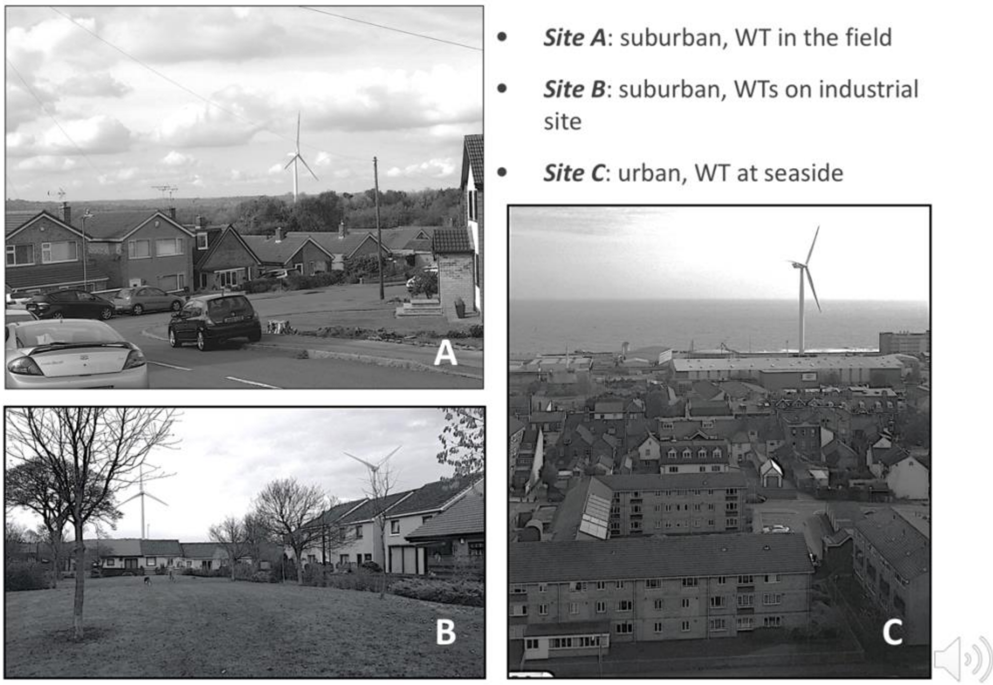


Figure 1. 2 Photos of wind turbines near residential areas. (Photos taken by the author; names of the towns are anonymus for ethical considerations)

However, noise pollutions to surrounding premises are obstacles of wind energy exploitation. Noise emission from a wind turbine at the hub height is larger than typical urban noise sources, which is normally 98-102dBA for a modern wind turbine at wind velocity of 8m/s at 10 m height (Pedersen & Waye, 2004). Noise from wind turbines in residential areas consist of large components at low-frequencies (below 200Hz), which is less attenuated by buildings than mid- to high-frequency sound (Nilsson, Bolin, Bluhm, Eriksson, & Nilsson, 2011).

To date there is little research towards noise impact of large-scale wind turbines in suburban-urban environments with large coverage of residential buildings. The existing calculation methods for flat, rural landscapes might overestimate the noise exposure in built-up areas (F. van den Berg, Pedersen, Bouma, & Bakker, 2008). Urban morphology – such as the height, shape, and orientation of the building, as well as the spacing between adjacent buildings – can largely influence localised noise exposure on and around receptors' building façades and may contribute to obtain reduced levels of noise pollution from wind turbines. 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.

1.3 Impact of Wind Turbines on Health and Well-being

Health generally refers to the soundness of body and mind. In the literature of noise and health, respondent's health is usually assessed as a series of adverse health effects or symptoms, such as noise-induced annoyance, sleep disturbance, dizziness (Passchier-Vermeer & Passchier, 2000), and mental distresses such as tension and mood swings (S.A. Stansfeld, Haines, Burr, Berry, & Lercher, 2000). Health is also measured by self-reported general health in national health surveys (e.g Health Survey for England, the HSE), from excellent to poor, to represent the overall status of health. In this thesis, health includes both health effects and general health status.

Well-being is a general term for a positive condition of an individual or a group, while subjective well-being (SWB) is often used as a term for how an individual thinks and feels about his/her life (Dolan, Peasgood, & White, 2008). SWB is normally measured by life satisfaction and self-confidence to various measures of physical and mental health, including happiness (Herbst, 2011). In this thesis, the terms of health and well-being refer to the overall wellness of people, while subjective well-being represents the self-reported life satisfaction and happiness.

The potential adverse impacts of wind turbine noise on health and well-being have attracted substantial attention, as outlined in the literature review in Chapter Two. There are numerous reports of adverse health impacts associated with wind turbine noise, such as decreased quality of life, sleep disturbance, headache, nausea and concentration problems, however, some of them have not found evidence in large field studies.

A limited number of cross-sectional studies have conducted questionnaire surveys to investigate the impact of wind turbine noise on noise evaluations and human well-being. Dose-response relationships between exposure to wind turbine noise and annoyance have been found in five studies conducted in Sweden, the Netherlands, Poland and Canada, successively (Michaud et al., 2016; Pawlaczyk-Łuszczyńska, Dudarewicz, Zaborowski, Zamojska-Daniszewska, & Waszkowska, 2014; Pedersen, van den Berg, Bakker, & Bouma, 2009; Pedersen & Waye, 2004, 2007). In addition, wind turbine noise was associate with self-reported sleep disturbance (Nissenbaum, Aramini, & Hanning, 2012; Pawlaczyk-Łuszczyńska et al., 2014; Pedersen, 2011), and related to psychological distress with noise annoyance as a mediator (Bakker et al., 2012). It can further negatively impact health-related quality of life (Shepherd, McBride, Welch, Dirks, & Hill, 2011).

Much of the existing research has focused on rural settings and there is a need to investigate the noise impact in urbanised environments. It has been found that the relations between wind turbine noise level and annoyance are not statistically significant in noisy environments, but the question remains whether it is because noisier environments better mask the wind turbine noise, or because people living in noisier areas have adapted more (Bakker et al., 2012). Therefore, there is a need to assess the noise impact in urban settings and to investigate the architectural and personal factors involved in the health and well-being of wind farm residents in urbanised areas.

1.4 Effects of Quiet Façade and Traffic Noise

In previous studies, 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 the outdoor sound propagation formula (Bakker et al., 2012; Pedersen & Waye, 2004), which mainly presents the noise at the most exposed place but considers less the variance among all the façades of the building. Noise might have wide-ranging impacts on the enjoyment of quiet places. It is indeed important to examine the presence of a quiet façade, which has been proved to have positive effects on decreasing annoyance and noise-induced health problems (de Kluizenaar et al., 2013; Öhrström, Skånberg, Svensson, & Gidlöf-Gunnarsson, 2006; Van Renterghem & Botteldooren, 2012). The EU Environmental Noise Directive (END) (European Union, 2002) 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 the relationship between noise at quiet façade and wind turbine noise annoyance. These need to be investigated in the thesis.

In addition, very few studies have assessed wind turbine noise in the context of different background noise levels. As the current noise limits for onshore wind turbines by ETSU-R-97 consist of both absolute noise limits and noise limits relative to the existing background noise levels around the site, it is important to explore if background noise such as high volume of road traffic noise in urban areas can mask wind turbine noise and decrease the adverse impacts on residents.

1.5 Planning Policies and Regulations for Onshore Wind Turbines

In the UK, the local planning authority (LPA) has the authority to give permission to onshore wind projects. The Government policies encourage LPAs to maximum renewable energy development while at the same time ensure adverse impacts and community concerns are addressed satisfactorily (Department for Communities and Local Government, 2012). However, the current planning policies and regulations have several imperfections. Firstly, the Government policies and guidance on onshore wind farms (e.g. (Department for Communities and Local Government, 2012, 2015; Department of Energy and Climate Change, 2011)) did not set out clear criteria for LPAs to assess the adverse impacts, such as the definition of “suitable area” for wind energy and rules on “separation distances” from the residents. These increase the time and cost for permitting procedures and can set obstacles to projects without significant adverse impacts (EWEA, n.d.). Secondly, the current national guidance on the assessment of noise impact, known as ETSU-R-97 (Working Group on Wind Turbine Noise, 1996) published in 1996, has received heavily criticisms (Bowdler, 2005) (Bullmore & McKenzie, 2015). Thirdly, local community’s concerns have been given more weight in the planning process (Instruments Statutory, 2013) (Lewis, 2015) which increase the importance of pre-application consultations to address their concerns in order to get planning permissions.

Since noise is a significant concern for a local community that can determine planning decisions, noise modelling and detailed surveys during the planning phase are essential. Therefore, an interdisciplinary approach to research is necessary, which can bring the methods of noise mapping in the discipline of architecture and urban planning to the methods of social survey in the discipline of health-related research, to predict community noise exposures before construction and address potential noise impact on human well-being of the residents living in particular locations of the local and neighbourhood plan. An understanding of the noise-resisting effect of a kind of urban morphology will help developers and LPAs to identify suitable areas for wind energy. An understanding of the relationship between wind turbine noise and human health and well-being will inform policy makers about the assessment and rating of noise impact, and give new guidance for noise limits and separation distances for different environments with an aim to protect residents' amenities. Both understandings can increase local awareness in the planning process, which will help developers to have the backing of local communities and to decrease social resistance to wind energy. In addition, an understanding of the social and economic contexts involved in public resistance to wind energy can guide the pre- and post-construction community involvement and help to conduct mitigation and compensation techniques for the developers.

1.6 Research Objectives

The aim of this thesis is to model the distribution of wind turbine noise in suburban-urban residential areas and to investigate the relationships between exposure to wind turbine noise, resident's response to the noise, and their health and well-being. Another intention of the thesis is to explore if noise exposures at relatively quiet façades and higher traffic noise in urban contexts have effects on the resident's noise evaluation and well-being. An illustration of the objectives is shown in Figure 1.3.

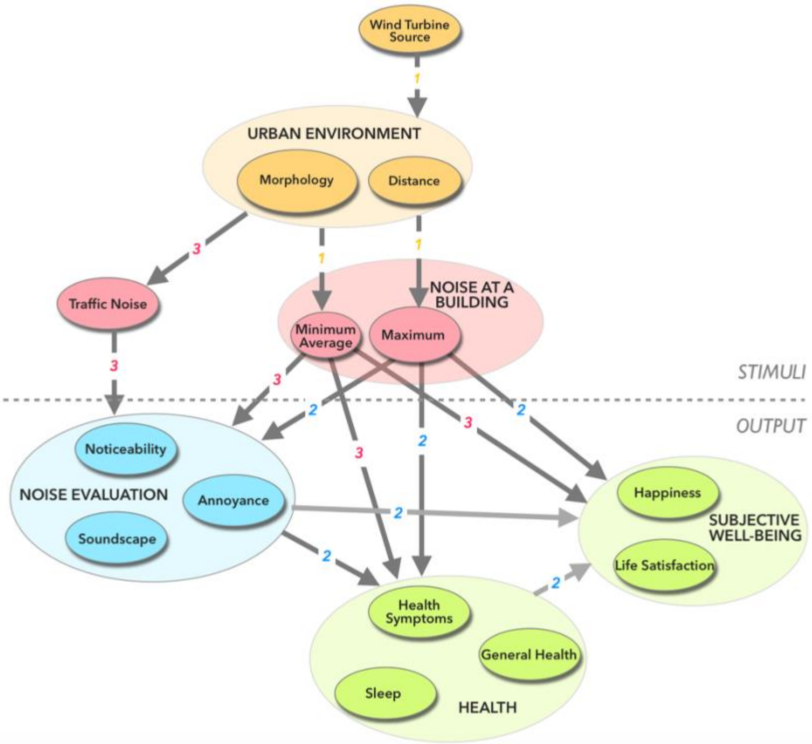


Figure 1. 3 Objectives of the thesis, where the number on an arrow shows the corresponding number of the objective.

Specific objectives are:

Objective 1 (Chapters 3, 4): To understand the effects of built environment factors such as morphology on the wind turbine noise distribution using noise mapping techniques.

Objective 2 (Chapters 5, 6, 7): To investigate the relationships between the maximum wind turbine noise exposure at a dwelling and residents' noise evaluation; and the impact of that noise on health and subjective well-being, controlling for the socio-economic and personal factors interacting in this process.

Objective 3 (Chapter 8): To examine the well-being impact of wind turbine noise at quiet façades and relative to existing major traffic noise levels at the building.

1.7 Research Methodology Overview

The thesis used a multidisciplinary approach to research, which integrates physical aspects of the built-environment with social aspects of human well-being. It carried out noise mapping to graphically show the distribution of wind turbine noise in suburban-urban areas. On-field measurements were used to validate the methods of noise mapping calculations. This thesis explored the noise-resisting effects of built environment morphology in generic suburban areas. Three kinds of typical suburban sites 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. Single frequency analyses were also carried out to examine the effect of built environment factors on wind turbine noise exposure at different frequencies.

To investigate the relationship between exposure to wind turbine noise and human well-being, paper questionnaire surveys were conducted on selected residents of three real-world sample sites across the UK in the vicinity of large wind turbines in suburban-urban settings. A-weighted sound pressure levels (SPLs) were calculated using noise mapping techniques, for the most exposed façade of each target dwelling. The relationships between SPLs and human health and well-being were investigated through quantitative analysis of the questionnaire data. The subjective well-being of the study respondents were also compared with those reported in the national survey. Possible focusing bias associated with asking people for their perceived causes of health problems was minimised by recruiting a separate control group without any focusing on wind turbine noise. Differences between the main and control groups in relation to reported health and well-being were examined.

Noise mappings were used to calculate the wind turbine noise exposures at different sides of the dwelling and estimate the noise from major roads and railways in the day and night periods at each receptor's dwelling. Noise exposures at the least exposed façade of a dwelling and at all façades on average were correlated to noise evaluations obtained from questionnaire surveys, to examine the quiet façade effect. Evaluations on wind turbine noise were also regressed on both wind turbine noise and traffic noise to investigate the potential masking effect of background noise in urbanised areas.

1.8 Thesis Outline

The thesis consists of 3 key parts of original studies: 1) Part 1. Effects of urban morphology on wind turbine noise exposure; 2) Part 2. Impact of wind turbine noise exposure on human well-being; and 3) Part 3. Implementation in design and planning. A diagram of the relations between chapters is shown in Figure 1.4

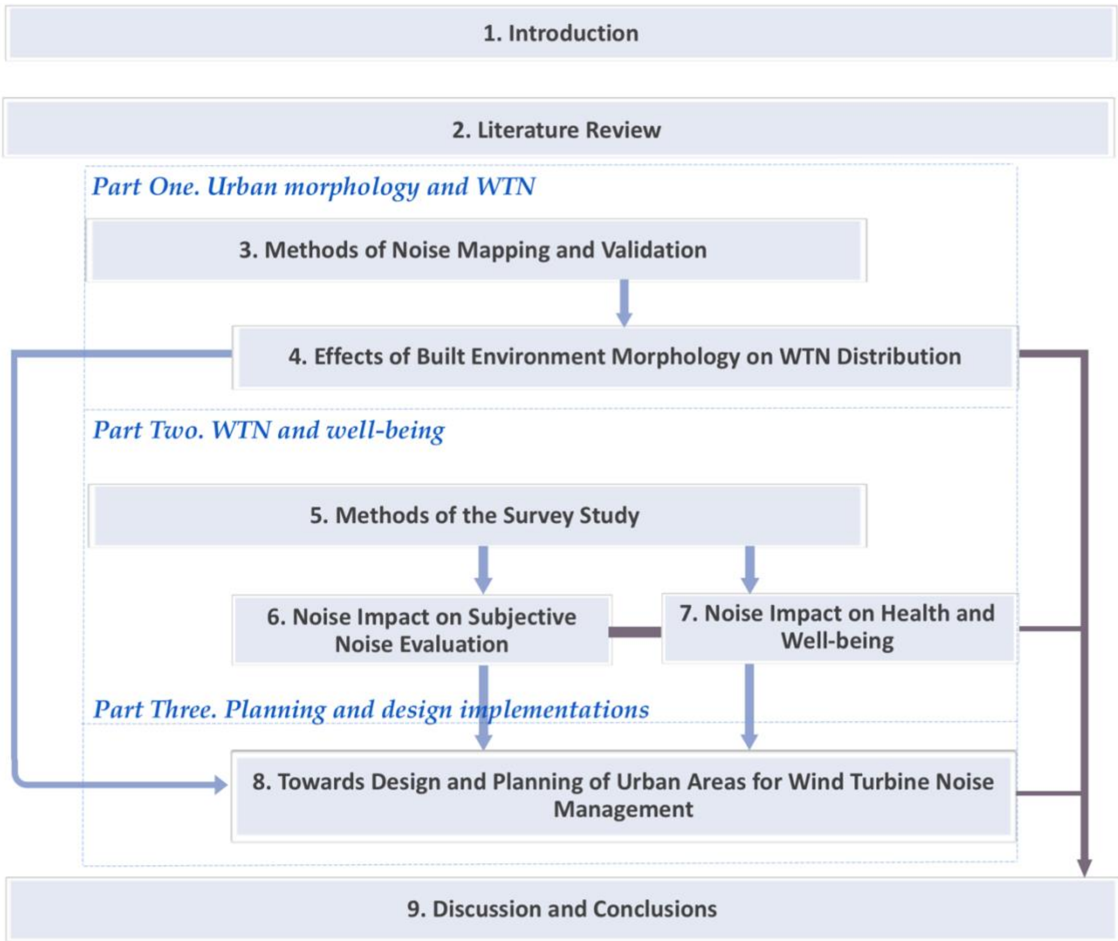


Figure 1. 4 Relations between parts and chapters of the thesis.

The rest of the thesis is organised in eight chapters. A brief summary of each is given below:

Chapter 2, *'Literature Review'*, firstly reviews the broad literatures on environmental noise that provide evidence for an association between noise and well-being, taking into account the non-acoustic factors. Then, it summaries the evidence from current studies on the well-being effects of wind turbine noise.

Part one: Effects of Urban Morphology on Wind Turbine Noise Exposure:

Chapter 3, *'Methods of Noise Mapping and Validation'*, outlines the methods of calculating the wind turbine noise in built environments using the noise mapping technique. The first part of the chapter shows the detailed calculation settings for the source, obstacles, the receiver, and topographical parameters, as well as the guidance standards which accord to. The remaining part of the chapter presents the validation of the noise mapping methods using on-field measurement of the wind turbine noise.

Chapter 4, *'Effects of the Built Environment Morphology on Wind Turbine Noise Distribution'*, presents the noise-resisting effects of built environment morphology in suburban residential areas. It starts with a noise mapping of noise from a typical wind turbine on generic building configurations, followed by mapping the hypothesised noise distribution at different residential areas. Noise reduction levels of five morphological indices are given in terms of resisting wind turbine noise with different source-receiver (S-R) distances, and at different frequencies.

Part two: Impact of Wind Turbine Noise Exposure on Human Well-being:

Chapter 5, '*Methods of the Survey Study*', demonstrates the design of the questionnaire survey including variants, themes and variables in the survey. It provides detailed evidence for the inclusion of specific questions and response items related to key objectives of the survey. Methods on the site selection and sampling strategy to recruit participants are stated. Finally, the chapter presents the statistical analyses performed in the thesis.

Chapter 6, *'Noise Impact on Subjective Noise Evaluation*, presents the results of the questionnaire survey on how respondents evaluate wind turbine noise. It investigates the dose-response relationship between wind turbine noise level at the most exposure façade of a dwelling and residents' evaluation of the noise, regarding the effect of wind turbine noise on noticeability of and annoyance with the noise, and on evaluation of the overall sound environment. The dose-response relationships in the suburban context of this study are then compared with those of the previous studies in rural settings.

Chapter 7, *'Noise Impact on Health and Well-being'*, presents the results of the survey on health and well-being, including the noise effects on sleep, adverse health problems, and subjective well-being. It includes a comparison between the well-being of this study and the national health surveys.

Part three: Implementations in Design and Planning:

Chapter 8, *'Towards Design and Planning of Urban Areas for Wind Turbine Noise Management'*, estimates the road traffic noise at respondent's dwelling in urban areas. It examines the effect of traffic noise planning on wind turbine noise evaluation and reveals the important role of morphological design on reducing the noise impact on well-being. Planning and design solutions for noise managements in suburban-urban areas based on the findings of the thesis are provided.

Chapter 9, *'Discussion and Conclusions'*, firstly summarises the key findings of the thesis, then discusses the implications of the findings for developers, planners, and the general public involved. It acknowledges the limitations of the research and finally gives suggestions for further work.

Chapter 2

Literature Review

2.1 Introduction

Noise is generally defined as an unwanted sound and is perceived as an environmental nuisance that may adversely affect people. There is sufficient literature of epidemiological studies that found the link between exposure to environmental noise and human well-being, in terms of annoyance (OUIS, 2001; Passchier-Vermeer & Passchier, 2000), sleep problems (Basner et al., 2014; Muzet, 2007; Zaharna & Guilleminault, 2010), and health-related symptoms (W Babisch, 2011; S.A. Stansfeld et al., 2000). On the contrary, the field of wind turbine noise studies is relatively new and limited evidence has been presented for the health effects of wind turbine noise (Hanning & Evans, 2012). In addition, there are several case studies reported health complaints related to wind turbine noise (Harry, 2007; Ontario, 2009; Pierpont, 2009; Thorne & Leader, 2012), most of which have not been supported in cross-sectional studies. These uncertainties could be caused by the special acoustic characteristics of wind turbine noise that function differently on human compared to other environmental noise, or might be due to limitations of the existing study such as lack of explanatory factors and potential information bias in measuring noise exposure.

Therefore, the aims of the review include two aspects. First, the review includes broad studies on environmental noise that provide evidence for an association between noise and well-being, with an aim to identify the noise threshold in which the effect occurs and to find out non-acoustic factors that modify the effect. These findings on exposure-response relationships between environmental noise and health effects could be consistent with those from the wind turbine studies or provide evidence to distinct wind turbine noise from other noise sources. Second, the review is conducted to reflect on the existing evidence on the relationship between wind turbine noise and health and well-being. The review on previous wind turbine noise studies also discovers the strengths and limitations of the method in collecting and analysing the data, from which suggestions on further investigation can be derived.

Section 2.2 reviews the impact of environmental noise on health and well-being, followed by Section 2.3 that summaries the evidence from studies on the well-being effects of wind turbine noise. Discussions are given in Section 2.4 to state the similarities and differences between evidence from studies on wind turbine noise and on other noise sources. Current research limitations and suggestions for further investigation are also discussed.

2.2 Impact of Environmental Noise on Health and Well-Being

Environmental noise is pervasive in urban environments, caused by transport, industrial and recreational activities. In this section, effects of environmental noise exposure on adults are reviewed, with a particular focus on non-auditory effects that usually occur with relatively low noise levels, comparable with the exposure level of wind turbine noise in residential areas. The review refers to original acoustical and epidemiological studies, as well as review articles.

According to previous findings, noise exposure could be associated with numerous health endpoints, some with sufficient evidences, while others with inconclusive ones for a causal relationship. The relationships between noise exposure and potential health effects are summarised in each section below, ranging from auditory health effect such as noise-induced hearing loss (Section 2.2.1), to non-auditory effects including annoyance (Section 2.2.2), sleep disturbance (Section 2.2.3), cardiovascular disease (Section 2.2.4), and psychological symptoms (Section 2.2.5). In each section, the review also presents the observation threshold for the effect in terms of the lowest noise level at which the effect was observed in studies. In addition, the review summarises non-acoustical factors and their modifying effects defined in previous studies, including the influence of age, sex, and individual noise sensitivity.

2.2.1 Noise-induced hearing loss

Chronic noise exposure can cause threshold shifts and hearing loss. Noise-induced hearing loss is normally classified as an auditory health effect because it is a direct consequence of the effects of sound energy on the inner ear (Stephen A. Stansfeld & Matheson, 2003). As stated in a review (Basner et al., 2014), noise-induced hearing loss can be caused by a one-time intensely exposure, or by long-term exposure to a sound higher than L_A 75-85 dB. This value is consistent with the value specified in 1990 by the International Standard (ISO, 1990), which gives relations between the equivalent sound level over an 8-hour work day ($L_{Aeq,8h}$) and noise-induced hearing impairment. These relations show that the effect mainly occurs at the frequency range of 3,000-6,000 Hz, and does not occur at $L_{Aeq,8h}$ levels below 75dBA (ISO, 1990). It is worth noting that the levels of wind turbine noise exposure in residential areas are much lower. Therefore, the effects on hearing loss of the residents are expected to be non-existent.

2.2.2 Annoyance

Annoyance is the most frequently reported as an effect of environmental noise, which is a feeling of displeasure, discomfort or anger when noise interferes with daily activities, feelings, thoughts, or rest (Öhrström et al., 2006; Passchier-Vermeer & Passchier, 2000). Relationships between noise annoyance and environmental noise exposure have been demonstrated in various studies, which are normally assessed using questionnaires with several modifying factors being controlled for. Dose-response relationships have been derived for exposure to road, railway, and aircraft noise. In general, 55 dBA (L_{day}) and 45 dBA (L_{night}) are commonly used as the limit for annoyance at façades (WHO, 1999). Annoyance induced by road, railway and aircraft noise differs at higher exposure levels. It has been reported that aircraft noise is statistically significantly more annoying than the others, and railway noise is the least annoying among the three (Miedema & Vos, 1998).

The degree of annoyance can vary considerably between individuals because of the modifying effect of so-called non-acoustical factors. These factors have been identified in a set of studies (Bluhm, Nordling, & Berglind, 2004; Fields, 1993; Guski, 1999; R. F S Job, 1996; R.F. Soames Job, 1999; Weinstein, 1978). Demographical factors such as age, employment and socio-economic status were found to affect the individual degrees of annoyance in previous studies (Fields, 1993; Bluhm et al., 2004). Personal sensitivity and attitude to the noise source have also been reported as important modifying factors in various socio-acoustic studies (e.g. Weinstein, 1978; Guski, 1999; Job, 1999). It has been proposed that people who were more critical and tended to give negative ratings of noise and the neighbourhood were typically more annoyed by a new community noise problem than people who were less critical (Weinstein, 1980). Fields (1993) found that noise annoyance is positively associated with the fear of the noise source, the belief that the noise could be prevented, expressed sensitivity to noise, and negatively associated with the belief that the noise source is important for the local area. Situational characteristics, such as dwelling insulation, are also found to affect noise annoyance. Previous studies have indicated a beneficial effect of a quiet facade on traffic noise exposure, stating that the existence of a quiet side of the dwelling reduces noise annoyance (Öhrström, 1991; Öhrström et al., 2006). In addition, dwelling orientation had been found to have an effect, resulting in up to 20% decrease of annoyance (Bluhm et al., 2004).

2.2.3 Sleep disturbance

Noise can cause disturbances in sleep and subsequent health effects. As stated in a review article, primary sleep disturbances encompass disorders including difficulty falling asleep, frequent awakenings, waking too early, and alterations in sleep stages and depth, such as Rapid Eye Movement (REM) sleep (Zaharna & Guilleminault, 2010). Human beings are able to perceive incoming noise stimuli and make responses even while asleep (Basner et al., 2014). Noise exposure during sleep may induce physiological reactions including increased blood pressure, heart rate, and autonomic arousals such as body movements and awakenings (Stansfeld & Matheson, 2003; Basner et al., 2014). Some after-effects following disturbed sleep have been found, including decreased perceived sleep quality, mood and reaction time (Stansfeld & Matheson, 2003). These are consistent with Muzet's review of noise and sleep (Muzet, 2007), in which the effects of noise are categorised as immediate effects referring to "responses occurring simultaneously after the noise emission", and secondary effects corresponding to "effects visible the next day or after a few days".

In previous studies, immediate effects of noise on sleep are usually assessed by objective measures, such as the most commonly used electroencephalograph (EEG) recording and actimetry. Sleep disturbance can be quantified by frequency and duration of nocturnal awakenings, modifications of shallow and deep sleep stages, and modifications in the autonomic functions such as blood pressure and heart rate) (Muzet, 2007). Epidemiological studies have provided evidence for a causal relationship between noise exposure and changes in sleep pattern, sleep stages, and awakenings (Passchier-Vermeer & Passchier, 2000; Zaharna & Guilleminault, 2010). In terms of sleep stages, REM sleep was reported to be affected by environmental noise (Muzet, 2007). In a study that investigated the effects of different traffic noise events on the sleep of 72 healthy subjects for 11 consecutive nights, the amount of deep sleep stage (SWS) were found to be significantly lower in the nights with noise exposure, with significantly higher number of arousals and changes of sleep stages (Basner, Müller, & Elmenhorst, 2011). Noise was also found to shorten the sleep period by increasing the time to fall asleep and extending the time of awakening (Muzet, 2007; Basner et al., 2014).

The secondary effects of night-time noise exposure include subjective reports of sleep quality, interference on daytime functioning and mood the next day (Muzet, 2007; Passchier-Vermeer & Passchier, 2000). Night-time noise exposure of certain intensity was found to affect self-reported sleep quality. Öhrström (1991) found that significantly more people in noisy area reported difficulties in falling asleep, lower sleep quality, and less rested in the morning. The use of sleep pills and earplugs was also greater in the noisy areas. Basner et al. (2011) used questionnaire to obtain subjective assessment of sleep quality in the morning and found that subjects being exposed to night-time noise reported significantly more disturbed and lighter sleep, as well as significantly more tiredness after waking up. However, in some studies, subjective complaints on sleep quality or on nocturnal awakenings have been found to be different from objective measures of sleep disturbance (Muzet, 2007). Several studies show that the level of total sleep disturbance may be not attributable to noise increase in noisy areas, this might be due to the fact that subjective assessment of sleep quality, as Stansfeld and Matheson (2003) argued, “suggested a symptom reporting or attribution effect rather than real noise effects”. Therefore, the validity of self-reported sleep quality needs to be considered.

The degree of noise-related sleep disturbance is related to the number of noise events and their acoustical properties, such as the type of noise, noise intensity and frequency, noise signification, and the difference between the peak amplitude of noise and background noise level (Muzet, 2007). A study that compared air, road and rail traffic noise found that road traffic noise was strongly related to changes in sleep time and structure, whereas air and rail traffic noise exposure led to worse subjective assessments of sleep after nights with (Basner et al., 2011). Whether noise will induce arousals also depends on "situational moderators", such as current sleep stage, and individual noise susceptibility (Basner et al., 2010; 2014). Several studies have focused on the modifying effects of habituation and noise sensitivity. It has been noted that personal characteristics, such as age, daily activities, and noise sensitivity are important individual factors (Öhström & Björkman, 1988). Muzet (2007) has indicated that elderly people, children, shift-workers, and people with a pre-existing sleep disorder are susceptible to noise at night. In addition, Zaharna and Guilleminault (2010) have reported that night-time workers, mothers with babies, vulnerable persons, and individuals who experience sleeping difficulty are more likely to experience disturbed sleep due to noise.

Noise-induced sleep disturbances may lead to short- and long-term consequences for cognitive performance, cardiovascular functions, and wellbeing. First, there is a number of studies that state the effects of chronic sleep disturbance on mood, behaviour, and cognition functions. These include excessive daytime fatigue, expression of anger, lack of concentration, and deterioration of normal behaviour (Muzet, 2007). Clinical studies have found that total or partial sleep deprivation may also influence reaction time, memory, attention, motivation, and performance (Bonnet & Arand, 2003). Basner et al. (2010) has added that in the studies since 2003, sleep fragmentation has been shown to affect creativity, risk taking behaviour, signal detection performance, and accident risk. Second, chronic sleep loss may contribute to cardiovascular disease. Poor sleep is reported to be associated with an increase in blood pressure and heart rate (Muzet, 2007). A cross-sectional study has found a significant relationship between the risk of hypertension and reported sleep disturbance on heavy road traffic noise (W Babisch, Ising, Gallacher, Elwood, & Sweetnam, 1990). Subjective assessment of sleep may have an effect on psychosocial well-being. Öhrström (1991) has found that psychosocial well-being was both related to the night-time traffic noise level in the bedroom and to the subjective sleep quality. However, an review of sleep and health states that causal relationships between sleep and mental and social well-being are yet to be confirmed (Zaharna & Guilleminault, 2010).

The noise levels that affect sleep have been reported. A review article of environmental noise and sleep summarises that noise levels of 45dBA and above can increase the time to fall asleep; while noise levels between 45 and 55dBA can provoke disturbance of normal sleep sequence; and the noise level of 55dBA and above can generate nocturnal awakenings (Muzet, 2007). The World Health Organization (WHO) guidelines for community noise noted that for a good sleep, the background noise level should not exceed 30dBA with no individual noise events over 45dBA (WHO, 1999). In 2009, WHO published the Night Noise Guidelines for Europe, in which the annual average noise levels over the 8 nocturnal hours (L_{night}) are categorised in four groups with corresponding negative health outcomes (WHO, 2009). It indicates that $L_{night,outside}$ of 30 dB is equivalent to the "no observed effect level (NOEL) for night noise". From $L_{night,outside}$ of 30 dB up to 40 dB, a number of effects on sleep are observed, such as body movements, awakening, self-reported sleep disturbance, and arousals. $L_{night,outside}$ of 40 dB is equivalent to the "lowest observed adverse effect level (LOAEL) for night noise". From 40 to 55 dB, adverse health effects are observed, such as insomnia with threshold level $L_{night,outside}$ of 42 dB. Self-reported sleep disturbance also observed to occur above $L_{night,outside}$ of 42 dB. Above 55 dB, adverse health effects occur with a number of people being sleep-disturbed, and the risk of cardiovascular disease increases.

2.2.4 Cardiovascular disease

There have been multiple studies on the relationship between noise, blood pressure, and cardiovascular disease. Long-term exposure to environmental noise may affect the cardiovascular system and cause diseases such as hypertension, ischaemic heart diseases, and stroke (W Babisch, 2011). Exposure to noise can cause an increase in heart rate, high blood pressure, increased peripheral vascular resistance, and the release of stress hormones (W Babisch, 2011; Stephen A. Stansfeld & Matheson, 2003).

The noise thresholds of environmental noise for observed hypertension and ischemic heart disease are reported to be above 70dBA (L_{dn}) (Passchier-Vermeer & Passchier, 2000). The thresholds of road traffic noise for ischemic heart disease are 60-65dBA during the day and 50-55dBA during the night, respectively (Wolfgang Babisch, 2008). In terms of aircraft noise, although sufficient evidence has noted a positive relationship between aircraft noise and high blood pressure, hypertension in adults, and the use of cardiovascular medication, no supported dose-response relationship can be confirmed yet (Wolfgang Babisch & Kamp, 2009).

2.2.5 Psychological symptoms and mental health

People living in high noise exposed areas have been seen to report psychological symptoms including depression, nervousness, irritability, tension and edginess, as well as mental instability. In a number of studies in the 1970s conducted near airport, aircraft noise has been related to reports of headaches, irritability and being tense and edgy, as stated in a review (S.A. Stansfeld et al., 2000). It is noted, however, a bias of over-reporting might be raised from interpreting the health impact of aircraft noise (Barker & Tarnopolsky, 1978). A study on the health impacts of aircraft noise from London Heathrow Airport investigated the prevalence of 27 individual acute and chronic mental health symptoms. It showed with evidence that acute symptoms such as irritability and depression were increased with noise (Tarnopolsky, Watkins, & Hand, 1980). In a review of studies on noise and mental health published between 1993 and 1998, it was suggested that intense environmental noise exposure was related to depression and anxiety but there was little evidence for serious effects such as clinical psychiatric disorder (Stansfeld et al., 2000; Stansfield & Matheson, 2003). This conclusion remains with more recent studies which found that environmental noise did not directly influence mental health, although proximity to large airports seemed to increase anxiety and depressive symptoms (Davies & Van Kamp, 2008).

In addition to the reported psychological symptoms, some studies reported effects of noise exposure on mental health measured by the SF-36 Mental Health Scale (Issarayangyun, Black, Black, & Samuels, 2005), but other studies show no direct effects (Schreckenberg, Meis, Peschel, & Eikmann, 2010).

Noise annoyance is an important mediator of the relationships between environmental noise and mental health (Davies & Van Kamp, 2008). Highly annoyed residents living near airports reported more mental health complaints (Meister & Donatelle, 2000). In terms of neighbourhood noise, people who reported severe annoyance were more likely to have depression and migraine (Niemann et al., 2006). In addition, housing type and quality, noise sensitivity, and accessibility to quiet areas have been also reported to moderate the effect of noise on psychological symptoms and mental health (Davies & Van Kamp, 2008).

2.3 Wind Turbine Noise and Well-Being

The potential adverse impacts of wind turbine noise on health and well-bing have been attracting interest both from researchers and media. Wind turbine noise has been suggested to be more annoying than other environmental noise (Hanning & Evans, 2012). Various problems such as annoyance, disturbed sleep, headache, dizziness and stress have been described by residents living near wind turbines, which were proposed to be caused by the infrasound and low-frequency noise from the wind turbines (Farboud, Crunkhorn, & Trinidade, 2013). The purpose of this review is to identify previously reported associations between wind turbine noise exposure and effects on health and well-being. In the sections below, information is firstly given on the nature and cause (Section 2.3.1) of wind turbine noise with focus on the low-frequency and infrasound emission from wind turbines (Section 2.3.2). The results from case series are reviewed to identify various adverse health effects reported in previous surveys (Section 2.3.3). Then the results from field studies that aimed to relate the adverse health to sound levels are reviewed (Section 2.3.4). The effects of the noise on health and well-being are classified in terms of annoyance, sleep disturbance, and well-being including health-related problems and quality of life.

2.3.1 Nature of wind turbine noise

There are a number of articles on the noise mechanisms of wind turbine sound. A book summarising such information has been published (Wagner, Bareiß, & Guidati, 1996), which notes that wind turbine noise consists of mechanical noise from the generator and the gearbox, as well as aerodynamic noise radiated from the blades interacting with the turbulence flow. Mechanical noise can be reduced by engineering methods, leaving the aerodynamic noise as the dominating noise mechanism. According to Wagner et al. (1996), there are two types of aerodynamic noise from wind turbines regarded as the main noise mechanism. One is inflow turbulence noise generating from the interaction of blades with atmospheric turbulence, which is the main noise mechanism for frequencies below 1000 Hz. The other one is trailing-edge noise from the "interaction of boundary layer turbulence with blade trailing edge", which is the main aerodynamic noise mechanism for higher frequencies (740-2k Hz). The measurement results show that broadband trailing edge noise is the dominant noise source of wind turbines (Wagner et al., 1996).

The source noise level of a wind turbine depends on meteorological conditions and increases with wind speed (Larsson & Öhlund, 2014). As a result, noise emission from wind turbines may differ from time to time and increase at night. In a study, measurements showed that source levels at night could be 15 dB higher than daytime levels, due to higher wind speed at hub height at night (G. P. Van Den Berg, 2004). The author also indicated that in a stable atmosphere at night, "there is a greater difference between rotor averaged and near-tower wind speed", which is associated to a more "clapping" or "beating" sound observed by residents near wind turbines in late afternoon or in the evening (G. P. Van Den Berg, 2004).

In addition, the occurrence of amplitude modulation (AM) could be created by sudden changes of wind directivity and uneven air velocities, which is subjectively described as the swishing and thumping sound from wind turbines. van den Berg (2004) states that the thumping, pulse-like character of the wind turbine noise may further increase annoyance. A report resulting from the measurements on three wind farms has also concluded that the common causes of complaints are associated with the audible modulation of the aerodynamic noise, especially at night (Hayes, 2007).

2.3.2 Effects of low-frequency noise and infrasound

The presence of low-frequency and infrasonic noise emissions from wind turbines has been investigated in a wealth of studies. Low-frequency noise is often defined as sounds at the frequency range between 20 and 200 Hz; while infrasound is normally at frequencies between 1 and 20 Hz. It has been shown that infrasound and low-frequency noise are more likely to increase annoyance and the noise is less attenuated by buildings than higher frequencies (Nilsson et al., 2011). It has been claimed that high levels of low-frequency and infrasonic components in wind turbine noise may cause health problems, such as vibroacoustic desease, but empirical support is currently lacking.

In terms of the source of low-frequency sound from wind turbines, van den Berg (2004) indicates that the sudden variation in air flow may contribute to the low frequency part of the sound. The low-frequency components of wind turbine noise may be audible, but are not as loud as the sound at medium to high frequencies (van den Berg, 2004). In residential areas, low-frequency noise from wind turbines can be audible, but the levels do not exceed existing background noise levels or the road traffic noise (Hayes, 2007; Nilsson et al., 2011). However, a number of health related problems, such as the “wind turbine syndrome”, have been claimed to be associated with low-frequency noise from wind turbines (Pierpont, 2009). On the other hand, research into the impact of low-frequency noise consistently point out that some adverse health risks are incorrectly attributed to low-frequency noise. A detailed review of human perception and response to low-frequency noise has been provided (Leventhall, 2009). It has been shown that the annoyance by low frequency noise was greater and high levels of low-frequency noise may cause aural pain (occur at levels above 145dB at 20Hz), body vibration (above 80dB), and vibroacoustic disease (above 90dB) (Leventhall, 2009). But it also has stated that the attribution of some symptoms to low levels of low-frequency noise has been unproven for many years. It has been revealed that to relate complaints of physical symptoms to low-frequency noise is difficult, due to the fact that low-frequency noise with continuous fluctuations cannot be measured properly as an average level over a period of time. In addition, there are a number of non-acoustic problems which might lead to the perception of low-frequency noise (Leventhall, 2009).

Wind turbines also generate infrasound, due to the varying aerodynamic loading of the rotor blade as it passes through the air (Jakobsen, 2012). Ocean waves, volcanoes, heartbeat and respiration are natural sources of infrasound (Farboud et al., 2013). To become audible, the SPL for a 20Hz infrasound needs to be approximately 75dB, compared with 4dB for a 1000Hz sound (Salt & Hullar, 2010). Jakobsen (2005) carried out a critical survey on infrasound from wind turbines and indicated that modern wind turbines with an upwind rotor produce very faint infrasound, which is far below the threshold of perception even within a short distance from the turbine. At longer distances, the impact is even smaller. This statement has been confirmed in a report by Hayes McKenzie (2006) on the basis of the measurement at three UK wind farms, which concludes that neither infrasound nor low-frequency noise could significantly affect people in residential areas at a separation distance. It is clearly indicated that infrasound from modern wind turbines is not a source of adverse health of a wind farm neighbour. However, Salt & Hullar (2010) reviewed the responses of the ear to infrasound and claimed that although infrasound from wind turbines may be not perceptible, some inner ear components are stimulated at non-audible levels. The body can be influenced by infrasound through “receptors or homeostatic processes in the inner ear”, which poses a need for further research. But currently, no evidence has showed the relationship between infrasound from wind turbines and perceived annoyance or other health effects (Nilsson et al., 2011).

“Vibroacoustic disease” (VAD) is proposed to be an outcome of wind turbine noise by wind farm opponents. The term of vibroacoustic disease was used to describe a whole-body, multi-system pathology, said to be related to long-term exposure to high amplitude and low frequency noise over 90 dB SPL (Chapman & George, 2013). It was claimed that the disease has three stages from mild stage such as slightly mood swings, to moderate stage such as chest pain and fatigue, to severe stage of psychiatric and neurological disturbance (Alves-Pereira & Castelo

Branco, 2007). However, it was noted that "VAD has received virtually no scientific recognition beyond the group who promoted the concept" (Chapman & George, 2013). Currently no evidence shows that wind turbine noise is associated with VAD.

2.3.3 Reported health effects by wind turbine noise

During the past few years there have been a number of reports of adverse health impacts associated with wind turbines. The reported health effects are normally based on complaints of affected subjects and contribute fairly week evidence towards the relationship between adverse health effects and the degree of noise exposure. They do generally show that decreased quality of life, sleep disturbance, headache, nausea and concentration problems are frequent symptoms among subjects exposed to wind turbine noise. In addition, concerns for aesthetic issues and shadow flickers are sometimes being mentioned in the complaints.

Harry (2007) investigated 42 subjects in different locations in the UK, living between 300 and 2k metres from the nearest wind turbine. The participants recruited already had some problems which they felt to be caused by wind turbines. Eighty-one percent of the participants indicated their health had been affected since the erection of turbines. The symptoms mentioned by complainants included headaches, sleep disturbance, anxiety, depression, stress, vertigo and tinnitus. People complained of the noise, vibration and shadow flicker. Disturbed respondents reported to be particularly aware of the problems at night (Harry, 2007).

Phipps (2007) conducted a survey of visual and noise effects experienced by residents living close to wind farms in New Zealand. Four-paged, self-reporting/self-returning surveys were delivered to about 1100 households in urban and rural areas with 614 returned. All 614 households responding to the survey were living between 2-10 km from operational turbines. The result showed that wind turbine has visual and noise effects at a much greater distance. Among 516 households reported visibility of the wind turbine, “visually intrusive” was reported by 80 percent, and 73 percent considered the turbines to be unattractive. At distances of 2-2.5km from the wind turbine, 52 percent of households reported that they could hear the wind turbine; while at 2.5-3 km away, 36 percent could hear the noise. Forty-two households reported their sleep were occasionally disturbed by wind turbine noise; 21 reported that the noise disturbed their sleep frequently and 5 were disturbed most of the time (Phipps, 2007).

Moorhouse et al. (2007) evaluated complaints about wind turbine noise. It was found that 27 out of the 133 operating wind farms had received formal complaints about noise. It was pointed out that descriptions of the noise such as “like a train that never gets there”, “distant helicopter”, “thumping”, “thudding”, “pulsating”, “thumping”, “rhythmical beat”, and “beating” could be indicative of aerodynamic modulation of the noise, which was thought to be a cause of complaints for 4 sites out of 27 wind farms (Moorhouse, Hayes, von Hunerbein, Piper, & Adams, 2007).

Pierpont (2009) studied 38 people in 10 families living between 300-1600m from wind turbines. Reported symptoms were documented and identified as a new health risk, termed “wind turbine syndrome”. There was a constellation of health problems associated with “wind turbine syndrome”, including “sleep disturbance, headache, tinnitus, ear pressure, dizziness, vertigo, nausea, visual blurring, tachycardia, irritability, problems with concentration and memory, and panic attacks with sensations of internal quivering when awake or asleep”. The most common symptoms reported were sleep disturbances and headache. In addition, 93% of the subjects also reported memory and concentration problems. It was proposed that the mechanism for these effects was the disruption stimulation of the inner ear's vestibular system by turbine infrasound and low-frequency noise. At the heart of Dr Pierpont's findings is that human vestibular system is very sensitive to low-frequency vibration and can perceive inaudible sound through ear bones. This, she claims, “overturns the orthodoxy of the way of measuring wind turbine noise by acousticians”, which is clearly outdated.

Wind Concerns Ontario (2009) conducted a self-reporting health survey, WindVOiCe, on 112 subjects mostly living between 400-800 metres from the wind turbines in Canada. Eighty-six subjects reported at least one adverse health effect they suspect is related to industrial wind turbine. Reported symptoms included altered quality of life, sleep disturbance, inner ear problems, mood disturbance, headache, stress and excessive tiredness. Sleep disturbance was the most common complaint (Ontario, 2009).

Thorne & Leader (2012) investigated the annoyance and health-related quality of life experienced on 25 subjects living near 2 wind farms in Australia. The subjects interviewed were living between 700-3500 metres from the turbines, with an average of 1400 metres. Twenty-one of the 25 respondents reported severe to moderate adverse health effects, including sleep disturbance, headaches, irritability, anxiousness, ear pressure, high blood pressure, eye-strain, nausea, and so on (Thorne & Leader, 2012). Of the 25 participants, 92 percent stated a change in sleeping patterns after the operation of the turbines. The study showed lower Pittsburg Sleep Quality Index (PSQI) compared to known population values. In addition, mental component scores of SF-36 were also lower compared to those of the general population, with only 4 participants were above average according to the US demonstration scoring system. It is also worth noting that 92 percent of the participants stated that the turbines annoyed them indoors (Thorne & Leader, 2012).

2.3.4 Large field studies relating health effects to noise exposure

There have been several field studies of reasonable sample size investigating the relationship between exposure to wind turbine noise and adverse health effects. A summary of the key studies published in peer-reviewed journals are shown in Table 2.1, where information on the methods, sites, sample size and noise exposure groups of each study are provided. All of these studies performed to date were cross-sectional and questionnaire-based. Five studies claimed that the true purpose of the questionnaire was masked by asking for subjects' responses to a set of environmental stressors. However, except for Shepherd et al. (2011), the other studies all used various questions to specifically assess subjects' attitude towards visual and auditory aspects of wind turbines (Pedersen & Waye, 2004; 2007; Pedersen et al., 2009; Bakker et al., 2012; Pawlaczyk-Luszczynska et al., 2014). For this reason, it is argued that the focusing bias may exist, which might have led people to focus on the well-being impact of the noise, consequently over-reporting adverse health impacts.

All studies used a stratified approach where people exposed to high levels of wind turbine noise were compared to lower exposure or control groups. The studied sites were mainly agricultural areas, except two studies that included built-up areas to enable comparison between degrees of urbanisation (Pedersen et al., 2009; Bakker et al., 2012). There were multiple wind turbines on each site and the noise exposure at the receptors were normally calculated as A-weighted sound pressure levels at the dwelling in accordance with ISO standard model (ISO, 1996), taking into account the contribution of each wind turbine.

Table 2. 1 Previous studies on wind turbine noise

Study (country)	Survey method	Sites	WT power	Sample	Number of participants (N)	Resp-onse rate	Noise modelling of exposure variable	Range of SPLs & distance	Sound/ distance category
Pedersen & Persson Waye, 2004 (Sweden)	Cross-sectional - unspecified/ masked questionnaire	5 sites - flat terrain - agricultural countryside or small village	600-650KW, 14WTs 150KW, 1WTs 500KW, 1WTs	- all household with calculated noise>30dBA - sample size=513	351	68.4%	calculated - outside the dwelling	<30 to >40 dBA; 150-1199m	<30 30-32.5 32.5-35 35-37.5 37.5-40 >40
Pedersen & Persson Waye, 2007 (Sweden)	Cross-sectional - unspecified/ masked questionnaire	7 sites - different terrain - 3 suburban & 4 rural	>500KW, 478WTs	- all household with calculated noise>30dBA or 35dBA (when population>500)	754	57.6%	calculated - outside the dwelling	31.4-38.2 dBA; 150-1200m	<32.5 32.5-35 35-37.5 37.5-40 >40
Pedersen et al., 2009 (The Netherlands) & **Bakker et al.**, 2012 (The Netherlands)	Cross-sectional - unspecified/ masked questionnaire	3 types: - built up area - rural area with a main road - rural area without a main road	≥500KW, 1846WTs	- 150 respondents required in each of noise group - sample size=1948	725	37%	calculated - outside the dwelling	21-54 dBA (average=35); ≤2.5km	<30, 30-35 35-40 40-45 >45
Shepherd et al., 2011 (New Zealand)	Cross-sectional - unspecified/ masked questionnaire	2 sites - hilly terrain - coastal areas	2.3WM, 66WTs	- 56 with WT - 250 control group	197 - 39 with WT - 154 control group	34%	collected from previous noise survey	20-50 dBA; <2 to 8km	exposure & control groups
Nissenbaum et al., 2012 (USA)	Cross-sectional - questionnaire	2 sites - flat terrain - rural areas	1.5MW, 28WTs 1.5MW, 3WTs	- all adults living within 1.5km - a random control group living 3-7km	79 - 38 (375-1400m) - 41 (3.3-6.6km)	58%	collected from previous noise survey	32-57 dBA; 375m-6.6km	375-750m 751-1400m 3300-5000m 5300-6600m
Pawlaczyk-Luszczynska et al., 2014 (Poland)	Cross-sectional - unspecified/ masked questionnaire	3 sites - flat terrain - populated ares - mainly agricultural	2MW, 42WTs 1.5MW, 60WTs 150KW, 6WTs	all households	156	71%	calculated - next to the dwelling	37-48dBA (M=43dBA); 235-2470m (M=740m)	30-35 35-40 40-45 45-50

As shown in Table 2.1, five studies classified the subjects into groups with 5 or 2.5 dB noise intervals to compare their responses to different levels of exposures; whilst two studies compared between wind turbine exposed and control groups (Shepherd et al., 2011; Nissenbaum et al., 2012) and between near and far distance groups (Nissenbaum et al., 2012). Relations between noise exposure to wind turbines and annoyance, sleep disturbance, quality of life and other adverse health problems have been demonstrated in these studies.

Annoyance

The evidence for effects of wind turbine noise on human is strongest for annoyance. Relationships between annoyance and noise exposure to wind turbines have been elucidated together with several effect-modifying factors, such as attitude and noise sensitivity. As shown in Table 2.2 that summarises existing results on annoyance, dose-response relationships between noise exposure and annoyance have been derived from five studies (Pedersen & Waye, 2004; 2007; Pedersen, 2011; Bakker et al., 2012; Pawlaczyk-Luszczynska et al., 2014). Among these studies, two studies draw the conclusion based on that the odds of being annoyed were related to sound categories (Pedersen & Waye, 2004; Pawlaczyk-Luszczynska et al., 2014), while the other studies showed that the odds of being annoyed was related to an increase in A-weighted sound pressure level (SPL).

Annoyance is also related to subjective factors such as attitude towards wind turbines, and noise sensitivity. Visual impact has been found to influence annoyance in the two Swedish studies. Pedersen & Waye (2004) revealed that "attitude to the visual impact of wind turbines on the landscape scenery" was a stronger predictor of annoyance than the "general attitude to wind turbines". Pedersen & Waye (2007) pointed out that aesthetics played a role in annoyance by showing that respondents who think of wind turbines as ugly were more likely to feel annoyed. Bakker et al. (2012) also reported a positive correlation between visual perception of wind turbines and the frequency of annoyance. Pedersen and Larsman (2008) further assess the impact of visibility and visual attitude to wind turbines. They concluded that respondents in areas that wind turbines were obvious and contrasting with the landscape more likely to be annoyed than those in areas where wind turbines were not obvious. Annoyance could be linked to visual attitude to wind turbines such as ugly, unnatural, and having a negative impact on the scenery (Pedersen & Larsman, 2008).

Relation between annoyance and wind turbine exposure was also modified by degree of urbanisation, with respondents living in rural areas more likely to report annoyance (Pedersen & Waye, 2007). It was also found that the dose-response relationship between annoyance and noise exposure was not significant among respondents in noisy areas (Bakker et al., 2012). One explanation of the difference between rural and suburban areas was the level of background sound, as well as expectations on the landscape. As Pedersen et al. (2009) argued, “wind turbine noise interfered with personal expectations in a less urbanised area”.

Table 2. 2 Studies investigating the relation between annoyance and wind turbine noise exposure

Study	*Measure*	*Main analysis*	*Results*	*Explanatory variables*
Pedersen & Waye, 2004; N=341 (Sweden)	**5-point verbal scale** 1=do not notice 2=notice but not annoyed 3=slightly annoyed 4=rather annoyed 5=very annoyed ***annoyed=4+5***	Binary multiple logistic regression	**Dose-response relationship:** Odds ratio for being annoyed increase with higher sound category	negative attitude on visual impact (+), negative attitude to WTs (+), sensitivity to noise (+),
Pedersen & Waye, 2007; N=754 (Sweden)	**5-point verbal scale** (Same to *Pedersen & Waye, 2004)*	Binary multiple logistic regression	**Dose-response relationship:** Odds ratio for being annoyed increase with A-weighted SPL	- negative attitude on visual impact (+), negative attitude to WTs (+), sensitivity to noise (+), rural area(+), low background noise (+), visibility (+), renovated the dwelling (+), high

Table 2. 2 Studies investigating the relation between annoyance and wind turbine noise exposure

Study	*Measure*	*Main analysis*	*Results*	*Explanatory variables*
				expectations (-)
Pedersen, 2011; N=1755 (Sweden) *Meta-analysis of 3 previous studies*	**Binary** - annoyed and not annoyed	Binary multiple logistic regression	**Dose-response relationship:** Odds ratio for being annoyed increase with increasing A-weighted SPL	age, sex, economic benefit
Shepherd et al., 2011; N=39+158 (New Zealand)	**7-point scale** (wind turbine noise self-specified by subject)	Not directly tested	WTN perceived as extremely annoying compared to other source	Not directly tested
Bakker et al., 2012; N=725 (The Netherlands)	**a) 5-point verbal scale** *(Same to Pedersen & Waye, 2004)* **b) 0-10 Likert scale** indoors and outdoors	Structural Equation Models (SEM)	**Dose-response relationship:** - between SPLs and annoyance both outdoors and indoors - among subjects in quiet areas, but not in noisy areas	age, economic benefit(-)
Pawlaczyk-Luszczynska et al., 2014; N=156 (Poland)	**5-point verbal scale** 1=not annoying at all, 2=a little annoying 3=rather annoying 4=annoying 5=extremely annoying ***annoyed=3-5***	Binary multiple logistic regression	**Dose-response relationship:** Odds ratio for being annoyed increase with higher sound category	general attitude to wind turbines (+), sensitivity to landscape littering (+), GHQ-12 score (+) Not significant: age, sex

Sleep disturbance

Table 2.3 summarises studies investigating the relationship between sleep disturbance and noise exposure to wind turbines. All studies were based on subjective evaluations of sleep disturbance.

Dose-response relationships have been found between self-reported sleep disturbance and A-weighted noise exposure in the meta-analysis study from Sweden (Pedersen, 2011). However, the meta-analysis indicated that sleep disturbance was not associated with wind turbine noise in the second Swedish study (Pedersen & Waye, 2007), which also included suburban areas with various sound sources.

Sleep quality has been found to be significantly related to the distance to wind turbines in another study (Nissenbaum et al., 2012). The study used two outcome measurements for sleep. One was the Pittsburg Sleep Quality Index (PSQI) collected information on sleep quality averaged over several weeks. The other was the Epworth Sleepiness Scale (ESS) assessed daytime sleepiness from the self-assessed propensity to fall asleep in different situations. The results from multivariate analysis indicated that both PSQI and ESS scores were related to distance from the wind turbines with respondents near to the wind turbine having significantly worse sleep and more daytime sleepiness.

The remaining three studies found significant differences between sleep satisfaction or interruption among high exposure respondents compared to low exposed controls. The sleep of respondents in the New Zealand study (Shepherd et al., 2011) was assessed as sleep satisfaction using the questionnaire of Health Related Quality of Life (HRQOL). The study reported significantly lower sleep satisfaction among the exposed respondents than those in the unexposed control group. Bakker et al. (2012) found that respondents exposed to wind turbine noise higher than 45dBA had a significantly higher frequency of disturbed sleep by sound compared to the low exposure group below 30dBA as controls. Pawlaczyk-Luszczynska et al. (2014) compared the sleep between high and low noise groups and found that the proportion of respondents often suffering from insomnia was significantly higher in the noise category of 40-45dBA than 35-40dBA.

In addition to the effects related to noise levels, associations between sleep and noise annoyance were also found in many studies. Reported sleep disturbance by a noise source was found only associated to annoyance in a previous study (Pedersen & Waye, 2007). In the meta-analysis study of Pedersen (2011), sleep interruption was found to be associated with annoyance and associated even more strongly with annoyance indoors in all three previous studies. The results from the Structural Equation Models in the study of Bakker et al. (2012) showed that among respondents who notice the sound annoyance was the only factor that predicts sleep disturbance. The study from Poland (Pawlaczyk-Luszczynska et al., 2014) also found an association between difficulty with falling asleep and outdoor annoyance.

Furthermore, it has been found that sleep disturbance became more prevalent at 40 and 45dBA. Pedersen (2011) indicated a sharp increase of the sleep interruption around 45dBA. Bakker et al. (2012) reported that the increase of sleep disturbance related to wind turbine noise exposure was only seen at high levels above 45dBA. Pawlaczyk-Luszczynska et al. (2014) found significantly greater proportion of insomnia in the group of 40-45dBA than 35-40dBA. It can be argued that the significant increase in sleep disturbance at 40-45dBA observed in the previous studies is in line with the night noise recommendation by the WHO (2009) of no more than 40dBA at an average.

Table 2. 3 Studies investigating the relation between sleep disturbance and wind turbine noise exposure

Study	*Measure*	*Main analysis*	*Results related to WTN*	*Explanatory variables*
Pedersen, 2011; N=1755 (Sweden) *Meta-analysis of 3 previous studies*	- 2004, 2007: Reported sleep disturbed by any noise source - 2009: sleep disturbance=once a month or more often	Binary logistic regression	**Dose-response relationship:** an association between A-weighted SPL and sleep disturbance in 2004, 2009 (sharp increase around 40 & 45 dBA)	Adjusted for: age, sex, economical benefit
Shepherd et al., 2011; N=39+158 (New Zealand)	Perceived sleep quality in Health Related Quality of Life (HRQOL)	Comparison between exposure and control groups (ANCOVA)	Significantly lower sleep satisfaction in the turbine group than in the control group. *(n: 39 vs 158)*	Not assessed
Bakker et al., 2012; N=725 (The Netherlands)	Frequency of disturbed sleep by sound: - 1=never, 2=at lease	Structural Equation Models (SEM)	- SEM: annoyance is the only factor in the equation that predicts sleep disturbance	Controlled for: age, sex, economical

Table 2. 3 Studies investigating the relation between sleep disturbance and wind turbine noise exposure

Study	*Measure*	*Main analysis*	*Results related to WTN*	*Explanatory variables*
	once a year, 3=at least once a month, 4=at least once a week, 5=daily - **disturbed=3-5**	& Binary logistic regression	- Regression: significantly more disturbance in group >45dBA than <30dBA *(n: 65 vs 185)*	benefit
Nissenbaum et al., 2012; N=79 (USA)	Pittsburgh Sleep Quality Index (PSQI), daytime sleepiness (Epworth Sleepiness Score - ESS)	Multivariate analysis	**Dose-response relationship** (related to distance): - PSQI and ESS both related to log-distance	Controlled for: age, sex, site
Pawlaczyk-Luszczynska et al., 2014; N=156 (Poland)	Insomnia: - 1=never, 2=almost never, 3=several times a year, 4=several times a month, 5=several times a week, 6=everyday, 7=almost everyday - **insomnia=5-7**	Comparison between hight and low exposure groups	Significantly greater proportion of insomnia in the group 40-45 dB than 35-40 dB *(n: 79 vs 60)*	Not assessed

Well-being

Table 2.4 summarises the studies investigating the association between wind turbine noise and well-being. There were two aspects of well-being assessed in the existing field studies. One was assessed as self-reported adverse health problems including chronic illnesses such as diabetes, tinnitus, and cardiovascular diseases, as well as symptoms related to general well-being such as headache, undue tiredness, tensed or stressed, and irritable. The other aspect of well-being was assessed as the score of self-reported quality of life or health status measured by a set of established questions such as health-related quality of life (HRQOL), short form 36 (SF-36) and general health questionnaire (GHQ). It can be seen that more studies of recent years moved the focus of assessment from health-related symptoms to general aspect of well-being in terms of overall quality of life and general health status.

The prevalence of health-related problems was assessed in five studies. The first two studies from Sweden showed that self-reported health problems were not statistically associated with noise levels (Pedersen & Waye, 2004; 2007). Tiredness and tense were positively associated with annoyance (Pedersen & Waye, 2007). The meta-analysis of three field studies further summarised that annoyance was associated with feeling tense or stressed, and irritable in all three studies (Pedersen, 2011). Pawlaczyk-Luszczynska et al. (2014) also found that feeling tense or stressed, dizziness, and headache were significantly related to outdoor annoyance. Pedersen (2011) also found that headache was associated with annoyance in two studies out of three, and undue tiredness was associated with annoyance in only one study. Tinnitus and diabetes were found to be statistically associated with noise levels in one of the three studies, which was not consistent throughout the three studies and was argued by the author as could result from random chance (Pedersen, 2011). Nissenbaum et al. (2012) collected information on psychiatric disorders and medication use of the respondents but the results related to these assessments were not reported. The study did conclude that noise emissions from wind turbines caused impaired mental health and suggest that adverse effects are observed at long distances over 1 km.

Quality of life or health status was measured in four studies using the questionnaire of HRQOL (Shepherd et al., 2011), GHQ (Bakker et al., 2012; Pawlaczyk-Luszczynska et al., 2014), and SF-36v2 (Nissenbaum et al., 2012). The wind turbine exposed group in the study of Shepherd et al. (2011) was reported to have significantly lower physical and environmental HRQOL compared with non-exposed control group. The author suggested that both noise annoyance and sleep disturbance may mediate the relationship between noise and HRQOL. Significantly lower overall quality of life was also observed in the exposed group. Respondents exposed to wind turbine noise were also found to have significantly degraded amenity and to be less satisfied with their living environment compared with the controls. Bakker et al. (2012) assessed psychological distress using GHQ score and found significant associations between wind turbine noise and psychological distress in quiet, and both quiet and noisy areas. The relation between noise exposure and psychological distress was not directly showed in Structural Equation Models (SEM), but was indirectly showed with annoyance as an intermediate variable. It is argued that annoyance was a mediator between sound exposure and psychological distress. Pawlaczyk-Luszczynska et al. (2014) also found a significant correlation between mental health (GHQ score) and annoyance. It should be noted that both mental health measured by GHQ score and self-assessment of physical health were served as explanatory variables in this study, which were found to significantly moderate the relationship between noise exposure and annoyance outdoors. Nissenbaum et al. (2012) reported a dose-response relationship between modelled mental component score of SF36 and the distance to wind turbines. There was no relation found between the distance and the physical component score.

Table 2. 4 Studies investigating quality of life and well-being

Study	*Assessed health-related symptoms*	*Measured quality of life*	*Results*	*Other moderating factors*
Pedersen & Waye, 2004; N=341 (Sweden)	**Chronic illnesses:** (diabetes, tinnitus, cardiovascular diseases, hearing impairment) **General well-being:** (headache, undue tiredness, pain and stiffness, feeling tensed/stressed, irritable)	Not assessed	Not related to WTN	
Pedersen & Waye, 2007; N=754 (Sweden)	**Chronic illnesses:** (diabetes, tinnitus, cardiovascular diseases, hearing impairment) **General well-being:** (headache, undue tiredness, pain and stiffness, feeling tensed/stressed, irritable)	Not assessed	Tired and tense significantly related to annoyance	

Table 2. 4 Studies investigating quality of life and well-being

Study	*Assessed health-related symptoms*	*Measured quality of life*	*Results*	*Other moderating factors*
Pedersen, 2011; N=1755 (Sweden) *Meta-analysis of 3 previous studies*	Chronic disease, diabetes, high blood pressure, tinnitus, cardiovascular diseases, hearing impairment, headache, undue tiredness, feeling tensed/stressed, irritable	Not assessed	- Tinnitus & diabetes significantly related to SPL - Headache, undue tiredness, tense and stressed & irritable significantly related to annoyance	Adjusted for age, sex, economic benefit
Shepherd et al., 2011; N=39+158 (New Zealand)	Not assessed	26-item Health Related Quality of Life **(HRQOL)**: - include physical, psychological, social, environmental HRQOL Self-rated general health and overall quality of life (**WHOQOL-BREF**)	- Significantly lower **physical and environmental HRQOL** in the exposed group - Significantly lower **overall quality of life** in the exposed group - Significantly lower **amenity** in the exposed group	Noise sensitivity is correlated with facets of HRQOL in the exposed group
Bakker et al., 2012; N=725 (The Netherlands)	Not assessed	Psychological distress:12-item General Health Questionnaire (**GHQ)** score	**Dose-response relationship:** - Significant correlation between SPL and the GHQ-score - Not significant in noisy areas - Not significant in Structural Equation Models (SEM) model	Annoyance can be considered as a mediator
Nissenbaum et al., 2012; N=79 (USA)	Psychiatric disorders, Medication use *(Result not reported)*	SF36v2 Mental Component Score (**MCS**) & SF36v2 Physical Component Score (**PCS**)	**Dose-response relationship** (related to distance): - modelled SF36 MSC related to log-distance	
Pawlaczyk-Luszczynska et al., 2014; N=156 (Poland)	**Chronic illnesses** (e.g. cardiovascular diseases, hearing impairment, etc) **General well-being** (e.g. headaches, undue tiredness, stressed, irritable)	Mental health status: 12-item Goldberg General Health Questionnaire (**GHQ-12**) & Self-assessment of physical health	- Mental health status (GHQ-12 score) significantly correlated to annoyance and served as an explanatory variable - Tense/stressed, dizziness, and headache significantly related to outdoor annoyance	Subjects with negative self-assessment of physical health reported symptoms more often

2.4 Discussions

2.4.1 Comparison of the well-being effect of wind turbine noise and other environmental noise

The most investigated non-auditory health endpoints associated to environmental noise exposure are annoyance and sleep disturbance. This is consistent with the studies on wind turbine noise, where the evidence for health effects is strongest for annoyance and sleep disturbance. Based on existing evidence on noise annoyance, dose-response relationships have been derived for exposure to road, railway, aircraft, and wind turbine noise. However, annoyance induced by these noise sources differs at higher exposure levels. It is reported that the annoyance due to wind turbine noise occurs at a relatively lower SPL and increases more rapidly with noise levels compared to other transportation noise. Possible reasons for this difference could be that the low-frequency components make wind turbine noise more annoying and the occurrence of amplitude modulation (AM) further increase the annoyance.

Field studies on wind turbine noise have demonstrated an association between sleep disturbance and noise exposure, which supports the findings from research on other environmental noise. Wind turbine noise has been found to increase the frequency of sleep disturbance when SPL reaches 40 to 45dBA. This is consistent to identified noise levels that affect sleep and the guideline levels of night noise in many European countries. However, unlike the large number of epidemiological studies on traffic and aircraft noise which provide sufficient evidence for a causal relationship between noise exposure and sleep pattern, cross-sectional studies on wind turbine noise do not establish cause. In addition, studies on wind turbine noise so far only use a subjective measurement of the sleep, in terms of self-reported sleep disturbance and self-assessed sleep quality.

Although it has been confirmed that night-time noise exposure of certain intensity may affect self-reported sleep disturbance and quality, it is argued in other environmental noise studies that subjective assessment of sleep quality may differ from objective measurement, which suggests a symptom attribution effect rather than real noise effects. Therefore, the validity of self-reported sleep needs to be considered. Furthermore, environmental noise has been found to affect sleep in various ways not limited to disturbance, including awakenings, change in sleep stages, difficulty in falling sleep, interference on daytime functioning and mood next day. These effects are related to different levels of environmental noise exposure but their relations to wind turbine noise have not been examined in existing studies.

In terms of the effect of noise on other aspect of well-being including health-related problems and health status, long-term exposure to transportation noise has been widely demonstrated to affect the cardiovascular system and cause diseases including hypertension, increased blood pressure, and ischaemic heart disease with supported exposure-response relationships. The noise level required for noise-induced cardiovascular risk for road traffic noise has been suggested as 60-65dBA outdoors during the day. This is argued to exceed the highest wind turbine noise exposure observed in residential areas of around 20dBA. Hence it is not surprising that field studies on wind turbine noise did not find evidence for cardiovascular risks, although symptoms have been reported in various case studies. Recent studies on wind turbine noise have paid more attention to the relationship between noise exposure and mental components of human health. Previous studies on environmental noise also related noise to a number of reported psychological symptoms including depression, nervousness, irritability, tension and edginess, headache, irritability, anxiety and mental instability. Of these symptoms, only tension and stress as well as irritability have been found to be associated with annoyance due to wind turbine noise but not directly related to noise levels. The over-reporting bias raised from interpreting an explicit link between noise and symptoms have been reported for both transportation noise and wind turbine noise studies. Overall, there has been limited evidence for direct association between a noise source and mental health. It is also worth noting that noise annoyance is constantly found to be an important mediator of the relationship between noise and health for both environmental noise and wind turbine noise studies.

There are also many non-acoustical factors identified in the previous studies. The review strongly states that the impact of wind turbine noise has been perceived differently among individuals and generates more debates and defence due to the existence of numerous confounding variables. The health complaints reported in various case studies demonstrate a set of symptoms that claimed to be caused by wind turbine noise. On the other hand, the wind energy authorities insist that wind turbines are quiet and safe. There are also reports focused on public attitude which suggest other factors of influence such as the "NIMBY" effect (not in my back yard) (Wolsink, 2000), fear of wind turbines (Rubin, Burns, & Wessely, 2014), the effect of scaremongers (Chapman & George, 2013), and flickers of the blade (Harding, Harding, & Wilkins, 2008). These studies are not reviewed in the main sections here but it can be seen that a series of non-acoustical factors influence the effects of wind turbine noise on human well-being, which supports the findings of identified non-acoustic factors classified as social, personal, and situational moderators as suggested by Guski (1999), Weinstein (1980), and Fields (1993) in previous socio-acoustic studies on other source of environmental noise. In large field studies on wind turbine noise, the stated modifying factors for noise annoyance include noise sensitivity and attitude, which are consistent with those identified in environmental noise studies. However, studies on other noise sources of environmental noise have controlled for more factors. It is argued that in the existing field studies on wind turbine noise, the explanatory variables included in the analysis are rather limited, which is not adequate to control for the considerable variation of the public.

2.4.2 Limitations of the previous studies

The review states that wind turbine noise is distinct from other environmental noise. Previous studies on wind turbine noise have shown remarkable findings and shed light on further research to investigate the uncertainties. However, it is argued that existing studies have limitations in the following aspects.

Absence of explanatory variables for suburban contexts

Most of the previous field studies are conducted in quiet rural areas. One previous study has found that the effects of environmental noise differ between suburban and rural areas. Disturbance by wind turbine noise has been more frequently reported in quiet rural areas. In densely populated areas with suburban characteristics, the health effect of wind turbine such as on sleep disturbance becomes less significant. However, no firmed explanation has been given in terms of why the effect is less common in suburban areas. It could be due to the influence of other background noise, or due to the lower expectations of quietness in suburban areas compared to the pursuit of tranquillity among rural residents. This can be addressed by modelling the traffic noise exposure and assessing the masking effect of road traffic noise on wind turbine noise evaluations. Another possible explanation could be made on the effect of built environment morphology that may reduce the noise exposure on the receptors' dwellings, such as the shielding effect of adjacent dwellings. In addition, it should be noted that the unique contexts of the suburban areas request more attention to be made on the situational factors that moderate the effect on human well-being. The influence of situational characters has been widely demonstrated in previous studies on traffic noise, including beneficial effects of housing insulation, a quiet facade, and dwelling orientation on reducing noise annoyance. However, these aspects have not been considered in studies of wind turbine noise. These issues warrant further investigation in this thesis within the contexts of urban areas.

The methodological limitations

The survey methods used in the previous field studies are quite varied. However, most of the studies performed to date on wind turbine noise have been cross-sectional, which makes it impossible to assess causality. In some studies, the statistical associations are only visible in some subgroups or use the low noise exposure groups as controls. The effect of wind turbine noise as a continuous variable has not been adequately stated. It is also found that some outcome measurements have been served as explanatory variables in other studies, as there are often alternative explanations for the results, such as noise annoyance might affect health related quality of life (HRQOL), while low HRQOL might also increase noise annoyance. The existence of reverse causality should be noted in statistical significant relationships. It is argued that in further studies, efforts should be made to avoid over-reporting of the relationships. Furthermore, focussing bias might exist in the subjective measurement of outcome variables. Four previous studies use a similar questionnaire to assess the responses of residents to wind turbine noise. Although responses to other environmental stressors are also assessed in the survey which is claimed to mask the purpose of the study, it is argued that the substantial questions on attitudinal and visual aspects of the wind turbine still imply the research topic, in which situation the results could be biased. It is suggested that such bias can be minimised by involving a control group to differentiate the objective impact of wind turbine noise from respondents' subjective perceptions of impact.

2.5 Conclusions

Investigators have gathered substantial data for noise exposures at various distances from the wind turbine and different aspect of well-being of the residents, based on which dose-response relationships were derived between noise and annoyance as well as sleep disturbance. The evidence that wind turbine noise affects other aspects of well-being such as inducing health-related symptoms is relatively poor. However, with more recent studies measuring well-being in terms of general quality of life and health status, statistical associations between wind turbine noise and well-being especially on the performance of mental components have been demonstrated.

It has been found that the findings from wind turbine noise studies well support those reported in the studies on other source of environmental noise. However, wind turbine noise, with large components of low-frequency and infrasonic sound, is more annoying than other transportation noise even at the same sound pressure level. Although several reports have raised concerns that low-frequency sound from wind turbines may lead to various adverse health problems, scientific evidence for the effects on adverse health symptoms has been lacking. Symptoms that reported to be related to low-frequency noise need to be investigated. The review suggests that the reported health effects are more prominent in quiet rural areas compared with suburban areas. Currently no evidence could support the reason of this difference in suburban areas. Taking into account the effect of major traffic noise and architectural factors in urban contexts might help to clarify this uncertainty. At the same time, more moderating variables should be controlled for, as non-auditory health effects of environmental noise might depend on personal factors. Potential focusing bias also exists in field studies including numerous questions on wind turbines, which might have led to over-reported health impacts.

Overall, the most important research gaps that emerged from the literature include the lack of explanatory variables, such as the effect of background noise, architecture, and situational factors. This will be addressed in the thesis by assessing the masking effect of traffic noise and controlling for more architectural and situational variables. The method of asking questions might introduce focusing bias. This will be addressed in the thesis by employing a control group with the research purpose masked, to minimise focusing effect on the effect of wind turbine noise. The thesis will also investigate the well-being impact of noise beyond annoyance and sleep, such as on subjective well-being, and will try to make comparisons with the health and well-being of the general population. Undoubtedly, there is a need for better design of the survey to differentiate the objective impact of wind turbine noise from respondents' subjective perceptions of impact. However, due to research limitations of a cross-sectional study, the thesis will not establish causality, consistent with the previous field studies on wind turbine noise.

Part One: Effects of Urban Morphology on Wind Turbine Noise Exposure

Chapter 3

Methods of Noise-mapping and Validation

3.1 Introduction

The noise mapping technique has been widely used to assess the impact of environment noise across Europe. A noise map can present a geographical distribution of noise in the form of interpolated iso-contours across a spatial area. In this study, the noise mapping technique was used to calculate wind turbine noise exposures in densely built residential areas using the software package CadnaA (DataKustik GmbH, 2006), according to the ISO 9613 (ISO 9613-2, 1996) sound propagation standard. The calculation can take into account the effect of ground, buildings, large water and foliage areas, and the terrain contours. The noise from roads were also calculated to examine the masking effect of major traffic noise.

The calculations using CadnaA for wind turbine noise need to be validated. This is because the accuracy of the ISO 9613 (ISO 9613-2, 1996) sound propagation standard for wind turbine noise across built up environments has not been specified in the literature. While noise mapping by the software CadnaA has been widely used to model noise exposure in residential areas from specific sources such as traffic (Wang & Kang, 2011) and aircraft noise (Hao & Kang, 2014), few studies have applied this technique on wind turbine noise, except a recent study carried out in relatively rural areas with less buildings (Keith et al., 2016). These is a need to verify the noise mapping of wind turbine noise in CadnaA on calculating the noise exposure around buildings at residential areas. More specifically and importantly, the purpose of the validation is to examine the noise distribution at the front and back of the building considering different frequencies, especially low frequencies where the noise of wind turbines is dominant. This is because conventional noise mapping is mainly for traffic noise and low frequency sound propagation around buildings has been paid less attention to. The validation will be carried out by comparing the modelled noise exposure from the software with the measured noise exposure from on-site recordings.

This chapter presents the methods of calculating the wind turbine noise in built-up environments using the noise mapping technique. Section 3.2 shows the calculation settings for the source, obstacles, the receiver, topographical and meteorology parameters, and their guideline standards. Section 3.3 presents the validation of the noise mapping methods. Conclusions are made and shown in Section 3.4.

3.2 Noise Mapping Methods

To simulate the spatial distribution of wind turbine noise levels in built-up environments, noise maps of studied areas were produced using CadnaA. The calculation in the software was based on the ISO 9613 (ISO 9613-2, 1996) 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 (Keith et al., 2016; G. P. Van Den Berg, 2004). 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 (G. P. Van Den Berg, 2004).

In the current study, noise emission from the wind turbine was simulated with generic settings in CadnaA to estimate noise exposures in downwind conditions. According to the IEC 61400-11 standard (IEC 61400-11, 2012), the wind turbine was simulated as a point source at the hub height. The spectra of the point sources were set based on those given by manufacturers of different wind turbine models (Haevernick, 2010; Wico & Saxony, 2005), where the sound pressure levels are normally higher at low-frequencies and attenuate by about 4dB per octave, with an equivalent sound power level of 96-104dBA. The sound power level given by manufacturers were based on different wind speeds. The maximum sound power level was chosen to represent the worst-case output, typically at the wind speed of 8m/s.

The noise mappings in suburban residential areas require detailed data collection and input of the site parameters. The site plan and topographical information were obtained from the EDINA Ordnance Survey Digimaps in the UK (Ordnance Survey, 2013). The contour of the terrain was obtained and input to the CadnaA software, where the heights of sources, shielding objects, and receiver points were all entered as relative values, to the height of the terrain contour. Large water and foliage areas were defined according to Ordnance Survey maps and were taken into account in the calculation. All buildings on the sites were considered in the calculation. The reflection loss of the building was set as 2.0 to represent typical brick houses. Due to the limit of time and expenses, the roof shape and the height of each building was not input based on detailed on-field measuring. As most residential buildings on the study sites were typical 2-storey dwellings, the height of these dwellings was set as 8m, with flat roofs. For several high level social houses, the height was calculated as 3m per storey, multiplied by the observed number of storeys. The uniformed settings of building heights can be argued to not qualitatively differentiate the noise exposures around buildings significantly. A test by CadnaA has confirmed that when the height of the building changed from 6 to 12 meters, the SPL at the receiver at 3 meters behind the building only changed by 3dBA (see Figure 3A.1 in Appendix I).

The ground absorption was set as 0.5 in accordance with the Good Practice Guide in the UK (Cand, Davis, Jordan, Hayes, & Perkins, 2013). Temperature was set to 10 ℃, relative humidity to 70% for atmospheric absorption, consistent with common practice (Keith et al., 2016). The reflection order by buildings was set as 3, based on a previous study calculating urban sound environments(Kang, 2006).

Examples of the noise maps on different suburban layouts are shown in Figure 3.1, which illustrate the graphical distribution of wind turbine noise coloured by SPL levels. A wind turbine was placed at the corner of each site (at the centre of the figure). Assuming such a short source-receiver distance is to examine the tendency of change in an extreme situation, where the colour coding of each 5dBA contour is more obvious.

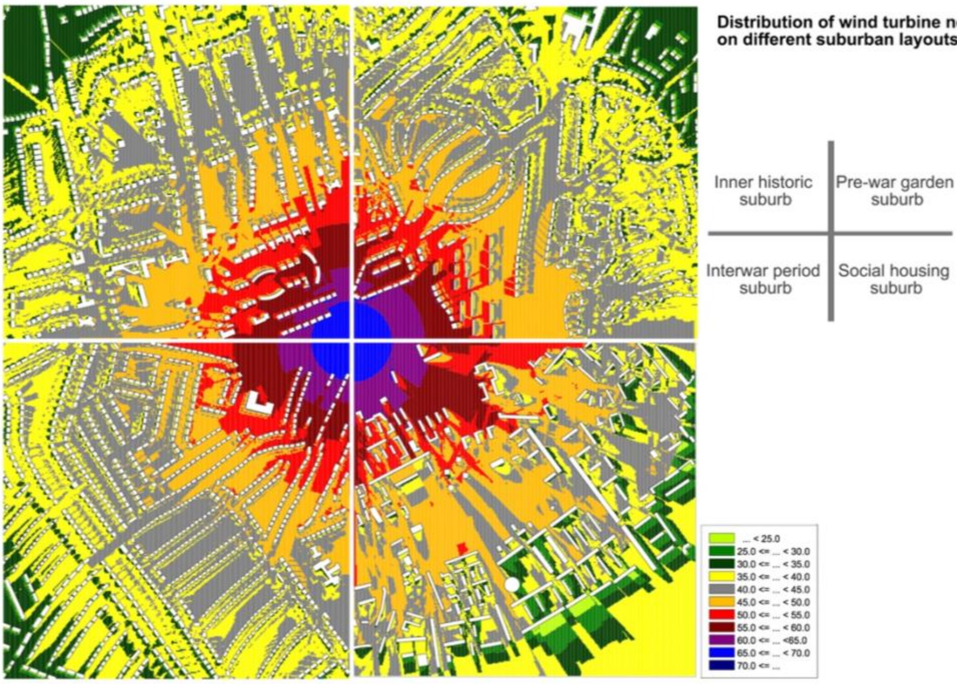


Figure 3. 1 Example of noise maps of wind turbine noise exposure in residential areas

The wind turbine was simulated as a point source at 100m height at the corner of each site, with an A-weighted equivalent sound power level of 100dB. The height and sound power level were set to represent typical modern wind turbines with an output capacity of 2 to 3MW, with the height in the range of 85-110m, and sound power level in the range of 94-104dBA. It can be seen from Figure 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.

The noise exposure at the household level that described the level of wind turbine noise received by the residents were calculated as SPL at the building façades, based on building noise maps using the same software CadnaA (DataKustik GmbH, 2006). The façade exposure in CadnaA was calculated as the noise level at a receiver that is very close to the façade. The façade-receiver distance was set to 0.05m. An example of the building noise map is shown in Figure 3.2. Three indicators of façade exposures were calculated for studied households - the maximum, minimum, and average façade exposures. The "maximum façade exposure", representing the wind turbine noise exposure at the most exposed façade, would rather depend on the source-receiver distance and was less related to the local effect of the building, except in a few cases that the building was fully obstructed by large object nearby. The "minimum façade exposure", representing the quiet façade effect, was the level of exposure at the least exposed façades, following the approaches in previous studies on road traffic noise (de Kluizenaar et al., 2013; Salomons & Berghauser Pont, 2012; Van Renterghem & Botteldooren, 2012). These were usually at the shielded side where the wind turbine noise was most obstructed by the building, hence also represented 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 (Van Renterghem & Botteldooren, 2012). 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. Sound from the wind turbine was also simulated as a single-band source at 50 and 250Hz, and compared with 1000Hz to investigate the effects of built environment morphology on resisting the low frequency component of the sound.

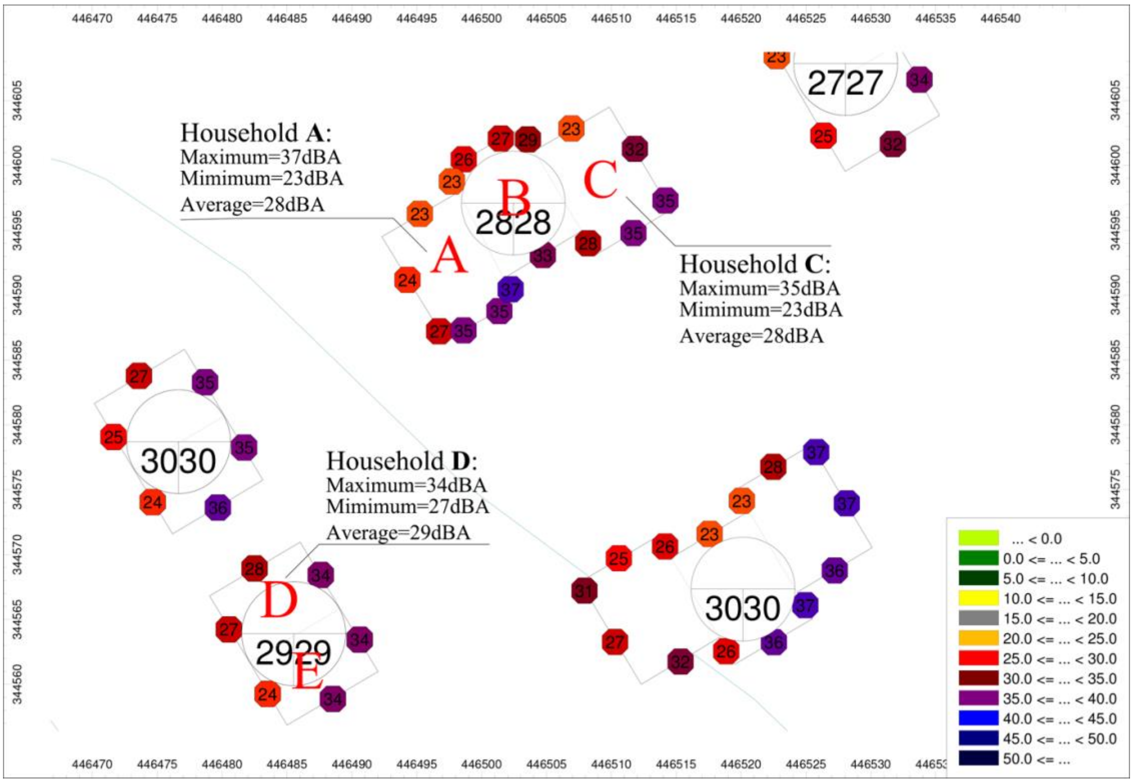


Figure 3. 2 Example of calculated wind turbine noise on studied building façades, with the output maximum, minimum and average façade SPLs for certain household (the wind turbine is located at the south-east direction).

3.3 Validation of Noise Mapping Methods

In this study, the calculations using CadnaA were verified by on-field measurements. In general, the focus of the validation was on relative noise differences around the building, which represents the noise-resisting effect of a building. The following sections state the procedure of the validation. It was designed to verify the calculations in three aspects: (1) The modelled spectra were compared with measured ones in terms of the SPLs at 1/3 octave bands; (2) The modelled effects of the building were examined regarding the spectral noise exposure at the quiet side of the building and (3) the noise attenuation around the building.

Section 3.3.1 introduces the methods of the validation including the studied sites, on-site noise measurement, and noise mapping calculations. Section 3.3.2 presents the validation of noise exposure in terms of the frequency spectra of wind turbine noise, followed by Section 3.3.3 which examines the noise exposure at the quiet side of the building. Section 3.3.4 examines the attenuation of wind turbine noise across a building.

3.3.1 Validation methods

Studied sites

Two wind turbine sites were selected for validation as shown in Table 3.1, each contains a modern wind turbine in an urbanised area. The investigations shown in the table correspond to the three objectives of the validation.

Table 3. 1 Wind farm sites for validation.

Site	*Turbine model*	*Sound power level (dBA)*	*Hub height (m)*	*Investigation*	*Duration and numbers of sound recordings*
A: **Gulliver, Lowestoft** *(Suffolk, East of England)*	Vestas2 NM923 (2.75MW)	105	80	(1) WTN spectrum	30s recording, 4 records
				(2) WTN behind a building	20s recording, 4 records
B: **Newthorpe Sewage Treatment Works** *(Nottinghamshire, England)*	Nordex N100 (3.4MW)	105.5	80	(3) WTN between the front and back of a building	30s recording, 1 record for each pair of points

Measurement methods

And Edirol R-44 Portable Recorder was used to measure the wind turbine noise exposures and record frequency spectra. Two microphones were used to record the sound synchronously when needed. Each microphone was attached to a separate channel on the recorder with a 10m long cable. Both microphones were equipped with windscreens/windshields of a diameter of 100mm which provided sufficient reduction of wind noise in most circumstances.

All the measurements were carried out during summer time with wind speed less than 8m/s. The measuring periods were mainly in the early evening between 8-9pm (as shown in Table 3.1) to avoid the disturbance of significant noise sources such as rush hour traffic and children playing outside. When measuring the noise exposure at specific locations, the microphones were handheld at a height of 1.5m above the ground and faced to the wind turbine. The sound recording for the two microphones were taken synchronously. The objective was to measure wind turbine noise with the lowest levels of background noise, such as road, aircraft, bird, and community noise. This was determined by extended measurements over a long period and choosing valid sound records without other significant noise. On-site calibration was carried out for both microphones and attached cables using an acoustic calibrator of 94dB 1000Hz sound source. The sound records of the calibrator were examined before analysis of measurement data.

Adobe Audition (version CS6) was used to clip each initial measuring record into several 20-30s valid sound records ready for analysis. The analyses of calibration and measurement data were carried out using 01dB software package. Signal analysis was applied for sound record of each channel using dBFA32 to calculate 125ms Leq at broad and narrow band spectra. The analysed file was then opened in dBTRAIT32 to display the sound recording in terms of time history at specific frequency spectrum, which also calibrated the records of both channels compared to a 94dB calibrator.

Modelling methods

Modelling of wind turbine noise to be compared with the measurement were carried out in CadnaA. The settings in the software were in accordance with those presented in Section 3.2. Single frequency calculations were also carried out at 1/3 octave band from 63 to 4kHz. The model did not take into account the variations under different weather conditions and the directionality of wind turbines. As a result, it calculated the maximum noise emission from the wind turbine, representative of the worst condition.

As noise mapping does not take into account complicated atmospheric conditions, some differences between calculated and measured noise exposures are expected. It is worth noting that the methods of validation do not allow judgment on the difference in absolute noise levels between measured and calculated noise exposures. The focus of the validation is on relative differences in receiving areas, especially around buildings. In addition, despite careful selection of clipped sound records, it should be expected that other noise sources can occur during the measurement. The use of L90[1] and Lmin[2] were expected to minimise the influence of other noise sources which could raise the measured noise levels. As wind turbine noise was assumed to work as a relative steady background noise in measured sound environment, where other intrusive noises (bird songs, dog barking, etc) would be above the level of wind turbine noise most of the time.

3.3.2 Comparison between modelled and measured wind turbine spectra

The validation of the wind turbine noise spectra at the receiver point was carried out on Site A, as shown in Table 3.1. The location of the receiver was 150m from the wind turbine with no obstacles in between. Noise exposures at the receiver were recorded and generated into four 30s sound records with minimised interference from other significant noise source. Two descriptors were used in the analysis, which were Lmin and L90. The measured SPLs of all analysed sound records were plotted on specific octave frequencies to be compared with modelled SPLs.

[1] L90 is the sound pressure level exceeded for 90% of the time.
[2] Lmin is the minimum sound pressure level over a time.

Spectral analysis was carried out to compare the modelled and measured noise exposures at the receiver. Figure 3.3 shows the measured and modelled SPLs at specific octave-band frequencies. The 125ms Lmin and L90 at 1/3 octave frequencies from 63 to 4k Hz of the four measured sound records were displayed as grey lines in Figure 3.3. Corresponding modelled SPLs of the receiver at the same frequencies were linked in dotted lines.

Generally, as shown in Figure 3.3, both modelled and measured noise exposures show higher SPLs at low frequencies that decrease gradually to high frequencies. This is in accordance with the spectrum of wind turbine noise indicated in other studies (e.g. Søndergaard et al., 2007). The modelled spectral attenuation from 250 to 4kHz matches the measured one to a large extent. However, the modelling might overestimate the noise at 63 and 125Hz, if compare to the measured level. This might be due to that the studied wind turbine did not achieve its maximum output at low frequencies as given by the manufacturer. This might also because that the measured noise exposure overestimate the noise at mid-high frequencies by taking into account the natural sounds.

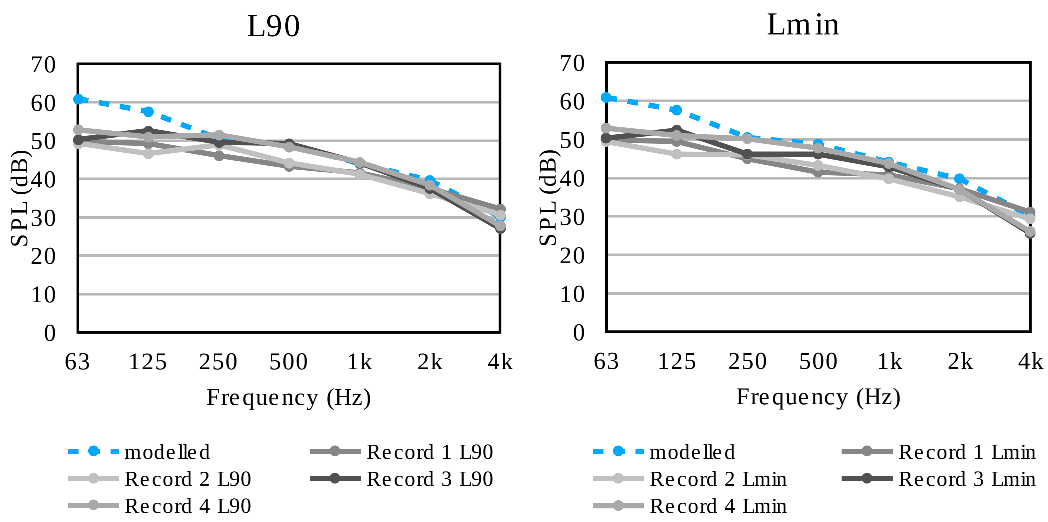


Figure 3. 3 Modelled and measured spectrum noise exposures at the receiver 150m from a wind turbine.

3.3.3 Comparison between modelled and measured wind turbine noise at the quiet side of the building

The building is 135m from the wind turbine shown as site A in Table 3.1. The receiver point is half metre from the back facade and is 140m from the wind turbine. Two sound records of 30s were put into analysis and the spectral distribution of measured L90 and Lmin were obtained and compared with the modelled one, shown in Figure 3.4.

For both L90 and Lmin, the slope of the modelled spectral attenuation at the receiver is larger than the measured one. This is similar to the findings in Section 3.3.2, where the measured spectra are more "flat" than modelled ones. This might imply an underestimation at high frequencies by the noise modelling. However, the difference might also due to the sound measurement, that the existence of higher frequency background noise in the sound records cannot be fully excluded.

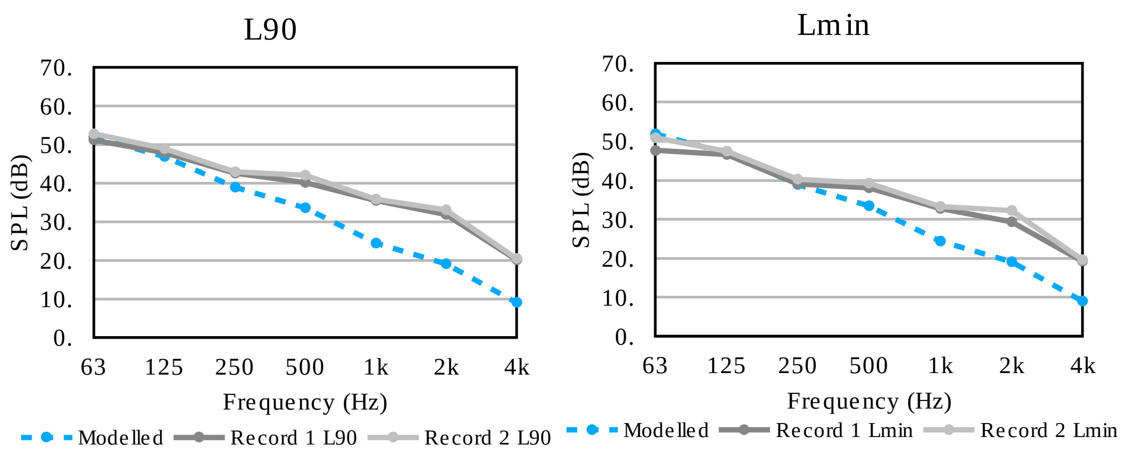


Figure 3. 4 Modelled and measured spectrum noise exposures of the receiver behind a building.

3.3.4 Comparison between modelled and measured noise attenuation across a building

To verify the modelled noise exposure around a building in receiving residential areas, modelled and measured noise attenuation around a building at

600m from the wind turbine were compared. Figure 3.5 illustrates the method of validation. One receiver point was set in front of the building and five receiver points were set behind the building with 4m space in between. The purpose was to examine the calculated difference between the most exposed and least exposure façades of a building and the attenuations among different locations at the quiet side of the building.

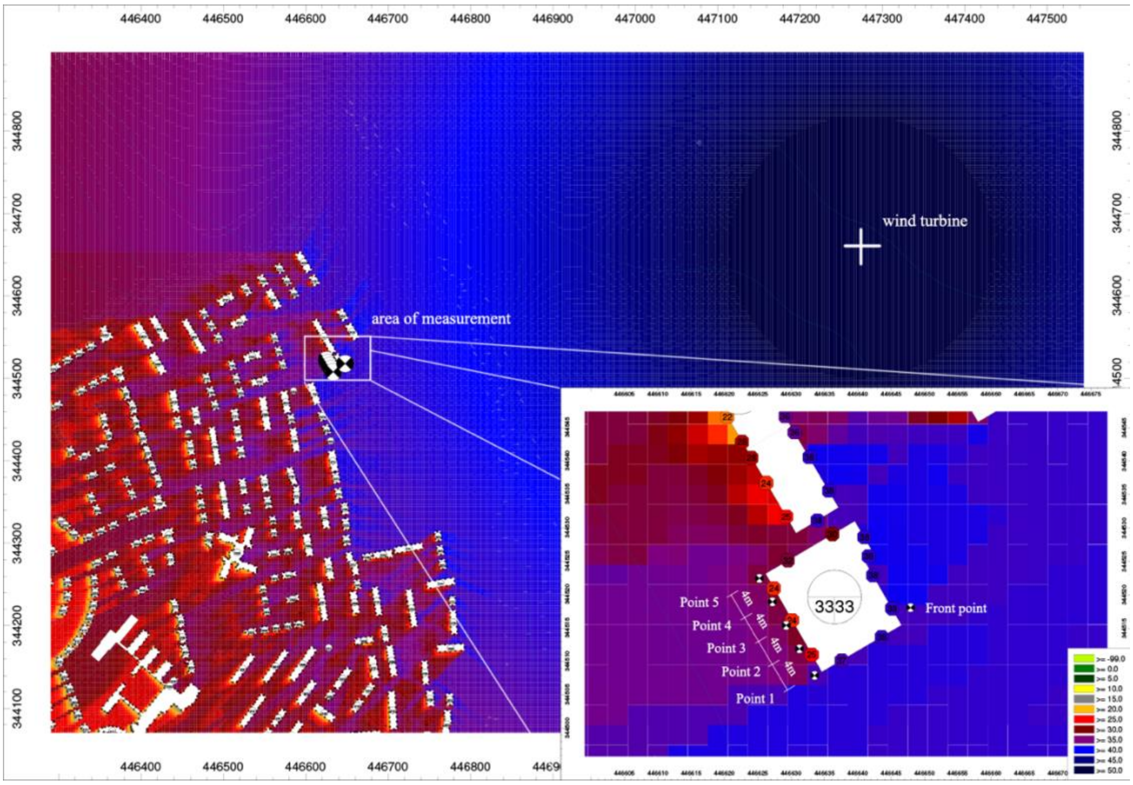


Figure 3. 5 Illustration of the validation on noise attenuation across the building with receiving points around the studied building in site B.

To measure the SPL difference, sound measurement was taken synchronously at front and back of the building with a duration of 30 seconds for each of the five locations. The measured differences in Lmin and L90 between the front and each back receiver point at given frequency were derived from spectral analysis of the sound records. Figure 3.6 shows the difference in measured Lmin between front and back at each receiver for eight frequencies, and Figure 3.7 shows the measured difference using L90. The modelled SPL difference between the front point and each back point at specific frequency is displayed in dotted lines. To make the comparison between modelled and measured differences independent of the absolute noise levels, the measured differences of the five points were shifted to have the same average value with the modelled ones.

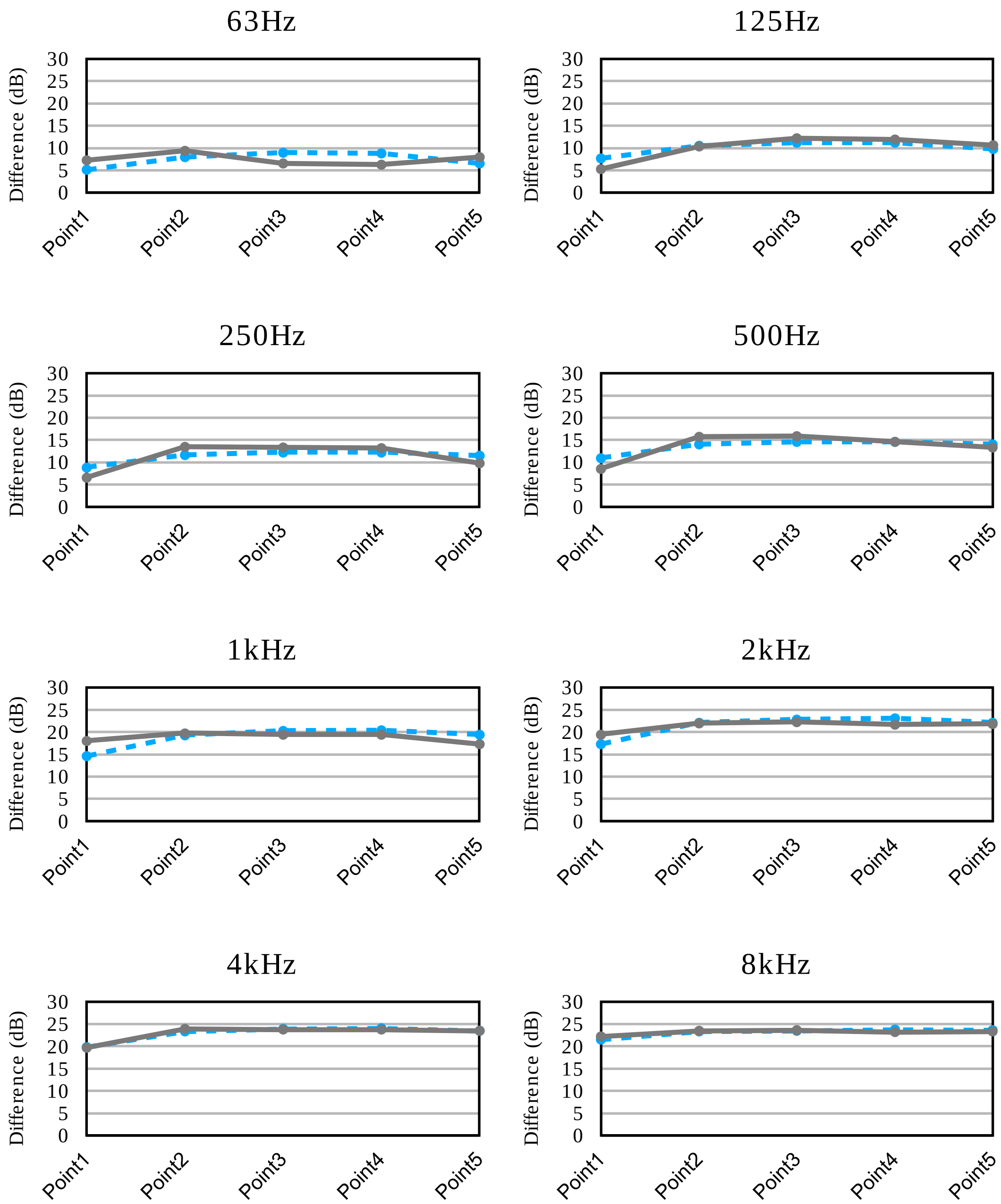


Figure 3. 6 Modelled and measured (Lmin) differences between the front point and each point at the back of a building (dotted line: modelled difference; Grey line: measured difference in Lmin)

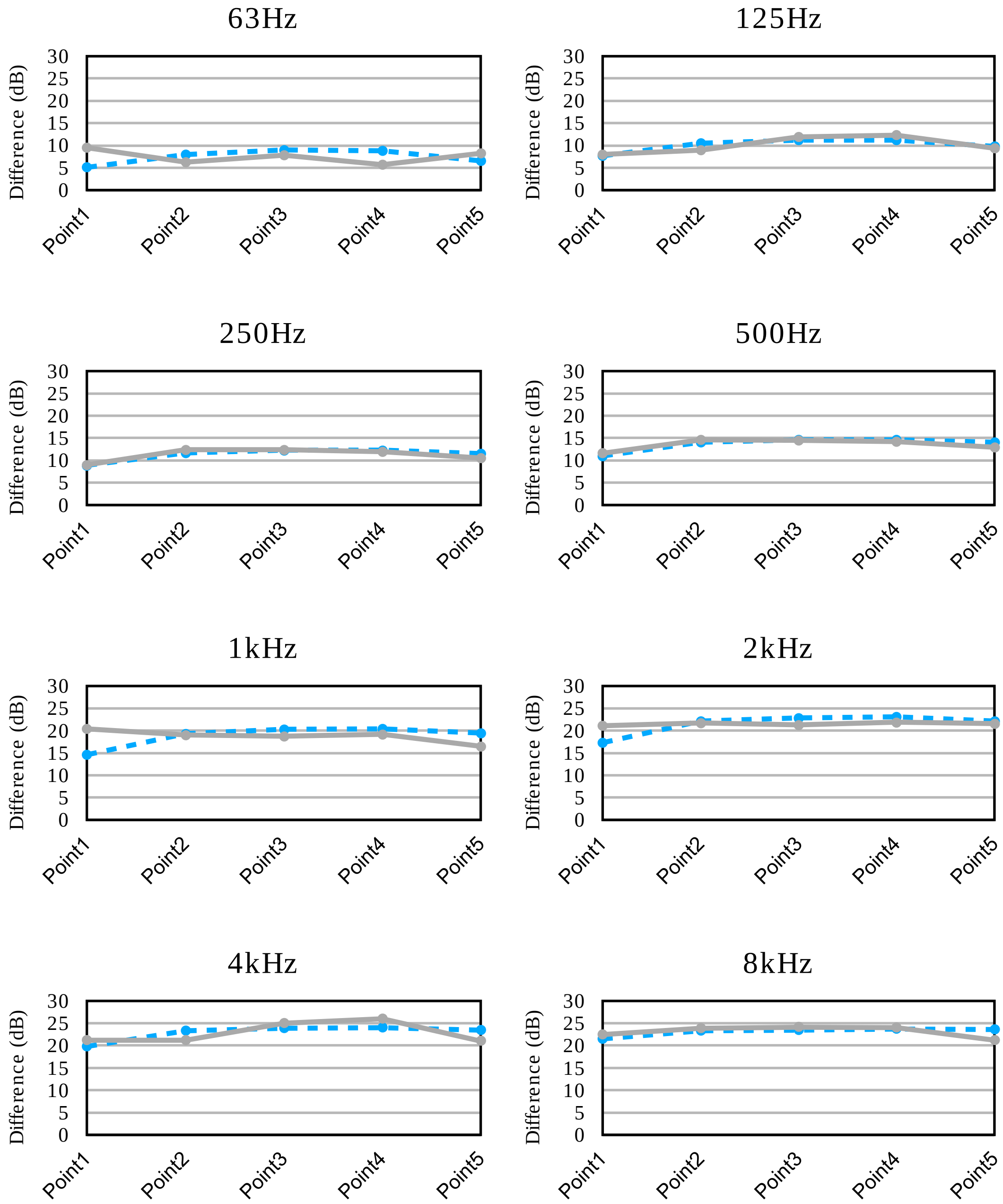


Figure 3. 7 Modelled and measured (L90) differences between the front point and each point at the back of a building

In general, as shown in Figures 3.6 and 3.7, the software model estimates that the receiver point in the middle (Point 3) of the quiet side has the highest difference with the most exposed side at all frequencies and the two points at edge (Points 1 & 5) are less different from the front point. The measured attenuations in Lmin (shown in Figure 3.6) generally agree well with the modelled ones, where the curves of the measured and modelled attenuations are almost overlapped. One exception is at 63Hz, where Point 2 has the highest attenuation and Points 3 and 4 have not attenuated as much as the other points. With the same average value of the five points, the maximum difference between modelled and measured attenuations among the five receiving points is 2.5dB at 63Hz. Overall, the software model better estimates the attenuation among five points at higher frequencies than low frequencies.

As shown in Figure 3.7, the measured differences in L90 are less fit to the modelled ones than Lmin especially at low frequencies such as 63Hz. The difference between the modelled and measured noise attenuations can be up to 5dB at 63Hz even with the same average value of the five points.

To conclude, by examining Figures 3.6 and 3.7 together, the modelled noise attenuation across the building agrees well with the measured one. One exception might be at 63Hz, differences between modelled and measured attenuations exist at Point 1 and Point 5, up to 3.4dB for Lmin and 5.8dB for L90. This might indicate that the software model overestimates the diffraction around the building at 63Hz, which might result in overestimated noise levels at 63Hz modelled at the edge of the quiet façade of the building. However, a 5dB higher low-frequency sound at the edge might hardly influence the minimum façade exposure used to investigate the quiet façade effect on well-being. Overall, the software model provides accurate estimates of the relative noise differences between the most- and least-exposed façades of a building.

3.4 Conclusions

This chapter presented the methods of using noise mapping to calculate the wind turbine noise exposure in built environments. The noise mapping of urban wind turbines using CadnaA enabled the topographical and architectural parameters of the site to be taken into account in the calculation, which largely influence the noise exposure at the receiving areas. Three indicators - the maximum, minimum and average façade SPLs – were chosen to represent the noise level received by the studied household, to cover the large difference between different sides of the building.

The software calculations of the noise exposure from wind turbines have been validated with comparison to on-field measurements. To justify the method of the validation, it should be noted that the validation may not examine the accuracy of absolute noise levels, especially at higher frequencies, where the ever present background noise in the sound records could not be fully excluded. This might explain the finding that the calculated noise exposures at higher frequencies are lower than the measurements. It can be concluded that the software is validated to model wind turbine noise around buildings. The model provides accurate estimate of the relative difference between locations at the most- and least exposed sides of a building, especially at middle-higher frequencies.

Chapter 4

Effects of Built Environment Morphology on Wind Turbine Noise Distribution

4.1 Introduction

This chapter explores the effects of built environment morphology on wind turbine noise distribution in suburban residential areas, which is the objective 1 of the thesis (see Figure 1.3).

It is well known that noise propagation in a densely built residential area is affected by the acoustical effects of absorption, reflection, and shielding from buildings (Attenborough, Li, & Horoshenkov, 2006), which promotes the creation of protected areas or shadow areas in an urban context (Oliveira & Silva, 2011). 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 (Qu & Kang, 2013). However, to date, very little work has been done on the effect of urban morphology on wind turbine noise.

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 (Guedes, Bertoli, & Zannin, 2011; Hao & Kang, 2014; Hao, Kang, & Krijnders, 2015; Silva, Oliveira, & Silva, 2014; Wang & Kang, 2011). Other studies focused 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 (Margaritis & Kang, 2016; Salomons & Berghauser Pont, 2012). 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. 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.

In addition, it is 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 (de Kluizenaar et al., 2013; Öhrström et al., 2006; Van Renterghem & Botteldooren, 2012). However, little has been done to demonstrate the effects of building and site parameters on the distribution of wind turbine noise at the quiet facades.

The aim of this study 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. Noise maps were created on three typical suburban sites in the UK. Five morphological indices were generated. This chapter demonstrates how the changing of a morphological index may reduce the noise level at the least exposed façade and at all façades on average. The relative importance of various morphological indices is examined on different levels of wind turbine proximity and at different sound frequencies.

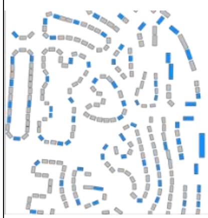
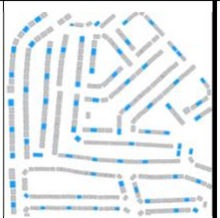
Section 4.2 introduces the methods of the study. Section 4.3 presents the results of the study. Discussions on the noise-resisting effect of morphological indices are presented in Section 4.4, followed by a conclusion on the chapter in Section 4.5.

4.2 Methods

4.2.1 Site selection

The distributions of wind turbine noise were modelled on typical residential areas representing the main categories of residential areas in the UK. Table 4.1 shows the study sites.

Table 4. 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)	Photographs of the sites (source: Google map street views)
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		

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 (Ishugah et al., 2014), the focus of the categorisation was on the suburban residential areas characterised by medium-high 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 (Williams, Joynt, Payne, Hopkins, & Smith, 2012), 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 4.1, 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. The sampling was based on a grid of 8 roles and 9 columns for each site, where the building that at the centre of the cell was chosen, accounting for a total of 72 buildings on each site.

4.2.2 Noise modelling settings

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 (Verheijen, Jabben, Schreurs, & Smith, 2011), 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. Other settings for the noise mapping have been demonstrated in the method chapter (see Section 3.2) and have been verified by on-field measurements (see Section 3.3).

4.2.3 Calculating noise levels at studied dwellings at four source-receiver distance ranges

Noise maps for the sampled sites are shown in Figure 4.1. 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[3], at distances ranging from 50-1700m from the wind turbine, consistent with the distance range attracting most attention in previous socio-acoustic studies (Bakker et al., 2012; Pawlaczyk-Łuszczyńska et al., 2014; Shepherd et al., 2011).

[3] The number of 864 was calculated as follows: 72 (sample buildings on each sites) multiply by 3 (number of sites) multiply by 4 (sets of S-R distances created by four setback distances of the wind turbine).

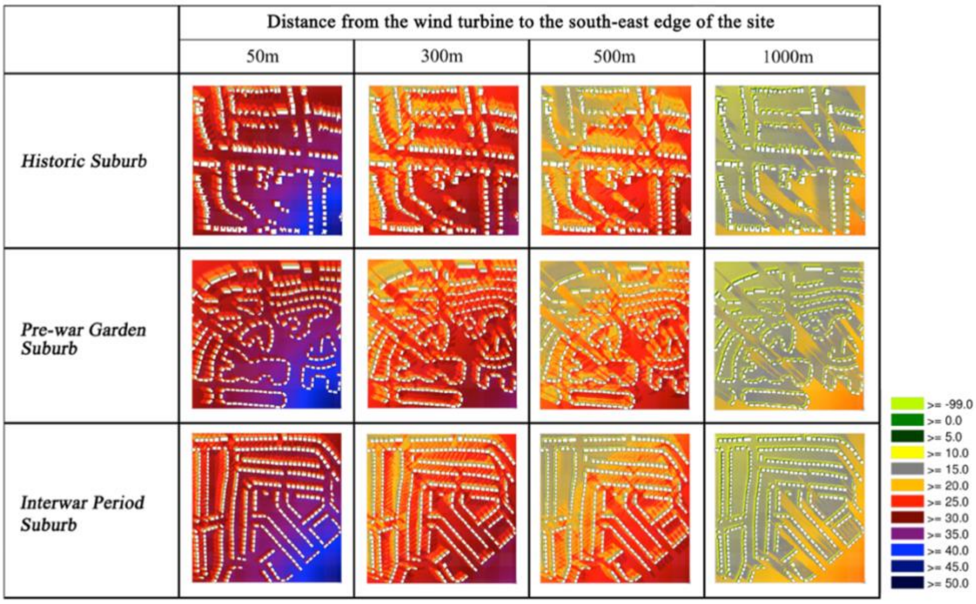


Figure 4. 1 Distribution of wind turbine noise on studied suburban layouts with different setback distances of the wind turbine

It can be seen from Figure 4.1 that in the residential areas, the noise exposure on buildings is affected both by distance attenuation and the morphology of the 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, 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, represented by the maximum, minimum, and average façade exposures (defined in Section 3.2). 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.

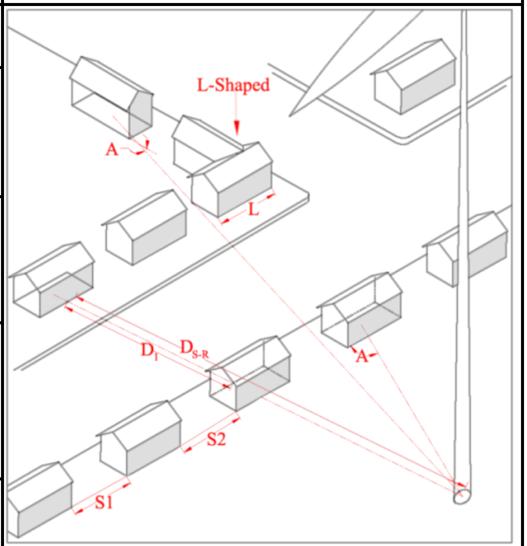
4.2.4 Morphological indices

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 (Hao & Kang, 2014; Hao et al., 2015), 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.

Based on the results of the part 1 study, five indices have been identified, as listed in Table 4.2, which describe the built environment morphology across three scales, each covering: the individual building, the neighbouring buildings, and the source-building.

The indices were chosen due to observed effects on wind turbine noise exposure in generic noise mapping experiments (as shown in Appendix I) and pilot studies (Qu & Kang, 2013, 2014; Qu, Kang, & Tsuchiya, 2015), as well as stated effects on the distribution of other environmental noise (Guedes et al., 2011; Kang, 2006; Silva et al., 2014). 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 4. 2 Studied morphological indices

Key Indices		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.	
Neighbour-hood 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	

4.3 Results

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

Figure 4.2 shows the maximum façade exposure of 864 buildings, plotted along its distance from the wind turbine, colour coded by four setback distances. In the same way, Figures 4.3 and 4.4 show the distributions of minimum and 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, it can be seen that the maximum façade exposure at buildings are similar to those calculated using outdoor propagation models in a free-field, while the minimum and average façade exposures are lower than the outdoor SPLs in a free-field. This finding suggests that the building itself has a considerable resistance effect on wind turbine noise. Moreover, the sound attenuation in built environments is greater than that in a free field. It can be more obviously seen from Figure 4.2 that the maximum façade exposures are scattered above the free-field attenuation curve at small S-R distances and falling below the curve at large distances. It might due to a strong noise reflection at close distance to the wind turbine that has enhanced the noise exposure at the most exposed façade; whilst the buildings far away from the wind turbine are more likely to be obstructed by the buildings in front, which can decrease the maximum façade exposure from the wind turbine. 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 Figures 4.3 and 4.4 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 4.1, 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 Figures 4.3 and 4.4). 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 4.3.2, the effects of the morphological indices will be examined by different S-R distance groups, which are 300-600m, 601-1000m, and over 1000m.

Furthermore, it is worth noting that buildings create up to 19dBA (mean=15dBA) difference between the maximum and minimum façade exposures. The difference is negatively correlated to S-R distance (Pearson's r=-0.213, p=0.000), indicating that buildings near the wind turbine have larger difference between the most and least exposed facades.

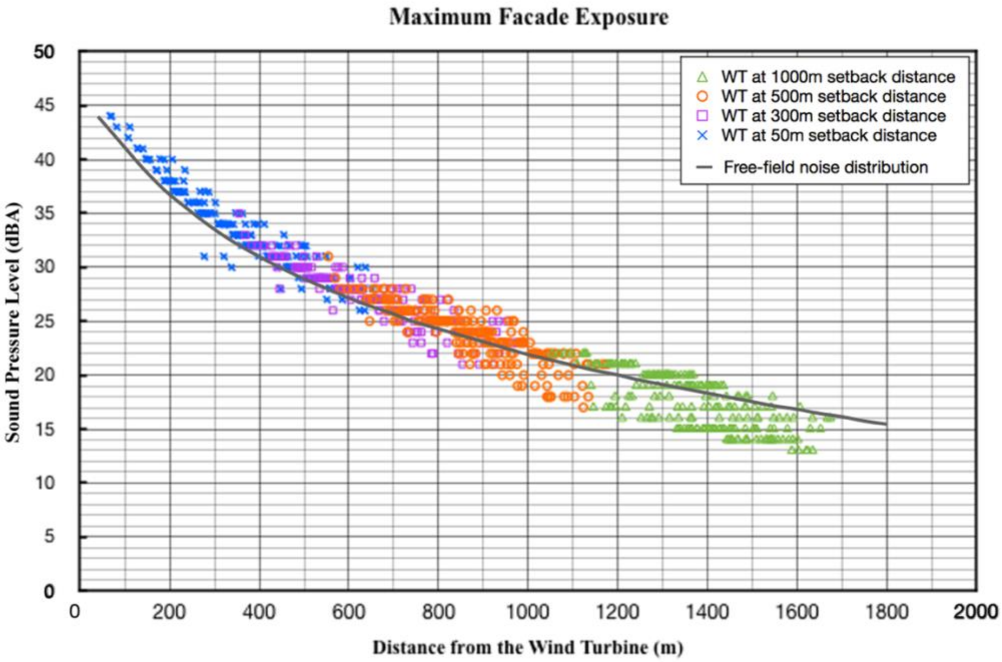


Figure 4. 2 Distance attenuation of the maximum exposure on building façades, where each sampled building has four values based on four setback distances of the wind turbine, which are colour-coded in the figure. N=864.

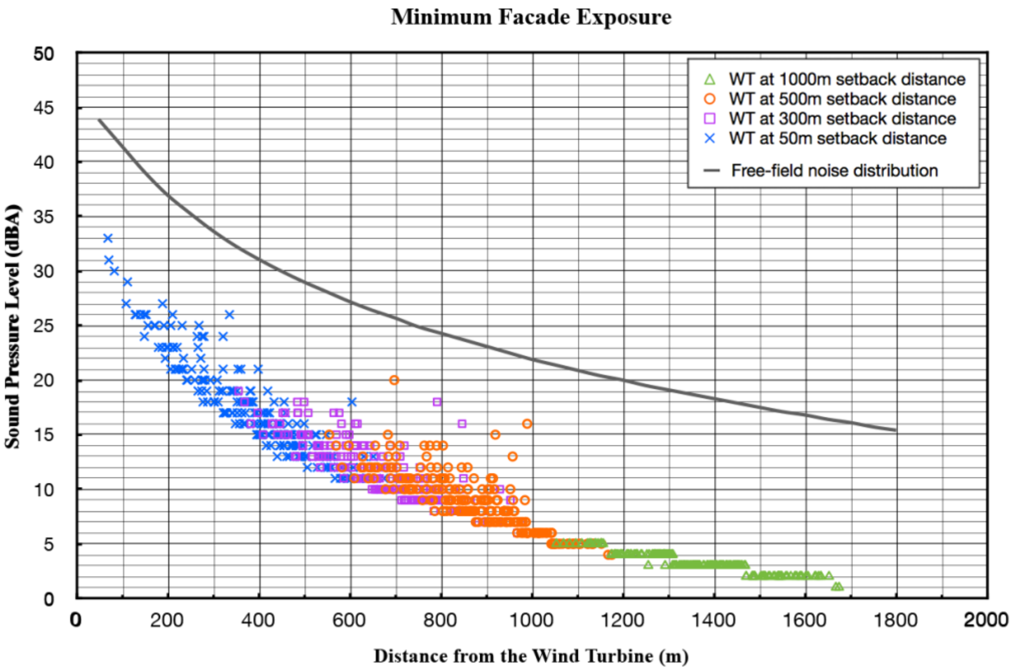


Figure 4. 3 Distance attenuation of the minimum exposure on building façades, where each sampled building has four values based on four setback distances of the wind turbine, which are colour-coded in the figure. N=864.

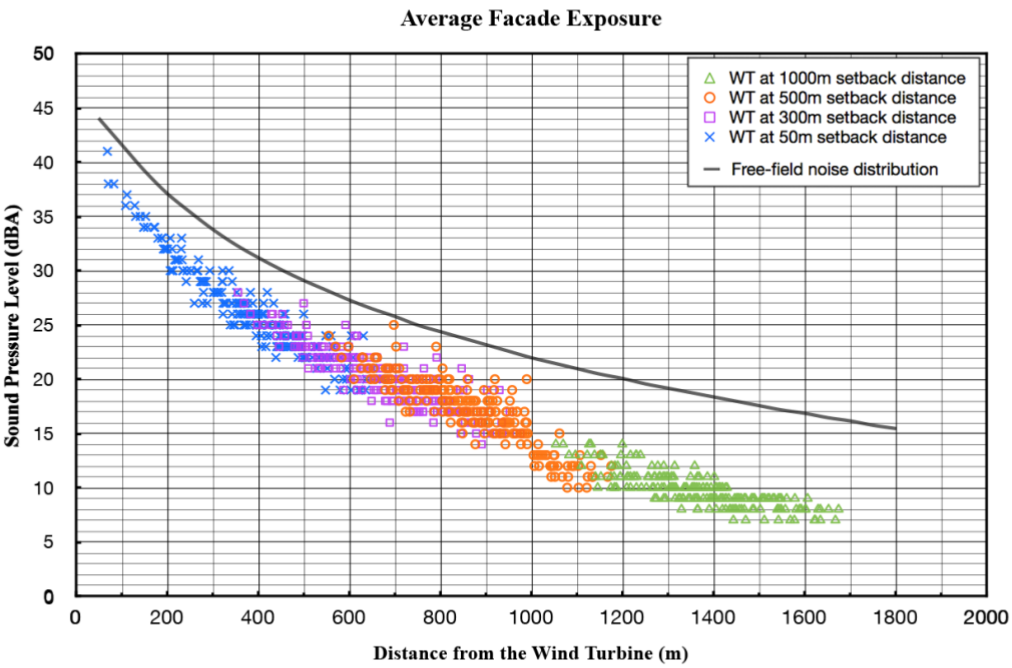


Figure 4. 4 Distance attenuation of the average exposure on building façades, where each sampled building has four values based on four setback distances of the wind turbine, which are colour-coded in the figure. N=864.

4.3.2 Relationship between morphological indices and building façade exposures

Before examining the effects of morphological indices at specific wind turbine proximities, the 864 buildings studied were 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 were 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 4.2) as independent variables. Squared terms were 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 Tables 4.3 and 4.4, respectively.

Table 4. 3 Results of three regressions modelling minimum façade exposure with slope coefficients and significance 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 (1=has U/L/H 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. 4 Results of three regressions modelling average façade exposure with slope coefficients and significance 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 (1=has U/L/H 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

Generally speaking, the 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 4.3 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. "*Shaped 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 4.3 and 4.4. 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.

4.3.3 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 4.5 and Table 4.6, respectively. These are calculated through multiplying the coefficient of each index (shown in Tables 4.3 and 4.4) 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 4.5 and 4.6, 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"* 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 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 4. 5 Estimated noise reduction in minimum façade exposure by 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 4. 6 Estimated noise reduction in average façade exposure by 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

4.3.4 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 among 50, 250 and 1000Hz for the three suburban areas. The wind turbine was placed at 300m from the corner of each studied area along the southeast diagonal of the plan, which was representative of the real sites where the residential areas were within 300-1000m from the wind turbine. Within this distance range, the noise impact of the low-frequency noise from the turbine has received wide attention (Hayes, 2007). The results of the OLS regressions of minimum and average exposures are shown in Tables 4.7 and 4.8, respectively, where estimated noise reduction is also shown, using the methods described in section 4.3.3.

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 4.7, 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.

Table 4. 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 Facade Exposure**		
		50Hz	250Hz	1000Hz
	S-R Distance	-.017***	-.015***	-.012***
Individual building scale:	**Length** (L)	-.066*** (-3.3dB)	-.024* (-1.2dB)	-.020
	Shaped layout (1=has U/L/H 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 4. 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 Facade 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;

4.4 Discussions

The study used 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 put emphasis on the noise exposure at the least exposed façade (minimum façade exposure), which has been found to be largely governed by built environmental morphology. Noise resistance effects of key morphological indices have been revealed and compared using statistical analysis. The conclusions can be summarised as follows:

4.4.1 Noise-resistance of built environment morphology for wind turbine noise

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 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 exposed 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 (Öhrström et al., 2006). 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 (de Kluizenaar et al., 2013) and leads to lower annoyance (Van Renterghem & Botteldooren, 2012). 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.

4.4.2 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 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 (Silva et al., 2014). 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 (Hao & Kang, 2014; Hao et al., 2015).

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.

4.4.3 Practical suggestions for design

The results presented here 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.

4.5 Conclusions

This chapter examined the effects of built environment morphology on wind turbine noise distribution. 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. It has been demonstrated that built environment morphology creates large variations of noise levels (up to 10dBA) around dwellings at the same source-receiver distance. Urban morphology – such as the orientation, shape, and length of the building, as well as the spacing between adjacent buildings – can largely influence localised noise exposure on and around receptors' building façades. Noise reduction levels of above morphological indices were given in terms of resisting wind turbine noise on the least-exposed façade and on all façades as an average. Among the five indices, building orientation was found to be most effective in resisting the noise exposure at quiet façades, followed by the length and shape of the building. The noise resistance effects varied by different S-R distances and differ by frequency. Four morphological indices were found to be effective in resisting noise at low frequencies, typically at 50Hz.

Part Two: Impact of Wind Turbine Noise Exposure on Human Well-being

Chapter 5

Methods of the Survey Study

5.1 Introduction

This chapter presents the methods of the survey study on the relationship between wind turbine noise and well-being, which is the method of objective 2 shown in Figure 1.3.

As shown in the review chapter (Chapter 2), potential adverse impacts of wind turbine noise have attracted substantial attention. Previous studies have found a dose-response relationship between wind turbine noise exposure and annoyance, sleep disturbance, and adverse health problems such as tension and stress. Other health-related effects such as psychological distress were found to be associated with wind turbine noise with noise annoyance as a mediator.

However, previous studies on wind turbine noise provide limited statistical evidence for the link between noise and adverse health problems other than annoyance, such as headache, cardiovascular diseases, tension, or stress. Shepherd et al. (2011) and Bakker et al. (2012) have argued that the problem might be due to the lack of main explanatory variables that moderate the effect of noise. It is also found that the effect of architectural factors has not been explored in previous studies, which has been widely demonstrated in studies on traffic noise (e.g. Orhstrom, 2006; Bluhm et al., 2004) and has been reported to affect the distribution of wind turbine noise in built-up areas in Chapter 4.

Furthermore, previous studies normally use a standard questionnaire with the assessment of living environment to assess the resident's response to wind turbine noise (Pawlaczyk-Łuszczyńska et al., 2014; Pedersen et al., 2009; Pedersen & Waye, 2004, 2007). Therefore, it may have been clear to the respondents that the purpose of the questionnaire was to investigate potential adverse health effects of wind turbines (Nissenbaum et al., 2012), and if so, such questionnaires may be susceptible to a focusing bias (Ubel et al., 2011; Wilson, Wheatley, Meyers, Gilbert, & Axsom, 2000), where the questions lead the respondents to pay more attention than they usually do to the noise, and thus answer differently. A related issue concerns attribution: surveys may ask respondents to specify the cause of any health problems, but perceived causes are not necessarily the actual causes of health problems.

Therefore, these is a need for questionnaires designed to take into account a wider range of factors and possible focusing bias and respondent attribution.

Aims and objectives of the survey

The aim of the questionnaire is to elicit the respondent's evaluation of various environmental noise including wind turbine noise; their self-reported sleep disturbance, health symptoms, general health and subjective well-being; and key features of their residence. Efforts were also made, to compare the well-being of people in this study to those of previous national surveys.

This survey had the following objectives:

Objective 1: To measure local resident's evaluation on wind turbine noise, self-reported sleep disturbance, the prevalence of health symptoms, self-reported general health, and their subjective well-being.

Objective 2: To assess the possible effect of modelled wind turbine noise levels at dwellings on resident's noise evaluation, and their health and subjective well-being.

Objective 3: To understand the impact of demographic, attitudinal, architectural, and situational factors interacting in this process.

Objective 4: To compare the well-being of the sample living near wind turbine(s) in this study with those of the general population with similar background characteristics reported in large scale national health surveys.

The following sections of this chapter report the final version of the questionnaire, which was based on a literature review, item design, piloting, and revision. A complete description of the questionnaire design stages, including the changes at each stage, is available from the author on request.

5.2 Questionnaire Variants

The survey is designed to measure the effects of wind turbine noise on human well-being among people who live near wind turbines. In order to minimise the potential bias caused by focusing effects, two variants of the questionnaire are designed. The main, "Questionnaire Variant 1", includes explicit questions on the impacts of the local wind turbines on the respondent's well-being, such as: rating their general health and well-being given wind turbine noise; reporting annoyance by environmental nuisances including wind turbine noise; identifying health problems they experience that may be caused by wind turbine noise; describing the sound of wind turbines; and indicating their attitudes to wind turbines. Some of the questions allow respondents to attribute well-being concerns they have to the presence of the local wind power project. A separate control group variant, "Questionnaire Variant 2", focuses on well-being and health, but without associations to wind turbines. There are no references to wind turbines, except in one question on noticeability of and annoyance with various environmental nuisances including wind turbine noise. All other questions that do not mention wind turbines are identical across the two Variants.

5.3 Questionnaire Themes and Variables

The design of the questions was guided by the relationships between well-being and wind turbine noise derived from the literature review (reported in Chapter 2 above), as well as proposed non-acoustical factors that related to noise evaluation and human well-being. The themes and variables addressed in the survey are shown in Table 5.1, grouped by themes. As indicated, all the variables are included in Variant 1, but not necessarily in Variant 2.

Table 5. 1 Questionnaire themes and variables

Themes	Variables	Question in Variant 1	Question in Variant 2
Outcome variables:			
1. Subjective evaluations on WTN	Notice and annoyance of environmental nuisances (e.g. Odor, neighbourhood noise, traffic noise, bugs, pollution, etc. including WTN)	Q5	Q5
	WTN annoyance (verbal scale)	Q9	Not included
	WTN annoyance (numeric scale)	Q10	Not included
	Response to WTN in different situations	Q13	Not included
	Perceived sound characteristics of WTN	Q14	Not included
2. Health problems	Sleep disturbance	Q4	Q4
	Perceived health impact of wind turbines	Q11	Not included
	Adverse health problems (physiological and psychological distress)	Q12 (**with** WTN as a possible cause)	Q9 (**without** reference to possible causes)
3. Subjective well-being	Happiness	Q1	Q1
	General health	Q2	Q2
	Satisfaction with life	Q3	Q3
Moderating variables:			
4. Demographics	Age, gender, employment long standing illness, educational qualification, marital status, household income	Q17-23	Q10-16
5. Personal/ attitudinal factors	Sensitivity and coping with environmental noise	Q6	Q6
	Attitude to environmental sustainability	Q7	Q7
	Attitude to wind turbines	Q15	Not included
	Financial stake in the wind farm	Q16	Not included
	Evaluation of overall sound environment	Q8	Q8
6. Architectural factors	Number of bedrooms	Q24	Q17
	Type of dwelling	Q25	Q18
	Orientation of dwelling	Q26	Q19
7. Residential factors	Visibility of wind turbine	Q27	Not included
	Length of residency	Q28	Q20
	Time spent indoors and outdoors everyday	Q29	Q21
	Ownership of the accommodation	Q30	Q22
	Double-glazed or sound-proofed windows	Q31	Q23

5.3.1 Outcome variables

To assess the potential impact of wind turbine noise on health and well-being, the questionnaire assessed respondent's subjective evaluation on wind turbine noise, their self-reported health problems and subjective well-being. As shown in Table 5.1, the respondent's evaluation on wind turbine noise is explored across four questions focused on annoyance. One question assesses how residents perceive and describe the sound characters of the noise, such as "swishing" and "pulsating".

The potential adverse health impacts of wind turbine noise were examined in four questions. These invited self-reports on the occurrence of sleep disturbance; perceived health impact of wind turbine noise; the prevalence of health-related problems; and general health.

Furthermore, the questionnaire asked two questions on subjective well-being, namely, self-reported happiness and satisfaction with various aspects of life.

5.3.2 Moderating variables

It is well-known that human reactions to noise also depend on a series of non-acoustical factors, which are termed as moderating variables[4] and were included in the survey. As shown in Table 5.1, moderating variables included in the questionnaire are categorised as demographic, personal/attitudinal, architectural, and residential factors.

Firstly, questions on demographical factors such as age, sex, and employment that are hypothesised to influence noise annoyance are asked. Variables such as longstanding illness, marital status and income are also added, which have been reported to be important determinants of subjective well-being (Dolan et al., 2008). The majority of questions are drawn from national surveys such as

[4] Moderating factors include variables that both positively and negatively associated with noise evaluations.

Understanding Society which enabled comparison of the well-being between the sample and national population controlling for identical sociodemographic measurements.

In addition, questions addressing personal noise sensitivity and attitude to the noise source were added, which had been demonstrated as important confounders of human reaction to noise in various socio-acoustic studies. Noise sensitivity was measured in one question with two items drawn from the established 21-items noise sensitivity questionnaire (Weinstein, 1978), shortened in line with findings of another study which tested the possibility of using a short version to assess individual noise sensitivity (Benfield et al., 2014). Belief that the noise source is important was found to decrease annoyance (Fields, 1993). This aspect was included in this survey with a question inviting resident's attitude to environmental sustainability, adapted from two questions in the British Household Panel Survey (BHPS, Brice, Nick, & Elaine, 1993). Respondents' attitudes to wind turbines were assessed using four pairs of antonyms describing wind turbines taken from previous studies (Pedersen & Waye 2004). There was a question to identify respondents with a financial stake in the wind farm, as this had been shown to be significantly negatively associated with annoyance with wind turbine noise (Pedersen et al. 2009).

Furthermore, the questionnaire included questions on architectural features of the respondent's residence, which have not been explored in the context of wind turbine noise. The effects of the architectural features of dwellings, such as having access to the quiet side of the dwelling, orientation of the dwelling, and housing types, in the context of exposure to traffic noise were demonstrated in a number of earlier studies (Öhrström et al. 2006). In this questionnaire, three questions on architectural factors asked about the number of bedrooms in the dwelling, and the type and orientation of the dwelling to identify the morphology of the building, which had been found to have effects on resisting the wind turbine noise in Chapter 4.

Finally, residential variables measured other variables associated with the respondent's relationship with their home. Among these variables, visibility was the factor that had most frequently been demonstrated to increase annoyance with wind turbine noise. Length of residency establisheed whether the respondent moved in before or after the wind turbine became operational. Time spent indoors and outdoors everyday collected information on the number of hours the respondent typically spent inside and around the house through their daily life.

5.4 Specific Questions and Response Items

Table 5.2 documents all the questions including their response items and scales. If the question was drawn from other established surveys, the source is given. Examples of the printed questionnaires are shown in Appendix II.

Table 5. 2 Questionnaire documentation

Domain	variant 1	variant 2	Variable	Question	Items/sub-questions	options/scales	Source/Reference
Well-being and Health	Q1	Q1	**Happiness**	**Taking all things together, on a scale of 0 to 10, how happy would you say you are? Here 0 means you are very unhappy and 10 means you are very happy.**		Very unhappy - Very happy, 11 scales (0-10)	Drawn from HSE 2010
	Q2	Q2	**General health**	**In general, would you say your health is...**		Excellent, Very good, Good, Fair, Poor	Drawn from Understanding Society (W4_individual questionnaire_general health module_SF1_SF12)
	Q3	Q3	**Satisfaction of life**	**Here are some statements on how you feel about your life. Please tick the box which you feel best describes how dissatisfied or satisfied you are with the following aspects of your current situation.**	a) Your life overall b) Your health c) Your household income d) Your social life e) Your living environment	Not satisfied at all - Completely satisfied, 7 scales	Drawn from Understanding Society & BHPS a):Sclfsat0; b):Sclfsat1; c): Sclfsat2; d): BHPS_RLFSAT6; e): BHPS_RLFSAT3
	Q4	Q4	**Sleep disturbance**	**Please choose ALL the statement(s) which describe your sleep.**	a) My sleep is not disturbed at all. b) It's hard for me to fall asleep. c) I sleep less deeply than I would like. d) I occasionally wake up but I soon go back to sleep. e) I often lie awake for a while. f) I have to take sleeping pills to fall asleep.		Adapted from Heathrow Second Survey of aircraft noise annoyance around London Heathrow airport (McKennel, 1979) also similar to Understanding Society_PQSI: b)_cannot get to sleep within 30mins:Tslp_30m; d)_wake-up in the night: Tslp_wak; e):Tsta_awk; f): Med_slp,
Evaluation of Environment	Q5	Q5	**Environmental nuisances**	**The following are several things that might exist in people's living environment. Please state for each thing of the below, whether you notice them and if so, whether you are annoyed by them when you spend time at home.**	a) unpleasant odor from outside b) noise from neighbours c) traffic noise d) noise from wind turbines e) other noise sources (please specify) f) bugs, pests or vermin g) vibration of the building h) pollution, grime or dust	1: notice? No, Yes, Don't know 2: If you notice, do you find it annoying? Not at all - Extremely, 5 scales	b, c, h adapted from BHPS_w18_H44 a, d, f f adapted rom Pedersen and Waye 2004
	Q6	Q6	**Sensitivity**	**In terms of environmental noise, how much do you agree or disagree with the following statements?**	a) I find it hard to relax in a place that's noisy. b) I get used to most noises without much difficulty.	Agree strongly - Disagree strongly, 6 scales	Adapted from "Testing noise in the field: a brief measure of individual noise sensitivity." (Benfield et al., 2012).

Domain	variant 1	variant 2	Variable	Question	Items/sub-questions	options/scales	Source/Reference
	Q7	Q7	**Sustainability**	**What are your views on environmental sustainability?**	a) The environmental sustainability is a low priority for me compared with a lot of other things in my life. b) I personally need to change my way of life so that future generations can continue to enjoy a good quality of life and environment.	Agree strongly - Disagree strongly, 6 scales	a: Adapted from BHPS_w18_RV108 (5-point scale) b: Adapted from BHPS_w18_questionnaire_Q7 (4-point-scale)
	Q8	Q8	**Sound environment**	**How do you evaluate the overall sound environment at your dwelling?**	a) quiet - loud b) interesting - boring c) pleasant - unpleasant d) continuous - discontinuous e) predictable - chaotic f) calming - agitating g) directional - everywhere h) natural - artificial	very, fairly, little, neutral, little, fairly, very	Adapted from soundscape evaluation form: "Semantic differential analysis of the soundscape in urban open public spaces" (Kang & Zhang, 2009)
Evaluation of Wind Turbine Noise (WTN)	Q9	Not included	**WTN annoyance (verbal)**	**Thinking about the last 12 months, when you are at home, how much does noise from wind turbines bother, disturb or annoy you?**		a) not at all b) slightly c) moderately d) very e) extremely	Drawn from ISO/TS 15666 Acoustics - Assessment of noise annoyance by means of social and socio-acoustic surveys
	Q10	Not included	**WTN annoyance (scale)**	**Thinking about the last 12 months, what number from 0 to 10 best shows how much you are bothered, disturbed or annoyed by wind turbine noise when you spend time *outdoors* and *indoors* at your dwelling?**	a) outdoors at your dwelling b) indoors in your dwelling	Not at all - Extremely, 11 scales (0-10)	Adapted from ISO/TS 15666 Acoustics - Assessment of noise annoyance by means of social and socio-acoustic surveys (add indoors and outdoors)
	Q11	Not included	**Perceived health impact**	**Would you say that the wind turbine noise has any effect on your health?**		a) No, not at all b) Yes, some of the time c) Yes, most of the time d) I don't know	Adapted from "Second survey of aircraft noise annoyance around London (Heathrow) airport" (McKennel, 1979)
	Q12	Q9 (symptoms/ disease only)	**Health problems**	**Did you experience any of the below during the past week? Please indicate whether you consider it to be caused by wind turbine noise.**	a) Headache b) Nausea c) Dizziness d) Ear discomfort e) Cardiovascular disease f) Stress g) Tension and edginess h) Difficulty in intellectual activities i) Mood swings j) Lack of concentration k) Other (please specify)	1: experienced any? - not at all, some of the time, all the time 2: Feel like it's caused by wind turbine noise? - Yes, possibly, no, I don't know	Newly created. g) Tension and edginess (Tense and edgy): from Heathrow Second Survey of aircraft noise annoyance around London Heathrow airport (McKennel, 1979) Others: impact of low frequency noise and infrasound (Hansen, 2007)

Domain	variant 1	variant 2	Variable	Question	Items/sub-questions	options/scales	Source/Reference
	Q13	Not included	WTN in different situations	**When you are at home, do you notice the noise from wind turbine(s) in each of the following situations? If you do, how much does it annoy you?**	a) When the wind is strong b) When you are inside your room with windows closed c) when these is heavy traffic flow outside your dwelling d) when at night	1: Notice? No, Yes, Don't know 2: Annoying? Not at all - Extremely, 5 scales	Newly created. a): Pedersen & Waye 2004; Pedersen et al., 2009; Pawlaczyk-Luszczynska et al., 2014. b): Pawlaczyk-Luszczynska et al., 2014. c): Pedersen & Persson Waye, 2004; Bakker et al., 2012. d): Pedersen & Persson Waye, 2004; Pedersen et al., 2009;
	Q14	Not included	Sound characteristics	**How would you describe the sound of the wind turbine(s)? Please choose ALL that apply.**	a) noiseless / quiet b) swishing c) beating d) wooshing e) whistling f) pulsating g) throbbing h) other (please specify)		Newly created. Swishing related to 2k-4k Hz, correlated to annoyance: Pedersen & Persson Waye, 2004. Whistling, throbbing: Pedersen et al., 2009 Beating, pulsating being indicative of AM: Moorhouse et al., 2007; Beating, pulsating at night & more annoying: van den Berg, 2004b
	Q15	Not included	Attitude to WT	**Please mark ALL the adjectives that you think are applicable to wind turbines:**	7 polarised items: a) environment-friendly b) not environment-friendly c) efficient d) inefficient e) dangerous f) harmless g) unnecessary h) necessary i) ugly j) pretty k) attractive/inviting l) threatening m) natural/green n) unnatural o) other (please specify)		Adapted from Pedersen & Persson Waye (2004) - eight polarised items (developed by Karin Hammarlund)
	Q16	Not included	Financial stake	**Do you or your family have a financial stake in the wind farm?**	a) joint owner / employee b) receive compensation / benefits c/ other (please specify)	1: You - yes, no 2: your family: - yes, no, I don't know	Adapted from Pedersen, 2011; Bakker et al., 2012.

Domain	variant 1	variant 2	Variable	Question	Items/sub-questions	options/scales	Source/Reference
Demographics	Q17	Q10	**Age**	**Your age in years:**			Drawn from HSE
	Q18	Q11	**Gender**	**Your gender**	a) male b) female		Drawn from HSE
	Q19	Q12	**Employment Status**	**Please indicate which one best describes your current situation.**	a) In full-time employment / self-employed b) In part-time employment / self-employed c) In full-time education d) On a training scheme e) Retired f) On maternity leave g) Looking after family or home h) Other (please specify)		Drawn from Understanding society
	Q20	Q13	**Illness**	**Are you suffering from any long-standing illness, disability or infirmity?**	a) Yes b) No		Drawn from HSE/ Understanding society (with minor adaption)
	Q21	Q14	**Educational qualification**	**What is the highest educational or school qualification have you obtained?**	a) No qualification b) GCSE / CSE / O Level c) A Leave or equivalent d) Higher education below degree e) Degree level qualification f) Other (please specify)		Drawn from Understanding society (with minor adaption)
	Q22	Q15	**Marital status**	**What is your current marital status?**	a) Single b) Married / In civil partnership / Cohabiting c) Separated / Divorced d) Widowed		Drawn from Understanding society (with minor adaption)
	Q23	Q16	**Household income**	**Which one represents the total annual income of your household before any deductions?**	a) Up to £20,000 b) £20,000 to £29,999 c) £30,000 to £49,999 d) £50,000 to £79,999 e) More than £80,000 f) I don't know		Adapted based on UK annual household income distribution
Accommodation	Q24	Q17	**Number of bedrooms**	**How many bedrooms are there at your dwelling?**			Drawn from Understanding society (hhresp_pos113)
	Q25	Q18	**Housing type**	**What type of accommodation does your household live in?**	a) Detached house/bungalow b) Semi-detached house/bungalow c) Mid-terraced house/bungalow d) End-terraced house/bungalow e) Purpose built or converted flat/ maisonette f) Other		Drawn from BHPS_w18 (with minor adaption)

Domain	variant 1	variant 2	Variable	Question	Items/sub-questions	options/scales	Source/Reference
	Q26	Q19	**Orientation**	**Please choose ONE from the following statements.**	a) All our rooms are at the front of the building facing the street/front yard. b) All our rooms are at the back of the building facing the back yard/ court. c) We have rooms at both sides of the building. d) We have rooms facing three sides of the building, or more.		Newly created.
	Q27	Not included	**Visibility of WT**	**Can you see any wind turbines from the place you live? Please choose ALL that apply.**	a) I can see it/them from the window of my dwelling. b) I can see it/them from my garden/ yard. c) I can't see any from my dwelling or garden/yard.		Newly created. based on Pedersen & Persson Waye, 2004; 2007, etc.
	Q28	Q20	**Length of residency**	**How long have you lived at your current address?**	Number of years (if less than a year please indicate number of months)		Drawn from Understanding Society_Mvyr_year moved to current address
	Q29	Q21	**Time at home**	**Please indicate the approximate number of hours PER DAY you spent (including sleeping) indoors or outdoors at your dwelling during the last week.**	a) Time spent indoors at your dwelling: ( ) hours at average PER DAY b) Time spent ourdoors around your dwelling: ( ) hours at average PER DAY		Newly created.
	Q30	Q22	**Ownership**	**Please choose ONE statement which best describes your household's ownership of the accommodation.**	a) owned outright b) owned/being bought on mortgage c) shared ownership (part-owned part-rented) d) rented e) rent free f) other		Drawn from HSE/ Understanding Society (hhresp_Pos115)
	Q31	Q23	**Double-glazed window**	**Is the window of your bedroom double-glazed or sound proofed?**	a) Yes b) No c) I don't know		Newly created.

Among the 31 questions, 14 (45%) were drawn from established national surveys or previous studies. In such cases, the wording of the question and the response items and scales were kept identical to those in the original. Ten (32%) questions were derived or adapted from existing questionnaires with several modifications to fit this survey. Seven (23%) questions were newly created for this survey. Their response items might be derived from the findings of previous studies on noise and well-being. The following section focuses on the questions and items that were adapted or newly created.

5.4.1 Evaluation on wind turbine noise

Annoyance to wind turbine noise has been assessed in a number of previous studies, and most commonly among a set of environmental nuisances (Pedersen & Waye, 2004; 2007). In this questionnaire, annoyance was assessed in four questions, as shown in Table 5.2. The first question (Q5) was adapted from a previous survey (Pedersen & Waye, 2004) and followed the practice, in which respondents were requested to state their responses to a series of environmental nuisances with wind turbine noise among them. Respondents were asked to first indicate whether they noticed any of the nuisances, and if yes, to rate their degree of annoyance on a 5-point scale from "not at all" to "extremely". Noise from neighbours and traffic were included to examine how wind turbines were reported relative to other annoying sound sources in the suburban context of this study. Odor and pests were included in accordance with the previous question (Pedersen & Waye, 2004). Building vibration was newly added to the question items which was frequently complained by residents near wind turbines (Harry, 2007; Pierpont, 2009; Phipps, 2007) and had not been assessed in previous studies. It is worth noting that this question (Q5) was the only wind turbine related question that existed in both Variants 1 and 2, which enabled comparison of the responses to wind turbine noise between two variants.

In questionnaire Variant 1, the annoyance of wind turbine noise was further examined in two questions drawn from the questions standardised by ISO Acoustics for assessing noise annoyance in surveys (ISO 15666, 2003). One question (Q9) used a verbal 5-point category scale (not at all, slightly, moderately, very, extremely) and the other question (Q10) used a numerical 0-10 scale (endpoints marked "not at all" and "extremely"). The latter question (Q10) assessed respondents' annoyance outdoors and indoors separately. Repeating the questions for annoyance was expected to eliminate the effects of scale points on answers and achieve higher reliability of the assessment.

The last question addressing notice and annoyance of wind turbine noise in questionnaire Variant 1 (Q13) was newly created for this survey which involved several situations. These are (a) when the wind is strong, (b) when indoors with windows closed, (c) when heavy traffic flow outside, and (d) when at night. Situation (a) and (d) had been reported to increase notice and annoyance in previous studies (e.g. Harry, 2007; Pedersen & Waye, 2004; Pedersen et al., 2009). Moreover, noise exposure at night (d) was also found to be better related to psychosocial well-being than day-time noise exposure in traffic noise studies (Öhrström, 1991). Less respondents were reported to be disturbed by wind turbine noise in situation (b) (Pawlaczyk-Luszcynska et al., 2014) and the masking effect of (c) had been demonstrated in two studies (Pedersen & Waye, 2004; Bakker et al., 2012).

This study also investigated respondent's evaluation of the overall sound environment using pairs of contrasting adjectives (Q8), such as "quiet – loud", "interesting – boring", "continuous – discontinuous", and so on. The items were adapted from a previous study on the soundscape in urban public spaces using semantic differential analysis (Kang 2006). Eight soundscape indices were used, which were hypothesised to be related to wind turbine noise. The indices covered various aspects of soundscape, for example, strength: quiet-noisy; satisfaction: pleasant-unpleasant, calming-agitating; fluctuation: directional-everywhere.

5.4.2 Sleep disturbance

Sleep disturbance in this survey was measured without making reference to noise and was kept identical in questionnaire Variants 1 and 2 (shown as Q4 in Table 5.2). The question was adapted from an established question used in aircraft noise surveys (McKennel, 1979), which had a number of items on sleep. Respondents were required to choose all the statements that described their sleep. The purpose was trying to identify the relationship between wind turbine noise and different degrees of sleep disturbance, such as difficulty to fall asleep, sleep lighter, occasionally and long-time awakening, and taking pills to sleep. Table 5.3 documents the assessed items of the question and the contexts in terms of the studies that have examined the item and related the sleep problems to noise. The included sleep problems have been reported to be affected by environmental noise in various studies but mostly have not been examined in existing wind turbine noise studies.

Sleep disturbance assessed in most previous studies on wind turbine noise was measured either with or without making reference to noise. Sleep disturbance by noise was normally measured by a single question, which asked the occurrence of disturbed sleep by any noise source using a binary scale (yes/no) (Pedersen & Waye, 2004; 2007), or asked how often sleep disturbance by environmental noise occurred on an ordinal scale (Bakker et al., 2012). It was argued, however, the number of respondents disturbed in their sleep by noise was too small for meaningful statistical analysis (Pedersen & Waye, 2004). More recent studies measured sleep outcomes without referring to noise by asking sleep satisfaction (Shepherd et al., 2011) or whether respondents had difficulty with falling sleep (Pawlaczyk-Luszcynska et al., 2014). One study measured general sleep quality by a set of questions of the Pittsburgh Sleep Quality Index (PSQI), which assessed the occurrence of various sleep problems such as cannot get to sleep within 30 minutes and taking pills to fall asleep (Nissenbaum et al., 2012).

In the broad environmental noise studies, different problems of sleep disturbance have been related to different levels of noise exposures. For example, noise with peak noise levels of 45dBA could increase the time to fall asleep, and nocturnal awakenings could be provoked for a level of 55dBA (Muzet, 2007). Self-reported sleep disturbance and insomnia were observed with a threshold level of 42dBA of night-time exposure outside the dwelling (WHO, 2009). These dose-response relationships were planned to be examined in this survey.

Table 5. 3 Question items of sleep disturbance

Question items *(Choose ALL that apply)*	*Examined in* ***wind turbine noise*** *studies:*	*Examined/confirmed in* ***other noise*** *studies:*
a) My sleep is not disturbed at all.	Disturbed sleep: Pedersen & Waye, 2004; 2007; Bakker et al., 2012;	Disturbed sleep: Muzet, 2007; Basner et al., 2011; WHO, 1999; etc.
b) It's hard for me to fall asleep.	- Assessed in PSQI_Cannot get to sleep within 30mins: Nissenbaum et al., 2012. - Having difficulty with falling asleep: Pawlaczyk-Luszczynska et al., 2014.	Noise increased the time to fall asleep: Öhrström, 1991; Muzet, 2007; Basner et al., 2014; etc.
c) I sleep less deeply than I would like.		Sleep lighter: Basner et al., 2011
d) I occasionally wake up but I soon go back to sleep.		Noise induced awakening: Muzet, 2007; Basner et al., 2014; Passchier-Vermeer & Passchier, 2000; Zaharna & Guilleminault, 2010; Persson, Clow, Edwards, Hucklebridge, & Rylander, 2003; etc.
e) I often lie awake for a while.		Noise induced awakening: Muzet, 2007; Basner et al., 2014; Passchier-Vermeer & Passchier, 2000; Zaharna & Guilleminault, 2010; Persson et al., 2003; etc.
f) I have to take sleeping pills to fall asleep.	Assessed in PSQI: Nissenbaum et al., 2012.	

Question items were adapted from McKennel (1979) - Second survey of aircraft noise annoyance around London (Heathrow) airport.

5.4.3 Adverse health impacts

The question addressing adverse health impact was newly created for this survey. There were ten physiological and psychological problems captured in Q12 for variant 1 (and Q9 for variant 2), as shown in Table 5.2. They were reported to be associated with noise in relevant studies on the effects of wind turbine noise and other noise sources normally with a low-frequency component such as aircraft noise. Table 5.4 lists the assessed health-related problems and the case studies that have reported the problem as well as previous field studies that have examined the relationship between the problem and levels of noise exposure.

It can be seen from Table 5.4 that all the problems included in this survey except (h) have been reported in case studies investigating the influence of wind turbine noise. Of them, headache, nausea, dizziness and concentration problems were reported by Pierpont (2009) as symptoms of the so-called "wind turbine syndrome" in a study that tracked patients over time. Most case series studies reported headache, tinnitus (ear discomfort) and stress as frequent symptoms. Headache, dizziness, tinnitus (ear discomfort), cardiovascular disease, stress and tension were also examined in large field studies with tinnitus (ear discomfort) found to be significantly related to noise levels, and headache, tense, stress and being irritable found to be significantly related to annoyance (Pedersen et al., 2011). In addition, headache, nausea, and dizziness were normally presented in low-frequency noise studies and feeling tense and edgy were frequently demonstrated in a number of aircraft noise studies.

There were three health-related problems captured in this survey which had not been assessed in previous field studies. Difficulty in intellectual activities (h) had been reported to be an effect of low-frequency noise and community noise, as well as an after effect of disturbed sleep. Mood swings and lack of concentration were asked about because they had been reported in case studies and were included in a cluster of symptoms related to low-frequency noise.

The question items asked how often the above health problems were experienced for all participants. In questionnaire variant 1, respondents were then given the opportunity to indicate whether they felt wind turbine noise might be their cause. The response scale was configured as "yes", "possibly", "no", and "I don't know".

Table 5. 4 Question items of health symptoms

Health Symptoms *1. experienced any? not at all, some of the time, all the time) - in Variant 1 & 2* *2. caused by WTN? (yes, possibly, no, I don't know) - in Variant 1 only*		
a)	**HEADACHE**	
	Reported in ***case series*** studies:	Harry, 2007; Pierpont, 2009; Wind concerns Ontario, 2009; Thorne, 2012.
	Examined in ***wind turbine noise*** studies:	Pedersen & Waye, 2004; 2007; Pedersen, 2011; Pawlaczyk-Luszczynska et al., 2014.
	Examined/confirmed in ***other noise*** studies:	- Low-frequency noise: Møller & Lydolf, 2002; Hansen, 2007. - Aircraft noise: Stansfeld, 2000; etc.
b)	**NAUSEA**	
	Reported in ***case series*** studies:	Pierpont, 2009; Thorne, 2012.
	Examined in ***wind turbine noise*** studies:	
	Examined/confirmed in ***other noise*** studies:	Low-frequency noise: Hansen, 2007.
c)	**DIZZINESS**	
	Reported in ***case series*** studies:	Pierpont, 2009; Farboud et al., 2003;
	Examined in ***wind turbine noise*** studies:	Pawlaczyk-Luszczynska et al., 2014
	Examined/confirmed in ***other noise*** studies:	Low-frequency noise: Møller & Lydolf, 2002;
d)	**EAR DISCOMFORT**	
	Reported in ***case series*** studies:	- Tinnitus: Harry, 2007; Pierpont, 2009; - Ear pressure: Wind concerns Ontario, 2009; Thorne, 2012.
	Examined in ***wind turbine noise*** studies:	Tinnitus: Pedersen & Waye, 2004; 2007; Pedersen, 2011;
	Examined/confirmed in ***other noise*** studies:	- Low-frequency noise: Møller & Lydolf, 2002; - Community noise: WHO, 1999.
e)	**CARDIOVASCULAR DISEASE**	
	Reported in ***case series*** studies:	High blood pressure: Thorne, 2012.
	Examined in ***wind turbine noise*** studies:	Pedersen & Waye, 2004; 2007; Pedersen, 2011; Pawlaczyk-Luszczynska et al., 2014.
	Examined/confirmed in ***other noise*** studies:	- Traffic noise: Babisch et al., 1990; Babisch, 2008; etc. - Aircraft noise: Katsouyanni et al., 2008.

Table 5. 4 Question items of health symptoms

		- Community noise: WHO, 1999 - Interfere with sleep: Muzet et al., 1980
f)	**STRESS**	
	Reported in ***case series*** studies:	Harry, 2007; Wind concerns Ontario, 2009; Farboud et al., 2013;
	Examined in ***wind turbine noise*** studies:	Pedersen & Waye, 2004; 2007; Pedersen, 2011; Pawlaczyk-Luszczynska et al., 2014.
	Examined/confirmed in ***other noise*** studies:	WHO, 1995; Persson et al., 2000; etc.
g)	**TENSION and EDGINESS**	
	Reported in ***case series*** studies:	Irritability: Pierpont, 2009; Thorne, 2012;
	Examined in ***wind turbine noise*** studies:	Feeling tense, irritable: Pedersen & Waye, 2004; 2007; Pedersen, 2011; Pawlaczyk-Luszczynska et al., 2014.
	Examined/confirmed in ***other noise*** studies:	Aircraft noise: Stansfeld et al., 2000; Tarnopolsky et al., 1980; Mckennel, 1979
h)	**DIFFICULTY IN INTELLECTUAL ACTIVITIES**	
	Reported in ***case series*** studies:	
	Examined in ***wind turbine noise*** studies:	
	Examined/confirmed in ***other noise*** studies:	- Low-frequency noise: Hansen, 2007. - Community noise: WHO, 1999. - After effect of disturbed sleep: Bonnet & Arand, 2003; Basner et al., 2010; WHO, 1995.
i)	**MOOD SWINGS**	
	Reported in ***case series*** studies:	Wind concerns Ontario, 2009;
	Examined in ***wind turbine noise*** studies:	
	Examined/confirmed in ***other noise*** studies:	- Low-frequency noise: Møller & Lydolf, 2002; Alves-Pereira & Branco, 2007; - After-effect of disturbed sleep: Muzet, 2007; WHO, 1995.
j)	**LACK OF CONCENTRATION**	
	Reported in ***case series*** studies:	Pierpont, 2009;
	Examined in ***wind turbine noise*** studies:	
	Examined/confirmed in ***other noise*** studies:	- Low-frequency noise: Møller & Lydolf, 2002; - After-effect of disturbed sleep: Muzet, 2007;
k)	**OTHER (please specify)**	

5.4.4 Sound characteristics

Respondents of questionnaire variant 1 were asked to describe the sound from wind turbine (Q14), choosing from a set of verbal descriptors of sound characteristics, such as swishing, beating, and pulsating. These descriptors were obtained from previous studies, as summarised in Table 5.5. All descriptors were reported in formal complaints by wind turbine affected residents, as evaluated in a previous study (Moorhouse et al., 2007).

Table 5. 5 Question items of sound characteristics

Question items *(Choose ALL that apply)*	*Examined in **wind turbine noise** studies:*
a) NOISELESS/QUIET	
b) SWISHING	- Related to 2-4k Hz & correlated to annoyance: Pedersen & Waye, 2004. - Most reported: Pedersen & Waye, 2004, 2007; Pedersen et al., 2009; Pawlaczyk-Luszczynska et al., 2014.
c) BEATING	- Being indicative of AM: Moorhouse et al., 2007; - More at night & more annoying: van den Berg, 2004b
d) WOOSHING	- van den Berg et al., 2008
e) WHISTLING	- Reported in Pedersen & Waye, 2004; Pedersen et al., 2009
f) PULSATING	- Being indicative of AM: Moorhouse et al., 2007; - More at night & more annoying: van den Berg, 2004b
g) THROBBING	- Reported in Pedersen & Waye, 2004; Pedersen et al., 2009
h) OTHER (please specify)	

All descriptors from b) to g) were reported in complains from Moorhouse et al. (2007) - Research into aerodynamic modulation of wind turbine noise: final report.

Swishing, whistling, and throbbing had also been captured in large field studies on wind turbine noise. Of them, swishing was most reported by respondents in a number of studies and was found to be related to annoyance (Pedersen & Waye, 2004). In addition, respondents' descriptors of sound were found to indicate different components of wind turbine noise. Swishing and whistling were reported to be related to the sound at 2-4k Hz. Beating and pulsating were reported to be more prominent at night and more annoying (van den Berg, 2004). Moreover, beating and pulsating were also stated to be indicative of amplitude modulation (AM) of the sound (Moorhouse et al., 2007), which is often considered to be the most annoying aspect of wind turbine noise and causing complains. An option of noiseless or quiet was added for respondents who did not notice the noise.

5.4.5 Order of questions

Considerable effort went into adjusting the order of the questions since this could influence the answers obtained. First of all, to control for possible self-reporting bias, reference to wind turbine and its noise was minimised in variant 1 and fully removed from variant 2. The questionnaire and associated paperwork informed the participants that they were taking part in a general survey on well-being and living environment, in which they were invited to provide information on health and well-being, evaluation of environment, and reactions to noise. As a result, taking questionnaire variant 1 as an example, the final version that people received entailed five sections in the following order: a section on well-being and health, a section related to the evaluation of the neighbouring environment, a section addressing the response to wind turbine noise, and last two sections on demographic and architectural variables (see Table 2). This structure also followed a logical progression of getting people engaged in an issue, by making them aware of the issue, getting general feelings, to getting answers on specific aspects of the issue. Furthermore, efforts were made to hold the participant's interest throughout the questionnaire and reduce non-responses. For example, the questionnaire started with the section on subjective well-being that was straightforward to answer and left the sensitive topics such as income until last. When determining the position of questions addressing key variables of noise impact, the conditioning effect of the earlier questions were considered. For instance, the annoyance questions were placed early in the question sequence, without mentioning the potential adverse health impact before, so that respondents were more likely to give their direct responses to wind turbine noise. Control variables such as attitude on wind turbines were also placed later, to reduce their influence on the answer to key variables placed earlier.

5.5 Participants

The target population of the survey was defined as residents who lived within two kilometres of modern wind turbine(s) in suburban areas in the UK. Participants were selected using multi-stage sampling and questionnaires were mailed or door dropped by the student.

5.5.1 Site selection

Firstly, to simplify the fieldwork of the survey, three typical wind farm sites were selected to concentrate the sample in three clusters of households for further sampling. During the process of site selection (Jan - Mar 2014), 480 onshore wind farms in operation at the time across the UK were investigated with focus on their locations, mechanical factors of power capacity, and configurational factors of any residential areas in the vicinity.

The shortlist of study sites was based on the following two criteria: (1) Each wind turbine on the site should be a modern large turbine with power capacity more than 1MW and height over 80m. (2) The wind farm should have a sufficient number of residents living within two kilometres (with the population density of over 1000/km^2), ideally in a suburban context with densely populated residences. A further four criteria were used for the final selection: (3) The site should cover residences with different levels of exposure to the wind turbine noise. (4) The characteristics of the residents should not vary greatly from the UK general public at large, e.g. not remote industrial areas where the majority are factory workers. (5) The site should be accessible from a fieldwork practicality point of view. (6) No other dominant noise source should be present, e.g. large noise from railways or heavy vehicles.

Based on the UKWED online dataset, which lists data on operational onshore and offshore wind energy projects in the UK (UKWED), and the map of each wind farm on Google Earth, the initial shortlist including 23 wind farms that met criteria (1) and (2) above was drawn.

The properties of these wind farms are shown in Table 5A.1 in Appendix III, sorted by the year of operation. The final sites of study are listed on top, shown as Sites A, B, and C anonymously for ethical reasons. Following criterion (3), eight sites surrounded by thinly populated communities in rural areas were excluded. Four sites were further excluded by criterion (3), for the wind turbines were far away from the edge of the communities which would result in inadequate residents in higher noise exposure areas. Another two wind farms served industrial estates along the River Thames were also excluded for criterion (4). Two sites in the Highlands and Northern Ireland were then excluded based on criterion (5), because access was not practical. Further investigation and site visits were carried out on the remaining seven sites to identify the sites meeting the above conditions and with variation in morphological contexts across them. Four sites were excluded for criterion (6). Finally, three sites were remaining. One more site (Lindhurst Wind Farm in Nottingham) was also selected for a field-test pilot.

Characteristics of the selected sites are shown in Table 5.6. One site was in a suburban area in East Midland (Site A), one site was in the suburb of a large city in Scotland (Site B), and one site was near a town by the eastern coast of England (Site C). They were selected for further sampling of individual respondents.

Table 5. 6 Characteristics of the study sites

Site	*Characteristics*	*Turbine model*	*Population density (approximate value)*	*Location*
A.	- Surrounded by 3 suburban areas - Separated by a highway, a railway and a motorway - Highly visible - Semi-detached dwellings	1 turbine 3.4 MW Year 2014	2800/km^2	Midlands of England

Table 5. 6 Characteristics of the study sites

B.	- Inside industrial area in the city - Proximity to suburban residential areas - Relatively low traffic noise	2 turbines 2 MW Year 2006	2250/km^2	Scotland
C.	- At seaside with strong wind - Surrounded by highly populated urban area - Long terrace dwellings - Occasionally shut down	1 turbine 2.75 MW Year 2005	3100/km^2	Suffolk, East England

Source: UKWED, Google Map, site visits

5.5.2 Sampling frame

Postal addresses and names of the residents in the three selected sites were purchased from the edited electoral register, which comprised people eligible to vote in the UK aged 18 or over and had not opted out their data from being sold for wider purposes (MoJ, 2012). Although the edited electoral register has been widely used as a sampling frame, it is known to be an incomplete list of electors. For example, it does not list adults who have requested removal of their names. Research showed that the coverage of the full electoral register was lower among single adult households, those in privately rented accommodation, and for individuals who had moved in the previous 12 months (Foster, 1993). The edited version of the register was estimated to cover only 60% of the households in the full register. Nonetheless, the survey still used the edited electoral register as the basis for sampling, because there was no alternative listing of postal addresses which provided the same level of coverage and included full names of individuals that enabled the covering letter to be personalised to the sampled individual.

5.5.3 Sampling strategy

To create a sample from the edited electoral register of each site, disproportionate stratified sampling was applied with wind turbine noise levels as the strata. The purpose was to ensure that residents exposed to different levels of noise were adequately represented in the sample. Noise modeling was carried out for the three sites to predict the distributions of wind turbine noise based on different wind turbine models and terrain conditions. Using noise mapping techniques, each site was displayed with estimated noise level contours of 5dBA intervals. According to the addresses of the individuals in the edited electoral register, each individual was allocated to one of the estimated noise exposure intervals. The individuals were then grouped into four noise strata: below 35dBA, 35-40dBA, 40-45dBA, and above 45dBA. Two independent samples were retrieved from each stratum for the two questionnaire variants. Based on statistical advise[5], unequal size samples were set so that the first main variant had more respondents than the second control variant, with a ratio between group 1 and 2 of 3:1 in this study, in each noise stratum. The sample addresses for group 1 and 2 in each noise stratum were randomly selected from the edited electoral register. Where there were several adults at the same address, one individual was selected at random.

5.5.4 Sample size

The sample size needed for each noise stratum was determined by sample size calculation. For this study, the sample size should be sufficient for three aspects: (1) to report the population mean/proportion of key variables with an acceptable margin of random error; (2) to compare the mean/proportion of key variables to the results of a national survey with certain power and significance level; and (3) to conduct statistical tests between adjacent noise groups (e.g. 35-40dB v.s. 40-45 dB). A detailed description of the sample size calculation can be obtained by request. Ideally, the aim was to include a total of 637 people for the analysis. Such sample size could detect a 0.3 difference in the mean of “happiness” scores on a n 11-point scale between the study samples near wind farms and those in the Health Survey of England (HSE) (with 95%CI, 0.8 power). In addition,

[5] University of Sheffield Statistical Advise Service, June 2014.

it could report the proportion of annoyed people in each noise group with 95% confidence that the population proportion is no more than 8% higher or lower than the reported proportion. Furthermore, the sample size was sufficient to detect the difference between the percentage of annoyed people in adjacent noise groups if the difference was up to 15% (with 95%CI, 0.8 power level). Based on an estimated 20% response rate that was also achieved in the pilot test, a total of 3185 individuals were sampled.

Table 5A.2 in Appendix III shows detailed sampling in each noise stratum for the two variants over three sites. The row of proportional allocation lists the sample needed if the total sample size of 3185 were allocated uniformly to each site and stratum. However, it can be seen from the sample actually created that the sampling fraction is not the same within each stratum. The samples were re-weighed according to available individuals in the noise strata (as shown in the row of final allocation). This final disproportionate allocation can be justified in several ways. First, all addresses in the noise group with the highest exposure were included to reach the proportionate sample. Second, if there were insufficient addresses in a stratum of a site, more addresses were sampled at the same stratum of other sites. Third, if an unusually low response rate was found in a stratum in counting the return questionnaire, the sample size of this stratum could be increased. In general, the total sample size of each noise stratum was sufficient and the samples were balanced across the three sites.

5.6 Survey Procedures

The survey procedures consisted of three phases: pre-testing, field-testing, and the formal surveying.

The draft version of the questionnaire was completed in a face-to-face interview by a convenience sample of 10 contacts at the University, who provided feedback on the design, content and clarity of the questionnaire. As a result of their comments, the design of the questionnaire was changed. Around 50% of the questions were modified, taking into account suggestions for wording improvement.

The revised version resulting from the feedback was pilot tested in Lindhurst wind farm in June 2014. The participants for the pilot survey were residents within 1km from the nearest wind turbine. 88 and 28 questionnaire packages were delivered for sample group of variant 1 and 2 respectively, with 22 and 10 returned in each group. The response rate for variant 1 was 25%, lower than that of variant 2 which was 35.7%. According to the completion of answers, one question on main outcome variable drawn from GHQ was replaced by a newly created question. Two questions on sensitivity and attitude were changed from four sub-questions to two. Two demographic questions were modified with simplified items in a clear order. Several questions were reworded to be easy to comprehend. The procedure resulted in a pre-final version of the questionnaire.

The final survey questionnaire was distributed to the sampled individuals during September to December 2014. The survey was originally intended to be conducted during the summer time when people were more likely to spend time outside and the wind turbine noise might have been more likely to be perceived. However, due to the delay of piloting test, the survey was finally carried out during autumn-winter time. Most of the questionnaires were distributed by post. Where it was convenient to do so, the questionnaire was delivered by door-drop to reduce postage costs. A small sample in Variant 2 of Site A was recruited by face-to-face delivery.

A covering letter (shown in Appendix II) was attached in the questionnaire package informing the participant about the survey, confidentiality, potential impact and risk, and asked for their consent to participate by completing and returning the questionnaire. A separate sheet was also enclosed to invite respondents' open comments on the survey or on any specific topic related to the survey. The package contained a free-return envelope addressed to the university mailbox to return the completed questionnaires. Three £50 cash prizes were offered for the participants to win by completing the questionnaire survey, to encourage responding. The participants who chose to enter in to the prize draw needed to provide their contact information on a separate contact sheet and enclose it in the questionnaire return.

Returned questionnaires were recorded as soon as they were received and the response rate for each district was calculated. For areas with extremely low responses, additional sampling of the area was conducted and new questionnaires were sent by post that would increase the sample size in that area. Hand-written personal greetings were also used for areas with particularly low response rates. However, the survey did not use reminders to increase response rate since people who did not respond to the first mailing might be less keen to be helpful, and hence a reminder might have been ineffective.

5.7 Statistical Analysis

Statistical analyses were performed using SPSS version 22.0 (Statistics, 2009). Descriptive statistics were provided for the characteristics of the participants. Response to wind turbine noise was presented as proportions of the number of respondents in each 5 dB(A) stratum with 95% confidence intervals (CIs). Annoyance measured on verbal and ordinal scales were dichotomised, with slightly annoyed to extremely annoyed classified as “annoyed”. In the analysis of questions with multiple items, such as sleep disturbance which had six, each item was treated as a variable such as “difficulty in falling asleep”, “sleep less deeply” and “lie awake”. In the analysis of variables with two questions, such as sensitivity and sustainability, a derived variable was created on a 6-point ordinal scale computed by the numeric sum of the two original variables. Oblique rotated principle axis factor analysis was employed to extract the oblique factor underlying the 14 inter-related adjectives for the respondents' attitudes to wind turbine noise.

Differences in distribution of observations and respondent characteristics between Variants 1 and 2 were tested using Pearson's chi-square for categorical variables, and *t*-test for continuous variables, with *p*-values below 0.05 considered statistically significant. Comparisons were made across the two variants to see if the data could be pooled. Differences between the two variants in outcome variables with ordinal scales (e.g. general health) were tested with the Mann-Whitney's *U* test. Differences in distribution of respondent characteristics across four sound categories were also examined using Pearson's chi-square for categorical variables, the Gamma for ordinal variables or analysis of variance (one-way ANOVA) for continuous variables.

Binary logistic regression was applied to analyse the effects of noise on awareness of and annoyance with the noise. The main explanatory variable, noise exposure, was represented by the A-weighted SPL, calculated for the most exposed façade of a dwelling. Preliminary regression analyses were carried out to select the variables for the final models presented in the thesis by exploring the influence of personal factors, where possible moderating factors were added to the regression model one-by-one, always keeping the A-weighted SPL in the model. Though the site dummies did not have any influence in some preliminary regressions, these variables were included in the analyses to exclude bias from social and acoustic differences between areas. Odds ratios (ORs) were reported for each variable with 95% confidence intervals (CIs), with *p*-value below 0.05 considered statistically significant. The Nagelkerke psudo-R^2 was applied as a measure of explained variance. Hosmer-Lemesow goodness-of-fit [$p_{(H\text{-}L)}$] was presented for each logistic regression model, with *p*-value >0.05 indicating no statistically significant difference between the modelled and the observed data, which implies a good fit of the model.

The prevalence of various sleep disturbance and adverse health problems were regressed on wind turbine noise levels, controlled for age, sex, having longstanding illness, and other covariates. Sleep and health problems were also regressed on annoyance with noise levels kept in the model, to examine if noise annoyance can be regarded as an intermediate state between noise and health.

Subjective well-being in terms of happiness and life satisfaction of the respondents were compared across sound categories. General health and subjective well-beings of the respondents in this study were also compared to those reported in the national survey using out-of-sample predictions. Socio-demographic variables measured by questions drawn from the national surveys allowed comparison between respondents with similar characteristics, in terms of age, gender, employment, illness, qualification, marital status, and income. The first step was using OLS regression analyses to analyse the factors underlying individuals' assessments of well-being in the dataset of the national survey. Then out-of-sample predictions were carried out using the results of the regression models to predict the well-being of the study sample adjusted for demographical variables. The observed and predicted levels of well-being for each respondent were compared using Wilcoxon signed-rank test. The difference between observed and predicted levels was then related to the level of wind turbine noise.

The results of above analyses are shown in Chapters 6 and 7.

5.8 Conclusions

The survey design was guided by a review of the large cross-sectional studies that provide the current best evidence on wind turbine noise, reported in Chapter 2 above. The present study investigated the effect of wind turbine noise on human well-being in suburban-urban contexts, to address the evidence gap of evaluating wind turbine noise impacts in noisy and urbanised settings.

Paper questionnaires were delivered to selected residents of three sample sites across the UK in the vicinity of large wind turbines in suburban-urban settings. The relationships between SPLs and human health and well-being were investigated through quantitative analysis of the questionnaire data. The inclusion of more socio-demographic and architectural factors could provide more explanatory variables in the relationship between wind turbine noise and well-being. This also helped to understand the impact of personal, architectural, and situational factors interacting in the process.

Most questions on subjective well-being and socio-demographic factors were taken verbatim from those in the large national surveys, including their response items and scales. This enabled comparison between the well-being of communities living near wind turbines in this study to those of the general population with similar characteristics but not living near wind turbines.

Possible bias associated with asking people for their perceived causes of health problems was minimised by recruiting a separate control group without any focusing on wind turbine noise. Differences between the main and control groups in relation to reported health and well-being were examined.

Chapter 6

Noise Impact on Subjective Noise Evaluation

6.1 Introduction

This chapter presents the results of the survey on subjective evaluation of wind turbine noise, which is the first part of objective 2 of the thesis (see Figure 1.3). The subjective evaluation of the noise includes noticeability of and annoyance with wind turbine noise, and evaluation on local sound environment. As previous field studies in other countries have found the dose-response relationship between wind turbine noise level and annoyance with the noise (Michaud et al., 2016; Pawlaczyk-Łuszczyńska et al., 2014; Pedersen et al., 2009; Pedersen & Waye, 2004, 2007), this chapter further investigates the dose-response relationship in urbanised areas controlling for moderating factors, and compares the results of this study to those found in previous studies. The effects of minimum and average façade exposures are also examined, as they could be reduced by morphological design as found in Chapter 4. This chapter also investigates whether the level of wind turbine noise influences respondent's evaluation of the local sound environment, using questions established in soundscape studies.

Figure 6.1 illustrates the structure of this chapter. Descriptive statistics on the response rate, characteristics of the respondents, and a comparison between the two questionnaire variants are reported in Section 6.2. It is followed by descriptive statistics on questionnaire responses related to wind turbines (Section 6.3). The main analyses are then presented in two sections: noise effects on noticeability (Section 6.4) and on annoyance (Section 6.5). Effects of the quiet façade exposures (minimum and average SPL) are demonstrated in Section 6.6. Comparison to the results of previous studies in rural areas are presented in Section 6.7. Finally, effects of wind turbine noise on soundscape evaluations are stated in Section 6.8. Discussions are given on the noise effects and the effects of covariates (Section 6.9), before conclusions are drawn on the impact of wind turbine noise on subjective noise evaluations.

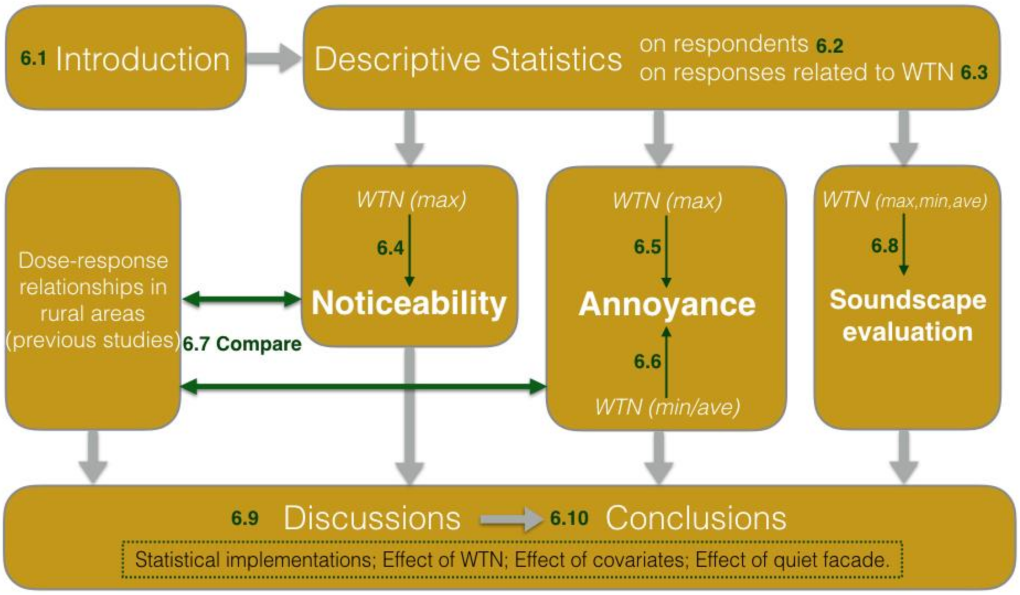


Figure 6. 1 Flow chart of Chapter 6

6.2 Descriptive Statistics on Respondents

6.2.1 Response rate and noise exposure

The numbers of respondents of the two questionnaire variants were 262 and 97, respectively, with a total of 359. The overall response rate was 12.0%, with 11.7% for Variant 1 and 13.1% for Variant 2. Table 6A.1 in Appendix III shows detailed response rates in each sampling group of the three sites. The response rates for Variant 2 in Site A, ranging from 20.0% to 28.8%, were higher than those in the other sampling groups, which may have been due to the face to face delivery of the questionnaires (only for variant 2) in this area. Except these respondents, the response rates of Variant 1 and Variant 2 using normal door-drop delivery were similar, of 11.7% and 10.7%, respectively. The response rate was highest in Site A, of 17.2% (15.5% for door-drop delivery); and lowest in Site C, of 9.3% overall.

The noise exposure on the dwelling of each respondent was calculated, and Table 6.1 presents the distribution of the respondents according to 5-dB(A) noise intervals of maximum facade exposure. Overall, there were fewer respondents with noise exposures over 40 dB(A). The proportion of respondents in the other three noise intervals was similar. There was no statistically significant association between noise intervals and the two variants (X^2=3.332, p=0.343). A Mann-Whitney U also indicated the distribution of respondents in four noise groups was the same across categories of questionnaire variant [$U(n_1=262, n_2=97)=10962.5$, p=0.304].

Table 6. 1 Number of respondents and proportions according to 5-dB(A) sound level intervals.

	Calculated A-weighted sound pressure levels [dB(A)]				Total
	>40	35-40	30-35	<30	
Variant 1	44 (17%)	64 (25%)	74 (29%)	80 (31%)	262 (100%)
Variant 2	9 (9%)	26 (27%)	28 (29%)	34 (35%)	97 (100%)
Overall	53 (15%)	90 (25%)	102 (28%)	114 (32%)	359 (100%)

Pearson Chi-square X^2=3.332, p=.343. Mann-Whitney U=10,962.5, p=.304.

6.2.2 Study group characteristics related to noise categories

The mean age in the study population was 56 (SD = 17.7), and 49% were male. Most of the respondents were employed (43%) or retired (41%). Over half (55%) of the respondents reported to be sensitive to noise based on the two questions on sensitivity. Overall, 49% of the respondents lived in detached or semi-detached houses, while 34% of the respondents lived in mid-terrace or end-of-terrace dwellings. In total, 68% of the respondents privately owned their accommodation, while the remaining lived in rented dwellings.

Table 6.2 shows the characteristics of the study group with frequency of respondents in each 5-dB sound level category. A statistical test examining the difference in distribution across four sound level categories was performed for each variable. No statistically significant differences in variables related to gender, long-standing illness, education, or household income were found across sound level categories. The mean age in the study population was 56 (SD = 17.9). There was a significant difference between age in each noise category [$F_{(3, 352)}=9.879$, $p=0.000$], with a significant quadratic trend [$F_{(1, 352)}=19.601$, $p=0.000$], indicating that the respondents in the lowest and highest sound categories were significantly older than those in the middle sound categories. Employment ($X^2=22.275$, $p=0.008$) and marital status ($X^2=23.950$, $p=0.004$) were significantly associated with sound categories with respondents in high exposure categories more likely to be retired and widowed. Participants in both Variant 1 and 2 were asked to indicate their personal degree of noise sensitivity and environmental sustainability of lifestyle (sustainability for short). No statistically significant differences in noise sensitivity and sustainability were found across sound level categories.

Statistically significant correlations were found between sound categories and architectural factors. Respondents in lower sound categories had more bedrooms [$F_{(3, 343)}=10.512$, $p=0.000$]. There was a significant association between sound categories and type of dwelling ($X^2=37.246$, $p=0.000$). Overall, 49% of the respondents lived in detached or semi-detached houses, while 34% of the respondents lived in mid-terrace or end-of-terrace dwellings. The former were more often in lower sound categories, and the latter were more likely to be in higher sound categories. The orientation of the building was significantly associated with sound categories ($X^2=33.941$, $p=0.000$), with more respondents having rooms facing three sides of the building in the lower sound categories than in the other categories. A statistically significant correlation was found between sound categories and ownership of the accommodation ($X^2=30.163$, $p=0.003$). Overall, 68% of the respondents privately owned their accommodation, while the remaining lived in rented dwellings. The ownership of the accommodation decreased with higher sound categories. No statistically significant differences in variables related to length of residency, time spent outdoors and indoors, sound-proofed windows or giving additional comments were found between different sound categories.

Table 6. 2 Characteristics of the respondents related to wind turbine noise categories

Characteristic	Respondents: Total	Calculated A-weighted sound pressure levels [dB(A)]: <30	30-35	35-40	>40	One-way ANOVA (*F*) or Chi-square test (χ^2)
n	359	114	102	90	53	
***Age**: M (SD)	56 (17.9)	55 (17.3)	53 (16.9)	52 (18.2)	66 (16.1)	***F* (3, 352)=9.879**
Gender (%)						
male	49	52	48	47	50	χ^2=.735
female	51	48	52	53	50	
***Employment** (%)						
full-time employed	34	38	39	27	27	**χ^2=22.275**
part-time employed	9.9	8	14	13	2	
retired	41.2	46	30	39	58	
other	15.2	9	22	22	14	
Have long standing illness (%)	39.2	33	38	46	45	χ^2=4.140
Education (%)						
no qualification	32.1	31	31	27	46	χ^2=14.790
GCSE/O Level/A Level	33.8	31	34	41	28	
Higher education below degree	11.7	9	15	11	12	
degree level	18.1	27	15	16	10	
other	4.4	4	5	5	4	
***Marital status** (%)						
single	20.4	18	16	30	17	**χ^2=23.950**
married/in civil partnership	58.0	67	64	47	46	
separated/divorced	9.8	10	9	9	12	
widowed	11.8	5	11	14	25	
*Household income (%)						
up to £20,000	47.4	42	42	51	66	χ^2=22.940
£20,000 - £29,999	16.5	15	19	21	7	
£30,000 - £49,999	19.3	27	17	16	16	
£50,000 - £79,999	6.5	8	10	2	2	
more than £80,000	0.9	2	0	1	0	
I don't know	9.3	6	13	10	9	
***No. of bedrooms:** M (SD)	2.5 (0.9)	2.8 (0.9)	2.7 (0.9)	2.3 (0.7)	2.0 (1.1)	***F* (3, 343)=10.512**
Noise sensitivity						
hard to relax in a noisy place	54.7	48	62	58	47	χ^2=5.938
Environmental sustainability (ES)						
ES is a low priority in my life (%	47.3	46	48	49	47	χ^2=0.216
***Type of dwelling** (%)						
detached house	21.6	37	23	11	6	**χ^2=37.246**
semi-detached house	27.7	22	30	33	27	

Table 6. 2 Characteristics of the respondents related to wind turbine noise categories

Characteristic	Respondents					One-way ANOVA (F) or Chi-square test (χ^2)
	Total	Calculated A-weighted sound pressure levels [dB(A)]				
		<30	30-35	35-40	>40	
mid-terrace house	25.9	24	27	25	31	
end-of-terrace house	8.4	7	7	7	17	
flat/maisonette/other	16.4	11	13	25	19	
***Orientation of dwelling** (%)						
all rooms facing the street	4.4	3	1	8	8	
all rooms facing the back yard	3.8	3	2	5	8	**χ^2=33.941**
rooms at both sides	79.1	69	91	80	76	
rooms facing three sides or more	12.8	26	6	8	8	
Years living at current address: M (SD)	16.9 (14.1)	19.0 (15.4)	16.4 (13.6)	15.1 (14.0)	17.0 (12.4)	F (3, 350)=1.024
Time spent indoors and outdoors						
average hours indoors/day: M (SD)	16.7 (11.5)	18.0 (16.1)	15.2 (8.6)	17.0 (10.7)	16.6 (4.5)	F (3, 343)=.964
average hours outdoors/day: M (SD)	4.0 (5.8)	4.0 (4.0)	3.8 (3.6)	4.3 (9.7)	4.2 (3.9)	F (3, 319)=.113
***Ownership of accommodation** (%)						
owned	68.3	78	68	63	58	**χ^2=30.163**
rented	31.7	22	32	37	42	
Sound-proofed windows (%)	90.2	92	92	89	85	χ^2=2.966
Give additional comments (%)	11.4	8.5	13.7	16.7	3.8	χ^2=6.829
Give positive comments (%)	8.3	9.4	7.8	10.0	3.8	χ^2=1.907

*p<0.1; **p<0.05; ***p<0.01. M - mean; SD - standard deviation.

Bivariate correlations were performed between the above socio-economic variables, using spearman's coefficient (r_S). Noise sensitivity was positively correlated to living in a flat (r_S=0.150, p=0.005) as opposed to other housing types. Sustainability was negatively correlated to living in a flat (r_S=-0.201, p=0.000) and positively correlated to the number of bedrooms (r_S=0.151, p=0.005), household income (r_S=0.204, p=0.000), and having a degree (r_S =0.224, p=0.000). Housing type and orientation were inter-correlated. Respondents living in detached house were more likely to have windows facing three sides or more (r_S =0.171, p=0.001), and were more likely to be married (r_S =0.242, p=0.000) and not single (r_S =-0.203, p=0.000), less likely to have a long-standing illness (r_S =-0.170, p=0.001), and have more household income (r_S =0.327, p=0.000). On the contrary, respondents living in a flat were more likely to be single (r_S =0.256, p=0.000) and not married (r_S =-0.320, p=0.000), have lower household income (r_S =-0.311, p=0.000), more likely to have rooms all seeing the front (r_S =0.362, p=0.000) or back (r_S =0.224, p=0.000) of the dwelling. Having windows facing three sides or more was also positively correlated to household income (r_S =0.157, p=0.007). Respondents living in a mid-terrace house were more likely to face both sides of the building (r_S =0.179, p=0.001).

6.2.3 Comparison between Variant 1 and Variant 2

Characteristics of respondents

No statistically significant differences in the distribution of the four sound categories were found between the variants. Table 6.3 shows the characteristics of respondents in Variant 1 (n=262) and 2 (n=97). Overall, the respondents of the two variants were similar. No statistically significant differences in variables related to age, gender, education, marital status or household income were found between the two variants. No statistically significant differences in noise sensitivity, sustainability, housing type, or orientation were found between variants. On average, respondents in Variant 1 were younger (M = 55, SE = 17.8) than those in Variant 2 (M = 58, SE = 17.3), but this difference, -3, BCa 95% CI [-7.7, 0.4], was not significant t (349) = -1.72, p = 0.687. A statistically significant difference was found between variants as to whether respondents had long standing illness (X^2=4.826, p=0.036), with 39% in Variant 1 and 48% in Variant 2.

Table 6. 3 Characteristics of the respondents in questionnaire variants 1 and 2

Characteristic	Respondents			Chi-square test (χ^2) or t-test (t) for difference between variants
	Total	Questionnaire variants		
		1	2	
n	359	262	97	

Table 6. 3 Characteristics of the respondents in questionnaire variants 1 and 2

Characteristic	Respondents: Total	Respondents: Questionnaire variant 1	Respondents: Questionnaire variant 2	Chi-square test (χ^2) or *t*-test (*t*) for difference between variants
Age: M (SD)	55.5 (17.7)	55 (18)	58 (17)	*t* (349)=-1.72, *p*=.687
Gender (%)				
male	49	48	51	χ^2=.308, *p*=.579
female	51	51	48	
Employment (%)				
full-time employed	34	34	31	χ^2=2.783, *p*=.426
part-time employed	9.9	11	8	
retired	41.2	39	48	
other	15.2	16	13	
**Have long standing illness (%)	39.2	35	48	**χ^2=4.826, *p*=.036**
Education (%)				
no qualification	32.1	29	42	χ^2=9.479, *p*=.050
GCSE/O Level/A Level	33.8	33	34	
Higher education below degree	11.7	13	6	
degree level	18.1	20	12	
other	4.4	4	5	
Marital status (%)				
single	20.4	22	16	χ^2=2.803, *p*=.423
married/in civil partnership	58.0	57	62	
separated/divorced	9.8	10	8	
widowed	11.8	10	15	
Household income (%)				
up to £20,000	47.4	45	40	χ^2=2.494, *p*=.777
£20,000 - £29,999	16.5	15	17	
£30,000 - £49,999	19.3	17	19	
£50,000 - £79,999	6.5	6	6	
more than £80,000	0.9	1	1	
I don't know	9.3	8	13	
No. of bedrooms: M (SD)	2.5 (0.9)	2.6 (1.0)	2.4 (0.9)	*t* (343)=1.15, *p*=.267
Type of dwelling (%)				
detached house	21.6	21	28	χ^2=4.922, *p*=.295
semi-detached house	27.7	25	31	
mid-terraced house	25.9	27	20	
End-terraced house	8.4	9	6	
flat/maisonette/other	16.4	17	15	
Orientation of dwelling (%)				
all rooms facing the street	4.4	4	5	χ^2=2.427, *p*=.489
all rooms facing the back yard/court	3.8	5	2	

Table 6. 3 Characteristics of the respondents in questionnaire variants 1 and 2

Characteristic	Respondents			Chi-square test (χ^2) or *t*-test (*t*) for difference between variants
	Total	Questionnaire variants		
		1	2	
rooms at both sides	79.1	76	82	
rooms facing three sides or more	12.8	14	10	
Years living at current address: M (SD)	16.9 (14.1)	16.6 (14.6)	17.7 (12.7)	t (350)=-.663, p=.645
Time spent indoors and outdoors				
hours indoors per day: M (SD)	16.7 (11.5)	16.9 (12.9)	16.1 (5.9)	t (319)=.461 p=.322
hours outdoors per day: M ((SD)	4.0 (5.8)	4.1 (6.4)	4.0 (3.8)	t (319)=.111, p=.583
Ownership of accommodation (%)				
owned	68.3	67	68	χ^2=0.771, p=.942
rented	31.7	30	30	
Sound-proofed windows (%)	90.2	89	90	χ^2=0.529, p=.912

**p<0.05; M - mean; SD - standard deviation.

Main outcome variables

The proportions of respondents who noticed noise from wind turbines were no different (X^2=0.446, p=0.800) across the two variants, as shown in Table 6.4.

Table 6. 4 Evaluations on wind turbine noise across the two questionnaire variants.

Outcome variables	Questionnaire variants 1	Questionnaire variants 2	Statistical test of distribution between variants
Notice WTN			
no [*n* (%)]	210 (80.5)	77 (80.2)	Chi-square test: χ^2=0.446, p=.800
yes [*n* (%)]	42 (16.1)	15 (15.6)	
don't know [*n* (%)]	3 (1.1)	2 (2.1)	
WTN annoyance			
not at all [*n* (%)]	47 (18.0)	19 (19.8)	Chi-square test: χ^2=3.488, p=.746
slightly [*n* (%)]	12 (4.6)	5 (5.2)	
moderately [*n* (%)]	10 (3.8)	3 (3.1)	
very [*n* (%)]	4 (1.5)	1 (1.0)	
extremely [*n* (%)]	1 (0.4)	1 (1.0)	
N/A not notice [*n* (%)]	178 (68.2)	62 (64.4)	
not given [*n* (%)]	1 (0.4)	2 (2.1)	

When those who noticed wind turbine noise were further asked for annoyance with the wind turbine noise, 64% of them in Variant 1 indicated to be annoyed, compared to 67% in variant 2. This difference was not statistically significant (X^2=3.488, p=0.746).

The characteristics of the respondents and their responses to main questions in the two variants looked reasonably similar, therefore, in the following analysis, effects of wind turbine noise on noise evaluation is examined by pooling the data across the two variants, controlling for long-standing illness that differed significantly between variants.

6.3 Descriptive Statistics on Questionnaire Responses to Wind Turbine Noise

6.3.1 Noise evaluations

Evaluations on wind turbine noise among other nuisances

The proportions of respondents who noticed and were annoyed by wind turbine noise and other environmental nuisances are shown in Fig. 6.2. Overall, 16% of the respondents (n=59) noticed the wind turbine noise and 11% of the respondents (n=39) were being annoyed by it when asked alongside a set of environmental nuisances. At the same time, 38% (n=138) were annoyed by the noise from neighbours and 41% (n=147) were annoyed by traffic noise. Of those who noticed wind turbine noise, 41% were not annoyed by the noise. This proportion of respondents who noticed but were not annoyed by wind turbine noise was higher than the proportion of those who noticed but were not annoyed by any other environment nuisance.

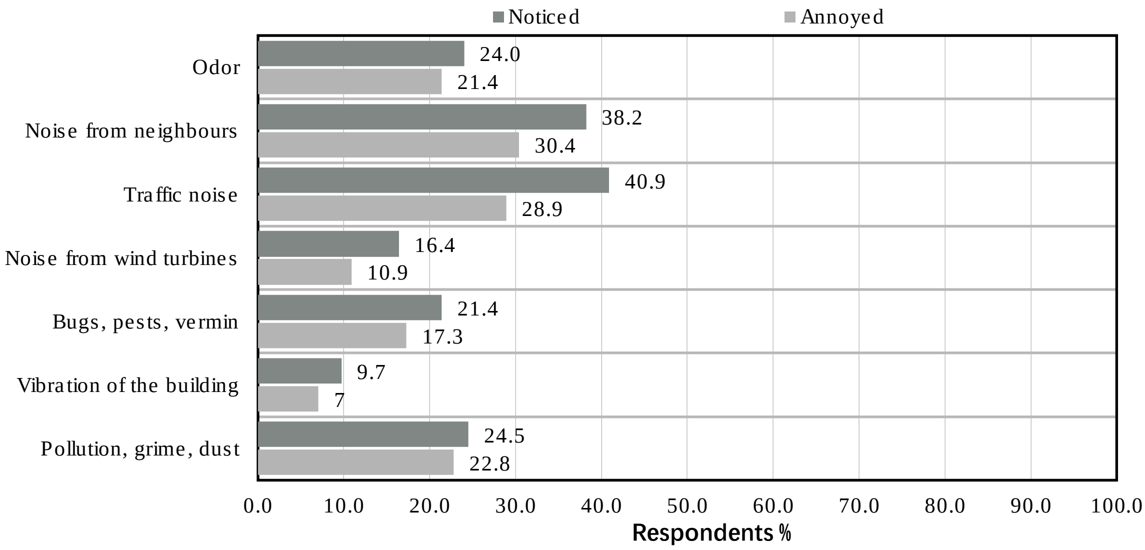


Figure 6. 2 Respondents who noticed and were annoyed by wind turbine noise and other environmental nuisances (n=368).

Evaluation on wind turbine noise related to source-receiver distance

Figure 6.3 shows the percentage of 'noticed' and annoyed respondents in different distance ranges. The percentage of disturbed respondents decreased with source-receiver distance. When the wind turbine was over 900m away from the residence, the percentage of noticed and annoyed respondents decreased to 8.1% and 2.7% respectively. Further increasing the distance made small difference on the percentage of disturbed respondents.

In addition, it was also found that 80% of the annoyed respondents were living within 850m, and 90% were living within 900m from the wind turbine. Therefore, from the above result, 900m might work as a proper separation distance between the wind turbine and the nearest residence for the noise management of suburban wind farms with one or two modern turbines.

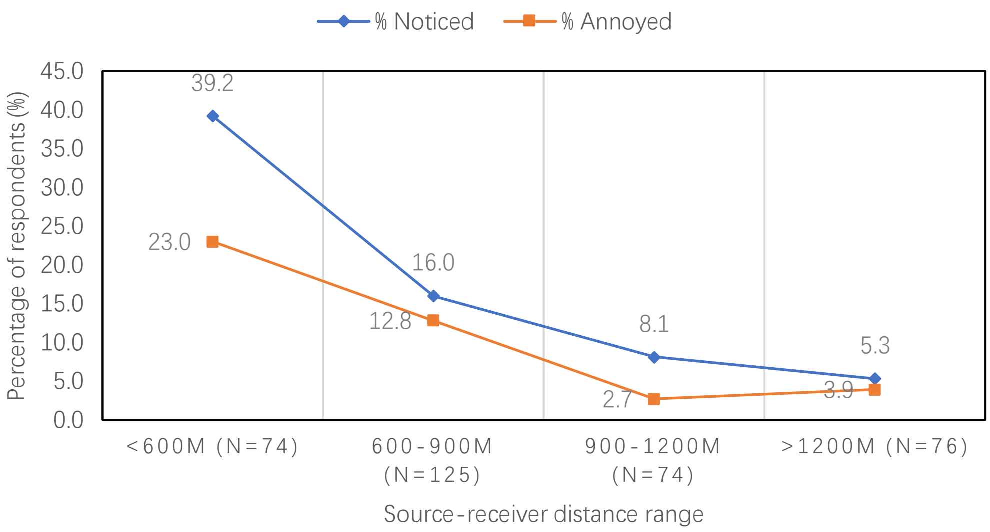


Figure 6. 3 Percentage of noticed and annoyed respondents in each distance range.

Annoyance with wind turbine noise

When respondents in Variant 1 were further asked for annoyance with wind turbine noise in a separate question, 12% (n=32) indicated they were annoyed by the noise overall and 16% (n=45) were annoyed outdoors and 9% (n=25) were annoyed indoors. The proportions of respondents who noticed and were annoyed by wind turbine noise when wind is strong, when inside the dwelling, and when at night were even lower, as 9%, 2% and 6% of the respondents, respectively.

Similar questions on annoyance were used to test the internal consistency of the responses, by reliability analysis using Cronbach's alpha (Cronbach, 1951). The results indicate a high reliability of the questionnaire (details are shown in Table 6A.2 in Appendix IV). There was a high correspondence across the respondents to the question at the beginning of the questionnaire and in the more specific questions later (Cronbach's Alpha=0.883). In addition, all data had item-total correlations above 0.3, which indicated that all items correlated well with the total. Dropping item "Q13 annoyed when inside with window closed" would slightly increase the overall alpha from 0.883 to 0.888. The deletion of other items did not improve reliability.

Evaluations on local sound environment

Figure 6.4 shows the percentage of respondents on each evaluation of sound environment at their dwelling. Overall, respondents had positive views on the sound environment at their dwellings. A high proportion of respondents evaluated the sound environment as quiet (71%), pleasant (58%), predictable (57%), calming (50%), and natural (46%). In terms of indices of interesting-boring, continuous-discontinuous, and directional-everywhere, more respondents maintained a neutral attitude. From a soundscape point of view, it might be better to introduce more natural and human sounds, such as bird songs and children's playing sound, to enhance the evaluation of an interesting sound environment.

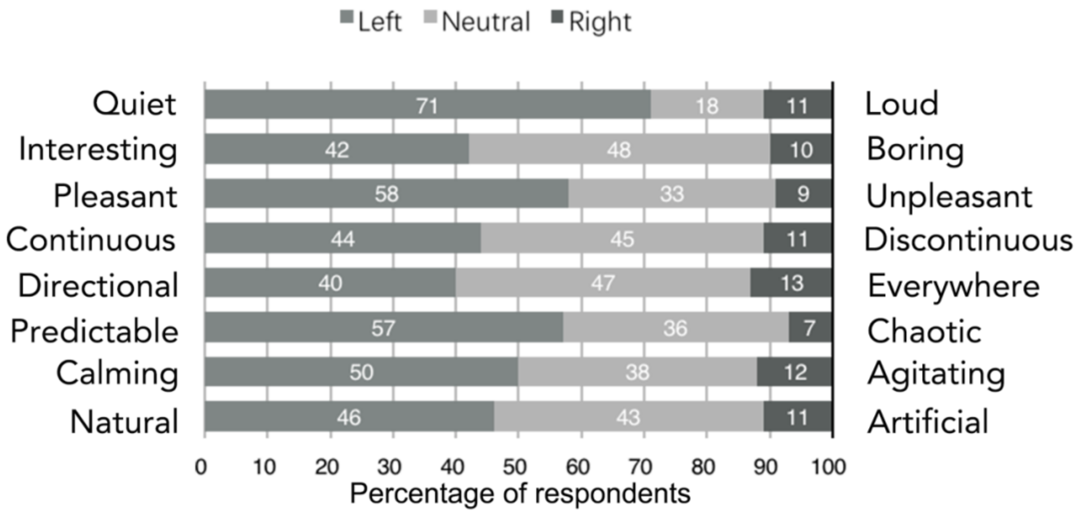


Figure 6. 4 Evaluation of overall sound environment at the dwelling. n=351.

Sound characteristics

More than half of the Variant 1 respondents (55%) described the wind turbine as noiseless/quiet. Swishing (29%) and whooshing (20%) were the most common sound characteristics described by the respondents, which are verbal descriptors of low frequency components of the sound from wind turbines. The other verbal descriptors of the sound character, including beating, whistling, pulsating and throbbing, were each mentioned by less than 6% of the respondents.

6.3.2 Attitudinal and visual factors

Attitude

Participants in Variant 1 were asked for their judgments on wind turbines using 14 adjectives. The adjectives that were agreed to by the most respondents were environmental friendly (71%), efficient (41%), necessary (38%), and harmless (37%). “Ugly” was the most often selected among the negative adjectives (23%), while “pretty” was much less selected by the respondents (6%). “Dangerous” and “threatening” were the least often selected, by 4% and 2% respectively.

Factor analysis was performed using SPSS to identify the main factors for the respondents’ attitudes to wind turbines. The results are shown in Table 6.5. Oblique rotated principle axis factoring analysis was employed to extract the oblique factors underlying the 14 inter-related adjectives. Five factors were determined, which accounted for 42% of the total variance. It can be seen that factor 1 (22%) was mainly associated with a positive attitude to the utility of wind turbines, including environmental friendly, efficient, harmless, necessary and natural/green. Factor 2 (7%) was related to a positive attitude to the appearance of wind turbines, including pretty and attractive. Factor 3 (6%) was mostly associated with a negative attitude to the necessity of exploiting wind energy, including unnecessary and threatening. Factor 4 (5%) was about a negative attitude to their efficiency, concentrating on not efficient. Factor 5 (3%) was principally related to a negative attitude to environmental impacts, including not environmental friendly, dangerous, ugly and unnatural.

Table 6. 5 Factor analysis of attitudes to wind turbines

		Pattern Matrix				
Question items (*n*%)	n%	Factor 1 *(Positive to utility)*	Factor 2 *(Positive to appearance)*	Factor 3 *(Negative to necessity)*	Factor 4 *(Negative to efficiency)*	Factor 5 *(Negative to environmental impact)*
% of variance (total 42.092)		21.533	7.134	5.939	4.750	2.736
1. Environmental friendly	71%	-0.690				
2. Not environmental friendly	6%					0.332
3. Efficient	41%	-0.456				
4. Not efficient	15%				0.843	
5. Dangerous	4%					0.306
6. Harmless	37%	-0.525				
7. Unnecessary	11%			-0.308		
8. Necessary	38%	-0.520				
9. Ugly	23%					0.589
10. Pretty	6%		0.736			
11. Attractive	13%		0.534			
12. Threatening	2%			-0.920		
13. Natural / green	26%	-0.360				
14. Unnatural	17%					0.577

Factor analysis of the attitude evaluation. Kaiser-Meyer-Olkin Measure of Sampling Adequacy, 0.757; cumulative 42%; extraction method, principal axis factoring; rotation method, oblique rotations (Oblimin with Kaiser Normalization); N=261.

Negative correlations were found between factor 1 (positive attitude to the utility of wind project) and being retired (r_S=-0.179, p=0.004). Factor 1 was also negatively correlated to age (r_S=-0.159, p=0.011). Factor 4 (negative attitude to the efficiency of wind project) and factor 5 (negative attitude on the environmental impact) were negatively correlated to being female. Self-reported degree of sustainability in life was positively correlated to factor 1 (positive attitude to the utility) (r_S=0.197, p=0.001) and factor 2 (positive attitude to the appearance) (r_S=0.143, p=0.020). Factor 1 and 2 were also positively correlated to being single. Attitudes to wind turbine noise were not correlated to income, educational qualification, housing type or orientation.

Visibility of wind turbine(s) from home

Of the 262 respondents in Variant 1 who were asked to indicate the visibility of wind turbine(s) from their residence, 31% (n=80) responded that they could not see any from home; 31% (n=80) could only see wind turbine(s) from a window; 12% (n=30) could only see it/them from the garden or front yard; and 25% (n=66) could see wind turbine(s) from both a window and the garden/yard.

Having wind turbine(s) within sight from both a window and the garden was positively correlated to site B (r_S =0.194, p=0.002) and negatively correlated to site C (r_S =-0.190, p=0.002). Visibility of wind turbine(s) was not correlated to attitudes to the local wind turbine(s), housing type, or orientation.

Other factors related to wind turbines

Participants were invited to give additional comments, on their living environment, well-being, and anything about the questionnaire. Of the respondents, 23% (n=81) gave additional comments, of which half (n=40) mentioned wind turbines; 75% of those comments (n=30) were positive and the rest 25% (n=10) were negative. Most of the comments about wind turbines were from respondents in Variant 1, who were informed about the purpose of the survey. Four respondents from Variant 2, who were not informed about the purpose, also gave comments about wind turbines, with three of them positive and one negative. No respondents in this study had a financial stake or were employees of the local wind farm.

6.4 The Relationship between Wind Turbine Noise and Noticeability of the Noise

Overall, 16% of the respondents indicated they notice the wind turbine noise. The proportion of 'noticed' respondents increased from 5% (n = 5, 95%CI:

1%-11%) at sound category below 30dBA to 47% (n = 25, 95%CI: 33%-61%) at sound category above 40dBA. Results of bivariate correlations indicated that noise exposures were strongly correlated to noticeability of wind turbine noise (r_S =0.346, p<0.001).

Moderating factors

To explore the influence of personal factors, binary multiple logistic regressions were used to identify variables that had significant effects on noticing the sound. The modelled maximum SPL at dwelling was added to the regression to represent wind turbine noise exposures. Personal factors that were hypothesised to have an effect were then added to the regression model one-by-one. Twenty-four regression models were created (full results see Table 6A.3 in Appendix IV). It was found that when adding demographic, attitudinal, and architectural factors as independent variables, the influence of the SPL was still statistically significant. The odds of noticing wind turbine noise were not statistically different between questionnaire variants but were significantly different across sites. Age and having a degree level of qualification were found to have a significant influence. Noticing wind turbine noise was not associated with sex or income, and was not different statistically among susceptible respondents who had long-standing illness, being retired or on maternity leave. Ownership and length of residency related to wind turbine installation were not associated with noticing the sound.

Of the items measuring attitudinal factors, “environmental sustainability is a low priority for me compared to other things in life” was negatively associated with noticing wind turbine noise. Of the factors measuring attitudes to wind turbine projects in questionnaire variant 1, having a negative attitude to the environmental impact of wind turbines, expressed as not environmental friendly, dangerous, ugly or unnatural, were positively associated with the odds of noticing the sound. Having positive attitudes to wind turbines was not associated with their noticeability of the sound.

Architectural factors were found to influence respondent's noticeability of wind turbine noise. Living in an end-terraced house and flat compared to semi-detached house decreased the odds of noticing the sound. Building orientation was not a significant predictor of noticing wind turbine noise. Self-report of visibility of the turbine only from a window or the garden/yard did not statistically significantly increase the odds of noticing wind turbine noise, but those seeing the wind turbine from both a window and garden/yard were four times more likely to notice the sound compared to those who cannot see any from home.

A multivariate regression model for the whole respondents was created to predict the dependent variable of noticeability of wind turbine noise using the independent variable of SPL and personal factors that had significant influence as noted above. Another regression model was created for Variant 1 respondents to examine the effects of attitude and visibility that were only included in Variant 1. Age and housing type were excluded from the model because they were no longer statistically significant. Site dummies were always kept in the model to control for the difference between sites, although they were no longer significant. As shown in Table 6.6, qualification and sustainability were associated with noticeability of wind turbine noise, to a higher degree than when tested one by one. Having rooms facing three sides or more increased the probability of noticing the noise than facing two sides of the building. In Model 2, respondents who could see the local wind turbine from both window and garden were four times more likely to notice the noise than those cannot see any from home. Respondents who had a negative attitude to environmental impact were three times more likely to notice the sound compared to those who did not indicate such negative impact.

Table 6. 6 Association between noticed wind turbine noise, SPLs, and covariates

Model	Variables	*p*-value	Odds Ratio (OR)	95% CI for OR
	Noticed WTN *[n=357, R^2=0.341, $p_{(H-L)}$=0.764]*			
1	SPL (maximum)	0.000	**1.21**	(1.11-1.30)
(Variant 1+2)	*Highest qualification (ref: O-level)*			
	- No qualification	0.293	0.63	(0.27-1.48)
	- A-level	0.466	0.67	(0.23-1.93)
	- Higher education below degree	0.015	**0.20**	(0.05-0.72)
	- Degree level	0.007	**0.17**	(0.04-0.61)
	- Other (professional certificate)	0.631	0.683	(0.14-3.22)
	Sustainable (1-6)	0.003	**1.50**	(1.15-1.97)
	Building orientation (ref: facing both sides)			
	- All rooms facing front	0.307	0.32	(0.03-2.82)
	- All rooms facing back	0.345	0.43	(0.07-2.42)
	- Rooms facing three sides or more	0.027	**3.09**	(1.13-8.43)
	Site (ref: Site C)			
	- Site A	0.688	0.82	(0.31-2.14)
	- Site B	0.137	1.89	(0.81-4.40)
	Variant 2	0.901	1.04	(0.4902.24))
	Noticed WTN *[n=254, R^2=0.339, $p_{(H-L)}$=0.331]*			
2	SPL	0.003	**1.17**	(1.05-1.29)
(Variant 1)	*Highest qualification (ref: O-level)*			
	- No qualification	0.326	0.57	(0.19-1.73)
	- A-level	0.097	0.32	0.08-1.22)
	- Higher education below degree	0.014	**0.15**	(0.03-0.68)
	- Degree level	0.008	**0.13**	(0.03-0.58)
	- Other (professional certificate)	0.646	0.62	(0.08-4.75)
	Sustainable (1-6)	0.007	**1.58**	(1.13-2.19)
	Building orientation (ref: facing both sides)			
	All rooms facing front	0.356	0.30	(0.02-3.75)
	All rooms facing back	0.404	0.43	(0.05-3.12)
	Rooms facing three sides or more	0.038	**3.28**	(1.06-10.07)
	Site (ref: Site C)			
	- Site A	0.289	0.53	(0.16-1.70)
	- Site B	0.719	0.81	(0.27-2.44)
	Variables only in Variant 1 below:			
	Visibility of the WT (ref: can't see any from home)			
	- See WT from window	0.459	1.60	(0.46-5.59)
	- See WT from garden	0.655	0.68	(0.13-3.61)
	- See WT from both window & garden	0.025	**4.54**	(1.20-17.11)
	Negative attitude to the environmental impact of WT (no/yes)	0.007	**3.21**	(1.37-7.54)

Statistically significant associations in boldface.

6.5 The Relationship between Wind Turbine Noise and Annoyance with the Noise

Annoyance with wind turbine noise was examined alongside several other environmental nuisances in both Variants 1 and 2. Respondents in Variant 1 were further asked to indicate their annoyance with wind turbine noise in specific situations. Table 6.7 shows the proportion of respondents who were annoyed with wind turbine noise by categories of noise exposures. The proportion of those annoyed by wind turbine noise increased with sound category, from 3% (n=3, 95%CI: 0%-6%) in the lowest to 30% (n=16, 95%CI: 17%-43%) in the highest. In the answer to the specified questions in Variant 1, 12% of the respondents reported annoyance with wind turbine noise, where 16% reported annoyance outdoors and 9% annoyed indoors. In terms of response to wind turbine noise in different situations, more respondents were annoyed by the noise when wind was strong or at night, fewer were annoyed when they were inside the dwelling with the windows closed. Chi-square tests show that annoyance with wind turbine noise were significantly different between sound categories.

Table 6. 7 Noticeability of and annoyance with wind turbine noise related to sound exposures shown as percentage within each sound category with 95% CI.

	Total	Maximum sound pressure levels at dwelling [dB(A)]				Chi-square test
Percentage (95% CI)		<30	30-35	35-40	>40	
Variant 1+2						
Annoyed among other nuisances	11 (8-15)	3 (0-6)	8 (3-14)	13 (7-21)	30 (17-43)	χ^2=24.598, *p*=**.000**
Variant 1						
Annoyed overall	12 (8-16)	1 (0-4)	9 (3-16)	20 (10-31)	25 (12-39)	χ^2=20.042, *p*=.**000**
Annoyed outdoors	16 (12-21)	4 (0-9)	14 (6-23)	22 (12-32)	35 (20-50)	χ^2=20.950, *p*=.**000**
Annoyed indoors	9 (6-13)	3 (0-7)	5 (0-10)	15 (7-25)	23 (10-37)	χ^2=16.255, *p*=.**001**

Table 6. 7 Noticeability of and annoyance with wind turbine noise related to sound exposures shown as percentage within each sound category with 95% CI.

Percentage (95% CI)	Total	Maximum sound pressure levels at dwelling [dB(A)]				Chi-square test
		<30	30-35	35-40	>40	
Annoyed when wind is strong	9 (5-12)	1 (0-4)	9 (3-16)	7 (2-14)	25 (11-40)	χ^2=24.735, *p*=**.000**
Annoyed when inside with window closed	2 (0-4)	0	2 (0-5)	2 (0-6)	8 (0-17)	χ^2=7.871, *p*=**.049**
Annoyed when at night	6 (3-9)	1 (0-4)	6 (1-12)	8 (2-16)	13 (3-24)	χ^2=9.381, *p*=**.025**

Results of bivariate correlations indicated that noise exposures were more strongly correlated to noticeability of wind turbine noise (r_S=0.346, p<0.001) than to annoyance (r_S =0.238, p<0.001). Among all the situations, noticeability of and annoyance with wind turbine noise at night had the lowest correlation with noise exposures, but were both significant at the 0.05 level.

Moderating factors

Using a similar method as for noticeability, binary logistic regression was used to examine the influence of personal factors on annoyance (see Table 6A.4 in Appendix IV). The dependent variable annoyance that measured on a 1-5 scale was dichotomised into “not annoyed” (1) and “annoyed” by various degrees (2-5). The results of the 24 regression models show that the odds of being annoyed by wind turbine noise increased significantly with SPL. The odds of annoyance were not statistically different between questionnaire variants and sites (model 2, 3). Age and qualification were significantly associated with annoyance. The odds of annoyance were not significantly associated with sex, income, illness, ownership and other socioeconomic factors as shown in Table 6A.4.

Attitudinal factors including noise sensitivity, sustainability and environmental friendly were not significantly associated with annoyance. Of the five factors measuring attitude to wind farms in Variant 1, only negative attitude to environmental impact was significantly associated with annoyance. Holding a positive attitude to the utility and appearance of the wind farm, expressed as environmental friendly, necessary, natural or pretty, did not significantly decreased the odds of annoyance. Respondents who were negative to the necessity and efficiency of developing wind energy, described as unnecessary, threatening, or inefficient, were not significantly different in whether being annoyed by wind turbine noise or not. Similar to the result for noticing the noise, having the wind turbine(s) within sight from both a window and the garden/yard significantly increased the odds of being annoyed by wind turbine noise by four times than cannot see any from home.

Table 6.8 shows the association between annoyance with wind turbine noise and maximum SPL, controlling for known covariates. Model 1 predicted the annoyance using the whole data and Model 2 predicted annoyance only using the main sample from variant 1. For both models, annoyance with wind turbine noise were positively associated with SPLs. Age was positively associated with annoyance at a diminishing rate. Taking both variant 1 and 2 into account, having degree level qualification as opposite to O-level significantly decreased the probability of being annoyed, while having higher education below degree was found to decrease the odds of annoyance in variant 1. Annoyance with wind turbine noise was not significantly different between variants and sites. In model 2, visibility of the wind turbine was no longer significantly changing the odds of being annoyed when controlling for other covariates. Holding a negative attitude to the environmental impact of wind turbines was positively associated with annoyance.

Table 6. 8 Association between annoyed by wind turbine noise, SPLs, and covariates

Model	Variables	*p*-value	Odds Ratio (OR)	95% CI for OR
	Annoyed by WTN *[n=356, R^2=0.264, $p_{(H-L)}$=0.308]*			
1	SPL	0.000	**1.18**	(1.08-1.28)
(Variant 1+2)	Age	0.011	**1.24**	(1.05-1.47)
	Age squared	0.006	**0.81**	(0.69-0.94)
	Highest qualification (ref: O-level)			
	- No qualification	0.153	0.49	(0.18-1.31)
	- A-level	0.087	0.29	(0.07-1.19)
	- Higher education below degree	0.077	0.31	(0.08-1.14)
	- Degree level	0.047	**0.25**	(0.06-0.98)
	- Other (professional certificate)	0.602	1.51	(0.32-7.22)
	Site (ref: Site C)			
	- Site A	0.928	0.94	(0.30-2.93)
	- Site B	0.242	1.77	(0.67-4.68)
	Variant 2	0.799	0.89	(0.38-2.11)
	Annoyed by WTN *[n=254, R^2=0.339, $p_{(H-L)}$=0.331]*			
2	SPL	0.050	**1.12**	(1.00-1.26)
(Variant 1)	Age	0.025	**1.24**	(1.03-1.48)
	Age squared	0.016	**0.80**	(0.67-0.96)
	Highest qualification (ref: O-level)			
	- No qualification	0.167	0.40	(0.11-1.48)
	- A-level	0.074	0.21	(0.04-1.17)
	- Higher education below degree	0.039	**0.22**	(0.05-0.93)
	- Degree level	0.073	0.25	(0.06-1.14)
	- Other (professional certificate)	0.634	1.69	(0.20-14.41)
	Site (ref: Site C)			
	- Site A	0.599	0.69	(0.17-2.78)
	- Site B	0.962	1.03	(0.29-3.68)
	Variables only in Variant 1 below:			
	Visibility of the WT (ref: can't see any from home)			
	- See WT from window	0.249	2.43	(0.54-10.98)
	- See WT from garden	0.851	0.82	(0.10-6.80)
	- See WT from both window & garden	0.062	4.81	(0.93-24.95)
	Negative attitude to the environmental impact of WT (no/yes)	0.001	**4.84**	(1.84-12.73)

Statistically significant associations in boldface.

Annoyance outdoors and indoors

The main sample in Variant 1 were asked to indicate their annoyance outdoors and indoors by wind turbine noise using specified and standardised questions (ISO, 2003). Binary logistic regressions were used to compare factors that influence a respondent's annoyance outdoors and indoors, controlling for identical personal factors. The results of the regression models are shown in Table 6.9. Age was no longer significantly associated with annoyance outdoors and indoors, hence excluded from the table.

One dB(A) increase of sound levels increased the odds of annoyance outdoors by 1.14, slightly lower than annoyance indoors. Respondents having O-level as the highest qualification were most likely to be annoyed outdoors, but were not significantly different in being annoyed indoors. Noise sensitivity and sustainability in life did not significantly change annoyance outdoors and indoors of the main sample.

Living in a dwelling with windows facing three sides or more significantly increased the probability of both outdoor and indoor annoyance. Besides, having all rooms facing the front of the building was associated with significantly higher probability of annoyance outdoors. Visibility of the wind turbine from both a window and garden/yard significantly increased the odds of annoyance indoors, but not significant for annoyance outdoors.

The effects of negative attitudes to environmental impact on annoyance were further explored by adding three specific descriptions in the models. It was found that annoyance outdoors was positively associated with "not environmental friendly"; while annoyance indoors was positively associated with "dangerous". Ugly was the rating that associated with both annoyance outdoors and indoors.

Table 6. 9 Regressions modelling respondent's annoyance outdoors and indoors using the Variant 1 sample

Noise and moderating variables	**Annoyed outdoors** *N=254; R^2=0.430, $p_{(H-L)}$=0.392*		**Annoyed indoors** *N=253; R^2=0.413, $p_{(H-L)}$=0.996*	
	p-value	OR (95%CI)	*p*-value	OR (95%CI)
SPL (maximum SPL at dwelling)	0.021	**1.14** (1.02-1.28)	0.045	**1.15** (1.03-1.32)
Site (ref: Site C)				
- Site A	0.609	1.37 (0.41-4.57)	0.747	1.31 (0.25-6.74)
- Site B	0.540	1.46 (0.43-4.92)	0.288	2.32 (0.49-10.95)
Highest qualification (ref: O-level, n=51)				
- No qualification (n=75)	0.000	**0.09** (0.02-0.33)	0.078	0.25 (0.06-1.17)
- A-level (n=35)	0.023	**0.19** (0.04-0.79)	0.110	0.25 (0.05-1.37)
- Higher education below degree (n=34)	0.002	**0.08** (0.02-0.40)	0.125	0.28 (0.06-1.42)
- Degree level (n=51)	0.016	**0.21** (0.06-0.75)	0.159	0.26 (0.04-1.68)
- Other (such as professional certificate, n=11)	0.883	1.15 (0.18-7.32)	0.603	1.80 (0.20-16.60)
Sensitivity to noise (1-6)	0.226	1.22 (0.89-1.67)	0.271	1.25 (0.84-1.85)
Sustainability (1-6)	0.968	1.01 (0.72-1.40)	0.742	0.93 (0.61-1.42)
Orientation (ref: rooms facing both sides, n=197)				
- All rooms facing front (n=10)	0.006	**10.89** (1.99-59.48)	0.999	0.00 0.00
- All rooms facing back (n=12)	0.918	0.91 (0.14-5.76)	0.470	0.41 (0.04-4.57)
- Rooms facing three sides or more (n=36)	0.009	**4.62** (1.47-14.59)	0.011	**5.51** (1.48-20.45)
Visibility of the WT (ref: see from window, n=80)				
- Canot see any, n=80	0.817	1.16 (0.32-4.23)	0.236	2.83 (0.51-15.79)
- See WT from garden (n=30)	0.716	1.33 (0.29-6.02)	0.369	0.29 (0.02-4.36)
- See WT from both window & garden (n=66)	0.083	2.74 (0.88-8.58)	0.040	**4.95** (1.08-22.73)
Negative attitude to WT				
- Not environmental friendly (n=22)	0.003	**6.01** (1.86-19.44)	0.448	1.71 (0.43-6.80)
- Dangerous (n=10)	0.345	2.34 (0.40-13.64)	0.034	**7.73** (1.16-51.44)
- Ugly (n=60)	0.002	**4.61** (1.77-12.04)	0.014	**4.26** (1.34-13.61)

6.6 Effect of Quiet Façade Exposure on Noise Evaluation

It was demonstrated in Chapter 4 that building morphological design can create large variations of wind turbine noise levels around a dwelling. The difference between the noise at the most and least exposed façades can be up to 13dBA. In this section, two more indicators of noise exposures were used to represent the noise received by each respondent - the *minimum* and *average* A-weighted SPLs at the dwelling façade. They presented the noise levels at the least-exposed or quietest façades, and at all façades as an average, respectively.

The minimum and average SPLs at each respondent's dwelling were obtained using noise mapping in CadnaA, as presented in Section 3.2 in the method chapter. As the effects of maximum façade SPLs on noise evaluation, health and well-being had been demonstrated in the previous section, this section used the same regression model but replaced the explanatory variable of maximum SPL with minimum and average SPLs, in a purpose to compare the strength of the associations between different noise indicators (max/min/average) and noise evaluation.

The minimum façade SPLs at respondents' dwellings ranged from 5 to 39dBA, with a mean of 21.7dBA. The average façade SPLs ranged from 9 to 39dBA, with a mean of 26.0dBA. The difference between maximum and minimum façade SPLs were in the range of 0 to 17dBA, the mean of which was 10.8dBA.

As shown in Table 6.10, the Pearson correlation *r* between each pair of noise illustrates high correlations between the maximum, average, and minimum SPLs, where all correlations are significant at the 0.01 level.

Table 6. 10 Bivariate correlations between maximum, minimum, average facade exposures, and the difference between maximum and minimum exposures.

Pearson Correlation	Maximum SPL	Average SPL	Minimum SPL	SPL Difference (Max-Min)
Maximum SPL	1	**.942****	**.883****	**.346****
Average SPL		1	**.951****	.089
Minimum SPL			1	**-.135***
SPL Difference (Max-Min)				1

***. Correlation is significant at the 0.01 level (2-tailed); *. Correlation is significant at the 0.05 level (2-tailed)*

It is also important to note that the differences between maximum and minimum façade SPLs were also significantly correlated to maximum SPLs at the 0.01 significant level. It showed that larger differences between the most- and least-exposed façades were more likely to exist among dwellings with high maximum façade exposures.

Table 6.11 shows the bivariate correlations between subjective noise evaluations and different indicators of wind turbine noise exposures, where all correlations were significant at the 0.05 level. It indicated that maximum, minimum, and average SPLs were all significantly related to noticeability of and annoyance with wind turbine noise. It is worth noting that the difference between maximum and minimum SPLs was not correlated to noise evaluations.

Table 6. 11 Bivariate correlations between different noise indicators and subjective noise evaluations

Spearman's r	Sound pressure level (SPL) of wind turbine noise		
	Maximum SPL	Minimum SPL	Average SPL
Variant 1+2			
a) Noticeability among other nuisances *(binary)*	**0.346*****	0.330***	0.340***
b) Annoyance among other nuisances *(5-scale)*	0.238***	**0.242*****	**0.242*****
Variant 1			
c) Annoyance overall *(5-scale)*	0.264***	**0.268*****	0.245***
d) Annoyance outdoors *(11-scale)*	0.246***	**0.252*****	0.251***
e) Annoyance indoors *(11-scale)*	**0.213****	0.210**	0.203**
f) Noticeability when at night *(binary)*	0.210**	**0.217*****	0.208**
g) Annoyance when at night *(5-scale)*	0.155*	**0.174****	0.152*

****. correlation is significant at the 0.001 level; **. correlation is significant at the 0.01 level; *. correlation is significant at the 0.05 level. Higher Spearman's r in darker colour.*

Comparing the strength of the three correlations for each noise evaluations of the whole sample, as shown in Table 6.11, it was found that maximum SPL at the dwelling had the strongest correlation to noticeability (a), while minimum and average SPLs at the dwelling were more strongly correlated to annoyance (b), although the difference in Spearman's *r* was small. In terms of annoyance in specific situations obtained in Variant 1, levels of noise exposure on the quietest facade were associated slightly more strongly with annoyance overall and outdoors (c, d) than exposure on the most exposed facade, while the latter was strongly correlated to annoyance indoors (e).

Comparing the significance level of the correlations, it was found that the minimum SPL at the dwelling was more significantly associated to both noticeability of and annoyance with wind turbine noise at night (f, g) than the other two indicators. It indicated that noise exposure at the quietest façades was an important indicator for noise impact management at night.

Binary logistic regressions were carried out using being annoyed by wind turbine noise or not (asked among other nuisances) as a dependent variable, minimum or average SPL at the dwelling as an independent variable, controlling for other covariates. As visibility of the turbine and attitude to wind power projects were only included in Variant 1, regression analyses were also carried out using the Variant 1 sample to investigate the effect of these factors. The moderating variables included in the regressions were identical to those in the final regression model with maximum SPL, as presented in Section 6.5 (Table 6.8). The results of regression analyses are shown in Table 6.12 for minimum SPL and Table 6.13 for average SPL.

As shown in Tables 6.12 and 6.13, the minimum and average SPLs were both positively associated with annoyance. One dB(A) increase in minimum SPL increased the odds of annoyance by 1.166. The odds ratio of average SPL was slightly higher, of 1.182, which was also slightly higher than the odds ratio of maximum SPL tested in previous chapters, which was 1.177 (see Table 6.8).

It is worth noting that the difference between maximum and minimum SPLs was not associated with annoyance if added to the model. The significant association between minimum/average SPLs and annoyance was not changed. It indicated that the *levels* of noise rather than the *differences* between the maximum and minimum levels at the dwelling took a main explanatory role on noise annoyance due to wind turbines.

The effects of personal factors were similar to the results for maximum SPL as reported in Section 6.5. Age, negative attitude to wind energy, and visibility of the turbine from both a window and the garden were positively associated with annoyance. Having an A-level, or other higher education, or degree level qualifications compared to having O-level as the highest qualification moderated the annoyance with wind turbine noise.

Table 6. 12 Association between annoyed by wind turbine noise, minimum SPL, and covariates

Model	Variables	*p*-value	Odds Ratio	95% CI
	Annoyed by WTN *[n=354, R^2=0.256, $p_{(H-L)}$=0.943]*			
1	SPL (minimum)	0.000	**1.17**	(1.07-1.26)
(Variant 1+2)	Age	0.008	**1.26**	(1.06-1.49)
	Age squared	0.005	**0.80**	(0.69-0.93)
	Highest qualification (ref: O-level)			
	- No qualification	0.126	0.47	(0.18-1.24)
	- A-level	0.043	**0.23**	(0.05-0.96)
	- Higher education below degree	0.093	0.33	(0.09-1.20)
	- Degree level	0.055	0.26	(0.07-1.03)
	- Other (professional certificate)	0.619	1.48	(0.32-6.86)
	Site (ref: Site C)			
	- Site A	0.999	1.00	(0.32-3.14)
	- Site B	0.162	2.01	(0.76-5.37)
	Variant 2	0.865	0.93	(0.39-2.19)
	Annoyed by WTN *[n=254, R^2=0.341, $p_{(H-L)}$=0.898]*			
2	SPL (minimum)	0.040	**1.12**	(1.01-1.26)
(Variant 1)	Age	0.020	**1.24**	(1.01-1.49)
	Age squared	0.013	**0.80**	(0.67-0.96)
	Highest qualification (ref: O-level)			
	- No qualification	0.142	0.37	(0.10-1.40)
	- A-level	0.042	**0.16**	(0.03-0.93)
	- Higher education below degree	0.051	**0.24**	(0.06-1.01)
	- Degree level	0.075	0.26	(0.06-1.15)
	- Other (professional certificate)	0.696	1.51	(0.19-12.02)
	Visibility of the WT (ref: can't see any from home)			
	- See WT from window	0.210	2.65	(0.58-12.10)
	- See WT from garden	0.891	0.86	(0.11-7.06)
	- See WT from both window & garden	0.026	**6.13**	(1.24-30.07)
	Negative attitude to the environmental impact of WT	0.001	**4.95**	(1.88-13.07)
	Site (ref: Site C)			
	- Site A	0.600	0.69	(0.17-2.74)
	- Site B	0.971	0.98	(0.27-3.60)

Table 6. 13 Association between annoyed by wind turbine noise, average SPL, and covariates

Model	Variables	*p*-value	Odds Ratio	95% CI
	Annoyed by WTN *[n=354, R^2=0.268, $p_{(H-L)}$=0.123]*			
1	SPL (average)	0.000	**1.18**	(1.09-1.29)
(Variant 1+2)	Age	0.008	**1.26**	(1.06-1.49)
	Age squared	0.004	**0.80**	(0.69-0.93)
	Highest qualification (ref: O-level)			
	- No qualification	0.131	0.47	(0.18-1.25)
	- A-level	0.050	**0.24**	(0.06-0.99)
	- Higher education below degree	0.076	0.31	(0.08-1.13)
	- Degree level	0.049	**0.25**	(0.06-0.99)
	- Other (professional certificate)	0.662	1.41	(0.30-6.68)
	Site (ref: Site C)			
	- Site A	0.944	0.96	(0.31-2.96)
	- Site B	0.315	1.66	(0.62-4.46)
	Variant 2	0.781	0.89	(0.37-2.09)
	Annoyed by WTN *[n=254, R^2=0.345, $p_{(H-L)}$=0.881]*			
2	SPL (average)	0.030	**1.13**	(1.01-1.27)
(Variant 1)	Age	0.019	**1.25**	(1.04-1.51)
	Age squared	0.013	**0.80**	(0.67-0.95)
	Highest qualification (ref: O-level)			
	- No qualification	0.144	0.37	(0.10-1.40)
	- A-level	0.047	**0.17**	(0.03-0.98)
	- Higher education below degree	0.038	**0.22**	(0.05-0.92)
	- Degree level	0.073	0.25	(0.06-1.14)
	- Other (professional certificate)	0.727	1.46	(0.18-12.09)
	Visibility of the WT (ref: can't see any from home)			
	- See WT from window	0.214	2.62	(0.57-11.96)
	- See WT from garden	0.919	0.90	(0.11-7.18)
	- See WT from both window & garden	0.034	**5.64**	(1.14-28.00)
	Negative attitude to the environmental impact of WT	0.001	**4.80**	(1.83-12.62)
	Site (ref: Site C)			
	- Site A	0.565	0.67	(0.17-2.61)
	- Site B	0.862	0.89	(0.24-3.29)

Being annoyed by wind turbine noise at night was also regressed on the three noise indicators one by one, controlling for personal covariates. It was found that minimum SPL was the only indicator that significantly increased the odds of annoyance at night. The results of the regression analysis are shown in Table 6.14.

Table 6. 14 Association between annoyed by wind turbine noise at night, minimum SPL, and covariates

Model	Variables	*p*-value	Odds Ratio	95% CI
	Annoyed by WTN at night *[n=248, R^2=0.539, $p_{(H-L)}$=0.997]*			
1	SPL (minimum)	0.025	**1.27**	(1.03-1.55)
(Variant 1)	Age	0.618	1.05	(0.87-1.27)
	Age squared	0.581	0.95	(0.78-1.15)
	Highest qualification (ref: O-level)			
	- No qualification	0.035	**0.07**	(0.01-0.83)
	- A-level	0.173	0.21	(0.02-2.00)
	- Higher education below degree	0.104	0.18	(0.02-1.42)
	- Degree level	0.648	0.61	(0.07-5.13)
	- Other (professional certificate)	0.869	1.50	(0.01-176.54)
	Visibility of the WT (ref: can't see any from home)			
	- See WT from window	0.413	2.86	(0.23-35.12)
	- See WT from garden	0.998	0.00	0.00
	- See WT from both window & garden	0.089	10.53	(0.70-159.51)
	Negative attitude to the environmental impact of WT (no/yes)	0.000	**65.69**	(9.37-460.41)
	Site (ref: Site C)			
	- Site A	0.640	1.67	(0.20-14.13)
	- Site B	0.778	0.71	(0.07-7.43)

As shown in Table 6.14, one dB(A) increase in the noise exposure at the least exposed façade increased the odds of being annoyed at night by 1.27, higher than the change in being annoyed in general, of 1.12 as shown in Table 6.12. Having a negative attitude to wind energy projects was positively associated with being annoyed at night, having no qualification compared to O-level as the highest qualification significantly decreased the odds of annoyance at night. The R-square of the model indicated that the minimum SPL at the dwelling and the included covariates could explain 53.9% of the variance in annoyance at night, which was the highest among all regression models on annoyance. It could be confirmed that wind turbine noise at the least-exposed façade was an important indicator for predicting night-time annoyance due to wind turbine noise.

To conclude, Section 6.6 reveals the important roles of quiet façade exposures (minimum and average SPLs) on wind turbine noise evaluation. Wind turbine noise might have wide-ranging impacts on the enjoyment of quiet places. It was found that the maximum SPL at the dwelling had the strongest correlation to noticeability, while minimum and average SPLs at the dwelling were more strongly correlated to annoyance, although the difference in Spearman's *r* was small. Results of regression analyses confirmed that minimum and average SPLs were both positively associated with annoyance, where the average SPL had a slightly higher odds ratio than the maximum SPL. It was found that noise level at the least-exposed façade (minimum SPL) was the only indicator that significantly increased the odds of annoyance at night, which could be an important indicator for night-time noise management.

6.7 Comparison with Previous Studies in Rural Areas – Effect of Contextual Factors in Suburban-Urban Environments

Figure 6.5 shows the proportion of respondents who noticed or were annoyed by wind turbine noise by categories of noise exposures in this study and in two previous studies (Pedersen et al., 2009; Pedersen & Waye, 2004). Pedersen and Waye's study (2004) was carried out in rural areas in Sweden, with a sample size of 341. Pedersen et al.'s study (2009) took into account both rural and suburban areas, which was carried out in the Netherlands with 725 respondents. Both previous studies used the calculated outdoor SPL to represent the wind turbine noise level at a respondent's dwelling. To make the dose-response curves comparable, wind turbine noise at the most exposed façade in this study was subtracted by 3dBA to exclude reflections so that could represent the outdoor SPL at the most-exposed side of the dwelling. The annoyed respondents include those who are slightly, moderately, very and extremely annoyed by wind turbine noise for all the studies.

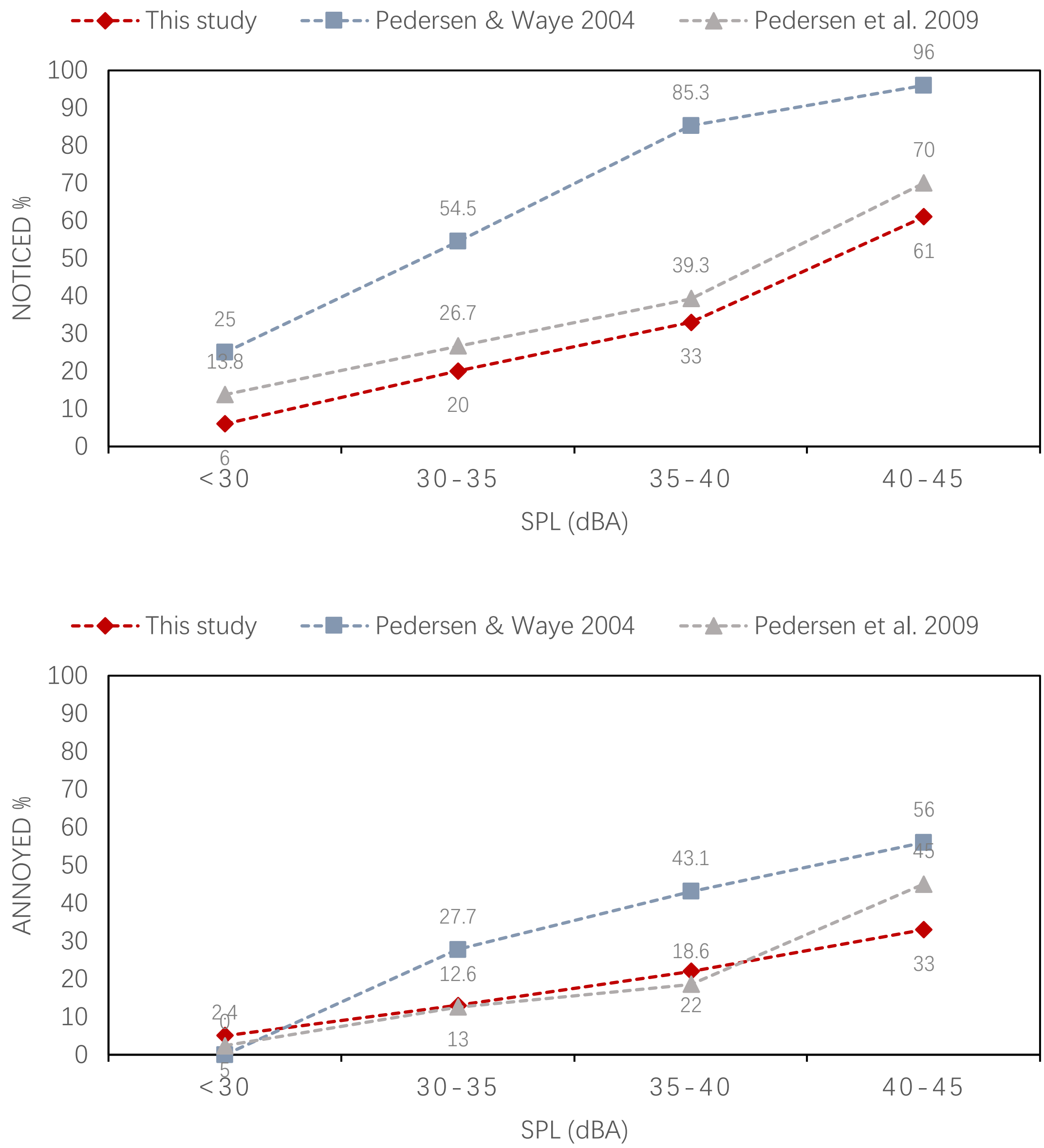


Figure 6. 5 Proportion of respondents in each 5-dBA sound interval who noticed or were annoyed by the noise from wind turbines.

It is found that in general, the dose-response relationships in this study agree well with previous studies, especially the study of Pedersen et al. 2009, where the percentage of noticed and annoyed respondents increased with sound categories in a similar gradient. However, as shown in Figure 6.5, noticeability of and annoyance with wind turbine noise was greater among the previous studies. The difference was larger for noticeability of the sound, especially for lower sound level intervals below 40dBA, where the percentage of respondents who reported noticing the sound in Pedersen & Waye 2004 was nearly 4 times higher than this study. Annoyance with wind turbine noise displays greater agreement across the studies for the lowest sound level intervals, then diverges for the middle noise intervals, and finally converges for the highest sound interval, as shown in Figure 6.5.

A two-sample z-test was carried out to examine if the proportions of noticeability or annoyance were significantly different between this study and each of the previous studies. Table 6.15 shows the results of z-tests. There was a statistically significant difference between the proportions of noise evaluation in each noise category of this study and the study of Pedersen & Waye 2004, which was carried out in rural areas of Sweden. The noise evaluation in each noise category in this study was not significantly different from the Pedersen et al.'s study (2009), which was carried out in both rural and suburban areas in the Netherlands.

Table 6. 15 Comparison of proportions of noticeability and annoyance in each noise category between this study and the previous study using 2-sample z-test

	This study		Pedersen & Waye 2004			Pedersen et al. 2009		
	P_0	n_0	P_1	n_1	z-score test	P_2	n_2	z-score test
Noticeability								
30-35dBA	0.24	102	0.54	208	z=5.8, p<0.001	0.26	219	z=1.3, p=0.194
35-40dBA	0.33	90	0.85	103	z=7.4, p<0.001	0.39	162	z=1.0, p=0.321
40-45dBA	0.61	53	0.96	25	z=3.2, p<0.001	0.70	94	z=1.1, p=0.266
All (30-45dBA)	0.35	245	0.67	336	z=7.6, p<0.001	0.39	475	z=1.0, p=0.294
Annoyance								
30-35dBA	0.13	102	0.27	208	z=2.9, p<0.05	0.12	219	z=0.1, p=0.920
35-40dBA	0.22	90	0.43	103	z=3.1, p<0.01	0.18	162	z=0.6, p=0.517
40-45dBA	0.33	53	0.56	25	z=1.9, p=0.053	0.45	94	z=1.4, p=0.155
All (30-45dBA)	0.21	245	0.34	336	z=3.4, p<0.001	0.20	475	z=0.3, p=0.752

P: sample proportion; n: sample size; p-value for each z-score test is two-tailed.

The results of regression analysis for wind turbine noise levels and noise evaluation also support the above differences. The odds ratio for each dB increase on noticing the noise was 1.22 (95%CI: 1.13-1.33) in this study, slightly lower than 1.3 (95%CI: 1.21-1.39) in the second Pedersen & Waye's (2007) field study also in rural areas of Sweden (n=754). On the other hand, the odds ratio for SPL on noise annoyance was 1.18 (95%CI: 1.08-1.28), quite similar but slightly higher than the odds ratio of 1.1 (95%CI: 1.01-1.25) in the same study (Pedersen & Waye 2007).

The comparison suggests that wind turbine noise in urbanised areas of this study are much less noticeable than in rural areas (Pedersen & Waye 2004). The noise below 30dBA was perceived as annoying by very few respondents across rural and urbanised areas. But higher levels of the noise could annoy more rural residents than urban inhabitants. When the noise level was 40dBA, more residents in the urban area noticed and were annoyed by the noise. The findings correspond well with that found in the study being compared with (Pedersen et al., 2009), which took into account both rural and suburban settings and indicated that the risk of being disturbed and distressed by wind turbine noise is pronounced in quiet areas compared to noisy areas.

It is worth noting that the percentage of “very” annoyed respondents in the present study was also much lower than the above studies (Pedersen et al., 2009; Pedersen & Waye, 2004, 2007), and those reported in the study carried out in the rural area of Poland (Pawlaczyk-Łuszczyńska et al., 2014) and in both rural and suburban areas in Canada (Michaud et al., 2016). Compared to other environmental nuisances, respondents noticed and were annoyed the least frequently by wind turbine noise in this study. This was the opposite to the results of the Michaud et al.’s (2016) and Pawlaczyk- Łuszczyńska’s (2014) studies, which suggested that wind turbine noise was most frequently assessed as annoying amongst a similar set of nuisances.

The reason for the above differences between the current study and previous ones can be explained from both acoustical and contextual aspects. From the acoustical aspect, the study area of the current study had a higher degree of urbanisation than the previous studies. In urbanised areas, the high level of road traffic and neighbourhood noise might have a masking effect on wind turbine noise, which will be stressed in Chapter 8. In addition, some respondents in this study found noise pollutions from other sources were more annoying, of which the most frequently reported included dogs barking, birds and seagulls, racing cars and motorcycles, helicopters, kids, music from pubs, and road constructions. It is possible that wind turbine noise causes less issues than other nuisances and stressors in an urban area.

To explain the difference from the contextual aspects, the visual impact might be more pronounced in rural areas when compared to more densely populated areas (Pedersen & Larsman, 2008). The wind turbine in rural areas of previous studies could be more obvious and intrusive, which might increase the risk of annoyance. In addition, one could argue that in urban areas wind turbine noise is less prominent than other general environmental nuisances, such as street litter, street dogs, parked vehicles, antisocial behaviours, lack of playing ground for children, which have been reported to be more annoying than wind turbine noise in the additional comments provided by respondents of the survey. Another factor that could be of importance for explaining the differences is that peoples' beliefs about the importance of the source of the noise decrease annoyance (Fields, 1993). In addition to the positive attitude to wind turbines such as environmental friendly, it has been found that environmental sustainability is a high priority for the respondents in this study, and over half of the respondents indicated that they need to change their way of life for a good environment. This is also supported by the comments left by the respondents after finishing the questionnaire where many of them talked about various solutions for a sustainable lifestyle, such as recycling waste, and fitting solar panels. This gives the picture of a phenomenon that urban residents of this UK study are concerned about energy saving and are open to new clean energy devices. Many comments from the respondents were rather optimistic about wind energy. Some of them are listed below:

> "Please install more wind turbines on this land."
>
> "I like the area I live in since the wind turbine has been put up. I have not noticed anything different. I would rather see them than have a big power station next to us."

"Five more wind turbines could be sited near the Newthorpe Sewage Works. Bring them on."

"The wind turbine has enhanced our areas."

"I am in favour of any nature source of energy. I have solar panels on my house."

"Wind turbine doesn't bother me. I don't find it unattractive, as I would rather have wind turbines than the other power devices. Wind turbines are more eco-friendly. I like to see them working."

The difference in observed noise annoyance of this study and those reported by other studies might also be due to the difference in survey timing and other unobserved factors. The survey was performed during September to December in 2014, when the time spent for outdoor activities was expected to be lower than in summer period. As wind turbine noise annoyance was reported to be more likely when spending time outdoors (Pedersen & Waye, 2004), the results of this survey might have underestimated the prevalence of annoyance than other surveys that were performed during summer time. Furthermore, the difference in noise reception might be because of the masking effect of other environmental noise, such as the existence of noisy roads in high wind turbine noise exposed areas. This will be investigated in Chapter 8.

6.8 Evaluation of Local Sound Environment

As previous soundscape studies have demonstrated that various noises in the urban area influence people's evaluation on the local sound environment (Kang, 2006; Kang et al., 2016), this study investigated respondent's evaluation of the overall sound environment using eight binary indices such as quiet - loud, interesting - boring, continuous - discontinuous, and so on.

Factor analysis was carried out using SPSS to identify main factors underlying the negative evaluation of the sound environment. As shown in Table 6.16, two factors were determined which accounted for 51% of the total variance. Factor 1

(36%) was mainly associated with the evaluation of the sound, including loud, agitating, artificial, unpleasant, and boring. Factor 2 (15%) was mostly associated with the description of the status of the sound, including discontinuous, chaotic and directional. Factor 1 described the intensity and content of the sound which involved psychological preference of the sound; while Factor 2 was more related to the physical status of the sound and was related to time (e.g. discontinuous, chaotic) and direction.

Table 6. 16 Factor analysis of the evaluation of sound environment

	Pattern Matrix	
	Factor 1	Factor 2
% of variance (total 51.205)	36.301	14.904
Loud (v.s. quiet)	**0.741**	
Agitating (v.s. calming)	**0.736**	
Artificial (v.s. natural)	**0.678**	
Unpleasant (v.s pleasant)	**0.661**	
Boring (v.s. interesting)	**0.652**	
Discontinuous (v.s. continuous)		**0.778**
Chaotic (v.s. predictable)	0.378	**0.693**
Directional (v.s. everywhere)	-0.332	**0.435**

Kaiser-Meyer-Olkin Measure of Sampling Adequacy, 0.794; cumulative 51%; extraction method, principal

Of the eight binary indices, only the evaluation of discontinuous and unpleasant were significantly associated to wind turbine SPLs. Table 6.17 shows the binary logistic regression models of discontinuous (yes/no) and unpleasant (yes/no) related to the maximum, minimum, and average SPLs, respectively. Age, gender, noise sensitivity, site and the questionnaire variant dummies were controlled for in the model.

Table 6. 17 Regression modelling respondent's evaluation of a discontinuous sound environment

Variables	*p*-value	Odds Ratio (OR)	95% CI for OR
Discontinuous *[n=351, R^2=0.098, $p_{(H-L)}$=0.213]*			

Table 6. 17 Regression modelling respondent's evaluation of a discontinuous sound environment

Variables	*p*-value	Odds Ratio (OR)	95% CI for OR
SPL **(maximum**)	0.003	**1.12**	(1.04-1.21)
Age	0.028	**0.98**	(0.96-0.99)
Female	0.903	0.96	(0.48-1.92)
Sensitivity to noise (scale 1-6)	0.439	1.10	(0.86-1.41)
Site A	0.082	2.28	(0.90-5.77)
Site B	0.966	1.02	(0.39-2.69)
Variant 2	0.230	0.58	(0.24-1.41)
Discontinuous *[n=351, R^2=0.075, $p_{(H-L)}$=0.361]*			
SPL (**minimum**)	0.018	**1.09**	(1.02-1.17)
Age	0.053	0.98	(0.96-1.00)
Female	0.917	0.96	(0.48-1.92)
Sensitivity to noise (scale 1-6)	0.403	1.11	(0.87-1.41)
Site A	0.109	2.12	(0.85-5.33)
Site B	0.829	1.11	(0.42-2.91)
Variant 2	0.258	0.60	(0.25-1.45)
Discontinuous *[n=351, R^2=0.088, $p_{(H-L)}$=0.409]*			
SPL (**average**)	0.007	**1.10**	(1.03-1.19)
Age	0.048	**0.98**	(0.96-1.00)
Female	0.917	0.96	(0.48-1.93)
Sensitivity to noise (scale 1-6)	0.459	1.10	(0.86-1.39)
Site A	0.102	2.13	(0.86-5.31)
Site B	0.983	0.98	(0.37-2.63)
Variant 2	0.242	0.59	(0.24-1.42)
Unpleasant *[n=351, R^2=0.180, $p_{(H-L)}$=0.547]*			
SPL (**maximum**)	0.060	1.08	(0.99-1.16)
Age	0.002	**0.97**	(0.94-0.99)
Female	0.632	0.83	(0.38-1.81)
Sensitivity to noise (scale 1-6)	0.520	1.09	(0.83-1.44)
Site A	0.005	**0.24**	(0.09-0.65)
Site B	0.010	**0.27**	(0.10-0.73)
Variant 2	0.123	1.99	(0.83-4.76)
Unpleasant *[n=351, R^2=0.223, $p_{(H-L)}$=0.940]*			
SPL (**minimum**)	0.001	**1.15**	(1.06-1.25)
Age	0.003	**0.97**	(0.95-0.99)
Female	0.669	0.85	(0.38-1.87)
Sensitivity to noise (scale 1-6)	0.515	1.10	(0.83-1.46)
Site A	0.023	**0.30**	(0.11-0.85)
Site B	0.006	**0.24**	(0.08-0.66)
Variant 2	0.096	2.13	(0.87-5.21)
Unpleasant *[n=351, R^2=0.206, $p_{(H-L)}$=0.638]*			
SPL (**average**)	0.007	**1.13**	(1.03-1.23)

Table 6. 17 Regression modelling respondent's evaluation of a discontinuous sound environment

Variables	*p*-value	Odds Ratio (OR)	95% CI for OR
Age	0.002	**0.97**	(0.95-0.99)
Female	0.701	0.86	(0.38-1.90)
Sensitivity to noise (scale 1-6)	0.595	1.08	(0.82-1.42)
Site A	0.011	**0.27**	(0.10-0.75)
Site B	0.005	**0.23**	(0.08-0.64)
Variant 2	0.123	2.00	(0.83-4.84)

Statistically significant associations ($p<0.05$) in boldface.

The results illustrated that every dB increase of maximum wind turbine noise at the dwelling increased the odds of evaluating the sound environment as discontinuous, by 1.12 times. The effects of minimum and average SPLs were also significant, with slightly lower odds ratio than the maximum SPL. An increase in age decreased the odds of reporting discontinuous. However, the models on discontinuous had a relatively lower R^2, indicating that the noise and other covariates could estimate less than 10% of the variance in reporting a discontinuous sound environment.

The evaluation of unpleasant was not significantly associated with the maximum SPL, but with exposures at relatively quiet façades – the minimum and average SPLs. One dB increase in minimum SPL increased the likeliness of reporting a unpleasant sound environment by 1.15. Age was negatively associated with the evaluation. Respondents in Site C were more likely to describe their local sound environment as unpleasant. The R^2 for models on unpleasant sound environment was relatively high, where more than 20% of the variance in the probability of reporting an unpleasant environment could be explained by minimum or average SPLs and the studied covariates.

It is worth noting that the evaluations of discontinuous and unpleasant were not different across questionnaire variants and not related to whether being annoyed by wind turbine noise.

To conclude, Section 6.8 has set the basis for soundscape studies on wind turbine noise. Two factors were found underlying respondent's negative evaluation on the local sound environment – one factor related to psychological evaluation and the other one related to physical status of the sound. Levels of wind turbine noise were positively associated with describing the local sound environment as discontinuous - a time-related evaluation of the status of the sound. This might suggest that environmental impact assessments (EIAs) on wind turbine noise should consider measuring time and include more indicators to examine time based evaluations. Noise level at the quiet façade was positively associated with the evaluation of an unpleasant sound environment, which was not related to annoyance due to wind turbine noise. This suggested that future studies should involve more indicators for noise impact other than annoyance, such as respondent evaluations including psychological feelings and subjective preference on the sound.

6.9 Discussions

6.9.1 Statistical implementations of the results

The response rate was relative lower than previous studies, of around 12%. This was limited by the survey mode of using self-returned letters. The respondents in this study have certain representativeness of the study population with balanced male (49%) and female (51%) and age structure that was not significantly different from the UK population (Census, 2011). In addition, as using self-returned letters have led to subjects with particular views on the topic and who would like to make comments, involving a control group of the sample with research purpose masked had helped to decrease the focusing bias of the results. The distribution of respondents in the four noise groups was the same across questionnaire variants. No statistically significant differences were found in age, gender, education, household income, noise sensitivity, or housing type across two variants, except that the control group (Variant 2) had a higher proportion of longstanding illness, which was not related to noticeability and annoyance due to wind turbine noise.

Results in this chapter illustrate a dose-response relationship between noise levels and annoyance, controlling for moderating factors. It is important to note that respondent's characteristics were significantly different across noise categories, where respondents in the higher exposure group were also lower in sociodemographic status (as demonstrated in section 6.2.2). This increased the difficulty in isolating the effect of wind turbine noise by itself, although some demographic variables were controlled for in the regression model. In addition, effects of attitudinal factors on noise annoyance should be interpreted carefully. Reverse causality might also exist between attitude to wind projects and annoyance, that respondents who were annoyed by the noise became negative about wind turbine projects. Furthermore, a limitation might be the use of additive models with no interactions between explanatory variables. For example, the effect of attitude on annoyance might depend on gender or education, which was not controlled for.

6.9.2 Evaluation on wind turbine noise

Dose response relationships were found between levels of wind turbine noise and self-reported noticeability of and annoyance with the noise, in line with the finding of previous field studies (Michaud et al., 2016; Pawlaczyk-Łuszczyńska et al., 2014; Pedersen et al., 2009; Pedersen & Waye, 2004, 2007). As stated in Section 6.7, respondents in this study were less disturbed by wind turbine noise than those in the previous study carried out in rural areas (e.g. Pedersen & Waye 2004). One of the reason might be that urbanised area of this study had high background noise and more environmental stressers that might decrease the focus on wind turbine noise. The masking effect of main background noise will be investigated in Chapter 8.

More than 70% of the respondents in this study described wind turbines as environmental friendly. The other most supported adjectives were efficient, necessary, harmless, and ugly, which agree well with those queried in the previous study, as environmental friendly, necessary, ugly and effective (Pedersen & Waye, 2004). This implies that wind turbines are appreciated for their positive contribution to the environment, but are regarded as a negative contribution to the aesthetics of the landscape.

In terms of the character of the wind turbine noise, swishing (29%) and whooshing (20%) were the most common sound characteristics described by the respondents, which are consistent with the literature on descriptors of the sound from wind turbines (Pawlaczyk-Łuszczyńska et al., 2014; Pedersen et al., 2009; Pedersen & Waye, 2004, 2007). It is worth noting that the verbal descriptors of pulsating and beating, which were stated to be indicative of amplitude modulation (AM) of the sound and reported to be more prominent at night and more annoying (G. P. Van Den Berg, 2004), were each mentioned by less than 6% of the respondents in this study, which differs from previous studies of rural settings where more than 20% of the respondents indicated the noise to be pulsating (Pedersen & Waye, 2004). The evaluation on AM of the noise from urban wind turbines will need to be investigated in future studies.

6.9.3 Effect of moderating factors

The degree of noise annoyance can vary considerably between individuals of different characteristics as identified in the literature (Fields, 1993; Guski, 1999; Job 1996, 1999; Bluhm et al., 2004; Weinstein, 1978). In this study, the effects of wind turbine noise on health and well-being were assessed controlling for a series of demographic, attitudinal, architectural, and situational factors. The results suggest that age, educational qualification, and housing type significantly affect the individual degrees of noise noticeability and annoyance, which were not reported as significant in previous wind turbine noise studies. Noticeability of and annoyance with wind turbine noise were not associated with sex or income, and were not different statistically among vulnerable respondents who had long-standing illness, being retired or on maternity leave. Noise sensitivity that significantly influenced noise noticeability and annoyance in previous studies, was not found to have a significant impact on noise evaluations in this study.

Negative attitudes to the environmental impact of wind turbines, described as not environmental friendly, dangerous, and ugly, were positively associated with the risk of annoyance. This finding agrees well with the literature that annoyance could be linked to visual attitude to wind turbines such as ugly, unnatural, and having a negative impact on the scenery (Pedersen & Larsman, 2008). It is consistent in previous studies that the negative attitudes to wind turbines especially to their visual impacts positively influence the possibility of annoyance (Pawlaczyk-Łuszczyńska et al., 2014; Pedersen & Waye, 2004, 2007). Support for this finding can also be found in the literature that noise annoyance is positively associated with the fear of danger from the noise source and negatively associated with the belief that the noise source is important for the local area (Fields, 1993). In addition, results of this study illustrate that the degree of annoyance with wind turbine noise was positively correlated to annoyance with other noise. This can be found in theory that people who were more critical and tended to give negative ratings of noise and the neighbourhood were typically more annoyed by a new community noise problem than people who were less critical (Weinstein, 1980).

Having at least one wind turbine visible from the dwelling has been found to increase noise annoyance in a previous study (Pedersen & Waye, 2007). The present study found, however, that visibility of the wind turbine from only a window or around the garden did not increase annoyance compared to being invisible. But the respondents who could see the turbine from both a window and the garden were significantly more annoyed compared to those cannot see any from home. This is consistent with the previous finding that the visual impact was more pronounced in rural areas when compared to more densely populated areas (Pedersen & Larsman, 2008). An explanation for this result might be that visibility of the wind turbine did not bother the urban residents as much as rural inhabitants, as the wind turbine in urban areas could be less obvious and intrusive than in aesthetics rural land. However, for the respondents who can see the wind turbine from both a window and the garden, it is expected that the wind turbine was perceived as more obvious and contrasting with the landscape, in which situation more annoyance might occur as stated by Pedersen and Larsman (2008).

6.9.4 Effect of quiet façade exposures

The results of Section 6.8 revealed the important role of minimum and average wind turbine noise exposures at the dwelling on noise evaluations. It was found that minimum and average SPLs were slightly more strongly correlated to annoyance than the maximum SPL at the dwelling. Wind turbine noise level on the quietest façade was the only noise indicator that significantly related to annoyance with the noise at night. An explanation of these results could be found in the study of wind turbine noise distribution in Chapter 4. In some conditions when the building was parallel to the direction of the wind turbine, the noise exposures around the building were rather similar, making the front and back of the dwelling equally noisy. In this situation, not enough protected areas were created around the dwelling and the average façade exposure was increased. This could increase the risk of annoyance by failing to provide an “escape” from the noise. This agreed well with the results from previous studies on the quiet side effects of the road traffic noise, which indicated that higher exposures at the least exposed façade significantly increase noise annoyance (de Kluizenaar et al., 2013; Renterghem & Botteldooren, 2012).

The difference between the most- and least-exposed facades did not significantly influence noise annoyance due to wind turbines. This was different from the quiet façade effects found in road traffic noise, which indicated that a large difference in exposure (10-20 dB) between the most- and least-exposed sides of a dwelling was associated with significantly lower noise annoyance and less prevalence of noise-induced health problems (Öhrström et al., 2006). The results for wind turbine noise suggested that the actual exposure level at the least-exposed façade itself had a direct effect on annoyance, independent of that at the most exposed façade.

6.10 Conclusions

Compared to other environmental nuisances, respondents in this study noticed and were annoyed least frequently by wind turbine noise. Evaluations on wind turbine noise were significantly different between sound categories. Dose response relationships were found between levels of wind turbine noise and self-reported noticeability and annoyance due to the noise.

Educational qualification, housing type and orientation made a significant contribution to respondent noticeability of wind turbine noise. Annoyance due to wind turbine noise was found to be higher among older people and those having an O-level as the highest qualification compared to having higher educations. Negative attitudes to the environmental impact of wind projects, especially the judgement of ugly, were positively associated with the probability of noticeability and annoyance. Responses to wind turbine noise did not differ between visibility of the turbine or not. But seeing wind turbine(s) from both a window and the garden/yard significantly increased the probability of being noticed and annoyed than those who could not see any from home. Respondent's self-reporting of noticeability and annoyance were not different between variants, and were not associated with gender, income, illness, ownership, and length of residency.

Compared to previous studies on wind turbine noise in more ruralised settings, dose-response relationships between wind turbine noise and noticeability of the noise agreed well with the previous study in both rural and suburban areas (Pedersen et al. 2009). Respondents in this study were much less affected by wind turbine noise than respondents in rural areas of Pedersen & Waye's (2004) study with the same category of wind turbine noise exposure. Higher levels of wind turbine noise seemed to generate more annoyance in rural areas than urban environments, which further confirmed the finding in the previous study that found less annoyance in urbanised areas partly due to less visual distractions than in aesthetic rural areas (Pedersen et al. 2009). This study found the reason might also include the existence of other environmental nuisances in urban areas such as traffic noise and street litters, as well as more local awareness and optimistic views on sustainable energy, as stated in respondents' additional comments of the survey.

The results of this chapter also revealed the important role of quiet façade noise exposures on noise evaluations. Minimum and average SPLs at the dwelling were slightly more strongly correlated to annoyance, while the maximum SPL was strongly correlated to noticeability of the noise. Noise exposure on the quietest façade was the only noise indicator that significantly influenced whether being annoyed at night.

Most respondents living near wind turbines had a positive evaluation of the sound environment at their dwellings, such as quiet, pleasant and calming. However, respondents exposed to higher wind turbine noise were significantly more likely to evaluate the sound environment as discontinuous and unpleasant. This sets the basis for future soundscape studies on wind turbine noise.

Chapter 7

Noise Impact on Health and Well-being

7.1 Introduction

This chapter presents the results of the survey on health and well-being, which is the second part of objective 2 of the thesis (see Figure 1.3).

Previous studies have addressed the effect of wind turbine noise on sleep disturbance and various health symptoms. This chapter further investigates the effect of wind turbine noise and health among suburban-urban residents. This study will also assesses health and well-being using established questions on self-reported general health level, happiness, and life satisfaction. The maximum, minimum, and average levels of wind turbine noise at respondent's dwelling have all been investigated. The annoyance with the noise is also examined in terms of their effects on health and well-being.

In the latter half of this chapter, general health and well-being of respondents in this study are compared to those in national surveys in the UK, controlling for the background characteristics of the respondents[6]. The difference between the observed level in the current study and the predicted level based on the national surveys are calculated to see if there is a decrease in health and well-being among residents living near wind turbines. The difference in observed and predicted values is linked to wind turbine noise levels - either the maximum, minimum, or averaged levels - to see if the noise increases the difference in health and well-being.

Figure 7.1 illustrates the sections in this chapter. Descriptive statistics of the responses to the questions related to health and well-being are reported in section 7.2. The main analyses are then presented across four sections: the effects on sleep (Section 7.3) and adverse health problems (Section 7.4), as well as the effects on subjective well-being (Section 7.5). A comparison between the levels of well-being found in this study and in national data is presented in Section 7.6.

[6] Respondent background characteristics, also written as sociodemographic variables, represent the variables such as age, sex, income, marital status, educational qualification, and whether have long-standing illness.

Discussions are presented in Section 7.7 before conclusions are drawn on the impact of wind turbine noise on human health and well-being in Section 7.8.

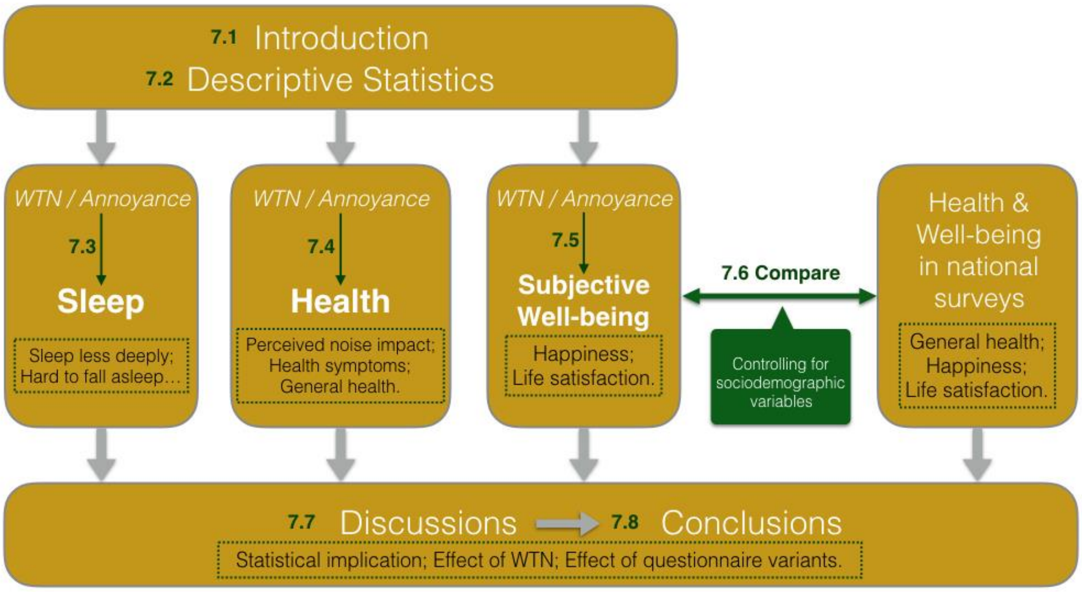


Figure 7. 1 Flow chart of Chapter 7

7.2 Descriptive Statistics on Health and Well-being

7.2.1 Sleep

Respondents in both Variants 1 and 2 indicated their self-reported sleep disturbances without making reference to noise. Figure 7.2 shows the proportion of respondents having different degrees of sleep problems. There was no significant difference between variant 1 and 2 regarding the prevalence of each type of sleep disturbance. Of the whole respondents, only 13% had their sleep not disturbed at all. The problems that most chosen were c) "sleep less deeply" and d) "lie awake for a while".

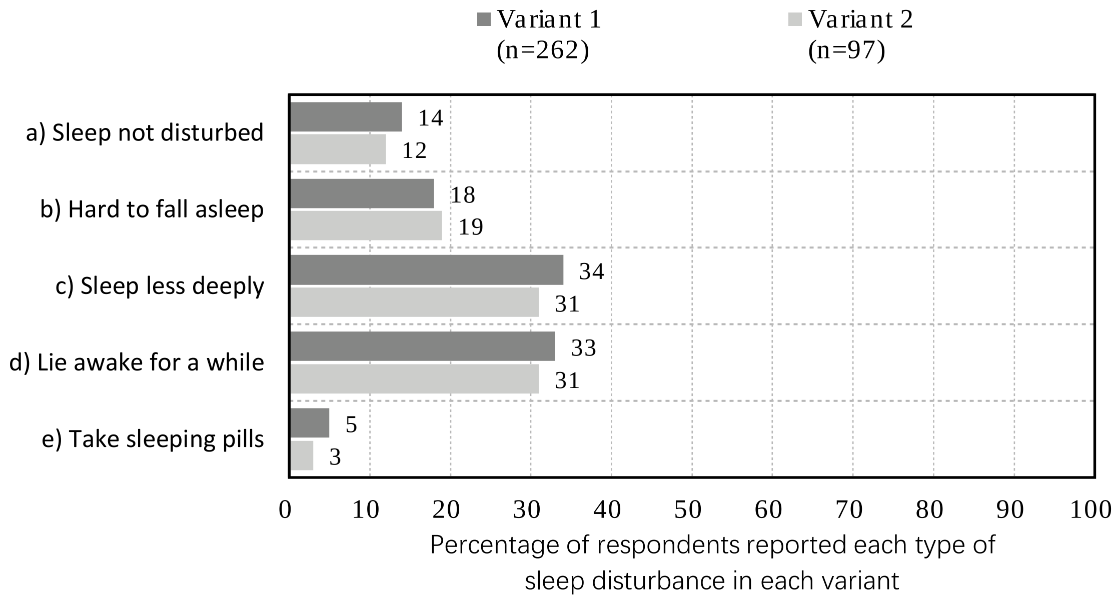
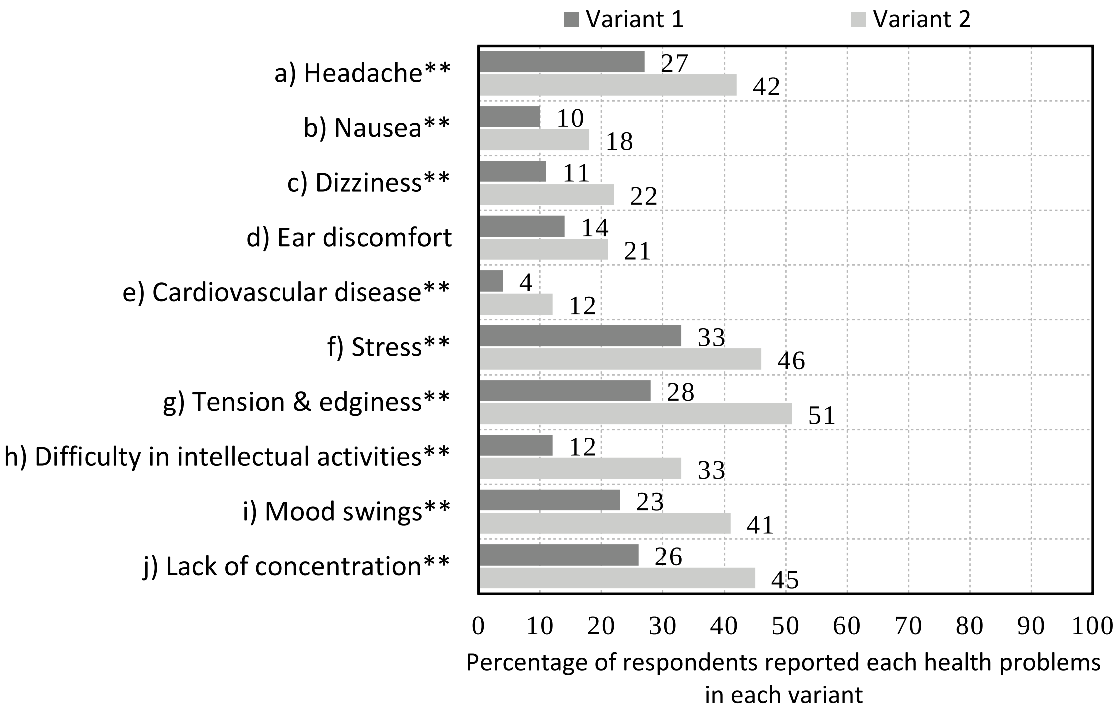


Figure 7. 2 Clustered bar chart showing the percentage of reported sleep disturbance among respondents in Variant 1 and Variant 2 respectively

7.2.2 Health symptoms

Respondents in variant 1 were asked for their perceived impact of wind turbine noise on health before identifying health problems. Overall, 89% of respondents indicated that this had no effect on their health. Only 1% of respondents reported wind turbine noise had an effect on health some of the time, while 8.4% of respondents chose “I don’t know”.

Respondents in both Variants 1 and 2 indicated whether they experienced any of the listed health symptoms during the past week, such as headache, nausea, dizziness, stress etc. The percentage of respondents in each variant who experienced each health symptom is shown in Figure 7.3.



**significant differences across variants with p<0.05 for Chi-square tests

Figure 7. 3 Clustered bar chart showing the percentage of respondents reported health problems in Variant 1 and Variant 2 respectively

Of all respondents, the most prevalent physical symptom was headache (30%, n=108) and the most reported mental distress were stress (35%, n=127) and tension edginess (32%, =118). Cardiovascular disease was least reported by the respondents (6%, n=20).

As shown in Figure 7.3, the prevalence of each health symptom in Variant 2 was significantly higher than that in Variant 1 (except ear discomfort), examined using chi-square tests.

The respondents who experienced a symptom were further asked if they felt the cause of the symptom was wind turbine noise in Variant 1 (n=261), by indicating “yes”, “possibly”, “no”, and “I don't know”. The proportions of each item are shown in Figure 7.4. Respondents in Variant 1 indicated the cause for more psychological symptoms (e.g. stress, tension, mood swings) than physical problems (e.g. nausea, dizziness, cardiovascular disease) to be related to wind turbine noise ("yes" or "possibly"), though only accounting for less than 5% of the respondents who had the health problem. More respondents indicated "I don't know" when attributing the cause of physical health problems, especially cardiovascular disease (33%), nausea (21%), and dizziness (21%).

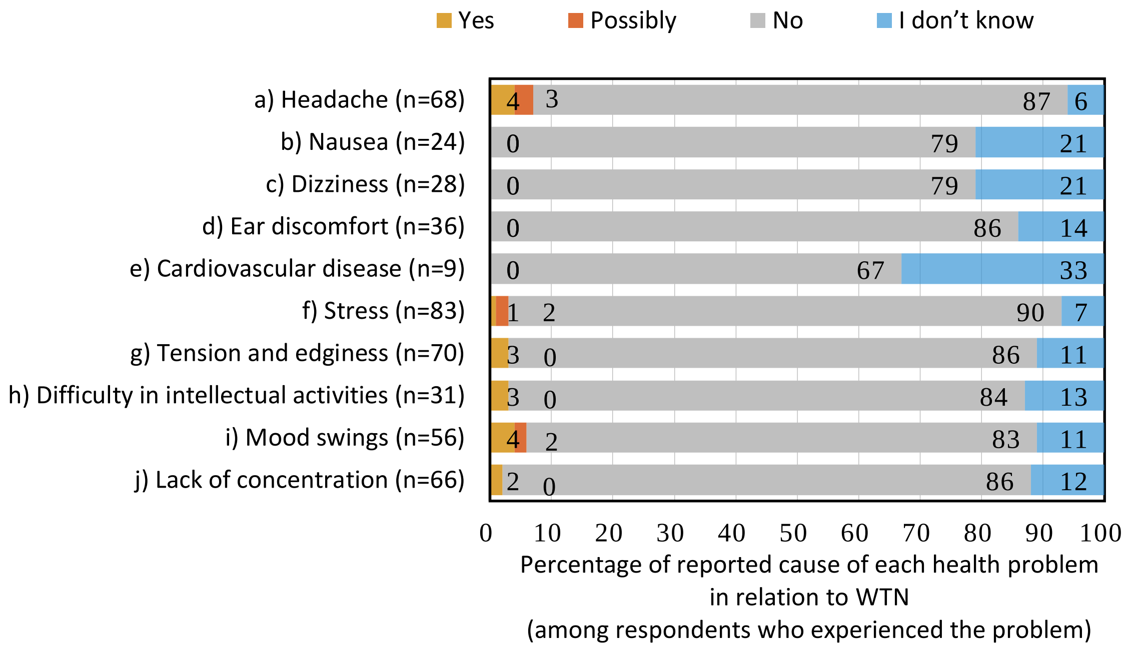


Figure 7. 4 Proportion of reported cause of each health symptom in relation to wind turbine noise in Variant 1.

Overall, most of the respondents in Variant 1 who experienced a certain symptom did not attribute the cause to wind turbine noise, by indicating "no" in response to the question. Thus, because respondents to Variant 1 could tell that the motivation of the survey was to link their reported health symptoms to wind turbine noise exposure, it is possible that at least some respondents under-reported their health problems unless they thought they were caused by WTN. In addition, the higher prevalence of health problems in Variant 2 is also in line with the significantly higher proportion of respondents having long-standing illness in Variant 2 than in Variant 1, as shown in Table 6.3 in Section 6.2.3. The reason for significant differences in health problems between the variants are further examined in the regression analysis of Section 7.4.

7.2.3 General health and subjective well-being

Table 7.1 shows the comparison between the two questionnaire variants regarding general health and subjective well-being. No statistically significant differences in variables related to subjective general health and well-being were found between variants.

Table 7. 1 Self-reported levels of general health and subjective well-being of respondents across the two questionnaire variants.

Outcome variables	Questionnaire variants 1	Questionnaire variants 2	Mann-Whitney test (*U*) of distribution between variants
General health: M (SD)	2.92 (0.99)	2.95 (0.97)	*U*=12498.5, *p*=.763
Subjective well-being			
Happiness: M (SD)	7.23 (2.20)	7.27 (2.08)	*U*=11732, *p*=.998
Satisfaction overall: M (SD)	5.09 (1.42)	5.23 (1.34)	*U*=13025, *p*=.405
Satisfaction with health: M (SD)	4.72 (1.51)	4.81 (1.48)	*U*=13031, *p*=.437
Satisfaction with income: M (SD)	4.41 (1.64)	4.65 (1.64)	*U*=13105, *p*=.215
Satisfaction with social life: M (SD)	4.62 (1.66)	4.41 (1.60)	*U*=11185, *p*=.239
Satisfaction with living environment: M (SD)	5.06 (1.50)	5.44 (1.19)	*U*=13628.5, *p*=.055

M - mean; SD - standard deviation

7.3 The Relationship between Wind Turbine Noise and Sleep

Sleep was not related to wind turbine noise but to annoyance with the noise. Annoyance with wind turbine noise overall and indoors, rather than the SPL itself, were significantly associated with sleeping less deeply and with difficulty in falling asleep. No associations were found between annoyance with wind turbine noise and lying awake or taking sleeping pills. Table 7.2 shows the relationships between maximum wind turbine SPL at a dwelling, annoyance, and different degrees of sleep disturbance, controlling for respondent background characteristics and sites.

Table 7. 2 Association between sleep, WTN annoyance, and covariates

Model	Variables	*p*-value	Odds Ratio (OR)	95% CI
1	***Sleep less deeply (no/yes)*** *[n=335, R^2=0.110, $p_{(H-L)}$=0.827]*			
(Variant 1+2)	SPL	0.317	0.98	(0.94-1.02)
	Annoyance overall (scale 1-5)	<0.05	**1.54**	(1.06-2.25)
	Age	<0.01	**1.02**	(1.01-1.04)
	Female	0.599	0.88	(0.54-1.42)
	Longstanding illness (no/yes)	<0.05	**1.69**	(1.02-2.78)
	Sensitivity to noise (scale 1-6)	0.369	1.08	(0.92-1.27)
	Site A	0.329	0.74	(0.40-1.36)
	Site B	0.514	1.23	(0.66-2.29)
	Variant 2	0.148	0.66	(0.38-1.16)
2	***Sleep less deeply (no/yes)*** *[n=242, R^2=0.209, $p_{(H-L)}$=0.949]*			
(Variant 1)	SPL	0.234	0.97	(0.91-1.02)
	Annoyance overall (scale 1-5)	<0.05	**1.83**	(1.11-3.03)
	Age	<0.01	**1.03**	(1.01-1.05)
	Female	0.973	0.99	(0.54-1.80)
	Longstanding illness (no/yes)	<0.05	**1.86**	(1.00-3.44)
	Sensitivity to noise (scale 1-6)	0.930	0.99	(0.81-1.22)
	Negative attitude to the environmental impact of	0.781	1.10	(0.58-2.09)
	Visibility of the WT (ref: see WT from window)			
	- Cannot see WT	0.198	1.67	(0.77-3.62)
	- See WT from garden	0.755	0.85	(0.29-2.44)
	- See WT from both window and garden	<0.05	**2.78**	(1.20-6.42)
	Site A	0.111	0.54	(0.25-1.15)
	Site B	0.601	1.22	(0.58-2.58)
3	***Hard to fall asleep (no/yes)*** *[n=242, R^2=0.085, $p_{(H-L)}$=0.224]*			
(Variant 1)	SPL	0.592	1.02	(0.95-1.09)
	Annoyance indoors (scale 0-10)	<0.05	**1.33**	(1.01-1.76)
	Age	0.908	1.00	(0.98-1.02)
	Female	0.263	1.50	(0.74-3.07)
	Longstanding illness (no/yes)	0.078	1.88	(0.91-3.90)
	Sensitivity to noise (scale 1-6)	0.312	1.14	(0.89-1.45)
	Negative attitude to the environmental impact of	0.201	0.58	(0.26-1.33)
	Visibility of the WT (ref: see WT from window)			
	- Cannot see WT	0.248	1.72	(0.69-4.31)
	- See WT from garden	0.798	0.85	(0.24-3.00)
	- See WT from both window and garden	0.973	1.02	(0.37-2.81)
	Site A	0.652	0.81	(0.32-2.05)
	Site B	0.756	1.15	(0.47-2.79)

Statistically significant correlations in boldface.

Annoyance with wind turbine noise was positively associated with sleeping less deeply both for the whole data and for the main sample of Variant 1. Annoyance indoors, as measured in variant 1 only, was also positively associated with hard to falling asleep.

The positive associations between annoyance and sleep disturbances were moderated by personal factors. Fixing the degree of annoyance overall, higher age and having a long-standing illness increased the odds of sleeping less deeply. Being female and sensitive to noise did not make a significant difference. Of the models on the Variant 1 sample, visibility of the wind turbine from both a window and garden significantly increased the odds of less deep sleep by 2.78 times than those who only saw it from a window. A negative attitude to wind turbine projects was not significantly associated with sleep disturbance. It should be noted that the R^2 of the regression model was low, such as 0.110 for model 1, indicating that the studied variables only described 11% of the variance in the probability of sleeping less deeply. The measured sleep problems were not associated with annoyance of wind turbine noise outdoors, or at night.

The study also compared the prevalence of each problem of disturbed sleep across the highest (>40dBA) and the lowest (<30dBA) exposure groups, with no significant difference found. It is important to note that sleep disturbance might be caused by other noise sources. Using the same regression model of the whole sample, the annoyance with wind turbine noise was replaced by the annoyance with neighbourhood noise and road traffic noise as indicated by the respondents using the same scale as for wind turbine noise (see Table 7A.1 in Appendix IV). The other three sleep problems, which were not associated with wind turbine noise annoyance, were positively related to annoyance with other noise sources. The probability of lying awake for a while at night was significantly associated with the annoyance with neighbourhood noise, while taking sleeping pills was associated with the annoyance with road traffic noise. Sleeping less deeply was associated with neighbourhood annoyance to a lesser degree than with wind turbine noise annoyance. Hard to fall asleep was only related to annoyance with wind turbine noise indoors.

To conclude, sleep disturbance was not related to wind turbine noise directly but to noise annoyance. Annoyance with wind turbine noise overall was positively associated with sleeping less deeply. Annoyance indoors was positively associated with hard to falling asleep in Variant 1. Visibility of the wind turbine from both a window and garden significantly increased the probability of sleeping less deeply. Annoyance with wind turbine noise did not influence lying awake for a while or taking sleeping pills, which were found to be related to annoyance of the noise from neighbours and roads.

7.4 The Relationship between Wind Turbine Noise and Health

7.4.1 Perceived health impact

The distribution of respondents across perceived noise impact on health related to four sound categories are shown in Table 7.3. The proportion of respondents who indicated no health effect varied from 93.8% to 92.1% at low SPLs, but at SPLs>40 dBA the proportion decreased to 77.3%. The proportion of respondents who said "I don't know" increased sharply from 6.3% to 22.7% when SPL exceeded 40 dBA. A Chi-square test indicated that the difference between sound categories was statistically significant.

Table 7. 3 Perceived health impact of wind turbine noise related to sound level categories

Moderating variables	Respondents	Statistical test of association

	Total	Calculated A-weighted sound pressure levels [dB(A)]				between noise groups and each response item
		<30	30-35	35-40	>40	
Would you say that the wind turbine noise has any effect on your health?						
No, not at all**	89.3	93.8	93.1	92.1	77.3	Gamma=-0.368, *p*=**0.030**
Yes, some of the time	1.1	1.3	1.4	1.6	0.0	Gamma=-0.176, *p*=0.641
I don't know**	8.4	5.0	5.6	6.3	22.7	Gamma=0.368, *p*=**0.030**
n	*262*	*80*	*74*	*64*	*44*	

**: significant association between noise groups and question response.*

Binary logistic regressions were carried out to investigate the relationship between no perceived noise impact and modelled noise exposure from wind turbines using the main sample of Variant 1. For the dependent variable, respondents who said "no, not at all" were noted as "1" (n=234). Those who chose "yes, some of the time" and "I don't know" were combined together and noted as "0" (n=25). Results of the regression models on perceived no health impact are shown in Table 7.4. The maximum SPL at the dwelling was used as an independent variable in Model 1. The annoyance with wind turbine noise was added to Model 2 as another independent variable. Both models controlled for age, sex, attitudes to wind turbine projects, and sites. Visibility of the wind turbine, noise sensitivity, and other socio-economic variables were found to have no significant impact, thus were excluded from the models.

As shown in Table 7.4, the SPL was negatively associated with no perceived impact of wind turbine noise on health. When adding annoyance of wind turbine noise into the model, the maximum SPL was still negatively associated with the report of no health impact, but was no longer significant at the 0.05 level. Respondents who were annoyed by wind turbine noise were much less likely to report no health impact than those not annoyed.

Table 7. 4 Association between no health concerns, sound pressure levels (SPLs), and covariates

Model	Variables	*p*-value	Odds Ratio	95% CI
	No health impact *[n=255, R^2=0.203, $p_{(H-L)}$=0.672]*			
1 (Variant 1)	SPL (maximum)	0.012	**0.89**	(0.81-0.97)
	Age	0.034	**1.03**	(1.00-1.06)
	Female	0.038	**0.34**	(0.12-0.94)
	Positive attitude to the utility of WT (no/yes)	0.018	**4.36**	(1.29-14.69)
	Negative attitude to the necessity of WT (no/yes)	0.169	0.38	(0.10-1.51)
	Negative attitude to the environmental impact of WT (no/yes)	0.951	0.97	(0.32-2.89)
	Site (ref: Site C)			
	- Site A	0.986	0.99	(0.29-3.43)
	- Site B	0.869	0.91	(0.28-2.92)
	No health impact *[n=255, R^2=0.252, $p_{(H-L)}$=0.833]*			
2 (Variant 1)	SPL (maximum)	0.053	0.91	(0.83-1.00)
	Age	0.053	**1.03**	(1.00-1.06)
	Female	0.022	**0.28**	(0.10-0.84)
	Positive attitude to the utility of WT (no/yes)	0.016	**4.91**	(1.35-17.93)
	Negative attitude to the necessity of WT (no/yes)	0.244	0.42	(0.10-1.82)
	Negative attitude to the environmental impact of WT (no/yes)	0.695	1.26	(0.40-4.01)
	Site (ref: Site C)			
	- Site A	0.878	1.10	(0.32-3.86)
	- Site B	0.891	1.09	(0.32-3.70)
	Annoyed by WTN overall (no/yes)	0.008	**0.22**	(0.07-0.67)

Statistically significant associations with p<0.1 in boldface.

Personal factors of age, sex, and attitude to wind turbines were found to influence the perceived health impact. Age was positively associated with the report of no health impact. Being female significantly decreased the odds of reporting no health impact. Having positive attitudes to the utility of wind turbines increased the odds of reporting no health impact. Having negative attitudes to the necessity and environmental impact of wind turbines, and sites, were not significantly associated with perceived health impact.

7.4.2 Health symptoms

As stated in previous sections, the prevalence of health symptoms was higher in Variant 2, where significantly more respondents had long-standing illness or disability (LSID). Thus, the hypothesised effect of SPL on the prevalence of health symptoms should be examined controlling for both LSID and questionnaire variants. Because having LSID was positively correlated to SPL (r=0.112, p=0.037) in this study sample, to avoid bias caused by the collinearity between explanatory variables of SPL and LSID, regressions modelling each health symptoms were carried out separately for the sample with and without illness, in Variant 1 and Variant 2, respectively. The following paragraphs of this section present both the effects of wind turbine noise SPLs (maximum, minimum and average SPLs) and the effects of noise annoyance, on the probability of reporting each health symptom.

Effects of wind turbine noise

Binary logistic regressions were carried out using each health symptom as an outcome variable, maximum, minimum or average SPL at respondent's dwelling as an explanatory variable, controlling for age, sex, and self-reported noise sensitivity (at 1-6 ordinary scale). Sites dummies were not associated with health problems so were excluded from the regression model. Results of the logistic regression analysis in Variant 1 are shown in Table 7.5, and results in Variant 2 are shown in Table 7.6, which only show the regression models with significant associations between SPL and health symptoms.

In Variant 1, as shown in Table 7.5, reported difficulty in intellectual activities (for those with LSID) and stress (for those without LSID) were *negatively* associated with wind turbine noise, indicating that higher prevalence of these health problems was found among those respondents exposed to *lower* SPLs in Variant 1.

Table 7. 5 Association between health problems, wind turbine noise (SPLs), and covariates in Variant 1

Model (sample)	Variables	*p*-value	Odds Ratio (OR)	95% CI for OR
1	***Difficulty in intellectual activities*** *[n=91, R^2=0.280, $p_{(H-L)}$=0.808]*			
(Variant 1,	SPL ***(max)***	0.022	**0.870**	(0.77-0.98)
Had LSID,	Age	0.173	0.972	(0.93-1.01)
n=91)	Female	0.287	2.111	(0.53-8.36)
	Sensitivity to noise (scale 1-6)	0.118	1.588	(0.89-2.84)
2	***Difficulty in intellectual activities*** *[n=91, R^2=0.310, $p_{(H-L)}$=0.908]*			
(Variant 1,	SPL ***(min)***	0.013	**0.815**	(0.69-0.96)
Had LSID,	Age	0.075	**0.962**	(0.92-1.00)
n=91)	Female	0.369	1.897	(0.47-7.66)
	Sensitivity to noise (scale 1-6)	0.114	1.582	(0.90-2.79)
3	***Difficulty in intellectual activities*** *[n=91, R^2=0.280, $p_{(H-L)}$=0.934]*			
(Variant 1,	SPL ***(average)***	0.026	**0.849**	(0.74-0.98)
Had LSID,	Age	0.102	0.966	(0.93-1.01)
n=91)	Female	0.318	2.021	(0.51-8.05)
	Sensitivity to noise (scale 1-6)	0.109	1.595	(0.90-2.82)
4	***Stress*** *[n=163, R^2=0.163, $p_{(H-L)}$=0.767]*			
(Variant 1,	SPL***(max)***	0.085	**0.947**	(0.89-1.01)
Had ***no*** LSID,	Age	0.001	**0.965**	(0.94-0.99)
N=48)	Female	0.021	**2.381**	(1.14-4.98)
	Sensitivity to noise (scale 1-6)	0.754	0.963	(0.76-1.22)

Statistically significant associations with p<0.1 in boldface.

Among the respondents in Variant 2, reported health problems were *positively* related to wind turbine noise. The results in Table 7.6 indicate that each dB increase in maximum SPL significantly increased the probability of having ear discomfort among respondents who either had LSID or had no LSID ($p<0.05$), and could increase the odds of dizziness for those had LSID and nausea for those had no LSID.

Table 7. 6 Association between health problems, wind turbine noise (SPLs), and covariates in Variant 2

Model (sample)	Variables	*p*-value	Odds Ratio (OR)	95% CI for OR
1	***Dizziness*** *[n=46, R^2=0.342, $p_{(H-L)}$=0.780]*			

Table 7. 6 Association between health problems, wind turbine noise (SPLs), and covariates in Variant 2

Model (sample)	Variables	*p*-value	Odds Ratio (OR)	95% CI for OR
(Variant 2,	SPL***(max)***	0.051	**1.161**	(0.99-1.35)
Had LSID,	Age	0.355	0.978	(0.93-1.03)
n=46)	Female	0.063	**4.658**	(0.92-23.53)
	Sensitivity to noise (scale 1-6)	0.059	**1.856**	(0.98-3.53)
2	***Dizziness*** *[n=46, R^2=0.317, $p_{(H-L)}$=0.108]*			
(Variant 2,	SPL***(average)***	0.083	**1.135**	(0.98-1.31)
Had LSID,	Age	0.332	0.977	(0.93-1.02)
n=46)	Female	0.068	**4.497**	(0.90-22.58)
	Sensitivity to noise (scale 1-6)	0.058	**1.842**	(0.98-3.47)
3	***Ear discomfort*** *[n=48, R^2=0.277, $p_{(H-L)}$=0.404]*			
(Variant 2,	SPL***(max)***	0.041	**1.159**	(1.00-1.34)
Had LSID,	Age	0.148	1.039	(0.99-1.09)
n=46)	Female	0.092	**3.895**	(0.80-18.92)
	Sensitivity to noise (scale 1-6)	0.607	1.157	(0.66-2.02)
4	***Ear discomfort*** *[n=48, R^2=0.379, $p_{(H-L)}$=0.836]*			
(Variant 2,	SPL***(max)***	0.038	**1.187**	(1.01-1.39)
Had ***no*** LSID,	Age	0.185	1.049	(0.98-1.13)
N=48)	Female	0.291	0.316	(0.04-2.68)
	Sensitivity to noise (scale 1-6)	0.064	**2.100**	(0.96-4.61)
5	***Nausea*** *[n=48, R^2=0.655, $p_{(H-L)}$=0.849]*			
(Variant 2,	SPL***(min)***	0.077	**1.395**	(0.96-2.02)
Had ***no*** LSID,	Age	0.071	**0.904**	(0.81-1.01)
N=48)	Female	0.119	15.70	(0.49-502.59)
	Sensitivity to noise (scale 1-6)	0.058	**6.696**	(0.94-47.69)

Statistically significant associations with p<0.1 in boldface.

Females were found to be around four times more likely to report the above health problems among those who had LSID; while self-evaluated noise sensitivity level was positively associated with having dizziness (for those with LSID), ear discomfort and nausea (for those without LSID). All models had relatively high levels of R2, indicating that more than 32% of the variance in dizziness and 65% of the variance in nausea could be explained by the variables in the regression model. For ear-discomfort, the regression model using the respondents without

LSID explained more variance in the health problem than using the respondents with LSID. It is worth noting that in Variant 2, annoyance with the noise was not associated with the above health problems when added to the regression model, and the effect of SPL remained significant.

To further compare the effects of variants 1 and 2 as well as different indicators of wind turbine noise (maximum, minimum or average SPL) on adverse health problems, the effects of SPLs on health symptoms are summarised in Figure 7.5, where the points were plotted corresponding to the odds ratio (y-axis) and p-value (x-axis) of each noise indicator tested with regression analysis shown in Tables 7.5 and 7.6. The quadrants represent difference clusters of the sample, where being above or below the x-axis distinguishes the questionnaire variants; being at left or right of the y-axis indicated whether had LSID or not.

As shown in Figure 7.5, it has been found that questionnaire variant was an important confounder for the effect of wind turbines on adverse health problems. Statistically significant differences were found between variants as to whether a health problem was associated with wind turbine noise. Wind turbine noise levels were found to have a positive effect on adverse health in Variant 2 (OR>1), to whom the research purpose was masked; whilst in Variant 1, adverse health problems were negatively associated with noise levels (OR<1). If the negative relationships found in Variant 1 were not significant by chance, this might be explained by the following possibilities. One was that health problems such as difficulty in intellectual activities and stress might be under-reported by Variant 1 respondents who knew the purpose of the survey and perceived no noise impact on these problems. Another possibility might be that the effects of wind turbine noise on physical health were hidden and complex, partly due to the low-frequency component of the noise, so that respondents were unaware of or unconcerned about the noise impact on health.

Figure 7. 5 Scatter plot graph showing the effects of wind turbine noise (maximum, minimum, or average SPL) on the probability of reporting health symptoms corresponding to their odds ratio (OR) and p-values tested with binary logistic regressions. (x-axis: p-value; y-axis: Odds Ratio)

In terms of different noise indicators, most health problems were associated with maximum façade exposure. For example, the positive association between maximum SPL and experiencing ear-discomfort was no longer significant if maximum SPL was replaced with minimum or average SPLs. Minimum façade exposure was found to be positively associated with reporting nausea ($p<0.1$) among respondents in Variant 2 without LSID. Average façade exposure was positively associated with dizziness ($p<0.1$) among respondents with LSID in Variant 2. Comparing the strength of each association, it was found that noise exposure at quiet façades (minimum and average SPLs) had weaker associations with health problems than noise at the most exposed façade (maximum SPL), in terms of higher p-values of the association (the points farther away from y-axis as shown in Figure 7.5). However, minimum SPL was the only indicator that was associated with experiencing nausea among respondents who had no LSID in Variant 2.

Effects of noise annoyance

Using similar methods of regression analysis, the effects of noise annoyance on health symptoms were investigated separately among respondents with and without long-standing illness, in Variants 1 and 2, respectively. Table 7.7 shows the binary logistic regression models where annoyance has a significant association with health symptoms only in Variant 1, controlling for maximum SPL, age, sex and noise sensitivity.

As shown in Table 7.7, among the respondents with LSID in Variant 1, respondents who were annoyed by wind turbine noise were 16 time more likely to report cardiovascular disease than those not annoyed ($p<0.05$), while age significantly increase the probability of having the disease. Being annoyed by wind turbine noise was also associated with 2.7 times of the odds of reporting a headache among respondents who had no LSID in Variant 1. Having a headache was also found to be negatively associated with age and male. Other factors including employment, housing type, and visibility of the wind turbine were not associated with health problems thus excluded from the models.

The variables included in the models could explain 28% and 17% of the variance in cardiovascular disease and headache, respectively. However, it should be noted that reverse causality might exist between annoyance and health problems. For example, having a headache might increase the annoyance by wind turbine noise.

Table 7. 7 Association between health problems, annoyance, and covariates in Variant 1

Model (sample)	Variables	*p*-value	Odds Ratio (OR)	95% CI for OR
1	***Cardiovascular disease*** *[n=91, R^2=0.280, p(H-L)=0.805]*			
(Variant 1,	Annoyed by WTN (no/yes)	0.037	**16.768**	(1.18-238.48)
	SPL ***(max)***	0.193	0.902	(0.77-1.05)
Had LSID,	Age	0.044	**1.090**	(1.00-1.19)
n=91)	Female	0.588	0.592	(0.09-3.94)
	Sensitivity to noise (scale 1-6)	0.189	1.628	(0.79-3.27)
2	***Headache*** *[n=163, R^2=0.176, p(H-L)=0.400]*			
(Variant 1,	Annoyed by WTN (no/yes)	0.074	**2.736**	(0.91-8.27)
Had ***no*** LSID,	SPL ***(max)***	0.646	0.985	(0.92-1.05)
n=163)	Age	0.006	**0.969**	(0.95-0.99)
	Female	0.002	**3.572**	(1.60-7.97)
	Sensitivity to noise (scale 1-6)	0.573	0.932	(0.73-1.19)

Statistically significant associations with p<0.1 in boldface.

7.4.3 Self-reported general health

Respondents in this study self-reported their general health status on a five-point verbal scale from excellent (1) to poor (5). The level of general health was not related to wind turbine noise level. A One-way ANOVA test shows that there was no significant difference between the mean of general health levels and wind turbine noise categories with 5-dBA interval (F=1.228, p=0.299). No statistically significant correlations were found between general health and annoyance with wind turbine noise.

To model the hypothesised effect of wind turbine noise on general health controlling for personal factors, ordinary least squares (OLS) regressions were carried out to model general health (1-5) with maximum SPL as an independent variable, controlling for the effects of age, sex, income, and questionnaire variants, for respondents with and without long-standing illness separately. Results of the regression showed no significant associations between general health and wind turbine noise (see Table 7A.2 in Appendix IV), which was significantly associated with income and sex. In terms of the effects of different noise indicators, neither minimum nor average façade SPL was associated with general health levels, tested with OLS regression models controlling for the same covariates as used for maximum SPL.

To conclude Section 7.4, the maximum wind turbine noise level at a dwelling was found to be related to respondent's perceived health impact. Older respondents, females, and those who had positive views on the utility of wind turbines were more likely to say that wind turbines had no impact on health.

Respondents in Variant 1 who were enabled to attribute the cause of experienced health problems to wind turbine noise reported significantly less health problems than those in Variant 2 where the research purpose was masked. Less than 4% of the respondents in Variant 1 reported the cause of a certain health symptom was related to wind turbine noise. Of all the studied health symptoms, according to logistic regression results controlling for other covariates, difficulty in intellectual activities and stress were *negatively* associated with wind turbine noise in Variant 1; while dizziness, ear discomfort and nausea were found to be *positively* associated with wind turbine noise levels in Variant 2. This indicated an effect of questionnaire variants that differed the noise impact on health. Among respondents in Variant 1, reporting cardiovascular disease and headache were associated with being annoyed by wind turbine noise. Cardiovascular disease was significantly highly reported among annoyed respondents who had long-standing illness; while headache was significantly more frequently reported among annoyed respondents without long-standing illness. Prevalence of health problems significantly varied with age, sex, and noise sensitivity levels. Neither wind turbine noise level nor annoyance with wind turbine noise was found to influence respondent's self-reported general health.

7.5 The Relationship between Wind Turbine Noise and Subjective Well-Being

Subjective well-being was investigated in terms of happiness and life satisfaction among all respondents, which were not different between variants (see Table 7.1). Table 7.8 shows the descriptive statistics of self-reported subjective well-being across four 5-dB(A) sound categories of wind turbine noise. Results of one-way ANOVA tests showed that there was no significant difference between subjective well-being and sound categories.

Table 7. 8 Self-reported subjective well-being related to wind turbine shown as mean and SD within each sound category

Mean (SD)	Total	Maximum sound pressure levels at dwelling [dB(A)]				One-way ANOVA test
		<30 (*n*=114)	30-35 (*n*=102)	35-40 (*n*=90)	>40 (*n*=53)	
a) Happiness (0 very unhappy-10 very happy)	7.21 (2.16)	7.47 (2.06)	7.26 (2.23)	6.84 (2.38)	7.25 (1.74)	F=1.353, p=.257
b) Satisfaction with life overall (1 not satisfied-7 completely satisfied)	5.10 (1.40)	5.34 (1.31)	4.96 (1.52)	5.03 (1.44)	5.06 (1.22)	F=1.317, p=.259

Bivariate correlations between subjective well-being and SPL at the dwelling indicated a weak negative correlation between maximum SPL and happiness (r_S=-0.111, p=0.038), but stronger correlations between minimum SPL and happiness (r_S =-0.167, p=0.002), and between average SPL and happiness (r_S =-0.157, p=0.003). Similar results were found for life satisfaction, where minimum SPL had the highest correlation (r_S =-0.138, p=0.009), followed by average SPL (r_S =-0.123, p=0.021). However, these negative bivariate correlations might depend on the lower sociodemographic status of the respondents in high exposed areas (as shown in Table 6.2). No statistically significant correlations were found between subjective well-being and annoyance with wind turbine noise.

To model the effect of wind turbine noise on subjective well-being, ordinary least squares (OLS) regressions were carried out with maximum SPL as an independent variable, controlling for the effects of age, sex, income, employment, marital status, long-standing illness, and questionnaire variants. The results of regression analyses showed that SPL was not significant on modelling happiness and life satisfaction of the respondent (see Tables 7A.3 and 7A.4 in Appendix IV). Minimum and average SPLs were not related to happiness and life satisfaction either. The observed significantly lower happiness and life satisfaction in higher exposure areas might be due to the demographic composition of people living in the high exposure area, who were older, retired, with lower levels of qualifications and household income, and more likely to be living in terraced houses and flats (as shown in Table 6.2). Another reason for no significant change of subjective well-being in high exposure areas might be that happiness and life satisfaction were more stable over noise stimuli than annoyance and direct health problems. No statistically significant associations were found between subjective well-being and annoyance with wind turbine noise, negative attitudes to wind projects, and visibility of the wind turbine from home.

7.6 Comparison between Health and Well-Being of This Study and National Surveys

In this section, self-reported scores of general health and subjective well-being among the respondents of the current study were compared with those of national surveys, adjusted for sociodemographic variables. Secondary data from two national surveys - Understanding Society wave 6 and Health Survey of England 2011 (HSE) were used.

Understanding Society (US) is the national wide household longitudinal study in the UK. The dataset used in this study was Understanding Society wave 6, which covered a sample size of 39,844, and was carried out in 2014, the same year of current study. Self-reported general health and life satisfaction were assessed. More information of the survey can be found on the official website[7].

Health Survey for England (HSE) is a repeated cross section interview survey that provides information on many aspects concerning the public's health and the factors that affect health in England. The dataset of interest was HSE 2011, which was the latest year of survey that assessed self-reported happiness scale. For more details of the survey including the sampling method and conduct of interviews, see the documentation on the UK Data Service website[8].

Three steps of calculations were carried out to predict the scores of health and well-being (HWB) for the current study (CS) according to those in the national survey (NS), and calculate the difference between observed and predicted HWB. Figure 7.6 shows the details of each step.

[7] Understanding Society website: https://www.understandingsociety.ac.uk
[8] Documentation of HSE 2010 on the website of UK Data Service: http://discover.ukdataservice.ac.uk/catalogue/?sn=6986&type=Data%20catalogue

$$HWB_{(NS)} = \alpha + \beta_1 * age_{(NS)} + \beta_2 * female_{(NS)} + \beta_3 * income_{(NS)} + \beta_4 * employment_{(NS)} + \beta_5 * education_{(NS)} + \beta_6 * marital\ status_{(NS)} + \beta_7 * longstanding\ illness_{(NS)} + error$$

Step 1

(1) Obtain $\alpha,\ \beta_{1-7}$

Step 2

$$\widehat{HWB}_{(Predicted)} = \hat{\alpha} + \hat{\beta}_1 * age_{(CS)} + \hat{\beta}_2 * female_{(CS)} + \hat{\beta}_3 * income_{(CS)} + \hat{\beta}_4 * employment_{(CS)} + \hat{\beta}_5 * education_{(CS)} + \hat{\beta}_6 * marital\ status_{(CS)} + \hat{\beta}_7 * longstanding\ illness_{(CS)}$$

Step 2

(2) Calculate the predicted value of health and well-being (HWB) in current study

Step 3

$$\text{Difference} = HWB_{(CS)} - \widehat{HWB}_{(Predicted)}$$

Step 3

(3) Calculate the difference between observed HWB in current study (CS) and predicted HWB

Figure 7. 6 Flow chart showing three steps for out of sample prediction for the predicted value of health and well-being in current study using the results of national surveys ($\hat{\alpha}$ means the estimated value of α)

The first step was using OLS regression analyses to obtain the constant and beta coefficients of factors underlying individuals' assessments of health and well-being in the national surveys. The variables that included in the regression were age, sex, household income, employment status, highest educational qualification, marital status, and longstanding illness, all of which are available for the NSs and CS. Then step two was using out of sample prediction to calculate the predicted value of general health and well-being in the current study, by applying the estimated values of $\hat{\alpha}$ and $\hat{\beta}_{1-7}$. This gave the predicted level of health and well-being of each respondent in the current study, given their covariates, had they been in the national survey and not exposed to wind turbine noise. The difference between observed and predicted scores of well-being for each respondent was calculated in Step 3, which was going to be examined in terms of its association with the levels of wind turbine noise.

7.6.1 General health

OLS regression analysis was taken using the data of US wave 6 to model self-reported general health (5-point scale) among all respondents (n=39,844), controlling for personal variables which were included in both studies, as shown in the equation in Figure 7.6. The results of the regression are shown in Table 7A.5 in Appendix IV.

Based on the obtained regression coefficients (Step 1 in Figure 7.6), predicted general health scores for each respondent in the current study were calculated (Step 2 in Figure 7.6) using out-of-sample predictions. Figure 7.7 shows the distribution of the predicted and actual general health in the current study, and in the national survey, respectively (detailed percentage values can be found in Table 7A.6 in Appendix IV). With-in-sample predictions were also carried out, that used obtained coefficients to predict the responses in the US data itself, shown as the 3rd bar chart in Figure 7.7.

As shown in Figure 7.7, comparing the distribution of observed and predicted general health for US (4th vs 3rd bars), the predicted scores based on OLS model concentrate more on the mediate levels (e.g. 2, 3) but not on extreme outcomes (e.g. 1, 5)[9]. Similar to the predicted scores for US, the absence of extreme outcomes for predicted general health in the current study might largely depend on the estimation method, not the data of the study itself. The difference in distributions between predicted general health in the current study and the national survey (2nd vs 3rd bars) illustrate that the current study sample was predicted to have worse health than the national study sample, controlling for covariates using OLS.

[9] Strictly speaking, since the health categories are on an ordered categorical scale rather than a continuous scale, an ordered logistic regression was also carried out, but the overall results are not qualitatively different. See Figure 7A.1 in Appendix IV.

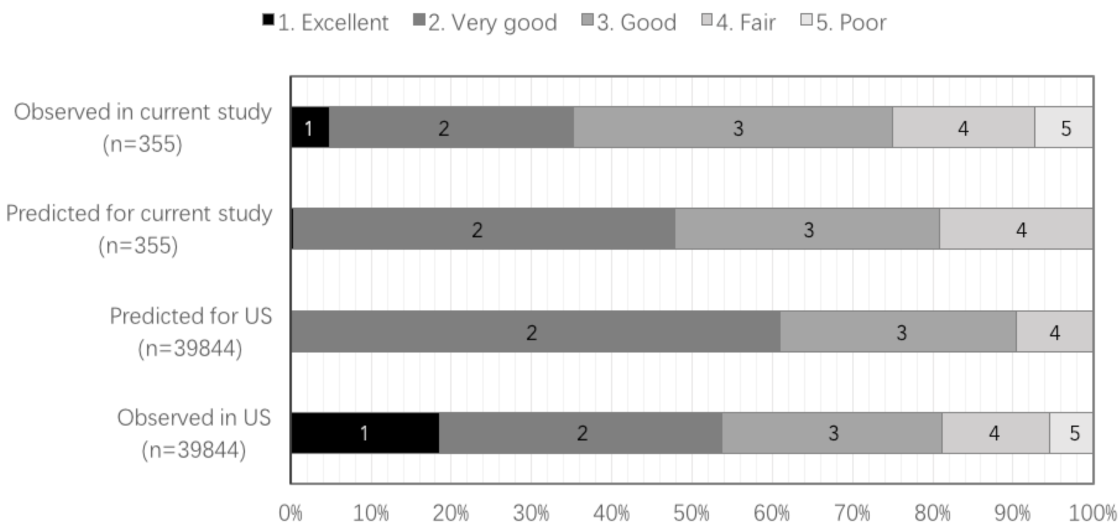


Figure 7. 7 Cluster stack bar charts showing the percentage of respondents in each score of general health observed in current study, predicted for current study, predicted for Understanding Society, and observed in Understanding Society, respectively

Within the current study, when looking at the difference between observed and predicted general health scores of each individual (Step 3 in Figure 7.6), positive differences accounted for 136, and negative differences accounted for 78. Results from the Wilcoxon signed-rank test showed that the observed scores of general health were significantly higher than the predicted ones (z=4.35, p=0.000). Noting that a higher score for general health question means poorer health, the results illustrated that the respondents near a wind turbine reported poorer health then they were predicted to be, using the national data controlling for respondent background characteristics. The distribution of the difference between observed and predicted general health scores was not significantly different between questionnaire variants (Gamma=-0.149, p=0.107).

The difference between observed and predicted general health scores was not correlated to wind turbine noise level, and was not related to noticeability or annoyance due to wind turbine noise. The decrease in general health comparing to predicted levels was only found to be related to sites, where Site C had significantly more respondents who had poorer general health than prediction (Gamma=0.294, p=0.002).

Binary logistic regressions were carried out to investigate the relationship between whether had poorer general health than prediction ($Observed_{(general\ health\ scale)}$-$Predicted_{(general\ health\ scale)}$ >0) and wind turbine noise, controlling for site dummies. The results are shown in Table 7.9. Maximum, minimum, average SPLs, the difference between maximum and minimum SPLs, and being annoyed by the noise were added to the model one by one.

Table 7. 9 Binary logistic regressions modelling having poorer health than predicted using SPLs at dwellings, the difference between maximum and minimum SPLs, and covariates

	Dependent variable: having poorer than predicted (yes/no)					
	Odds ratio					
	(1)	(2)	(3)	(4)	(5)	(6)
Maximum_SPL	0.980				0.984	
Minimum SPL		0.987				
Average_SPL			0.987			
$Difference_{(Max-Min)}$				0.965	0.977	
Annoyed by WTN						0.935
Site A	**0.386*** **	**0.394*** **	**0.396*** **	**0.424*** **	**0.397*** **	**0.416*** **
Site B	**0.440*** **	**0.433*** **	**0.436*** **	**0.429*** **	**0.440*** **	**0.427*** **
n	*355*	*355*	*355*	*355*	*355*	*355*
R^2	*0.051*	*0.049*	*0.049*	*0.050*	*0.052*	*0.047*
$p_{(H-L)}$	*0.301*	*0.075*	*0.806*	*0.890*	*0.358*	*0.121*

Note: *p<0.1; **p<0.05; ***p<0.01. Statistically significant associations (p<0.05) in boldface.

As shown in Table 7.9, no significant associations were found between wind turbine noise and whether had poorer general health than prediction. Being annoyed by wind turbine noise was not significant. Respondents in sites A and B were less likely to have poorer health than the prediction, compared to the reference group in Site C. Attitude to wind projects, visibility of the wind turbine from home, or whether lived in current address before or after the operation of the turbine were not associated with the odds of having poorer health, if added to the regression model.

7.6.2 Life satisfaction

Contributions of the socio-economic variables on variation in life satisfaction were modelled using the same dataset from Understanding Society (US) (see Table 7A.7 in Appendix IV). Using a similar method, the predicted levels of life satisfaction were calculated to compare with the observed data (for detailed values see Table 7A.8 in Appendix IV). The distributions of observed and predicted life satisfaction levels for the current study and the US are shown in Figure 7.8.

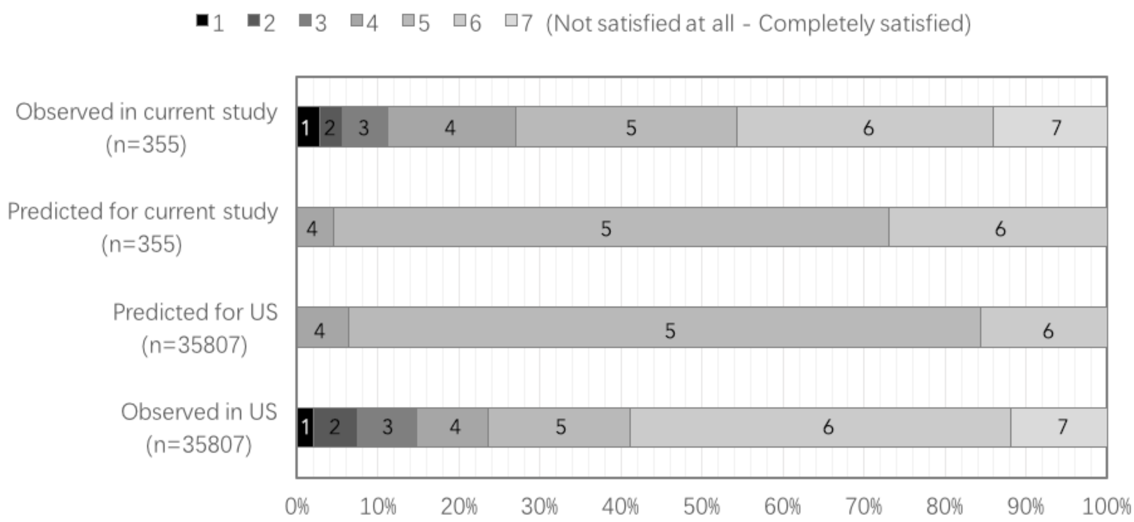


Figure 7. 8 Cluster stack bar charts showing the percentage of respondents in each level of life satisfaction observed in current study, predicted for current study, predicted for Understanding Society, and observed Understanding Society, respectively

The distribution of predicted life satisfaction for current study was not much different from that predicted for the national survey (2nd and 3rd Bars), with the current study sample predicted to have a slightly larger proportion in higher satisfaction levels.

When looking at the difference between observed and predicted levels of life satisfaction in the current study, the number of positive differences were 127, and 116 for negative differences. A Wilcoxon signed-rank test indicated no significant difference between observed data in this study and those predicted according to the national survey (z=-0.77, p=0.441). No significant difference was found in Variant 1 and Variant 2 separately.

7.6.3 Happiness

Using a similar method, self-reported happiness scales of the current study were compared to the predicted scales based on HSE 2011 sampling cross England (see Tables 7A.9 and 7A.10 in Appendix IV). Figure 7.9 shows the distribution of happiness scales, where the predicted happiness scale for the current study sample was not significantly different from the predicted happiness for the England sample. Comparing between the 2nd and 3rd bars, the current study sample was predicted to be slightly happier than the England sample, controlling for background characteristics of the sample

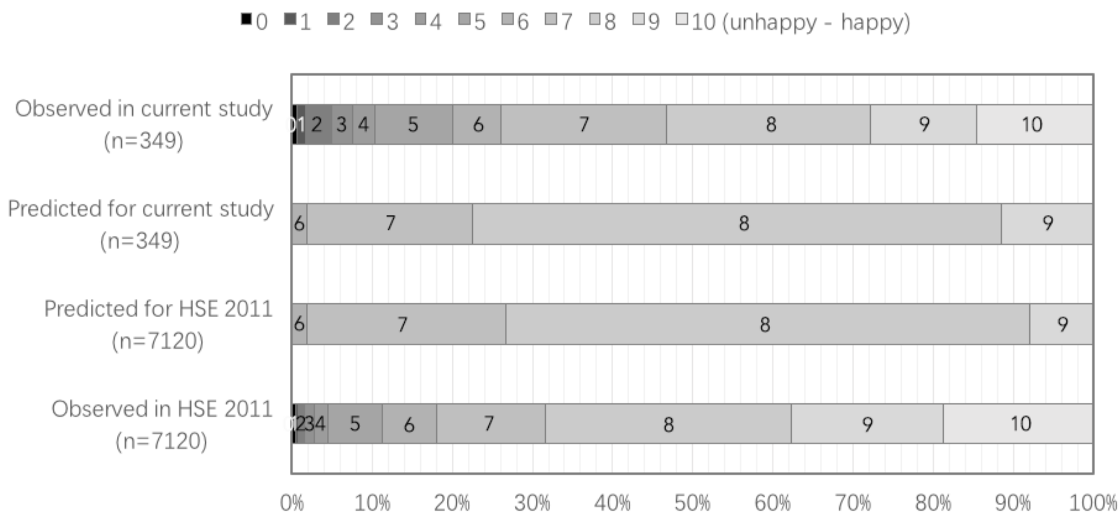


Figure 7. 9 Cluster stack bar charts showing the percentage of respondents in each scale of happiness observed in Understanding Society, predicted for current study, and observed in current study, respectively

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The differences between observed and predicted happiness for all individuals were 106 positive and 162 negative. Results from the Wilcoxon signed-rank test indicated that the happiness scales were significantly lower among the current study (z=-4.50, p=0.000). The differences between observed and predicted happiness were found to be significant in both Variants 1 and 2.

The difference between observed and predicted happiness scales was not related to the level of maximum wind turbine noise exposure at the dwelling, but was significantly correlated to the minimum SPL [r=-0.113, p=0.035], as well as the difference between maximum and minimum SPLs [r=0.103, p=0.054]. It indicated that reducing the noise exposure on the least-exposed façade and enlarging the difference between the most- and least-exposed façades could reduce the negative difference between observed and predicted happiness scales.

To further investigate the relationship between the decrease in happiness and different noise indicators, binary logistic regression analyses were carried out to model the relationship between being less happy than the prediction (dependent variable; $Observed_{(happiness)}-Predicted_{(happiness)}<0$) and wind turbine noise, controlling for site dummies and other covariates. Maximum, minimum, the difference in SPLs, and whether annoyed by the noise were added to the regression model one by one as independent variables. Table 7.10 shows the results of regressions.

It was found that the maximum SPL was not significantly associated with the odds of being less happy than predicted based on the national survey (model 1). Increasing minimum and average SPLs significantly increased the likeliness of being less happy (models 2 & 3). The difference between SPLs at the most- and least-exposed façades was significantly negatively associated with being less happy than predicted (model 4). Both maximum SPL and the difference in SPLs were significant when added to the regression together, indicating that with the same maximum exposure, enlarging the noise difference between the noisiest and quietest sides of the building decreases the odds of being less happy than the prediction (model 5). Being annoyed by the noise was not associated with the odds of less happiness. The results further confirmed that both the noise levels on the quietest façade and the difference between the most- and least-exposed façades were important in narrowing the gap in happiness between wind turbine communities and the sample of national survey controlling for background characteristics. It should be noted that the odds of being less happy was not associated with attitudes to wind projects, visibility of the turbine from home, or whether lived in current address before or after the operation of the turbine.

Table 7. 10 Binary logistic regressions modelling being less happy than predicted using SPLs at dwellings, the difference between maximum and minimum SPLs, and covariates

	Dependent variable: less happy than predicted (yes/no)					
	Odds ratio					
	(1)	(2)	(3)	(4)	(5)	(6)
Maximum_SPL	1.026				**1.051****	
Minimum SPL		**1.056*****				
Average_SPL			**1.044****			
$Difference_{(Max\text{-}Min)}$				**0.926****	**0.890*****	
Annoyed by WTN						1.577
n	*349*	*349*	*349*	*349*	*349*	*349*
R^2	*0.016*	*0.035*	*0.027*	*0.025*	*0.047*	*0.016*
$p_{(H\text{-}L)}$	*0.846*	*0.183*	*0.957*	*0.859*	*0.854*	*0.908*

*Note: All models controlled for site dummies (not significant). *p<0.1; **p<0.05; ***p<0.01. Statistically significant associations (p<0.05) in boldface.*

To conclude, Section 7.6 compared the levels of self-reported general health and subjective well-being observed in the current study to the predicted levels according to the national surveys of Understanding Society or Health Survey of England, controlling for sociodemographic variables that existed in both the current and the national surveys. It was found that respondents in the current study reported significantly poorer general health and lower happiness scales than they predicted to have based on the national survey data. Wind turbine noise levels did not have an effect on the decrease of general health. The noise level on the quietest façade had an important effect on the probability of having less happiness than the prediction. Having a small noise difference between the noisiest and quietest façades was positively associated with being less happy than the national sample controlling for sociodemographic variables.

7.7 Discussions

7.7.1 Statistical implication of the data

The chapter found that wind turbine noise was associated with variation in some aspects of health and well-being. It is worth noting that a significant relationship between noise annoyance and health should not be taken as evidence of a causal pathway from the noise to health, as the study method was not designed to establish causality between some variables, e.g., adverse health problems might cause annoyance, in the reverse direction.

Respondents' background characteristics were significantly different across noise categories, where respondents in the higher exposure group were also lower in socio-economic status (as demonstrated in Section 6.2.2). This increased the probability of multi-collinearity. Efforts had been made to deal with multi-collinearity between explanatory variables of SPL, longstanding illness, and questionnaire variants, by doing the analysis separately for four groups of samples - with or without longstanding illness, in Variant 1 or 2, respectively. Doing regressions in subgroups as a common method to deal with collinearity might introduce some risks, such as increased standard error and over-fitting (Dormann et al., 2013). The sample size in each group was reduced, which might not have been sufficient to detect significant associations for certain health problems. However, all models on health symptoms have relatively high *p*-values for the Hosmer-Lemeshow test and R^2, indicating that the model fitted well with the data and could account for certain variance in the odds of reporting that health symptom.

The comparison between the health and well-being of this study to the national data found decreased general health and happiness in the current study sample, controlling for respondent background factors. However, the difference could arguably be caused by other background factors that were not controlled for. Missing explanatory variables might include personality, religious, and socialising activities, which have been found to influence subjective well-being in some studies (Dolan et al., 2008). However, adding these variables did not increase the R^2 of the models on happiness and life satisfaction as much as the existing variables did, tested using secondary data of the US. As adding sociodemographic variables would also increase the length of the questionnaire, only key determinants of subjective well-being such as age, sex, income, and illness were included in this study. In addition, the association between wind turbine noise levels and decreased happiness might depend on other unobserved factors. For example, other environmental nuisances in high exposure areas might also cause a deceptive association between decreased happiness and wind turbine noise. This possibility could not be tested with the current survey data.

7.7.2 Effect of wind turbine noise on health and well-being

Sleep

In this study, sleep disturbance was self-reported by the respondents without referring to noise. Unlike the previous studies that asked the occurrence of disturbed sleep by noise using a single question (Bakker et al., 2012; Pedersen & Waye, 2004, 2007), the present study assessed the occurrence of various type of sleep disturbances such as difficulty in falling asleep, sleeping less deeply, and awakening. It has been found that noise levels were not associated with sleep, but the degree of noise annoyance significantly increased the possibility of sleep disturbance including sleeping less deeply and difficulty falling asleep. The results agree well with the previous findings that wind turbine noise does not directly influence sleep, but annoyance acts as a mediator (Bakker et al., 2012). But it should be noted that a reverse causality from sleep to annoyance might exists.

The association between noise annoyance and sleeping problems in this study is consistent with the findings of other environmental noise that noise-related sleep disturbance is associated more strongly to noise annoyance than noise exposures (F. van den Berg, Verhagen, & Uitenbroek, 2014). Respondents who were annoyed by the noise might be more likely to notice the noise at night and get disturbed in their sleep, though the causal pathway could not be established, as disturbed sleep might cause annoyance in the reverse direction.

No significant difference in sleep disturbance was found between the highest exposure (>40dBA) and the lowest exposure (<30dBA) groups, which is different from the findings of the previous studies (Pawlaczyk-Łuszczyńska et al., 2014; Shepherd et al., 2011) in rural areas that found significantly higher prevalence of insomnia and lower sleep satisfaction in the high exposure group.

The absence of a significant association between noise levels and sleep in this study might be also because urban respondents were more adaptive to noise. According to the findings of a meta-analysis study, a dose-response relationship between self-reported sleep disturbance and A-weighted noise exposure was not found in more densely populated suburban areas with various sound sources (Pedersen, 2011). Support for the absence of direct noise impact on sleep can be also found in the threshold noise levels for the occurrence of different sleep problems, reported by previous environmental noise studies. For example, the peak noise levels of 45dBA could increase the time to fall asleep, and nocturnal awakenings could be provoked for levels of 55dBA (Muzet, 2007), which are higher than the observed noise exposure from wind turbines in this study.

Adverse health effects

This study investigated the hypothesised effect of wind turbine noise on self-reported prevalence of physical health problems (e.g. headache, nausea, ear discomfort, cardiovascular disease) as well as psychological or mental distresses (e.g. stress, tension, mood swings) using regression analysis controlling for the effect of background factors. Wind turbine noise levels were positively associated with dizziness and ear discomfort, while annoyance with the noise was positively associated with cardiovascular disease and headache.

In general, the findings are in line with the literature that environmental noise with low frequency components such as aircraft noise was more likely to increase the risk of headache and irritability (S.A. Stansfeld et al., 2000). The association between headache and annoyance in this study agrees with findings in the first Swedish, the Dutch, and the Polish studies (Pawlaczyk-Łuszczyńska et al., 2014; Pedersen et al., 2009; Pedersen & Waye, 2004). But the association was only found in respondents who had no illness and have known the purpose of the study (in Variant 1). The effects of wind turbine noise on dizziness and ear discomfort have been pointed out in several reports based on local residents' complains (Harry, 2007; Thorne & Leader, 2012), but have not been found in previous field studies. The effect on cardiovascular disease has been stated as one of the "wind turbine syndrome"(Farboud et al., 2013) but has not found evidence in previous field studies.

It was found that A-weighted noise exposure from the wind turbine and annoyance with the noise were associated with the physical problems in this study, but did not affect mental health such as stress and tension. This was different from the findings of previous studies where noise annoyance was found to be an important mediator of the relationships between wind turbine noise and mental health measured by the general health questionnaire (GHQ) scores (Bakker et al., 2012; Pawlaczyk-Łuszczyńska et al., 2014). Annoyance with wind turbine noise (but not noise level itself) was also consistently associated with feeling tense or stressed in four previous studies (Pawlaczyk-Łuszczyńska et al., 2014; Pedersen, 2011). However, this link was not found in the current study.

It is worth noting that the prevalence of health problems was significantly different between questionnaire variants, and depending on whether respondents had longstanding illness. This is discussed in section 7.7.3.

General health and subjective well-being

There has been a trend that more recent studies on wind turbine noise assessed health and well-being in terms of overall quality of life and general health using established questions such as health related quality of life (HRQOL) (Shepherd et al., 2011), general health questionnaire (GHQ) (Bakker et al., 2012; Pawlaczyk-Łuszczyńska et al., 2014), and the short form 36 (SF-36v2) (Nissenbaum et al., 2012). The present study assessed the effect of wind turbine noise on self-reported general health, happiness and life satisfaction. It was found that wind turbine noise level was not significantly associated with general health and well-being within the studied sample, controlling for socio-demographic variables. However, significantly poor health and lower happiness were observed among the respondents of this survey than the predicted levels according to the secondary data of national surveys, controlling for respondent background characteristics. The findings correspond well with the New Zealand study which has found that the wind turbine exposed group have significantly lower physical HRQOL as well as lower overall quality of life compared with a non-exposed control group (Shepherd et al., 2011).

The poorer general health than predictions was not found to be related to wind turbine noise level nor the annoyance with the noise. It is worth stating that the difference between observed and predicted happiness was not related to wind turbine noise at the most-exposed façade, but with noise level at the least-exposed façade and the difference between most- and least-exposed façades. This confirmed the quiet façade effect that the existence of a quiet façade which was much less exposed than the noisy façade could reduce the decrease in happiness scale compared to national data. It is also possible that the degraded level of happiness and general health among the sample are not a function of noise or proximity to wind turbines, but due to other socio-economic and contextual factors that were not included, such as urbanisation (Hudson, 2006) and trust (Helliwell, 2006), which have been reported to affect happiness and general health. The noise effect on subjective well-being might also take more time to appear than effects on annoyance and health, and might depend on individual adaptation (Luhmann, Hofmann, Eid, & Lucas, 2012). Using longitudinal studies over a period of time can help to investigate long-term noise effects on subjective well-being. Nevertheless, the degraded level of health and subjective well-being in wind turbine exposed communities should not be ignored and can be explored in future studies.

7.7.3 Effect of questionnaire variants

Self-reported health and well-being were examined among the main sample (Variant 1) and control (Variant 2) groups, where the background characteristics of the respondents were similar and the only covariate that differed was longstanding illness (more in Variant 2). An important finding of the study lies in the difference between the two groups. Adverse health problems were more frequent in Variant 2 for whom the research purpose was masked. Unexpected *negative* associations were found between noise level and prevalence of health problems among respondents in the main group (Variant 1), while *positive* associations were found in the control group (Variant 2). The reason could be related to the effect of questions of the two variants. Unlike Variant 2, where the purpose of the research was masked, it was clear to participants in Variant 1 that their health data would be analysed in relation to wind turbine noise. This might have led to less health problems being reported by Variant 1 respondents, as 89%

of them had indicated wind turbine noise did not influence health. The unexpected higher prevalence of difficulty in intellectual activities and stress in low exposure areas in Variant 1 might be a result by random chance. Another possible reason might be that Variant 1 respondents living in the low exposure zones over-reported their health symptoms, as the survey asked them to attribute the cause of any health symptom to wind turbine noise, which made them to focus on adverse impact of wind turbines noise on health and introduced bias. This behaviour has been reported in a previous study on aircraft noise, that the wording of specific questions aimed at eliciting symptoms had a marked effect on the answers (Barker & Tarnopolsky, 1978). However, the higher proportion of positive answers was found in *high* noise areas, rather than *low* noise area as found in this study. Nevertheless, the differences in adverse health impacts between Variants 1 and 2 implied that results in Variant 1 with symptoms attributed to noise might represent symptom reporting or focusing effects based on respondent's knowledge rather than real noise effects.

The usefulness of the two variants is a methodological finding which is important to be noted. In four previous studies using a similar questionnaire to assess the impact of wind turbine noise (Pawlaczyk-Łuszczyńska et al., 2014; Pedersen et al., 2009; Pedersen & Waye, 2004, 2007), it is possible that the substantial questions on attitudinal and visual aspects of the wind turbine in the same questionnaire implied the research topic to respondents, and the existence of other environmental stressors failed to mask the purpose of the study. In this situation, the question get the respondents to focus on wind turbine noise, which would make it more prominent as a source of ill health, and respondents might choose the item they thought was most relevant to the study. Therefore, it is suggested that the discovered dose-response results should be considered carefully and future research could minimise the focusing bias by involving a control group with research purpose fully masked to differentiate the statistically modelled noise impact from the respondent's focusing impact.

7.8 Conclusions

Sleep was not directly related to wind turbine noise, but to noise annoyance. Being annoyed by wind turbine noise was positively associated with sleeping less deeply. The prevalence of other adverse health problems was found to be different between variants, with the subgroup who were not informed of the research purpose reporting more health problems. Self-reported dizziness, ear discomfort and nausea were found to be positively associated with wind turbine noise in Variant 2, while difficulty in intellectual activities and stress were associated with wind turbine noise in a negative way in Variant 1. Cardiovascular disease and headache were related to annoyance with the noise in Variant 1. Degraded general health and happiness was found among the study sample than the out-of-sample predictions using the national survey data. The decrease in happiness scale was positively associated with noise level at the least-exposed façade and negatively associated with the difference between the most and least exposed façades. Other moderating factors, including age, sex, and sensitivity to noise were found to have significant impacts on health and well-being.

An important finding lies in the difference between questionnaire variants, which indicated that subjective assessment of adverse health impact in Variant 1 to whom the purpose was not masked suggested a symptom reporting or focusing effect rather than real noise effects. This is also a contribution to knowledge that suggests the use of two variants in the studies on the health impact of noise. Future research could minimise the focusing bias by involving a control group with research purpose fully masked.

Part Three: Implementation in Design and Planning

Chapter 8

Towards Design and Planning of Urban Areas for Wind Turbine Noise Management

8.1 Introduction

In former parts of the thesis, Chapter 4 used noise mapping to understand the distribution of wind turbine noise in built environments and examined the effects of built environment morphology on resisting the exposure of wind turbine noise on building façades (shown as Objective 1 in Figure 1.3). Chapters 6 & 7 then calculated the SPLs at the most exposed façade of respondents' dwellings and linked these noise exposures to questionnaire responses on noise evaluation and human health and well-being (shown as Objective 2 in Figure 1.3). This chapter investigates the potential of urban planning and design on changing the evaluations on wind turbine noise (shown as Objective 3 in Figure 1.3).

It has been proposed in many studies (e.g. (Wang & Kang, 2011)) that the planning of residential areas at the urban scale can greatly influence the distribution of traffic noise. It is unconfirmed whether major background noise in suburban areas (e.g. noise from major roads) will influence residents' evaluation on wind turbine noise. This chapter firstly evaluates the role of design and planning of suburban areas on noise impact management, by linking both wind turbine noise and background noise to human well-being.

It has been confirmed in previous chapters that suburban morphology and wind turbine siting can greatly influence the noise exposure at the quiet façade (e.g. at the least-exposed façade of a building). It has also been presented that wind turbine noise at quiet façades have an impact on human health and well-being too. This implies that the design of dwellings at the local scale can change the wind turbine noise level, and hence has a potential to reduce noise impact on health and well-being. This chapter therefore evaluates the role of morphological design on noise impact management.

Figure 8.1 shows the flow chart of this chapter. Section 8.2 investigate the noise management at planning scale. It explores the masking effect of traffic noise in suburban areas on wind turbine noise evaluation. Section 8.3 focuses on the design of built environment morphology at a local scale, which examines the noise management through design that reduces the noise at quiet sides of the dwelling. Section 8.4 integrates the findings obtained across different chapters of this thesis that can inform design and planning implementations. Conclusions on design and planning solutions for wind turbine noise management are described in Section 8.5.

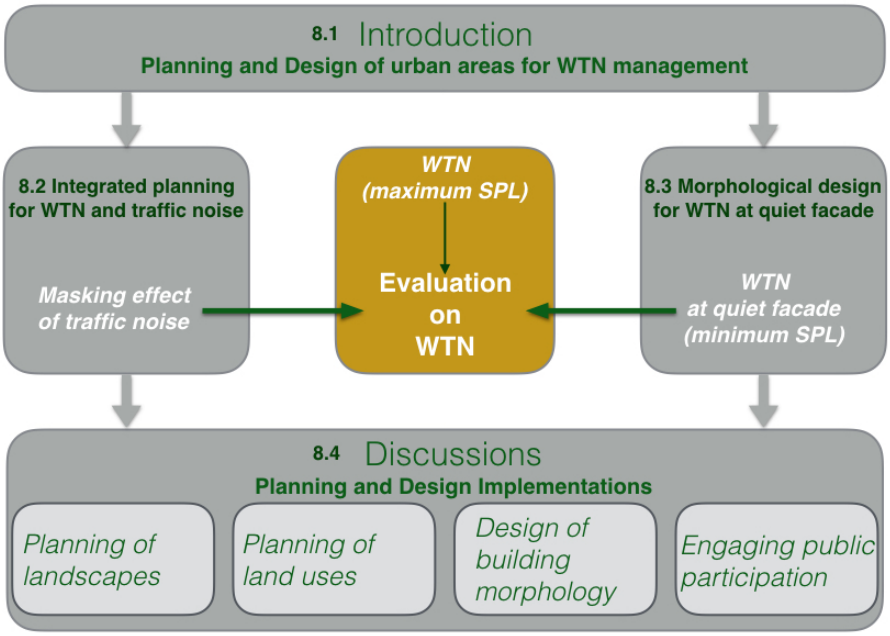


Figure 8. 1 Flow chart of Chapter 8.

8.2 Integrated Planning for Wind Turbine and Traffic Noise in Urban Areas

For the siting of wind turbines in suburban areas, the influence of the noise from major roads and railways should be considered. It has been found in previous studies on wind turbine noise that residents in urbanised areas were less disturbed by wind turbine noise (Bakker et al., 2012). However, it is not known whether this is due to the masking effect of higher traffic noise in urbanised areas compared to rural areas.

This section considers the wind turbine noise management at a planning scale, which investigates the layout of the road network in the studied area, estimates the traffic noise at each respondent's dwelling, and examines its impact on evaluation of the wind turbine noise.

To investigate the hypothesised masking effect of traffic noise in suburban areas, noise exposure at studied dwellings from major roads were calculated using CadnaA. An example of a building noise map of road traffic noise is shown in Figure 8.2. Using CadnaA, the sound emission of a road was simulated according to the RLS-90 guideline for calculating road noise, with inputs of the road width (m), average daily traffic density (counts of vehicles/18h), road type (motorway, federal, ordinary and local), and speed limit of the road (km/h). These parameters were obtained based on on-field observations and the street-level traffic counts data from the Department for Transport (DfT). The annual average daily flow (AADF) for a certain road in the year of the survey was downloaded from the DfT, which covered the traffic counts for each junction to junction link on the "A" road network in the UK (DfT, 2014). The counts of vehicles on a stretch of other major roads in the study sites were obtained from on-field observations. Noise from minor roads with an estimated 18h vehicle counts less than 2000 were not considered in this study. The emission level for railways was automatically calculated in CadnaA according to the chosen guideline based on selection of the local list of train classes from the list. As shown in Figure 8.2, the time-averaged levels of traffic noise exposure at the dwelling for day (Ld) and night (Ln) were calculated.

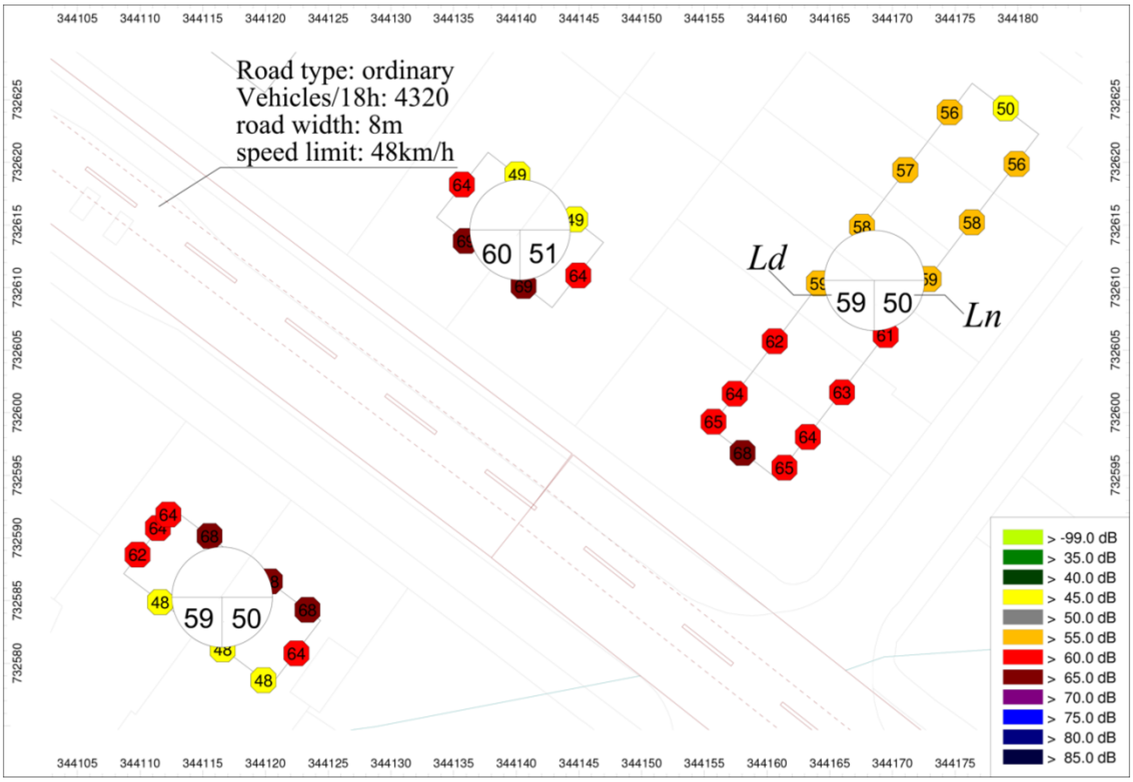


Figure 8. 2 Example of calculated traffic noise exposure at studied buildings

In this section, the masking effects of traffic noise are examined from two perspectives: the effect of RTN in relation to WTN (Section 8.2.1); and the masking effect of RTN by itself (Section 8.2.2). The threshold level of RTN that could reduce the impact of WTN is calculated (Section 8.2.3) and the effect of RTN above the threshold is demonstrated (Section 8.2.4). Planning suggestions are provided at the end of each section and highlighted in Section 8.2.5.

8.2.1 Masking effect of road traffic noise in relation to wind turbine noise

This section presents the difference between road traffic noise (RTN) and wind turbine noise (WTN) levels at respondent's dwelling and investigates whether this difference in RTN and WTN levels influence the evaluation on wind turbine noise, including noticeability and annoyance.

The calculated Ld and Ln of road traffic noise (RTN) at studied dwellings were correlated (Pearson's r=0.979, p<0.001). On all study sites, Ld ranged from 38 to 66dBA (mean=49.0, SD=5.3), Ln ranged from 29 to 60dBA (mean=41.2, SD=5.4). The difference between Ld and Ln was in the range of 2 to 10dBA, which was significantly correlated to Ln (Pearson's r=-0.233, p<0.001), but *not* significantly correlated to Ld (Pearson's r=-0.033, p=0.543). This indicated that high Ln implied less difference between day and night traffic noise exposures. In other words, the dwellings exposed to high levels of night-time traffic noise were likely to be noisy day and night, such as beside high ways that conveyed much transportation even at night.

In addition, it was found that the S-R distance from the wind turbine was significantly negatively correlated to RTN, suggesting that residents near wind turbines might be also exposed to higher level of RTN. There was a significant correlation between WTN and both Ld (Pearson's r=0.156, p=0.003) and Ln (Pearson's r=0.135, p=0.011)[10]. This finding corresponds with a trend of siting urban wind turbines near motorways and other large noise sources (Mezzofiore, 2016).

In the suburban areas of this study, respondents were exposed to higher RTN than WTN. For all studied dwellings, day-time RTN (Ld) exceeded WTN from 7 to 48dBA (mean=22.6, SD=7.2); night-time RTN (Ln) exceeded WTN mostly in the range of 2-42dBA (mean=14.8, SD=7.4), with only one exception where WTN exceeded Ln with 1dBA at one dwelling.

To investigate the hypothesised masking effect of RTN, the study sample was divided into three groups corresponding to the difference between levels of day-time RTN (Ld) and WTN, with the difference less than 20dBA (n=135), within 20-25dBA (n=101), and over 25dBA (n=113). Similarly, three sub-samples were created according to the difference between Ln and WTN, of below 10dBA (n=101), 10-15dBA (n=98), and over 15dBA (n=150).

Figures 8.3 and 8.4 compares the dose-response relationships between WTN intervals and subjective evaluations between different sub-samples. It can be seen

[10] The provided correlation coefficients were calculated using average façade exposure as an example for wind turbine noise exposures. Correlations between maximum/minimum SPLs and traffic noise levels were also significant and similar to average SPL.

that masking effects of RTN were found when the difference between day-time RTN (Ld) and WTN was higher than 20dBA (Figure 8.3), or higher than 10dBA between night-time RTN (Ln) and WTN (Figure 8.4). The masking effect of RTN did not occur within the above levels, where the percentage of respondents who noticed and were annoyed with WTN significantly increased with increasing of WTN intervals, approaching around 60% and 40% respectively in the highest exposure interval of WTN (>40dBA). Thus, the dose-response relationships for $Ld_{(RT)}$ exceeding $L_{(WT)}$ less than 20dBA or $Ln_{(RT)}$ exceeding $L_{(WT)}$ less than 10dBA were set as baselines with which relationships for higher relative values between RTN and WTN were compared.

As shown in Figure 8.3, when Ld exceeded WTN within the interval 20-25dBA, the percentages of noticed and annoyed respondents decreased in the highest exposure interval (WTN>40dBA), with 44% and 23% lower than the baseline where Ld exceeded WTN less than 20dBA. When Ld exceeded WTN over 25dBA, the reduction in noticeability and annoyance started when WTN was moderate (35-40dBA), as the percentages of 'noticed' and annoyed respondents were lower than the baseline at both moderate (35-40dBA) and high (>40dBA) WTN intervals.

Similarly, as shown in Figure 8.4, when night-time traffic noise (Ln) exceeded WTN within 10-15dBA, percentages of 'noticed' and annoyed respondents at the highest WTN interval (>40dBA) were 49% and 26% lower than the baseline where the difference between Ln and WTN was less than 10dBA. A difference between Ln and WTN over 15dBA was found to reduce noticeability and annoyance due to WTN with 12% and 11% respectively at a moderate level of WTN (35-40dBA), and reduced to 0 at the highest WTN interval (>40dBA).

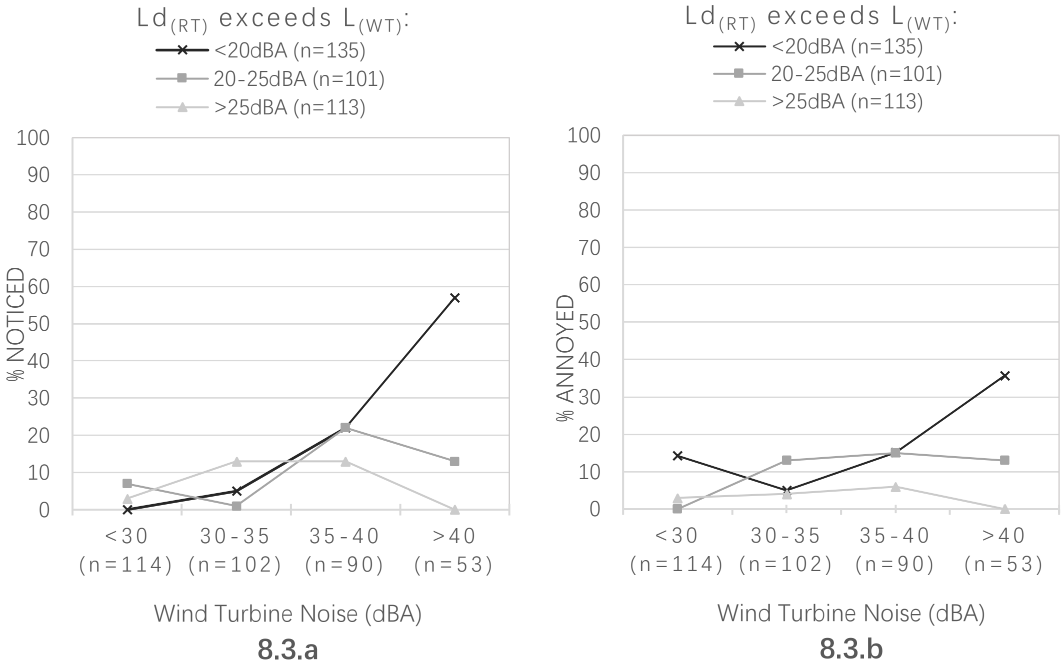


Figure 8. 3 Percentage of respondents who noticed (Fig.8.3.a) or were annoyed (Fig.8.3.b) by WTN in relation to WTN categories for three situations where day-time road traffic noise (Ld) exceeds WTN with <20, 20-25, or >25dBA.

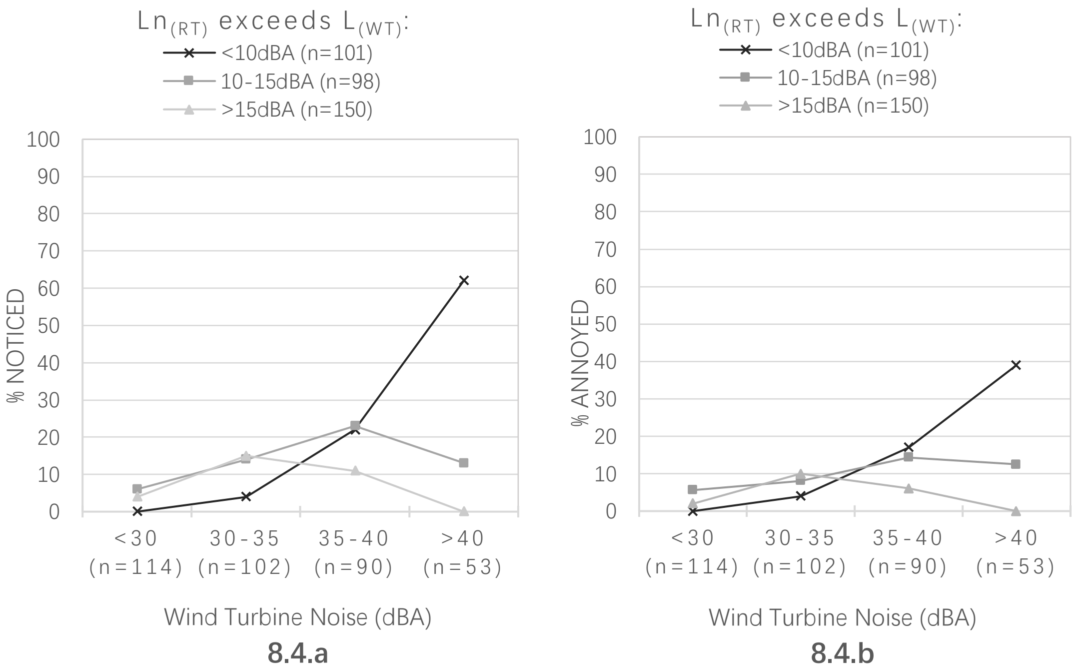


Figure 8. 4 Percentage of respondents who noticed (Fig.8.4.a) or were annoyed (Fig.8.4.b) by WTN in relation to WTN categories for three situations where night-time road traffic noise (Ln) exceeds WTN with <10, 10-15, or >15dBA.

These findings implied a possible masking effect of RTN on WTN when WTN levels were moderate or high (>35dBA) and day-time RTN levels exceeded that level over 20dBA, or night-time RTN levels exceeded that level over 10dBA. This is in line with a previous study which found that annoyance with WTN was reduced when the RTN level (Lden) exceeded WTN by 20dBA (Pedersen, van den Berg, Bakker, & Bouma, 2010).

It was found that the masking effect occurred when WTN levels were moderate (35-40dBA) or high (>40dBA). This finding was different from the previous one which only found a decrease in annoyance at an *intermediate* level of WTN (35-40dBA), but not in the *high* interval above 40dBA (Pedersen et al., 2010). This might be because in the suburban-urban area of this study, the relative levels between road traffic and wind turbine noise were higher than the previous study, which could mask wind turbine noise even at high levels over 40dBA. It is worth noting that when WTN was low (<35dBA), the presence of high RTN over WTN might increase the reported noticeability of and annoyance with WTN, probably due to the synergetic effect between RTN and WTN which will be stated in next section.

Therefore, in practical planning, the siting of wind turbines in existing traffic noisy areas can be supported, but the traffic noise should be substantially higher than wind turbine noise, with Ld over 20dBA higher than wind turbine noise, or Ln over 10dBA higher than wind turbine noise. In addition, the road should be planned in the area with high wind turbine noise exposures, but not placed at low wind turbine noise (<35dBA) areas, as high traffic noise in the less exposed area might increase the noticeability and annoyance with wind turbine noise.

8.2.2 Masking effect of road traffic noise level by itself

This section investigates the effect of RTN levels (without reference to WTN) on WTN evaluations. Noticeability of and annoyance with WTN in different RTN exposure groups were compared.

Figure 8.5 shows the proportions of respondents in each 5dBA day-time traffic noise (Ld) interval who noticed and were annoyed by wind turbine noise. Similarly, Figure 8.6 shows the proportions in 5dBA night-time traffic noise (Ln) intervals. It was found that when Ld was higher than 55dBA, and Ln higher than 45dBA, significantly fewer respondents reported noticing and being annoyed by wind turbine noise. As can be seen in Figure 8.5, when Ld increased from 50-55dBA to over 55dBA, the percentage of 'noticed' respondents decreased from 23% to 13% and the percentage of annoyance decreased from 14% to 10%.

As shown in Figure 8.6, there was a sharp decrease of noticeability and annoyance when the Ln increased from 40-45dBA to 45-50dBA. However, further increase of Ln from 45-50dBA to over 50dBA did not significantly decrease noticeability of WTN, and on the contrary, slightly increased the annoyance with WTN. This might because the synergetic effect at high levels of RTN, as RTN and WTN were significantly correlated. The annoyance with WTN could be increased due to being exposed to high levels of both RTN and WTN.

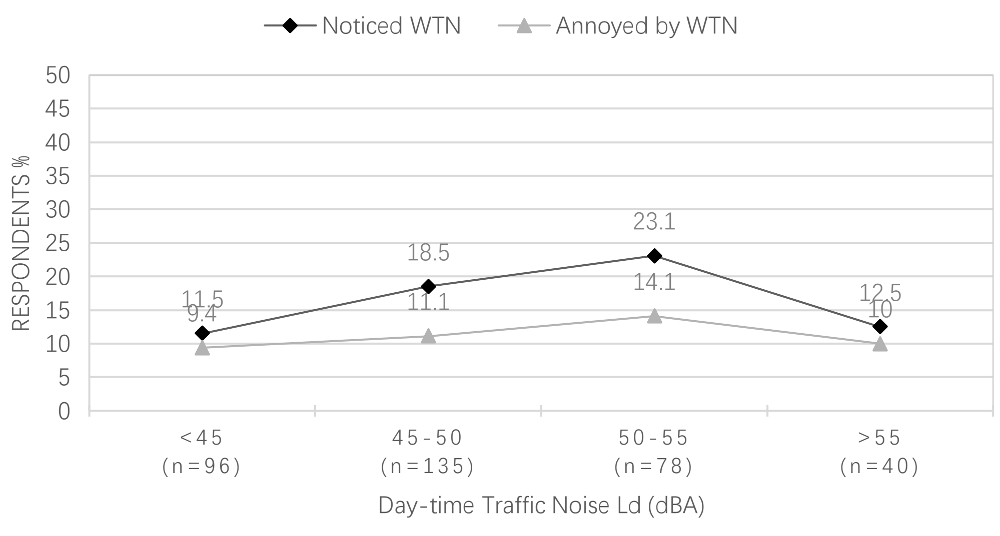


Figure 8. 5 Percentage of respondents who noticed and were annoyed by wind turbine noise (WTN) in relation to day-time traffic noise (Ld) categories with 5dBA intervals.

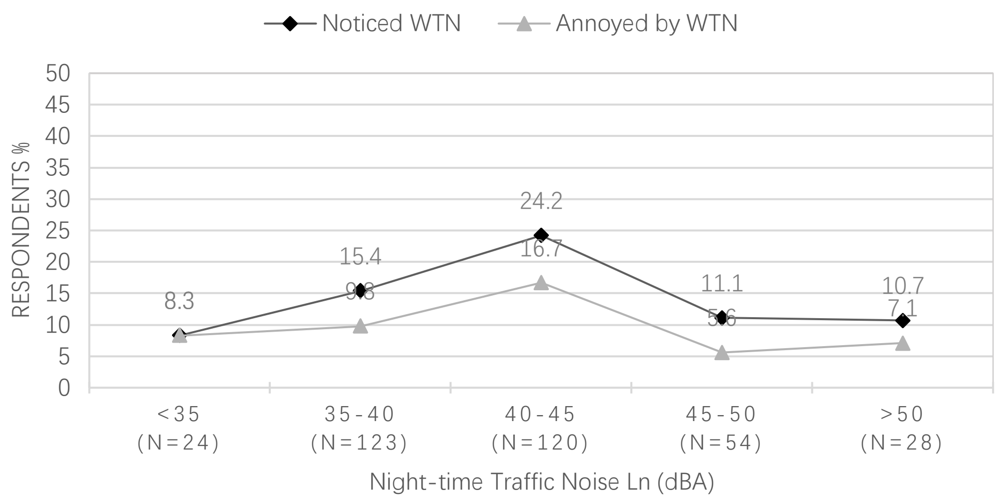


Figure 8. 6 Percentage of respondents who noticed and were annoyed by wind turbine noise (WTN) in relation to night-time traffic noise (Ln) categories with 5dBA intervals.

The results of this section suggest that high levels of traffic noise can provide a significant masking of wind turbine noise, which are important for planning of residential areas and siting of wind turbines in suburban areas. There was a sharp decrease in both noticeability and annoyance when Ld was at 50-55dBA and Ln was at 40-45dBA. This supports the integrated planning of main roads near wind farm affected communities. Respondents living alongside noisy roads are expected to be less disturbed by wind turbine noise if they are already exposed to day-time traffic noise of 50-55dBA or night-time traffic noise of 40-45dBA.

8.2.3 Threshold level of road traffic noise for the masking effect on wind turbine noise

This section investigates the threshold of RTN beyond which the masking effects occurred. As shown in Table 8.1, binary logistic regressions were carried out to examine the masking effect of traffic noise levels on noticeability of WTN, controlling for the maximum SPL from wind turbines at a dwelling, site and variant dummies. Using the same models, Table 8.2 shows the regressions for annoyance with WTN. As the relationships between RTN and WTN evaluations were non-linear (see Figures 8.5 and 8.6), squared variables of RTN were added to the regression models to calculate the turning points.

In terms of noticeability, as shown in Table 8.1, WTN levels still significantly increased the probability of noticing WTN. Night-time traffic noise Ln was positively associated with noticeability of WTN, while Ln^2 was negatively associated with noticeability, as shown in model 2. The calculated turning point of Ln was 41dBA, indicating that an increase of Ln was associated with an increase of noticeability of WTN until Ln reached 41dBA. When Ln exceeded 41dBA, an increase of Ln decreased the probability of noticing WTN, where the high level of RTN possibly masked the noticeability of WTN.

In terms of annoyance with WTN, as shown in Table 8.2, RTN levels were not significant, thus no turning points of RTN could be calculated for reducing annoyance. In addition, for both noticeability and annoyance, day-time traffic noise Ld and Ld^2 were not significant. As a result, the threshold of Ld that reducing WTN noticeability and annoyance could not be confirmed.

Table 8. 1 Binary logistic regressions modelling noticeability of wind turbine noise (WTN) using WTN levels and road traffic noise (RTN) levels controlling for site and variant dummies.

Model (sample)	Variables	B	*p*-value	Odds Ratio
1	***Notice WTN*** *[n=348, R^2=0.250, $p_{(H-L)}$=0.521]*			
(Variant 1+2)	Ld (Day-time RTN)	0.905	0.137	2.471
	Ld^2/100	-0.925	0.128	0.396
	Maximum SPL (WTN)	0.163	**0.000**	1.177
	Site (ref: Site C)			
	- Site A	-0.048	0.919	0.953
	- Site B	0.777	0.053	2.175
	Variant 2	0.157	0.665	1.170
2	***Notice WTN*** *[n=348, R^2=0.263, p(H-L)=0.437]*			
(Variant 1+2)	Ln (Night-time RTN)	1.136	**0.046**	3.114
	Ln^2/100	-1.391	**0.042**	0.249
	Maximum SPL (WTN)	0.161	**0.000**	1.174
	Site (ref: Site C)			
	- Site A	-0.178	0.710	0.837
	- Site B	0.722	0.080	2.058
	Variant 2	0.189	0.606	1.208

Statistically significant associations in boldface

Table 8. 2 Binary logistic regressions modelling annoyance with wind turbine noise (WTN) using WTN levels and road traffic noise (RTN) levels controlling for site and variant dummies.

Model (sample)	Variables	B	*p*-value	Odds Ratio
1	***Annoyed by WTN*** *[n=348, R^2=0.145, $p_{(H-L)}$=0.890]*			
(Variant 1+2)	Ld (Day-time RTN)	0.056	0.922	1.057
	$Ld^2/100$	-0.083	0.883	0.920
	Maximum SPL (WTN)	0.140	**0.001**	1.151
	Site (ref: Site C)			
	- Site A	0.091	0.869	1.096
	- Site B	0.597	0.198	1.817
	Variant 2	0.106	0.797	1.111
2	***Annoyed by WTN*** *[n=348, R^2=0.151, p(H-L)=0.509]*			
(Variant 1+2)	Ln (Night-time RTN)	0.462	0.381	1.588
	$Ln^2/100$	-0.586	0.352	0.556
	Maximum SPL (WTN)	0.133	**0.001**	1.142
	Site (ref: Site C)			
	- Site A	-0.044	0.936	0.957
	- Site B	0.545	0.252	1.725
	Variant 2	0.135	0.743	1.144

Statistically significant associations in boldface

In this study, only a night-time RTN of 41dBA worked as a threshold for the occurrence of a masking effect. This could be due to wind turbine noise was more likely to be noticed and more annoying at night than during the day (G. P. Van Den Berg, 2004), when it required a high level of masking sound at night. Thus, a high level of night traffic noise could possibly mask the noise from wind turbines. Another reason could be that dwellings with night-time traffic noise over 41dBA were more likely to be near highways that were noisy day and night, as Ld and Ln were positively correlated (Pearson's r=0.979, p<0.001). The masking effect on wind turbine noise might be enhanced in this situation where the road was noisy day and night.

This section provides guidance for planning by pointing out the minimum threshold of traffic noise which can mask wind turbine noise in studied suburban areas. It is suggested to use an express road or highway to separate wind turbines and residential areas. The volume of traffic on that road at night should be substantially high, with estimated Ln at the receptor dwelling over 41dBA.

The results also allow the prediction of potential effects of new or proposed wind turbines in urbanised areas with busy roads. One would expect less opposition to wind turbine development and less annoyance from a nearby wind farm if residents are already exposed to night-time traffic noise levels of over 41dBA.

8.2.4 Masking effects of road traffic noise with Ln exceeding the minimum threshold level

This section examines how each dB increase in RTN can decrease the noticeability and annoyance due to WTN, when Ln exceeds the calculated threshold level.

As stated in the paragraph above, 41dBA was the Ln threshold for the occurrence of a masking effect in this study. Thus, the study sample was divided into two groups, of Ln less than or equal to 41dBA (Group 1, n=204) and Ln over 41dBA (Group 2, n=144). Binary logistic regressions were used to examine the masking effect of RTN on both noticeability and annoyance in each group, controlling for maximum wind turbine noise SPLs, and other moderating variables.

It was found that levels of traffic noise were not associated with noticeability nor annoyance of WTN for Group 1 with Ln≤41dBA. Regression models are shown in Table 8A.1 in Appendix IV, which indicates that the SPL of WTN was the only variable that was significantly associated with noise evaluation when Ln≤41dBA.

For Group 2 with Ln over 41dBA, increasing RTN was associated with reduced WTN noticeability and annoyance. Table 8.3 shows the results of the four regressions modelling noticeability and annoyance using Ld and Ln, respectively. As shown in regression models 1 and 2 regarding noticeability of WTN, for the sample group with Ln>41dBA, one dB increase in Ld could decrease the odds of noticing wind turbine noise by 0.84 ($p<0.05$); and each dB increase in Ln decreased the odds by 0.80 (p<0.05). SPLs of wind turbine noise significantly increased the odds of noticing the noise. In terms of annoyance with WTN, as shown in models 3 and 4, both Ld and Ln were associated with reduced odds of annoyance at the significance level of p<0.1, while an increase in WTN level did not significantly increase annoyance. These findings confirmed the masking effect of road traffic noise where the night-time traffic noise exposure was over 41dBA, and indicated that the masking effect was more significant on reducing wind turbine noise noticeability than annoyance.

Table 8. 3 Binary logistic regressions modelling noticeability of wind turbine noise (WTN) for two sub-samples of different night-time road traffic noise (RTN) levels (Ln>41 or ≤41dBA) using WTN levels and RTN levels controlling for site and variant dummies.

Model (sample)	Variables	B	*p*-value	Odds Ratio
1	***Notice WTN*** *[n=143, R^2=0.343, p(H-L)=0.571]*			
(Group 1:	Ld (Day-time traffic noise)	-0.180	**0.042**	0.835
Ln>41dBA)	Maximum SPL (Wind turbine noise)	0.128	**0.007**	1.137
	Female	-1.446	**0.010**	0.231
	Site A	1.123	0.133	3.075
	Site B	2.380	**0.001**	10.808
	Variant 2	-0.664	0.286	0.515
2	***Notice WTN*** *[n=143, R^2=0.357, p(H-L)=0.521]*			
(Group 1:	Ln (Night-time traffic noise)	-0.225	**0.026**	0.798
Ln>41dBA)	Maximum SPL (Wind turbine noise)	0.118	**0.014**	1.126
	Female	-1.449	**0.011**	0.235
	Site A	0.773	0.305	2.165
	Site B	2.068	**0.002**	7.911
	Variant 2	-0.600	0.336	0.549
3	***Annoyed by WTN*** *[n=143, R^2=0.245, p(H-L)=0.683]*			
(Group 2:	Ld (Day-time traffic noise)	-0.173	0.079	0.841
Ln≤41dBA)	Maximum SPL (Wind turbine noise)	0.087	0.080	1.091
	Female	-1.119	0.054	0.326
	Site A	1.185	0.165	3.271
	Site B	2.257	**0.004**	9.557
	Variant 2	-0.355	0.594	0.701
4	***Annoyed by WTN*** *[n=143, R^2=0.254, p(H-L)=0.813]*			
(Group 2:	Ln (Night-time traffic noise)	-0.205	0.060	0.814
Ln≤41dBA)	Maximum SPL (Wind turbine noise)	0.076	0.128	1.079
	Female	-1.089	0.060	0.337
	Site A	0.864	0.314	2.372
	Site B	1.952	**0.010**	7.041
	Variant 2	-0.296	0.657	0.744

Statistically significant associations in boldface

In terms of moderating variables, as shown in Table 8.3, females were less likely to notice ($p<0.05$) and be annoyed ($p<0.1$) by WTN. Respondents in Site B were significantly more likely to notice wind turbine noise, given equal WTN and RTN levels. This might be due to that Site B had two turbines while other sites had one, which could make wind turbines easier to be detected both visually and audibly, and hence increased the reported noticeability and annoyance. Another reason might be that a high level of traffic noise could better mask the noise from a single wind turbine than multiple turbines, even at the same level of A-weighted wind turbine noise exposure.

Other personal variables were also added to the regression models one by one (not shown in this thesis). It was found that age, qualification, income, illness, noise sensitivity, ownership of the dwelling, housing type, and orientation were not significantly associated with noise evaluations in the studied group of Ln over 41dBA. Of the variables in questionnaire Variant 1, with Ln>41dBA (n=107), having negative attitude to the environmental impact of wind turbines was positively associated with noticeability (OR=7.0, $p<0.01$, $R^2=0.48$) of and annoyance (OR=7.5, $p<0.01$, $R^2=0.38$) with wind turbine noise, controlling for RTN (Ld), WTN, sex, site, and questionnaire variant dummies. Visibility of the turbines did not significantly change noise evaluations.

To conclude this section, as the previous study found no significant association between WTN annoyance and RTN as a continuous variable (Pedersen et al., 2010), this study selected the sample with Ln over the threshold of 41dBA and found that an increase in RTN significantly moderated the evaluations on WTN. Above 41dBA, each dB increase in RTN could decrease the odds of noticeability and annoyance by around 0.8. Exposed to equal levels of WTN and RTN, females were found to be less likely to notice and be annoyed by WTN. Living near Site B of two wind turbines increased the probability of noticing and being annoyed by WTN, which might be due to that a high level of traffic noise was more effective to mask the noise from a single wind turbine than multiple turbines. Visibility of the turbine did not significantly change the evaluation.

The results of this section provide evidence for planning by indicating the change of one dB increase in RTN on the reduction of noticeability and annoyance due to WTN. It should be noted that the planning of using high road traffic noise to mask wind turbine noise might be more effective on a single wind turbine than a wind farm with more than one turbine. Therefore, for wind turbine noise in an urban area where one stand-alone turbine is usually used, the integrated planning of roads and wind turbines should be applied for wind turbine noise management.

8.2.5 Conclusions on planning suggestions

Section 8.2 demonstrated the masking effect of road traffic noise (RTN) on wind turbine noise (WTN) evaluations. It was found that the masking effects occurred in the sample group where day-time RTN (Ld) was at least 20dBA higher than WTN, or night-time RTN (Ln) was 10dBA higher than WTN. The masking effect only works for dwellings with moderate or high wind turbine noise levels (>35dBA), but does not work for lower levels (<35dBA). It confirms that urbanised areas with high background noise are considered suitable for siting wind turbines. Noisy roads can be planned in high wind turbine noise exposure areas.

As modern wind turbines could produce more sound at night than in day-time (G. P. Van Den Berg, 2004), a high level of masking sound at night is required. This study provides guidance for planning by pointing out the minimum threshold of traffic noise (Ln>41dBA) which can mask wind turbine noise in studied suburban areas. With Ln higher than the threshold level, each dB increase in RTN significantly decreases the probability of noticing WTN by 0.8. Therefore, it is suggested to use noisy roads to separate wind turbines and residential areas. The volume of traffic on that road should be substantially high, especially at night, with estimated Ln at receptor's dwelling over 41dBA. Thus, express roads or highways with high night-time transport are preferred. In addition, a high level of traffic noise was more effective to mask the noise from a single wind turbine than multiple turbines.

The results also allow the prediction of potential effects of new or proposed wind turbines in urbanised areas with busy roads. One would expect less opposition to a wind turbine development and less annoyance from a nearby wind farm if residents are already exposed to night-time traffic noise levels of over 41dBA.

8.3 Morphological Design for Wind Turbine Noise Exposure at Quiet Façade

It has been demonstrated in Chapter 4 that building morphological design can create large variations of wind turbine noise levels around a dwelling and can decrease the noise level on the quiet façade; while Chapter 6 presented the effect of the quiet façade exposures on respondent's noise evaluation by providing the change in noise noticeability and annoyance associated with each dB change in minimum and average SPLs. The findings could inform the design of dwellings to reduce the noise on relative quiet façades, especially when the maximum noise exposure was largely governed by S-R distance thus was difficult for mitigation by design. Practical solutions towards design of residential areas with reduced exposure on quiet façade are generated for wind turbine noise management.

8.3.1 The important role of a quiet façade in noise evaluation

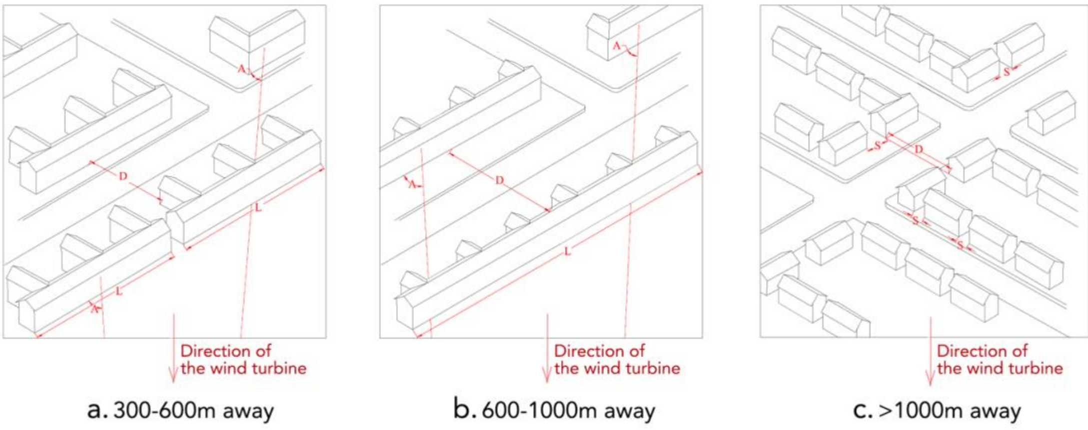
As found in Chapter 6, noise exposure at the quietest façades was an important indicator for noise evaluation. Levels of noise exposure on the quietest façade (minimum SPL) were correlated slightly more strongly with annoyance overall and outdoors than exposure on the most exposed facade, while the latter was strongly correlated to annoyance indoors. The minimum SPL at the dwelling was the only indicator that significantly associated with both noticeability of and annoyance with wind turbine noise at night, which confirmed that reducing the noise level at the quiet façade was an important solution for night-time noise management.

The minimum SPL was also found to be positively associated with experiencing nausea. In addition, it was found that the difference between observed happiness in this study and the predicted happiness according to the national data (shown in Table 7.9) was negatively associated with the minimum SPL as well as the difference between maximum and minimum SPLs. The results further confirmed that both the noise levels on the quietest façade and the difference between the most- and least-exposed façades were important in narrowing the gap in happiness between wind turbine communities and the rest of the nation controlling for sociodemographic factors.

The important role of quiet façades in wind turbine noise evaluation also agreed well with the results from previous studies on the quiet side effects of the road traffic noise, which indicated that higher exposures at the least exposed façade significantly increase noise annoyance by failing to provide an "escape" from the noise (de Kluizenaar et al., 2013; Renterghem & Botteldooren, 2012).

8.3.2 Design suggestions

In general, when a short separation distance has been set, it is important for morphological design of the residential area to provide a quiet side for each dwelling. As Chapter 4 has indicated the morphological indices that could resist the noise distributed at the least-exposed façade, practical design suggestions are generated towards design of residential areas for wind turbine noise management. Because the effects of morphological design on quiet façade exposures depend on different source-receiver distances, the detailed design solutions for a quiet façade are given in three distance categories as shown in Figure 8.7.



A: angle of incidence; **D**: distance from the front building;
L: length; S: spacing between adjacent dwellings

Figure 8. 7 Suggestions of morphological design for residential areas at different source-receiver distances.

Design of residential areas within 300-600m from the wind turbine:

Overall, as shown in Figure 8.7.a, high space ratio, densely built terraced houses are recommended for this distance range. It is also suggested to build high-level social housing with a long façade facing the wind turbine, and design U/L/H shaped floor plan extending to the quiet side.

Use high-level terraced house or social housing style with long façade length (L) can decrease around 2dBA of WTN at dwelling façades on average. The angle between the incidence wave and the longer façade (A) of each dwelling is best to be close to 56 degree or larger, which can reduce up to 2.6dBA at the quiet façade than 0 degree. A compact layout - a short distance from the dwelling at the front (D) - can decrease noise up to 1.5dBA at all façades on average. A design of U/L/H shaped floor plan can make about 0.9dBA decrease of WTN at the quiet side of the dwelling and 0.7dBA at all façades on average.

Design of residential areas at 600-1000m from the wind turbine:

Overall, as shown in Figure 8.7.b, recommend mid-high level, long terraced house with long façade facing the wind turbine. A compact layout and shaped floor plans are also recommended but not a priority.

The most effective design to resist WTN at this distance range is the use of long terraced house with a long front façade (L) facing the wind turbine, which can decrease the noise on the quiet façade by up to 2.7dBA. The angle of incidence at the long façade (A) is best to be close to 50 degree or larger, with an estimated decrease of 2.3dBA than 0 degree.

A compact layout (D) can only decrease 0.8dBA of the averaged façade exposure. Thus, the compactness between buildings can be compromised compared to the near site (<600m) design. A U/L/H shaped floor plan is also recommended, but only with a small reduction of 0.6dBA for averaged façade exposure.

Design of residential areas at over 1000m from the wind turbine:

Overall, as shown in Figure 8.7.c, densely built detached or semi-detached houses with various orientations can be used at this distance range.

Use densely built, compact layout – a short distance from the front dwelling (D) can reduce noise up to 2.4dBA at all façades on average. Less spacing (S) between adjacent dwellings is recommended, estimated to reduce 0.5dBA at the quiet side.

Detached or semi-detached houses with various orientations can be built at this distance range: length and orientation of the dwelling are not important on noise resistance.

8.4 Design and Planning Implementations

The findings of this thesis can be utilised to guide the planning authorities to define suitable areas for the placement of wind turbines within existing suburban contexts, and can help in the planning of residential areas and design of dwellings, rendering them less susceptible to the noise pollution caused by existing and/or future wind power projects.

This section is trying to set basis for design and planning guidelines for wind turbine noise management near residential areas. Based on the findings of all chapters above and the evidence from previous studies, the guidelines are put forwards from four perspectives, as shown in Figure 8.8. It explores the planning at macro- (8.4.1), meso- (8.4.2) and micro- (8.4.3) scales, and suggests public participation (8.4.4) in an early stage of the planning. It should be noted that the following guidelines are merely from the perspective of noise management, which can be considered with weighing other factors in practice, such as visual impacts and energy yielding.

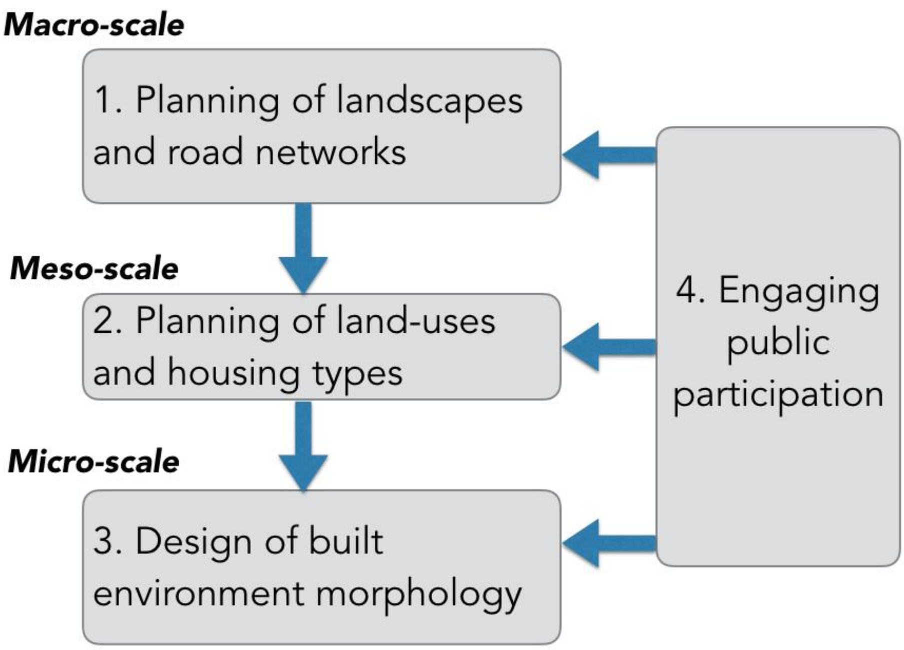


Figure 8. 8 Framework of design and planning suggestions

8.4.1 Planning of landscapes (*macro-scale planning*)

Suggestions:	Evidence:
• In general, to reduce annoyance with wind turbine noise, urbanised landscapes are considered more suitable for one or two stand-alone modern wind turbines than rural landscapes with natural values.	Section 6.7 & 8.2 in this study. Also in (Pedersen et al., 2009)
• Set a proper separation distance between the wind turbine and the nearest residence. The separation distance for one or two wind turbines in urbanised areas is suggested to be at least 900m. As in this study, 80% of the annoyed respondents were living within 850m, and 90% were living within 900m from the wind turbine.	Section 6.3.1
Planning road networks to mask the sound:	
• Use highways or motorways to separate the wind turbine and residential areas.	Section 8.2
• Plan major roads in areas near wind turbines with high wind turbine noise exposures (WTN>35dBA). The road should ideally convey high traffic transportations, especially at night, with Ln over 41dBA.	Section 8.2.1 & 8.2.3
• Increase the volume of traffic on current roads, to make the Ld exceed WTN by at least 20dBA, and Ln exceed WTN by at least 10dBA.	Section 8.2.1 & 8.2.4
• Reduce the traffic noise in low exposure	Section 8.2.1

	areas (WTN<35dBA), to avoid the synergetic effect of high traffic noise in these areas that might increase the annoyance with WTN.	
Planning of soundscapes to introduce more positive sounds:		
	• Plan more parks and green spaces between the wind turbine and residential areas to introduce more natural sounds, such as bird song and the sound of water flow. This can improve the soundscape of the area to increase the positive evaluation of the local sound environment as natural versus artificial, that is suitable for physical and mental restoration from the noise. Natural songs also can provide a informational masking on the sound.	Section 6.3.1 in this study Also in (Hao et al., 2015)
	• Build more public gardens or children playground near WTN affected communities to introduce positive human sounds, which can reduce the dominance of wind turbine noise in the area, and enhance the soundscape evaluation as interesting versus boring.	Section 6.3.1

8.4.2 Planning of land uses and the housing type (*meso-scale planning*)

Suggestions:		Evidence:
	• Place high-rise, board style buildings with a long façade as the front-line buildings that obstruct wind turbine noise from direct	Section 8.3.2

	incidence into the residential area. Change the land use of the front buildings that near wind turbines to commercial use that is less susceptible to the noise pollution.	
	• If the front buildings have to be residential, design them to be high-rise apartment buildings to attract more younger and highly educated residents, as they might be less likely to be affected by wind turbine noise based on the results of this study.	Section 6.5 & 6.9.3
	• Garden areas and bedroom windows are best to be at the quiet side of the building, opposite to the wind turbine. This can make the area for physical and mental restoration away from the most-exposed side. In addition, this can reduce visibility of the turbine from both a window and the garden, which was found to be more annoying in this study.	Section 8.3.1 & 6.9.3
	• Increase the green space ratio and use soft pavement that have high noise absorption.	(Margaritis & Kang, 2016)

8.4.3 Design of built environment morphology (*micro-scale planning*)

Suggestions:		Evidence:
	• In general, when a short separation distance has been set, it is important for morphological design of the residential area to provide a quiet side for each dwelling.	Section 6.9.4 & 8.3.1

	• If the residential area is at 300-600m from the wind turbine, recommend a high space ratio, densely built terraced houses or high-level social housing with a long façade facing the wind turbine, which can reduce noise up to 2.6dBA at quiet façade. The U/L/H shaped floor plan extended to the quiet side is also suggested, which can reduce 0.9dBA at the quiet side of the dwelling (see Figure 8.8.a for illustration).	Section 4.3 & 8.3.2
	• If the residential area is at 600-1000m from the wind turbine, recommend mid-high level, long terraced houses with a long façade facing the wind turbine, which can reduce up to 2.7dBA on the quiet façade. A compact layout and shaped floor plans are also recommended but not a priority (see Figure 8.8.b for illustration).	Section 4.3 & 8.3.2
	• If the residential area is over 1000m away from the wind turbine, densely built detached or semi-detached houses with various orientations can be used at this distance range, which can reduce up to 2.4dBA for average façade exposure (see Figure 8.8.b for illustration).	Section 4.3 & 8.3.2

8.4.4 Engaging public participation

Suggestions:		Evidence:
	• As personal factors are found to significantly influence subjective evaluations of wind turbine noise, public participation in an early stage of the planning can assist to increase the number of successful wind power applications.	Section 6.9.3
	• The results of this study can help to carry out scientific based consultations to acknowledge the potential noise impact to the public. Some findings of this study can be used for evidence of noise impact, such as only 16% of the respondents notice the noise from wind turbines, much lower than 41% of traffic noise and 38% of noise from neighbours.	Section 6.3.1
	• The results of this study can be used as evidence on the evaluation of noise from suburban-urban wind turbines, that the risk of being disturbed and annoyed by wind turbine noise is less pronounced in urbanised or noisy areas than rural areas (Pedersen et al., 2009).	Section 6.7 in this study Also in (Michaud et al., 2016; Pedersen et al., 2009)
	• Negative attitudes to the environmental impact of wind turbines, described as not environmental friendly, dangerous, and ugly, are positively associated with annoyance. Pre-construction consultations, advertising or	Section 6.9.3 in this study Also in previous studies e.g. (Pedersen et al., 2009; Pedersen & Waye, 2004)

	post-construction site visits might help to change resident's adverse impression and build public awareness and trust.	
	• Previous studies have found a significant decrease of annoyance among residents who benefit economically from the wind turbine. As no respondents in this study had such benefits, this study provides no evidence to support this approach. However, giving financial stake to residents in high exposure areas (>40dBA) might be a solution in the future, as a significantly higher proportion of respondents (from 13% to 30%) become annoyed in this area.	(Pedersen et al., 2009) Section 6.5 in this study

8.5 Conclusions

To conclude, this chapter focused on the planning and design of residential areas towards wind turbine noise management. This chapter also pointed out the important role of planning, in terms of siting wind turbines in relation to existing road networks, by indicating that high day-time traffic noise that exceeds wind turbine noise over 20dBA (or night-time traffic noise exceeds that noise over 10dBA) could greatly moderate the self-reported noticeability and annoyance due to wind turbine noise. It was also suggested that the masking effect occurs when the equivalent night-time traffic noise level exceeds 41dBA. Design solutions should also be taken to reduce the noise level at the quiet façade of the dwelling, which has been found to play an important role in reducing noise impacts, such as annoyance at night, nausea, and decreased happiness.

The discussion section of this chapter establishes a new framework (as shown in Figure 8.8) for planning and design guidelines towards noise management in residential areas from the perspectives of landscape planning, land-use planning, morphological design, and public participation. Detailed solutions have been proposed based on the findings of this thesis and previous studies.

It is hoped that this chapter can assist to increase the number of successful wind power applications, while helping to enhance the quality of approved developments.

Chapter 9

Discussion and Conclusions

9.1 Major Findings

In response to the advances in developing wind energy resource in urban environments, this thesis extends the existing basis for the environmental impact assessment (EIA) of wind turbine noise by further exploring the dose-response relationship between noise and human well-being in densely populated suburban-urban settings.

9.1.1 Built environment morphology and wind turbine noise distribution

The built environment morphology was found to considerably affect wind turbine noise exposure at buildings, creating large variations of noise levels (up to 10dBA) around dwelling façades in the distance range of 400-1000m, equivalent to the sound attenuation from 600m to 1600m in a free-field in downwind conditions. Given the fact that the noise exposure at the most exposed side of the dwelling could be hardly affected by planning, this thesis examined the potential of reducing the noise exposure at the quiet side of the dwelling by optimising the design and planning of the residential area near existing wind turbines. Noise resistance effects of key morphological indices were revealed. Using a long façade to face the wind turbine and increasing the length of the building both made the largest SPL variations, with a noise reduction of up to 2.7dBA on exposures at the quiet façade. The resistance effects varied with different source-receiver distances and frequencies. The applications of morphological design to secure a quiet façade away from wind turbine noise exposure were put forward in this thesis, depending on the targeted residential area at near, middle, or far distance ranges.

9.1.2 Noise levels and respondent noise evaluation

The thesis links empirical data of the noise impact to building scale noise exposures, using accurate noise mapping techniques. It found that the maximum A-weighted SPL at the dwelling was positively associated with noticeability of and annoyance with the noise, consistent with the previous studies which found a dose-response relationship between outdoor wind turbine noise and annoyance (Michaud et al., 2016; Pawlaczyk-Łuszczyńska et al., 2014; Pedersen et al., 2009; Pedersen & Waye, 2004, 2007). The proportion of respondents noticing WTN increased from 5% at the sound category below 30dBA to 47% at the sound category above 40dBA, where the proportion of those annoyed by wind turbine noise increased from 3% to 30%. Results of logistic regressions in this study indicated that the odds ratio of being annoyed by wind turbine noise increased with each dB increase in SPLs, controlling for the effect of moderating factors. An increase in age, having negative attitudes to wind energy and having the wind turbine in sight from both a window and the garden of the dwelling were positively associated with annoyance, which was in line with previous findings (Pawlaczyk-Łuszczyńska et al., 2014; Pedersen & Waye, 2004). This study also found that having higher qualifications than a O-level was likely to decrease annoyance.

Soundscape evaluations were investigated in this study for the first time. Most respondents living near wind turbines had positive evaluations on the sound environment at their dwellings, such as quiet, pleasant and calming, which were not related to wind turbine noise levels. But higher wind turbine noise increased the probability of evaluating the local sound environment as discontinuous and unpleasant.

It was found that respondents in the urban contexts of this study were less affected by wind turbine noise than those in previous studies in more rural settings (Pedersen et al., 2009; Pedersen & Waye, 2004). Respondents in this study were aware of and annoyed by wind turbine noise the least often compared to other environmental nuisances, in contrast with the results of Michaud et al.'s (2016) and Pawlaczyk- Łuszczyńska's (2014) studies which suggested that wind turbine noise was the most frequently assessed annoyance amongst a similar set of nuisances.

9.1.3 Noise levels and health and well-being

The thesis found that wind turbine noise was associated with variations in some aspects of health and well-being. It confirmed the finding of previous studies that noise levels were not associated with sleep directly, but with annoyance as a mediator (Bakker et al., 2012). The degree of noise annoyance significantly increased the possibility of sleep disturbance including sleeping less deeply and difficulty falling asleep.

This study established a method of employing a second variant of the questionnaire with the research aim masked to investigate self-reported health symptoms and to reduce focusing bias. The reported noise impacts on health varied by the questionnaire variants. The main sample (Variant 1), who knew the research purpose, reported less health problems than the control group. Self-reported ear discomfort, nausea and dizziness were found to be positively associated with wind turbine noise levels only among Variant 2 respondents to whom the research purpose was masked; while cardiovascular disease and headache were related to annoyance with the noise among Variant 1 respondents who were informed about the research purpose. As the main sample were enabled to attribute the cause of experienced health symptoms to wind turbine noise, it is possible that at least some respondents under-reported their health problems unless they thought they were caused by wind turbine noise.

This is the first study that made comparisons between the health and well-being of wind turbine communities to those of the general population. It was found that the sample of the current study reported poorer general health than predicted based on the national health survey datasets controlling for respondent background characteristics. But the difference in general health was not related to levels of wind turbine noise nor annoyance. Respondents in this survey were also less happier than they predicted to be, and the decrease in happiness was positively associated with levels of wind turbine noise at the quiet façade of the dwelling and negatively related to the noise difference between the most- and least-exposed façades. This revealed the important role of a relatively quiet façade in subjective well-being, which had not been stated in previous studies.

9.1.4 Planning and design suggestions towards wind turbine noise management

This thesis has opened a field for wind turbine noise management from the perspective of urban planning and morphological design.

The thesis put forward the important role of planning in terms of siting urban wind turbines in relation to existing road networks, by indicating that high day-time road traffic noise that exceeded wind turbine noise over 20dBA (or night-time traffic noise exceeded that noise over 10dBA) could greatly moderate the self-reported noticeability and annoyance due to wind turbine noise at moderate or high levels (>35dBA). This study also indicated the 41dBA threshold of equivalent night-time traffic noise for the occurrence of a masking effect on wind turbine noise, and the change of each dB increase in traffic noise on the reduction of noticeability and annoyance due to wind turbine noise, which provided evidence for integrated planning of wind turbines and road traffic noise in urban areas.

In addition, the study emphasised the important role of building morphological design in the quiet façade exposure that could considerably influence noise annoyance outdoors and at night. The association between quiet façade exposure and the prevalence of nausea was also discovered. The results further confirmed that both the noise levels on the quietest façade were important in subjective well-being in terms of narrowing the gap in happiness between wind turbine communities and the rest of the UK nation controlling for sociodemographic factors. These results suggested the implication of morphological design on residents' health and well-being as the noise levels on the quietest façade could be largely reduced by design of residential areas. In this thesis, practical suggestions for design were generated for residential areas at near, middle, and far distance ranges from the wind turbine.

The thesis established a framework (as shown in Figure 8.8) for planning and design guidelines towards wind turbine noise management from the perspectives of landscape planning, land-use planning, morphological design, and public participation. This thesis proposed detailed suggestions that planners can follow by integrating the findings of this thesis and previous studies, such as to separate wind turbines and residential areas with highways to reduce the dominance of wind turbine noise; to build more high-level apartment buildings to attract young and highly educated residents; and to use long façades (such as terraced houses) to face the wind turbine or design U/L/H shaped floor plans to sustain a quiet side of the dwelling. It also suggested public participations during early-stage planning to provide scientific based consultations about the potential noise impact on health and acknowledge compensation plans for highly exposed residents.

9.2 Policy Implications

The thesis aims to help overcome the key challenges of modelling the noise produced by wind turbines operating in built environments. It provides empirical support for policy makers, planners and other stakeholders in more accurately assessing the noise impacts of established wind power projects on health and wellbeing of those living close to them. An understanding of the noise impact on health and well-being in urbanised contexts will not only be used to inform siting decisions – for example in identifying suitable sites and separation distances – but might also benefit public engagement, help to build public awareness and trust, and promote understanding in wind energy developments.

For Developers:

By providing an enhanced understanding of the impact of the built environment morphology have upon the noise distribution and well-being of the local community, the thesis can help reduce uncertainty within the planning process, thus benefits wind project developers and their related supply chains from the following two aspects:

Firstly, the use of noise mapping will help to improve impact assessment techniques for estimating the likely noise impact in densely built residential areas with calculated dwelling scale noise levels. In addition, this thesis provides scientific evidence to developers by presenting the dose-response relationships between noise levels and annoyance as well as possible adverse impacts on health and well-being associated with long-term wind project developments.

Secondly, it will provide frameworks for new forms of public engagement. As developers are required to address any concerns from the local community and have their backing, publication of the predicted noise distribution and potential noise impact on human well-being can increase local awareness, which therefore have fundamental contributions to the development of wind energy. The thesis has pointed out that negative attitudes to the wind energy, especially to its impact on the landscape described as not environmental friendly, ugly and dangerous, are significantly associated with noise annoyance. Therefore, the developers can consider to deliver pre-construction consultations, advertising or post-construction site visits with local communities to change their adverse impressions and concerns.

For Local Planning Authorities (LPAs) / Decision Makers:

The findings of this thesis can be utilised to guide the LPAs to define suitable areas for the placement of wind turbines within existing suburban contexts and can even help in the design of buildings and residential layouts for noise management. This thesis presents the potential of reducing the adverse impact of wind turbine noise by integrated planning for the masking effect of road traffic noise and by design of five simple morphological indices to provide a quiet side of the dwelling. This is of particular importance when a short buffer distance from residential areas has been set and the maximum wind turbine noise exposure at a dwelling is difficult for mitigation. By providing the detailed suggestions for planning and design, the thesis will be useful for architects and urban planners in the wind energy field to determine the formation of residential areas and road networks that can better resist the noise from wind turbines and decrease the risk of adverse noise impacts, such as using a long façade to face the wind turbine; increasing the length of the building; and using L/U/H shaped floor plans .

Furthermore, it was found that residents in suburban-urban areas of this study were less affected by wind turbine noise than in remote rural areas, partly due to the existence of other environmental noise and stressors and higher public awareness of using renewable energy. This suggests a new approach for future wind turbine developments to be exploited in urban area if the benefits of energy yield have also been put forward. As half of the applications in rural areas do not gain planning approval, it is hoped that the thesis can assist to enhance the quality of successful wind power applications, while help to meet local and national government renewable energy targets.

For the Public:

The thesis can provide the public with scientific evidenced information about the likely noise impacts of wind turbines on health and well-being across a certain layout of densely built residential areas. Based on the findings of this thesis and previous cross-sectional studies, higher levels of wind turbine noise can increase the probability of annoyance but are not likely to affect sleep and subjective well-being over the longer term. The reported prevalence of adverse noise impacts largely depends on sociodemographic characteristics of the person and his/her attitude to the wind projects, as well as how the question was asked in terms of whether it masked the research purpose.

9.3 Limitations and Future Works

The thesis had several limitations, which could be worthwhile for future work.

One limitation related to the noise mapping was that the study only considered the wind turbine noise exposure in the worst case, such as in downwind conditions and with 8 m/s wind velocity for the near maximum noise output. This might overestimate the noise exposure at a receptor's dwelling. As indicated by other studies, the SD for the wind turbine sound power level in the current ISO (1996) method was 2 dB (Keith et al., 2016). However, the current results of the thesis were still useful to understand the prevalence of a noise impact related to the *increase* of wind turbine noise levels with focus on relative but not absolute levels. The noise simulation based on the worst case also enabled comparison to previous studies in other areas that used a similar calculation method. Further studies could develop sophisticated modelling procedures to account for short-term variations in sound propagation and characteristics (e.g., amplitude modulation and tonal noise). To continue the investigation on the quiet façade effect of wind turbine noise, future works can identify the location of bedroom windows, to not only calculate the noise level at the least-exposed façade, but also relate the level to noise sensitive places.

Another limitation of this survey was, as with the previous cross-sectional studies, that establishing causality was difficult. One of the reasons was that statistical association did not normally establish causality, for example, noise might cause negative attitudes which causes annoyance. Another reason was the possible existence of reverse causality, such as from disturbed sleep to noise annoyance. In addition, it is worth noting that for this study, it was difficult to isolate the effect of the noise itself due to the high positive correlation between increased noise and decreased socio-economic status, although many socio-economic characteristics were controlled for. Future works could conduct longitudinal studies before and after the operation of the wind farm, to establish causal relationships between noise and well-being. As some health and well-being effect might take some time to happen or might disappear with increased adaptation, longitudinal studies over a period of time can help to control for long-term noise effects.

Further limitations of this study were sampling participants from only three sites, which was subject to limited suburban-urban wind farms in the UK. The influence of unobserved local factors might not have been fully taken into account. Such factors might include possible reduction in property values, or temporary shut down of the wind turbines, which might lead to the results to be under or over stated, although they be reported in respondents' additional comments. However, such unobserved heterogeneity across sites had been partly addressed by controlling for site dummies in the analysis. Future research could sample across more sites to generalise the results of noise impact in urbanised areas.

Using an interdisciplinary approach of research, the thesis demonstrated the effect of urban morphology on noise levels which were further related to subjective noise evaluation and well-being. This allowed predictions of the longer term well-being impact on residents using measurable parameters of the site. It opened up opportunities for further studies using intelligent prediction models, such as artificial neural networks (ANN), which can replace the explanatory variable of calculated noise exposure by affecting physical parameters of the site and other moderating factors, to demonstrate the hypothetically complex and non-linear relationships between well-being and a wide range of geographical, architectural, and contextual variables.

Furthermore, while the urban environment has unique challenges in maximising the energy yielding and resisting more noise at the same time, future investigations could 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 (Gao et al., 2012; Ishugah et al., 2014; Ricciardelli & Polimeno, 2006). These give opportunity for an interdisciplinary study that investigates how urban morphology responds to the challenge in the energy-noise trade-off, in order to take maximum advantage of wind energy in the urban environment.

BIBLIOGRAPHY

Alves-Pereira, M., & Castelo Branco, N. A. A. (2007). Vibroacoustic disease: Biological effects of infrasound and low-frequency noise explained by mechanotransduction cellular signalling. *Progress in Biophysics and Molecular Biology*, *93*(1–3), 256–279. https://doi.org/10.1016/j.pbiomolbio.2006.07.011

Archer, C. L., & Jacobson, M. Z. (2007). Supplying baseload power and reducing transmission requirements by interconnecting wind farms. *Journal of Applied Meteorology and Climatology*, *46*(11), 1701–1717. https://doi.org/10.1175/2007JAMC1538.1

Attenborough, K., Li, K. M., & Horoshenkov, K. (2006). *Predicting of outdoor sound*. CRC Press.

Babisch, W. (2008). Road traffic noise and cardiovascular risk.

Babisch, W. (2011). Cardiovascular effects of noise. *Noise and Health*, *13*(52), 201.

Babisch, W., Ising, H., Gallacher, J. E. J., Elwood, P. C., & Sweetnam, P. M. (1990). Traffic noise, work noise and cardiovascular risk factors: The Caerphilly and Speedwell Collaborative Heart Disease Studies. *Environment International*, *16*(4–6), 425–435.

Babisch, W., & Kamp, I. (2009). Exposure-response relationship of the association between aircraft noise and the risk of hypertension. *Noise and Health*. https://doi.org/10.4103/1463-1741.53363

Bakker, R. H., Pedersen, E., van den Berg, G. P., Stewart, R. E., Lok, W., & Bouma, J. (2012). Impact of wind turbine sound on annoyance, self-reported sleep disturbance and psychological distress. *Science of the Total Environment*, *425*, 42–51. https://doi.org/10.1016/j.scitotenv.2012.03.005

Barker, S. M., & Tarnopolsky, A. (1978). Assessing bias in surveys of symptoms attributed to noise. *Journal of Sound and Vibration*, *59*(3), 349–354. https://doi.org/10.1016/S0022-460X(78)80003-0

Basner, M., Babisch, W., Davis, A., Brink, M., Clark, C., Janssen, S., & Stansfeld, S. (2014). Auditory and non-auditory effects of noise on health. *The Lancet*, *383*(9925), 1325–1332. https://doi.org/10.1016/S0140-6736(13)61613-X

Basner, M., Müller, U., & Elmenhorst, E.-M. (2011). Single and combined effects of air, road, and rail traffic noise on sleep and recuperation. *Sleep*, *34*, 11–23. https://doi.org/Research Support, Non-U.S. Gov't

Benfield, J. A., Nurse, G. A., Jakubowski, R., Gibson, A. W., Taff, B. D., Newman, P., & Bell, P. A. (2014). Testing noise in the field: A brief measure of individual noise sensitivity. *Environment and Behavior*, *46*(3), 353–372. https://doi.org/10.1177/0013916512454430

Bluhm, G., Nordling, E., & Berglind, N. (2004). Road traffic noise and annoyance-an increasing environmental health problem. *Noise and Health*, *6*(24), 43–49.

Bonnet, M. H., & Arand, D. L. (2003). Clinical effects of sleep fragmentation versus sleep deprivation. *Sleep Medicine Reviews*, *7*(4), 297–310. https://doi.org/10.1053/smrv.2001.0245

Bowdler, D. (2005). ETSU-R-97 Why it is Wrong ETSU-R-97 Why it is Wrong. *Government Executive*, (July).

Brice, J., Nick, B., & Elaine, P.-L. (1993). British household panel survey user manual. *Edited by Marcia Freed Taylor. University of Essex.*

Bullmore, A. J., & McKenzie, A. R. (2015). WHAT WOULD AN ALTERNATIVE TO ETSU-R-97 LOOK LIKE ? In *Institue of Acoustics* (Vol. 37, pp. 54–63).

Cand, M., Davis, R., Jordan, C., Hayes, M., & Perkins, R. (2013). *A Good Practice Guide to the Application of ETSU-R-97 for the Assessment and Rating of Wind Turbine Noise*. Institute of Acoustics.

Census. (2011). Census household questionnaire. *Office for National Statistics.*

Chapman, S., & George, A. S. (2013). How the factoid of wind turbines causing “vibroacoustic disease” came to be “irrefutably demonstrated.” *Australian and New Zealand Journal of Public Health*, *37*(3), 244–249. https://doi.org/10.1111/1753-6405.12066

Cooney, C., Byrne, R., Lyons, W., & O’Rourke, F. (2017). Performance characterisation of a commercial-scale wind turbine operating in an urban environment, using real data. *Energy for Sustainable Development*, *36*, 44–54. https://doi.org/10.1016/j.esd.2016.11.001

DataKustik GmbH. (2006). *Cadna/A Manual Version 3.6*. Greifenberg: DataKustik GmbH.

Davies, H., & Van Kamp, I. (2008). Environmental noise and cardiovascular disease: Five year review and future directions, (2002).

de Kluizenaar, Y., Janssen, S. A., Vos, H., Salomons, E. M., Zhou, H., & van den Berg, F. (2013). Road traffic noise and annoyance: a quantification of the effect of quiet side exposure at dwellings. *International Journal of Environmental Research and Public Health*, *10*(6), 2258–2270. https://doi.org/10.3390/ijerph10062258

DECC. (2011). UK Renewable Energy Roadmap. *Department of Energy & Climate Change.*

Department for Communities and Local Government. (2012). National Planning Policy Framework (NPPF). *Department for Communities and Local Government.*

Department for Communities and Local Government. (2015). Guidance - Renewable and low carbon energy. Retrieved May 25, 2017, from https://www.gov.uk/guidance/renewable-and-low-carbon-energy

Department of Energy and Climate Change. (2011). *National Policy Statement for Renewable Energy Infrastructure (EN-3). Planning for new energy infrastructure.*

DfT. (2014). Traffic counts - Transport statistics. Retrieved April 16, 2017, from http://www.dft.gov.uk/traffic-counts/

Dolan, P., Peasgood, T., & White, M. (2008). Do we really know what makes us happy? A review of the economic literature on the factors associated with subjective well-being. *Journal of Economic Psychology*, *29*(1), 94–122. https://doi.org/10.1016/j.joep.2007.09.001

Dormann, C. F., Elith, J., Bacher, S., Buchmann, C., Carl, G., Carr, G., … Lautenbach, S. (2013). Collinearity : a review of methods to deal with it and a simulation study evaluating their performance, (February 2012), 27–46. https://doi.org/10.1111/j.1600-0587.2012.07348.x

European Union. (2002). Directive 2002/49/EC relating to the assessment and management of environmental noise (END). *Official Journal of the European Communities*, (L189), 12–25.

EWEA. (n.d.). EWEA Position on the Review of the Environmental Impact Assessment Directive. Retrieved May 24, 2017, from http://www.ewea.org/fileadmin/files/library/publications/position-papers/121029_EWEA_Postion_on_Draft_EIA_Directive.pdf

Farboud, A., Crunkhorn, R., & Trinidade, A. (2013). "Wind turbine syndrome": fact or fiction? *The Journal of Laryngology & Otology*, *127*(3), 222–226. https://doi.org/10.1017/S0022215112002964

Fields, J. M. (1993). Effect of personal and situational variables on noise annoyance in residential areas. *The Journal of the Acoustical Society of America*, *93*(5), 2753–2763. https://doi.org/10.1121/1.405851

Gao, Y., Yao, R., Li, B., Turkbeyler, E., Luo, Q., & Short, A. (2012). Field studies on the effect of built forms on urban wind environments. *Renewable Energy*, *46*, 148–154. https://doi.org/10.1016/j.renene.2012.03.005

Grady, S. A., Hussaini, M. Y., & Abdullah, M. M. (2005). *Placement of wind turbines using genetic algorithms*. *Renewable Energy* (Vol. 30). https://doi.org/10.1016/j.renene.2004.05.007

Guedes, I. C. M., Bertoli, S. R., & Zannin, P. H. T. (2011). Influence of urban shapes on environmental noise: A case study in Aracaju - Brazil. *Science of the Total Environment*, *412–413*, 66–76. https://doi.org/10.1016/j.scitotenv.2011.10.018

Guski, R. (1999). Personal and social variables as co-determinants of noise annoyance. *Noise and Health*.

GWEC. (n.d.). Global status of wind power. Retrieved May 25, 2017, from http://www.gwec.net/global-figures/wind-energy-global-status/

Haevernick, R. (2010). Noise levels Nordex N90/2500. Retrieved from http://www.nordex-online.com/fileadmin/MEDIA/Produktinfos/EN/N90_2500_Broschuere_GB_web

Hanning, C. D., & Evans, A. (2012). Wind turbine noise. *British Medical Journal*, *344*(mar08 1), e1527–e1527. https://doi.org/10.1136/bmj.e1527

Hansen, C. (2007). *Effects of low-frequency noise and vibration on people*. Brentwood, UK.

Hao, Y., & Kang, J. (2014). Influence of mesoscale urban morphology on the spatial noise attenuation of flyover aircrafts. *Applied Acoustics*, *84*, 73–82. https://doi.org/10.1016/j.apacoust.2013.12.001

Hao, Y., Kang, J., & Krijnders, J. D. (2015). Integrated effects of urban morphology on birdsong loudness and visibility of green areas. *Landscape and Urban Planning*, *137*, 149–162. https://doi.org/10.1016/j.landurbplan.2015.01.006

Harding, G., Harding, P., & Wilkins, A. (2008). Wind turbines, flicker, and photosensitive epilepsy: Characterizing the flashing that may precipitate seizures and optimizing guidelines to prevent them. *Epilepsia*, *49*(6), 1095–1098. https://doi.org/10.1111/j.1528-1167.2008.01563.x

Harry, A. (2007). Wind Turbines, Noise and Health. Retrieved from http://waubrafoundation.org.au/wp-content/uploads/2013/02/Harry-Dr-Amanda-Wind-Turbines-Noise-Health-survey-Feb-2007.pdf.

Hayes, M. D. (2007). The Measurement of Low Frequency Noise at Three UK Wind Farms Why undertake the Study, (March).

Helliwell, J. F. (2006). Well-being, social capital and public policy: What's new? *Economic Journal*, *116*, C34–C45.

Herbst, C. M. (2011). “Paradoxical” decline? Another look at the relative reduction in female happiness. *Journal of Economic Psychology*, *32*(5), 773–788. https://doi.org/10.1016/j.joep.2011.07.001

Hoppock, D. C., & Patiño-Echeverri, D. (2010). Cost of Wind Energy: Comparing Distant Wind Resources to Local Resources in the Midwestern United States. *Environmental Science & Technology*, *44*(22), 8758–8765. https://doi.org/10.1021/es100751p

Hudson, J. (2006). Institutional trust and subjective well-being across the EU. *Kyklos*, *59*(1), 43–62.

IEC 61400-11. (2012). *Wind Turbine Generator Systems - Part 11: Acoustic Noise Measurement Techniques*. Geneva: International Electrotechnical Commission.

Instruments Statutory. (2013). Town and Country Planning (Development Management Procedure) (England) (Amendment) Order 2013, *2013*(1238).

Ishugah, T. F., Li, Y., Wang, R. Z., & Kiplagat, J. K. (2014). Advances in wind energy resource exploitation in urban environment: A review. *Renewable and Sustainable Energy Reviews*, *37*, 613–626. https://doi.org/10.1016/j.rser.2014.05.053

ISO. (1990). *Acoustics: Determination of occupational noise exposure and estimation of noise-induced hearing impairment*.

ISO 15666. (2003). *ISO/TS 15666 Acoustics - Assessment of noise annoyance by means of social and socio-acoustic surveys*.

ISO 9613-2. (1996). *Acoustics - Attenuation of sound during propagation outdoors - Part 2: General method of calculation*. Geneva: International Organization for Standardization.

Issarayangyun, T., Black, D., Black, J., & Samuels, S. (2005). Aircraft noise and methods for the study of community health and well-being. *Journal of the Eastern Asia Society for Transportation Studies*, *6*, 3293–3308.

Jakobsen, J. (2012). Danish Regulation of Low Frequency Noise from Wind Turbines. *Low Frequency Noise, Vibration and Active Control*, *31*(4), 239–246. https://doi.org/10.1260/0263-0923.31.4.239

Job, R. F. S. (1996). The influence of subjective reactions to noise on health effects of the noise. *Environment International*, *22*(1), 93–104. https://doi.org/10.1016/0160-4120(95)00107-7

Job, R. F. S. (1999). Noise sensitivity as a factor influencing human reaction to noise. *Noise & Health*, *3*, 57–68.

Kang, J. (2006). *Urban Sound Environment*. CRC Press.

Kang, J., Aletta, F., Gjestland, T. T., Brown, L. A., Botteldooren, D., Schulte-Fortkamp, B., … Lavia, L. (2016). Ten questions on the soundscapes of the built environment. *Building and Environment*, *108*, 284–294. https://doi.org/10.1016/j.buildenv.2016.08.011

Keith, S. E., Feder, K., Voicescu, S. A., Soukhovtsev, V., Denning, A., Tsang, J., … van den Berg, F. (2016). Wind turbine sound pressure level calculations at dwellings. *The Journal of the Acoustical Society of America*, *139*(3), 1436–1442. https://doi.org/10.1121/1.4942404

Knight, J. (2004). Urban wind power: Breezing into town. *Nature*, *430*(6995), 12–13. https://doi.org/10.1038/430012a

Larsson, C., & Öhlund, O. (2014). Amplitude modulation of sound from wind turbines under various meteorological conditions. *Journal of the Acoustical Society of America*, 67–73. https://doi.org/10.1121/1.4836135

Ledo, L., Kosasih, P. B., & Cooper, P. (2011). Roof mounting site analysis for micro-wind turbines. *Renewable Energy*, *36*(5), 1379–1391. https://doi.org/10.1016/j.renene.2010.10.030

Leventhall, G. (2009). Review: Low Frequency Noise. What we know, what we do not know, and what we would like to know. *Noise Notes*, *8*(4), 3–28.

Lewis, B. (2015). House of Commons: Written Statement (HCWS42). Retrieved from http://www.parliament.uk/documents/commons-vote-office/June 2015/18 June/1-DCLG-Planning.pdf

Luhmann, M., Hofmann, W., Eid, M., & Lucas, R. E. (2012). Subjective Well-Being and Adaptation to Life Events : A Meta-Analysis, *102*(3), 592–615. https://doi.org/10.1037/a0025948

Margaritis, E., & Kang, J. (2016). Relationship between urban green spaces and other features of urban morphology with traffic noise distribution. *Urban Forestry and Urban Greening*, *15*, 174–185. https://doi.org/10.1016/j.ufug.2015.12.009

McKennel, O. P. C. S. (1979). *Second Survey of Aircraft Annoyance Around London Heathrow Airport*. London: Her Majesty's Stationary Office.

Meister, E., & Donatelle, R. J. (2000). The impact of commercial-aircraft noise on human health: a neighborhood study in metropolitan Minnesota. *Journal of Environmental Health*, *63*(4), 9.

Mezzofiore, G. (2016). Line our motorways with wind turbines because they are already unattractive. Retrieved April 17, 2017, from http://www.dailymail.co.uk/news/article-3413131/Line-motorways-wind-turbines-unattractive-no-one-lives-claims-Government-s-green-energy-adviser.html

Michaud, D. S., Feder, K., Keith, S. E., Voicescu, S. A., Marro, L., Than, J., … Weiss, S. K. (2016). Exposure to wind turbine noise : Perceptual responses and reported health effects. *Jasa*, *139*(March), 1443–1454. https://doi.org/10.1121/1.4942391

Miedema, H. M., & Vos, H. (1998). Exposure-response relationships for transportation noise. *The Journal of the Acoustical Society of America*, *104*(6), 3432–3445.

Møller, H., & Lydolf, M. (2002). A questionnaire survey of complaints of infrasound and low-frequency noise. *Journal of Low Frequency Noise*, *21*(2), 53–63.

Moorhouse, A., Hayes, M., von Hunerbein, S., Piper, B., & Adams, M. (2007). *Research into aerodynamic modulation of wind turbine noise : Final report*.

Murakami, S., & Mochida, A. (1988). 3-D numerical simulation of airflow around a cubic model by means of the model. *Journal of Wind Engineering and Industrial Aerodynamics*, *31*(2–3), 283–303. https://doi.org/10.1016/0167-6105(88)90009-8

Muzet, A. (2007). Environmental noise, sleep and health. *Sleep Medicine Reviews*, *11*(2), 135–142. https://doi.org/10.1016/j.smrv.2006.09.001

Niemann, H., Bonnefoy, X., Braubach, M., Hecht, K., Maschke, C., Rodrigues, C., & Robbel, N. (2006). Noise-induced annoyance and morbidity results from the pan-European LARES study. *Noise and Health*, *8*(31), 63.

Nilsson, K. B. and G. B. and G. E. and M. E., Bolin, K., Bluhm, G., Eriksson, G., & Nilsson, M. E. (2011). Infrasound and low frequency noise from wind turbines: exposure and health effects. *Environmental Research Letters*, *6*(3), 35103. https://doi.org/10.1088/1748-9326/6/3/035103

Nissenbaum, M. A., Aramini, J. J., & Hanning, C. D. (2012). Effects of industrial wind turbine noise on sleep and health. *Noise & Health*. https://doi.org/10.4103/1463-1741.102961

Öhrström, E. (1991). Psycho-social effects of traffic noise exposure. *Journal of Sound and Vibration*, *151*(3), 513–517.

Öhrström, E., Skånberg, A., Svensson, H., & Gidlöf-Gunnarsson, A. (2006). Effects of road traffic noise and the benefit of access to quietness. *Journal of Sound and Vibration*, *295*(1–2), 40–59. https://doi.org/10.1016/j.jsv.2005.11.034

Öhström, E., & Björkman, M. (1988). Effects of noise-disturbed sleep—a laboratory study on habituation and subjective noise sensitivity. *Journal of Sound and Vibration*, *122*(2), 277–290.

Oliveira, M. F., & Silva, L. T. (2011). The influence of urban form on facades noise levels. *Transactions on Environment and Development*, *7*(5), 125–135.

Ontario, W. C. (2009). A selfreporting survey: adverse health effects with industrial wind turbines and the need for vigilance.

Ordnance Survey. (2013). EDINA Digimap Ordnance Survey Service. Retrieved August 26, 2014, from http://digimap.edina.ac.uk

OUIS, D. (2001). Annoyance From Road Traffic Noise: a Review. *Journal of Environmental Psychology*, *21*(1), 101–120. https://doi.org/10.1006/jevp.2000.0187

Passchier-Vermeer, W., & Passchier, W. F. (2000). Noise exposure and public health. *Environmental Health Perspectives*, *108*(Suppl 1), 123.

Pawlaczyk-Łuszczyńska, M., Dudarewicz, A., Zaborowski, K., Zamojska-Daniszewska, M., & Waszkowska, M. (2014). Evaluation of annoyance from the wind turbine noise: a pilot study. *International Journal of Occupational Medicine and Environmental Health*, *27*(3), 364–88. https://doi.org/10.2478/s13382-014-0252-1

Pedersen, E. (2011). Health aspects associated with wind turbine noise - Results from three field studies. *Noise Control Engineering Journal*, *59*(1), 47–53. https://doi.org/10.3397/1.3533898

Pedersen, E., & Larsman, P. (2008). The impact of visual factors on noise annoyance among people living in the vicinity of wind turbines. *Journal of Environmental Psychology*, *28*(4), 379–389. https://doi.org/10.1016/j.jenvp.2008.02.009

Pedersen, E., van den Berg, F., Bakker, R., & Bouma, J. (2009). Response to noise from modern wind farms in The Netherlands. *The Journal of the Acoustical Society of America*, *126*(2), 634–43. https://doi.org/10.1121/1.3160293

Pedersen, E., van den Berg, F., Bakker, R., & Bouma, J. (2010). Can road traffic mask sound from wind turbines? Response to wind turbine sound at different levels of road traffic sound. *Energy Policy*, *38*(5), 2520–2527. https://doi.org/10.1016/j.enpol.2010.01.001

Pedersen, E., & Waye, K. P. (2004). Perception and annoyance due to wind turbine noise--a dose-response relationship. *The Journal of the Acoustical Society of America*, *116*(6), 3460–70. https://doi.org/10.1121/1.1815091

Pedersen, E., & Waye, K. P. (2007). Wind turbine noise, annoyance and self-reported health and well-being in different living environments. *Occup Environ Med*, *64*(7), 480–486. https://doi.org/10.1136/oem.2006.031039

Persson, K., Clow, A., Edwards, S., Hucklebridge, F., & Rylander, R. (2003). ScienceDirect - Life Sciences : Effects of nighttime low frequency noise on the cortisol response to awakening and subjective sleep quality, *72*, 863–875.

Phipps, R. (2007). Evidence of Dr Robyn Phipps.

Pierpont, N. (2009). *Wind Turbine Syndrome: A report on a natural experiment*. Santa Fe, NM, USA.

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

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

Qu, F., Kang, J., & Tsuchiya, A. (2015). Effects of built environment morphology in residential areas on resisting wind turbine noise on building façades. In *6th International Meeting on Wind Turbine Noise*. Glasgow.

RenewableUK. (2017). UK Wind Energy Statistics. Retrieved May 25, 2017, from https://www.renewableuk.com/page/UKWEDhome

Renterghem, T. Van, & Botteldooren, D. (2012). Focused Study on the Quiet Side Effect in Dwellings Highly Exposed to Road Traffic Noise. *Environmental Research and Public Health*, 4292–4310. https://doi.org/10.3390/ijerph9124292

Ricciardelli, F., & Polimeno, S. (2006). Some characteristics of the wind flow in the lower Urban Boundary Layer. *Journal of Wind Engineering and Industrial Aerodynamics*, *94*(11), 815–832. https://doi.org/10.1016/j.jweia.2006.06.003

Rubin, G. J., Burns, M., & Wessely, S. (2014). Possible psychological mechanisms for "wind turbine syndrome". On the windmills of your mind. *Noise and Health*, *16*(69), 116–122.

Salomons, E. M., & Berghauser Pont, M. (2012). Urban traffic noise and the relation to urban density, form, and traffic elasticity. *Landscape and Urban Planning*, *108*(1), 2–16. https://doi.org/10.1016/j.landurbplan.2012.06.017

Salt, A. N., & Hullar, T. E. (2010). Responses of the ear to low frequency sounds, infrasound and wind turbines. *Hearing Research*, *268*(1–2), 12–21. https://doi.org/10.1016/j.heares.2010.06.007

Schreckenberg, D., Meis, M., Peschel, C., & Eikmann, T. (2010). Aircraft noise and quality of life around Frankfurt Airport. *International Journal of Environmental Research and Public Health*, *7*(9), 3382–3405.

Shepherd, D., McBride, D., Welch, D., Dirks, K. N., & Hill, E. M. (2011). Evaluating the impact of wind turbine noise on health-related quality of life. *Noise and Health*, *13*(54), 333–339.

Silva, L. T., Oliveira, M., & Silva, J. F. (2014). Urban form indicators as proxy on the noise exposure of buildings. *Applied Acoustics*, *76*, 366–376. https://doi.org/10.1016/j.apacoust.2013.07.027

Stansfeld, S. A., Haines, M. M., Burr, M., Berry, B., & Lercher, P. (2000). A review of environmental noise and mental health. *Noise and Health*.

Stansfeld, S. A., & Matheson, M. P. (2003). Noise pollution: Non-auditory effects on health. *British Medical Bulletin*, *68*, 243–257. https://doi.org/10.1093/bmb/ldg033

Tarnopolsky, A., Watkins, G., & Hand, D. J. (1980). Aircraft noise and mental health: I. Prevalence of individual symptoms. *Psychological Medicine*, *10*(4), 683–98. https://doi.org/10.1017/S0033291700054982

Thorne, B., & Leader, T. (2012). Wind Farm Generated Noise and Adverse Health Effects . Retrieved from http://docs.wind-watch.org/Thorne_Wind-farm-generated-noise-adverse-health-effects.pdf

Ubel, P. a, Loewenstein, G., Hershey, J., Baron, J., Mohr, T., Asch, D. a, & Jepson, C. (2011). Do nonpatients underestimate the quality of life associated with chronic health conditions because of a focusing illusion? *Medical Decision Making : An International Journal of the Society for Medical Decision Making*, *21*(3), 190–9. https://doi.org/10.1177/0272989X0102100304

van den Berg, F., Pedersen, E., Bouma, J., & Bakker, R. (2008). *Visual and acoustic impact of wind turbine farms on residents - Final report*.

van den Berg, F., Verhagen, C., & Uitenbroek, D. (2014). The relation between scores on noise annoyance and noise disturbed sleep in a public health survey. *International Journal of Environmental Research and Public Health*, *11*(2), 2314–2327. https://doi.org/10.3390/ijerph110202314

Van Den Berg, G. P. (2004). Effects of the wind profile at night on wind turbine sound. *Journal of Sound and Vibration*, *277*(4–5), 955–970. https://doi.org/10.1016/j.jsv.2003.09.050

Van Renterghem, T., & Botteldooren, D. (2012). Focused study on the quiet side effect in dwellings highly exposed to road traffic noise. *International Journal of Environmental Research and Public Health*. https://doi.org/10.3390/ijerph9124292

Verheijen, E., Jabben, J., Schreurs, E., & Smith, K. B. (2011). Impact of wind turbine noise in The Netherlands. *Noise and Health*, *13*(55), 459–463.

Wagner, S., Bareiß, R., & Guidati, G. (1996). *Wind Turbine Noise*. *Bulletin of Science, Technology & Society* (Vol. 31). Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-88710-9

Wang, B., & Kang, J. (2011). Effects of urban morphology on the traffic noise distribution through noise mapping: A comparative study between UK and China. *Applied Acoustics*, *72*(8), 556–568. https://doi.org/10.1016/j.apacoust.2011.01.011

Weinstein, N. D. (1978). Individual differences in reactions to noise: a longitudinal study in a college dormitory. *The Journal of Applied Psychology*, *63*(4), 458–466. https://doi.org/10.1037/0021-9010.63.4.458

Weinstein, N. D. (1980). Individual differences in critical tendencies and noise annoyance. *Journal of Sound and Vibration*, *68*(2), 241–248. https://doi.org/10.1016/0022-460X(80)90468-X

WHO. (1999). Guidelines for community noise. *World Health Organization*. Geneva: World Health Organization.

WHO. (2009). Night Noise Guidelines for Europe. *WHO Regional Office for Europe*. Copenhagen. https://doi.org/10.1093/ejechocard/jer095

Wico, R., & Saxony, L. (2005). *Measurement of noise emission of wind turbine Enercon E-70 E4 2.3MW*.

Williams, K., Joynt, J. L. R., 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. https://doi.org/10.1016/j.buildenv.2011.11.015

Wilson, T. D., Wheatley, T., Meyers, J. M., Gilbert, D. T., & Axsom, D. (2000). Focalism: A source of durability bias in affective forecasting. *Journal of Personality and Social Psychology*, *78*(5), 821–836.

WindEurope. (n.d.). Environment & planning. Retrieved May 25, 2017, from https://windeurope.org/policy/topics/environment-planning/

Wolsink, M. (2000). Wind power and the NIMBY-myth: Institutional capacity and the limited significance of public support. *Renewable Energy*, *21*(1), 49–64. https://doi.org/10.1016/S0960-1481(99)00130-5

Working Group on Wind Turbine Noise. (1996). *ETSU-R-97: The Assessment & Rating of Noise from Wind Farms. DTI.*

Zaharna, M., & Guilleminault, C. (2010). Sleep, noise and health: review. *Noise and Health*, *12*(47), 64.

Appendix I. Pilot study on the effect of building morphology using generic layouts

Effect of building height:

Figure 3A.1 shows how the noise level of a calculating grid of 3*3 m2 at 3 meters behind the building changes with the increase of building's height. When the height of the building increases from 5 to 20 meters, the average SPL of wind turbine noise in this grid decreases from 50 to 42dBA. The traffic noise radiation decreases more quickly shaping a reduction from 45 to 26dBA. It implies that increase of building height from 6-12m leads to small difference between wind turbine noise at the quiet side of the building.

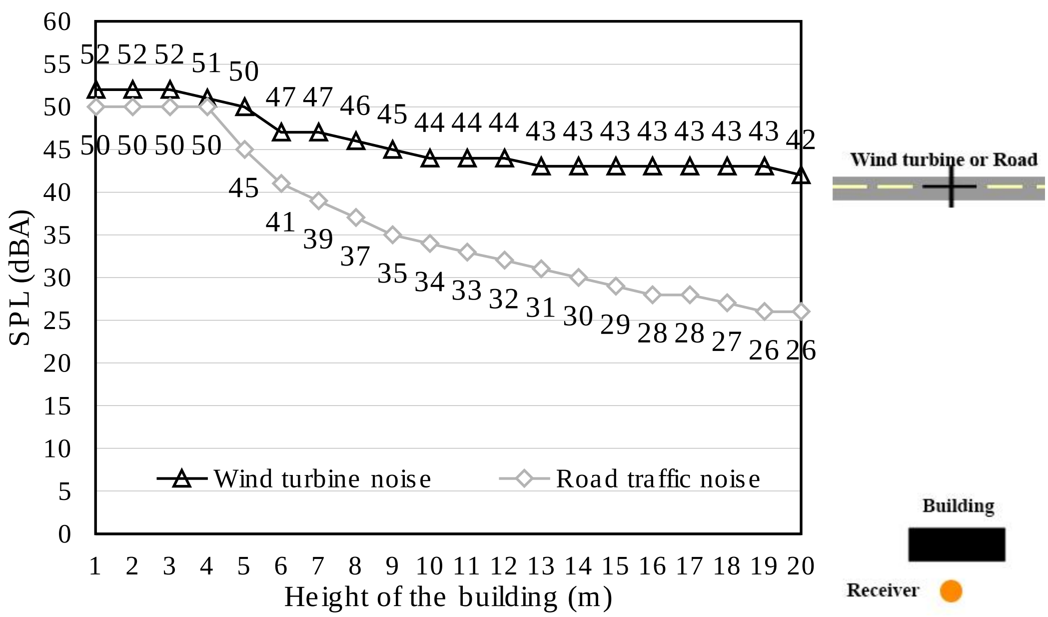


Figure 3A. 1 Changes of noise exposure at the back of the building with increases of building height.

Effect of building configuration:

To examine how parameters of building morphology affect noise exposures, 9 typical configurations of 66*66 m^2 were hypothetically created to address variables including orientation, density, width, openness, and relative distance (shown in Figure 3A.2). Noise mappings were conducted with a source of a wind turbine or a road set up at 39 m on the north of the boundary of each generic site. It should be noted that assuming such short source-receiver distance is to examine the tendency of change in an extreme situation, which is independent on distance. Distributions of wind turbine and traffic noises are examined separately based on SPL values in every 6*6 m2 grid of the site. For the sake of convenience, wind turbine is simulated as a point source at 100m height with a sound power level of 100dB(A) at wind velocity 8 m/s at 10m height, which can represent to a 2MW modern wind turbine. The road is classified as a local one (DTV=1000).

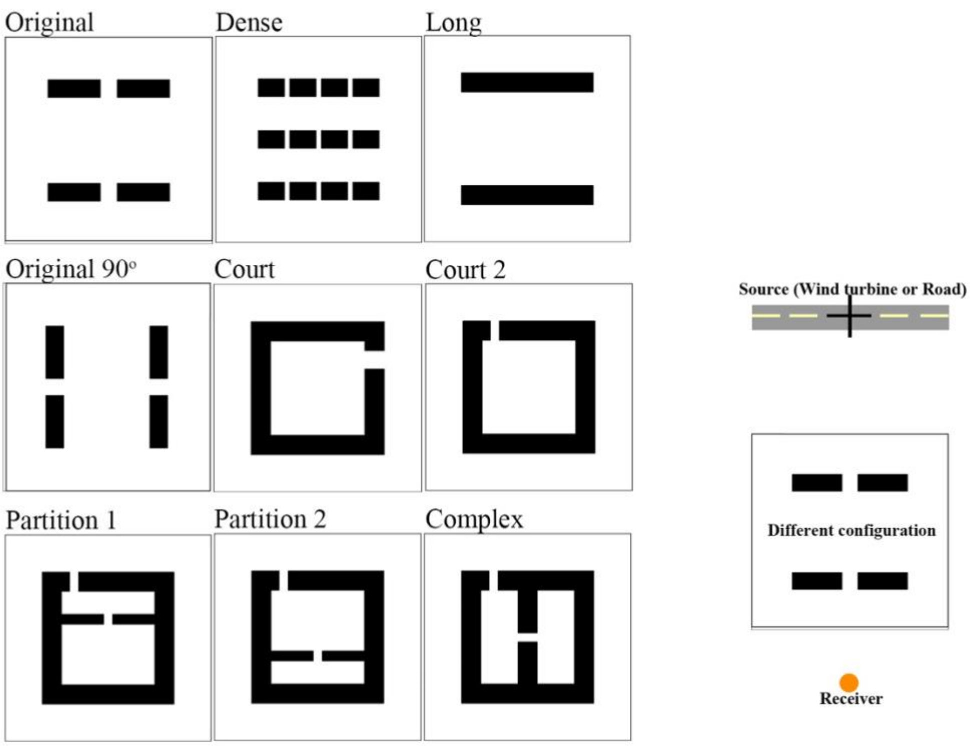
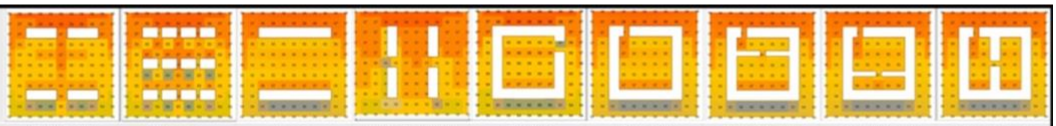


Figure 3A. 2 Generic building configurations and settings for noise mapping

The SPL values in every 6*6 m^2 grid are exported and statistically described in Table 3A.1.

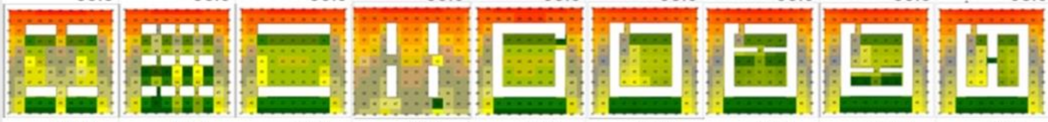
Table 3A. 1 wind turbine noise and traffic noise exposures on different building layouts (dBA)

Wind turbine noise



	Original	Dense	Long	Original 90	Court	Court2	Partition1	Partition2	Complex
Mean	55.6	55.5	55.4	56.0	55.3	55.5	55.4	55.4	55.4
Std. Dev.	1.8	2.0	1.9	1.4	2.1	2.0	2.1	2.1	2.1
Variance	3.3	4.0	3.8	2.0	4.3	4.1	4.3	4.2	4.3
Min	50.0	50.0	50.0	52.0	50.0	50.0	50.0	50.0	50.0
Max	58.0	58.0	58.0	58.0	58.0	58.0	58.0	58.0	58.0

Road traffic noise



	Original	Dense	Long	Original 90	Court	Court2	Partition1	Partition2	Complex
Mean	49.2	48.7	47.9	52.8	48.4	48.9	48.7	48.9	49.2
Std. Dev.	6.6	7.2	7.3	4.2	7.5	7.1	7.6	7.5	7.3
Variance	43.9	51.9	52.6	17.3	56.0	50.8	57.1	55.7	52.6
Min	37.0	37.0	37.0	39.0	37.0	37.0	37.0	37.0	37.0
Max	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0

Orientation: The orientation of building layout has a fundamental effect on noise exposures. The layout entitled "original 90^{o}" has the largest mean value of exposure both in terms of wind turbine noise (56dBA) and traffic noise (53dBA), due to its lowest level of barrier effects. Its standard deviation (1.4dBA) is also the lowest, indicating the least relatively quiet areas created, associated with the fact that the minimum noise level in this area are 2dBA higher than others.

Width: The mean values of both wind turbine noise and traffic noise distributed in "long" building layout are lower than in the "original" one. This long width configuration also generates considerable high variance levels (3.8 & 52.6dBA). It can be inferred that a long width will ensure a high level of barrier effect and at the same time limit the area influenced by diffraction, and hence creates high variance between noisy and quiet areas.

Density: Comparing the noise exposure in the "original" and "dense" configurations, a higher density enables a slightly lower mean and higher deviation for both noises. The generic dense layout reduces the space between buildings in line, which minimises the "break outs" allowed for incident radiation and diffractions. Such effects are more significant on traffic noise exposure. When the space between buildings decreases from large in the “original” to small in the “dense” layout, and disappears in the “long” layout, the mean value decreases in a notable scale (from 49.3 to 48.0dBA), partially due to the fact that semi-connected buildings with less linear discontinuous gaps give a strong first-layer barrier to the road traffic source.

Openness: As expected, building layouts with less openness will to some extent protect the enclosed area from high exposure. This is also confirmed in this study by generally small mean values and high deviations of noise for the 5 categories of court layouts. “court2” with openness to the source has higher means of both noises than “court”. In terms of wind turbine noise, court layouts with partition buildings have further lower means than “court2”, which is attribute to the low noise exposure at a further depth space of enclosure.

Relative distance: When traffic noise distributions in 3 categories of court with partitions are compared, “partition1” has the lowest mean relative to “partition2” and “complex”, indicating that the relative distance of each obstructing building to the road source is an important factor of traffic noise distribution. The denser layout of obstructers in close distance to the road, the quieter noise level ensured behind the obstructers and at the overall scale (48.7 v.s. 48.9, 49.2dBA).

Effect of different source type:

As can be seen from Table 3A.1, traffic noise exposure in each site contains a large range of sound levels and deviations from place to place. It has 2dBA higher maximum level than turbine source but generates minimum noise levels up to 15dBA lower than wind turbine noise. This is likely because each configuration has higher barrier effects on traffic noise in terms of reflecting back the noise and creating relatively much quiet area at the other side. It is found that wind turbine noise propagation through area is less influenced by the building layouts but by the attenuation based on source-receiver distance; whilst traffic noise through built-up area is influenced by the barrier effect of the buildings - especially the layout of buildings close to the road. This can result in up to 13dBA lower of traffic noise than wind turbine noise reaching the receiver through the layout of buildings.

Appendix II. Questionnaires and the cover letter

Variant 1 (side A) (Originally double sided printed on A3 sheet)

Main Questionnaire, University of Sheffield.

Are you the person this questionnaire is addressed to?

- ☐ Yes (1)
- ☐ No (2) *(family member / current occupant)*

Instructions

Please complete the questionnaire by ticking the box that best represents your answer or writing in the space provided in some cases. Some questions may look similar.

Q1. Taking all things together, on a scale of 0 to 10, how happy would you say you are? Here 0 means you are very unhappy and 10 means you are very happy.

Very unhappy										Very happy
0	1	2	3	4	5	6	7	8	9	10

Q2. In general, would you say your health is...

- ☐ Excellent (1)
- ☐ Very good (2)
- ☐ Good (3)
- ☐ Fair (4)
- ☐ Poor (5)

Q3. Here are some statements on how you feel about your life. Please tick the box which you feel best describes how dissatisfied or satisfied you are with the following aspects of your current situation.

	Not satisfied at all 1	2	3	4	5	6	Completely Satisfied 7
a) Your life overall							
b) Your health							
c) Your household income							
d) Your social life							
e) Your living environment							

Q4. Please choose ALL the statement(s) which describe your sleep.

- ☐ My sleep is not disturbed at all. (1)
- ☐ It's hard for me to fall asleep. (2)
- ☐ I sleep less deeply than I would like. (3)
- ☐ I occasionally wake up but I soon go back to sleep. (4)
- ☐ I often lie awake for a while. (5)
- ☐ I have to take sleeping pills to fall asleep. (6)

Q5. The following are several things that might exist in people's living environment. Please state for each thing of the below, whether you notice them and if so, whether you are annoyed by them when you spend time at home.

	Notice? No 1	Yes 2	Don't know 3	If you notice, do you find it annoying? Not at all 1	2	3	4	Extremely 5
a) Unpleasant odor from outside								
b) Noise from neighbours								
c) Traffic noise								
d) Noise from wind turbines								
e) Other noise sources ______________(Please specify)								
f) Bugs, pests or vermin								
g) Vibration of the building								
h) Pollution, grime or dust								

Q6. In terms of environmental noise, how much do you agree or disagree with the following statements?

	Agree strongly 1	2	3	4	5	Disagree strongly 6
a) I find it hard to relax in a place that's noisy.						
b) I get used to most noises without much difficulty.						

Q22. What is your current marital status?

- ☐ Single (1)
- ☐ Married / In civil partnership / Cohabiting (2)
- ☐ Separated / Divorced (3)
- ☐ Widowed (4)

Q23. Which one represents the total annual income of your household before any deductions?

- ☐ Up to £20,000 (1)
- ☐ £20,000 to £29,999 (2)
- ☐ £30,000 to £49,999 (3)
- ☐ £50,000 to £79,999 (4)
- ☐ More than £80,000 (5)
- ☐ I don't know (6)

Q24. How many bedrooms are there at your dwelling? ______

Q25. What type of accommodation does your household live in?

- ☐ Detached house/bungalow (1)
- ☐ Semi-detached house/bungalow (2)
- ☐ Mid-terraced house/bungalow (3)
- ☐ End-terraced house/bungalow (4)
- ☐ Purpose built or converted flat/maisonette (5)
- ☐ Other (6)

Q26. Please choose ONE from the following statements.

- ☐ All our rooms are at the front of the building facing the street/front yard. (1)
- ☐ All our rooms are at the back of the building facing the back yard/court. (2)
- ☐ We have rooms at both sides of the building. (3)
- ☐ We have rooms facing three sides of the building, or more. (4)

Q27. Can you see any wind turbines from the place you live? Please choose ALL that apply.

- ☐ I can see it/them from the window of my dwelling. (1)
- ☐ I can see it/them from my garden/yard. (2)
- ☐ I can't see any from my dwelling or garden/yard. (3)

Q28. How long have you lived at your current address?

______ years (If less than a year please indicate ______ months)

Q29. Please indicate the approximate number of hours PER DAY you spent (including sleeping) indoors or outdoors at your dwelling during the last week.

a) Time spent indoors at your dwelling: ______ hours at average PER DAY

b) Time spent outdoors around your dwelling: ______ hours at average PER DAY

Q30. Please choose ONE statement which best describes your household's ownership of the accommodation.

- ☐ Owned outright (1)
- ☐ Owned / being bought on mortgage (2)
- ☐ Shared ownership (Part-owned part-rented) (3)
- ☐ Rented (4)
- ☐ Rent free (5)
- ☐ Other (6)

Q31. Is the window of your bedroom double-glazed or sound proofed?

- ☐ Yes (1)
- ☐ No (2)
- ☐ I don't know (3)

You have complete the questionnaire. Please return it using the pre-addressed return-prepaid envelope best within two weeks of receiving this. Thank you very much for your participation!

Variant 1 (side B) (Originally double sided printed on A3 sheet)

Main Questionnaire, University of Sheffield.

Q7. What are your views on environmental sustainability?

	Agree strongly 1	2	3	4	5	Disagree strongly 6
a) The environmental sustainability is a low priority for me compared with a lot of other things in my life.	☐	☐	☐	☐	☐	☐
b) I personally need to change my way of life so that future generations can continue to enjoy a good quality of life and environment.	☐	☐	☐	☐	☐	☐

Q8. How do you evaluate the overall sound environment at your dwelling?

		Very 3	Fairly 2	Little 1	Neutral 0	Little -1	Fairly -2	Very -3	
a)	*Quiet*	☐	☐	☐	☐	☐	☐	☐	*Loud*
b)	*Interesting*	☐	☐	☐	☐	☐	☐	☐	*Boring*
c)	*Pleasant*	☐	☐	☐	☐	☐	☐	☐	*Unpleasant*
d)	*Continuous*	☐	☐	☐	☐	☐	☐	☐	*Discontinuous*
e)	*Predictable*	☐	☐	☐	☐	☐	☐	☐	*Chaotic*
f)	*Calming*	☐	☐	☐	☐	☐	☐	☐	*Agitating*
g)	*Directional*	☐	☐	☐	☐	☐	☐	☐	*Everywhere*
h)	*Natural*	☐	☐	☐	☐	☐	☐	☐	*Artificial*

Q9. Thinking about the last 12 months, when you are at home, how much does noise from wind turbines bother, disturb or annoy you?

☐ Not at all 1 ☐ Slightly 2 ☐ Moderately 3 ☐ Very 4 ☐ Extremely 5

Q10. Thinking about the last 12 months, what number from 0 to 10 best shows how much you are bothered, disturbed or annoyed by wind turbine noise when you spend time *outdoors* and *indoors* at your dwelling?

	Not at all 0	1	2	3	4	5	6	7	8	9	Extremely 10
Outdoors at your dwelling:	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Indoors in your dwelling:	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Q11. Would you say that the wind turbine noise has any effect on your health?

☐ No, not at all 1 ☐ Yes, some of the time 2
☐ Yes, most of the time 3 ☐ I don't know 4

Q12. Did you experience any of the below during the past week? Please indicate whether you consider it to be caused by wind turbine noise.

	Experienced any? Not at all 1	Some of the time 2	All the time 3	Feel like it's caused by wind turbine noise? Yes 1	Possibly 2	No 3	I don't know 4
Headache	☐	☐	☐	☐	☐	☐	☐
Nausea	☐	☐	☐	☐	☐	☐	☐
Dizziness	☐	☐	☐	☐	☐	☐	☐
Ear discomfort	☐	☐	☐	☐	☐	☐	☐
Cardiovascular disease	☐	☐	☐	☐	☐	☐	☐
Stress	☐	☐	☐	☐	☐	☐	☐
Tension and edginess	☐	☐	☐	☐	☐	☐	☐
Difficulty in intellectual activities	☐	☐	☐	☐	☐	☐	☐
Mood swings	☐	☐	☐	☐	☐	☐	☐
Lack of concentration	☐	☐	☐	☐	☐	☐	☐
Other ____________(Please specify)	☐	☐	☐	☐	☐	☐	☐

Q13. When you are at home, do you notice the noise from wind turbine(s) in each of the following situations? If you do, how much does it annoy you?

	Notice: No 1	Yes 2	Don't know 3	Annoying: Not at all 1	2	3	4	Extremely 5
a) When the wind is strong	☐	☐	☐	☐	☐	☐	☐	☐
b) When you are inside your room with windows closed	☐	☐	☐	☐	☐	☐	☐	☐
c) When there is heavy traffic flow outside your dwelling	☐	☐	☐	☐	☐	☐	☐	☐
d) When at night	☐	☐	☐	☐	☐	☐	☐	☐

Q14. How would you describe the sound of the wind turbine(s)? Please choose ALL that apply.

☐ Noiseless / Quiet 1 ☐ Swishing 2 ☐ Beating 3 ☐ Wooshing 4
☐ Whistling 5 ☐ Pulsating 6 ☐ Throbbing 7 ☐ Other ____________ 8 (Please specify)

Q15. Please mark ALL the adjectives that you think are applicable to wind turbines:

☐ Environment-friendly 1 ☐ Not environment-friendly 2
☐ Efficient 3 ☐ Inefficient 4 ☐ Dangerous 5 ☐ Harmless 6
☐ Unnecessary 7 ☐ Necessary 8 ☐ Ugly 9 ☐ Pretty 10
☐ Attractive/inviting 11 ☐ Threatening 12 ☐ Natural/green 13 ☐ Unnatural 14
☐ Other (Please specify)____________ 15

Q16. Do you or your family have a financial stake in the wind farm?

	You: Yes 1	No 2	Your family: Yes 1	No 2	I don't know 0
a) Joint Owner / Employee	☐	☐	☐	☐	☐
b) Receive compensation/benefits	☐	☐	☐	☐	☐
c) Other ____________(Please specify)	☐	☐	☐	☐	☐

Now, to help us analyse your answers, would you mind to tell us something about yourself?

Q17. Your age in years: ______

Q18. Your gender: ☐ Male 1 ☐ Female 2

Q19. Please indicate which one best describes your current situation.

☐ In full-time employment/self-employed 1 ☐ In part-time employment/self-employed 2
☐ In full-time education 3 ☐ On a training scheme 4
☐ Retired 5 ☐ On maternity leave 6
☐ Looking after family or home 7 ☐ Other ____________ 8 (Please specify)

Q20. Are you suffering from any long-standing illness, disability or infirmity?

☐ Yes 1 ☐ No 2

Q21. What is the highest educational or school qualification have you obtained?

☐ No qualification 1 ☐ GCSE / CSE / O Level 2
☐ A Level or equivalent 3 ☐ Higher education below degree 4
☐ Degree level qualification 5 ☐ Other ____________ 6 (Please specify)

Variant 2 (side A) (Originally double sided printed on A3 sheet)

Well-being and Living Environment Questionnaire, University of Sheffield.

Are you the person this questionnaire is addressed to?

☐ Yes (1) ☐ No (2) *(family / current occupant)*

Instructions

Please complete the questionnaire by ticking the box that best represents your answer or writing in the space provided in some cases.

Q1. Taking all things together, on a scale of 0 to 10, how happy would you say you are? Here 0 means you are very unhappy and 10 means you are very happy.

Very unhappy ☐0 ☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7 ☐8 ☐9 ☐10 Very happy

Q2. In general, would you say your health is...

☐ Excellent (1) ☐ Very good (2) ☐ Good (3) ☐ Fair (4) ☐ Poor (5)

Q3. Here are some statements on how you feel about your life. Please tick the box which you feel best describes how dissatisfied or satisfied you are with the following aspects of your current situation.

	Not satisfied at all 1	2	3	4	5	6	Completely Satisfied 7
a) Your life overall	☐	☐	☐	☐	☐	☐	☐
b) Your health	☐	☐	☐	☐	☐	☐	☐
c) Your household income	☐	☐	☐	☐	☐	☐	☐
d) Your social life	☐	☐	☐	☐	☐	☐	☐
e) Your living environment	☐	☐	☐	☐	☐	☐	☐

Q4. Please choose ALL the statement(s) which describe your sleep.

☐ My sleep is not disturbed at all. (1)
☐ It's hard for me to fall asleep. (2)
☐ I sleep less deeply than I would like. (3)
☐ I occasionally wake up but I soon go back to sleep. (4)
☐ I often lie awake for a while. (5)
☐ I have to take sleeping pills to fall asleep. (6)

Q5. The following are several things that might exist in people's living environment. Please state for each thing of the below, whether you notice them and if so, whether you are annoyed by them when you spend time at home.

	Notice? No 1	Yes 2	Don't know 3	If you notice, do you find it annoying? Not at all 1	2	3	4	Extremely 5
a) Unpleasant odor from outside	☐	☐	☐	☐	☐	☐	☐	☐
b) Noise from neighbours	☐	☐	☐	☐	☐	☐	☐	☐
c) Traffic noise	☐	☐	☐	☐	☐	☐	☐	☐
d) Noise from wind turbines	☐	☐	☐	☐	☐	☐	☐	☐
e) Other noise sources ________________(Please specify)	☐	☐	☐	☐	☐	☐	☐	☐
f) Bugs, pests or vermin	☐	☐	☐	☐	☐	☐	☐	☐
g) Vibration of the building	☐	☐	☐	☐	☐	☐	☐	☐
h) Pollution, grime or dust	☐	☐	☐	☐	☐	☐	☐	☐

Q20. How long have you lived at your current address?

________ years (If less than a year please indicate________ months)

Q21. Please indicate the approximate number of hours PER DAY you spent (including sleeping) indoors or outdoors at your dwelling during the last week.

a) Time spent indoors at your dwelling: ________ hours at average PER DAY

b) Time spent outdoors around your dwelling: ________ hours at average PER DAY

Q22. Please choose ONE statement which best describes your household's ownership of the accommodation.

☐ Owned outright (1) ☐ Owned / being bought on mortgage (2) ☐ Shared ownership (Part-owned part-rented) (3)
☐ Rented (4) ☐ Rent free (5) ☐ Other (6)

Q23. Is the window of your bedroom double-glazed or sound proofed?

☐ Yes (1) ☐ No (2) ☐ I don't know (3)

You have complete the questionnaire. Please return it using the pre-addressed return-prepaid envelope best within 2 weeks.

Thank you very much for your participation!

Variant 2 (side B) (Originally double sided printed on A3 sheet)

Well-being and Living Environment Questionnaire, University of Sheffield.

Q6. In terms of environmental noise, how much do you agree or disagree with the following statements?

	Agree strongly 1	2	3	4	5	Disagree strongly 6
a) I find it hard to relax in a place that's noisy.	☐	☐	☐	☐	☐	☐
b) I get annoyed when my neighbours are noisy.	☐	☐	☐	☐	☐	☐

Q7. What are your views on environmental sustainability?

	Agree strongly 1	2	3	4	5	Disagree strongly 6
a) The environmental sustainability is a low priority for me compared with a lot of other things in my life.	☐	☐	☐	☐	☐	☐
b) I personally need to change my way of life so that future generations can continue to enjoy a good quality of life and environment.	☐	☐	☐	☐	☐	☐

Q8. How do you evaluate the overall sound environment at your dwelling?

		Very 3	Fairly 2	Little 1	Neutral 0	Little -1	Fairly -2	Very -3	
a)	*Quiet*	☐	☐	☐	☐	☐	☐	☐	*Loud*
b)	*Interesting*	☐	☐	☐	☐	☐	☐	☐	*Boring*
c)	*Pleasant*	☐	☐	☐	☐	☐	☐	☐	*Unpleasant*
d)	*Continuous*	☐	☐	☐	☐	☐	☐	☐	*Discontinuous*
e)	*Predictable*	☐	☐	☐	☐	☐	☐	☐	*Chaotic*
f)	*Calming*	☐	☐	☐	☐	☐	☐	☐	*Agitating*
g)	*Directional*	☐	☐	☐	☐	☐	☐	☐	*Everywhere*
h)	*Natural*	☐	☐	☐	☐	☐	☐	☐	*Artificial*

Q9. Did you experience any of the below during the past week?

	Not at all 1	Some of the time 2	All the time 3
Headache.	☐	☐	☐
Nausea.	☐	☐	☐
Dizziness.	☐	☐	☐
Ear discomfort.	☐	☐	☐
Cardiovascular disease.	☐	☐	☐
Stress.	☐	☐	☐
Tension and edginess.	☐	☐	☐
Difficulty in intellectual activities.	☐	☐	☐
Mood swings.	☐	☐	☐
Lack of concentration.	☐	☐	☐
Other________ (Please specify)	☐	☐	☐

Now, to help us analyse your answers, would you mind to tell us something about yourself?

Q10. Your age in years: ________

Q11. Your gender: ☐ Male 1 ☐ Female 2

Q12. Please indicate which one best describes your current situation.

- ☐ In full-time employment/self-employed 1
- ☐ In part-time employment/self-employed 2
- ☐ In full-time education 3
- ☐ On a training scheme 4
- ☐ Retired / Looking after family or home 5
- ☐ Other ________ 6 (Please specify)

Q13. Are you suffering from any long-standing illness, disability or infirmity?

- ☐ Yes 1
- ☐ No 2

Q14. What is the highest educational or school qualification have you obtained?

- ☐ No qualification 1
- ☐ GCSE / CSE / O Level 2
- ☐ A Level or equivalent 3
- ☐ Higher education below degree 4
- ☐ Degree level qualification 5
- ☐ Other ________ 6 (Please specify)

Q15. What is your current marital status?

- ☐ Single 1
- ☐ Married / In civil partnership / Cohabiting 2
- ☐ Separated / Divorced 3
- ☐ Widowed 4

Q16. Which one represents the total annual income of your household before any deductions?

- ☐ Up to £20,000 1
- ☐ £20,000 to £29,999 2
- ☐ £30,000 to £49,999 3
- ☐ £50,000 to £79,999 4
- ☐ More than £80,000 5
- ☐ I don't know 6

Q17. How many bedrooms are there at your dwelling? ______

Q18. What type of accommodation does your household live in?

- ☐ Detached house/bungalow 1
- ☐ Semi-detached house/bungalow 2
- ☐ Mid-terraced house/bungalow 3
- ☐ End-terraced house/bungalow 4
- ☐ Purpose built or converted flat/maisonette 5
- ☐ Other 6

Q19. Please choose ONE from the following statements.

- ☐ All our rooms are at the front of the building facing the street/front yard. 1
- ☐ All our rooms are at the back of the building facing the back yard/court. 2
- ☐ We have rooms at both sides of the building. 3
- ☐ We have rooms facing three sides of the building, or more. 4

Cover letter (Variant 1)

The University Of Sheffield.

Fei Qu
WindNet Research Group
University of Sheffield
Western Bank
S10 2TN, Sheffield
Website: windnet.org.uk
Contact: fei.qu@sheffield.ac.uk

WINDNET

Dear Sir / Madam,

I am a PhD student at the University of Sheffield and am writing to invite you to participate in a short questionnaire survey with a focus on the impact of wind turbine noise on human well-being. You are selected from thousands of residents in your area near wind turbines. I do hope you are able to help my research by completing the enclosed questionnaire and returning it before 7th July 2014 using the pre-addressed envelope (there is no need to attach a postage stamp).

The questionnaire should not take longer than 15 minutes of your time to complete. It covers topics such as your health and well-being, your living environment, and your reactions to noise. We do not expect there are any risks to you from participating in this survey. However, if you have any related concerns, you can email the principal investigator at the email address provided below to ask for further advice. Your participation in this survey is voluntary and you are free to end your participation at any time. Completion and return of the questionnaire implies your consent to participate. Your participation is of utmost importance to my PhD study and the results of this survey will help inform policy guidelines for better development of wind energy projects.

The information you provide will be strictly confidential. Your name and address are not on the returned questionnaire, and they will not be used in any process of the research or reporting. For the analysis, we need to be able to work out the physical environment around your home. This is done through the code on your questionnaire (e.g. A9999), which locates your dwelling on the site map. The code on your questionnaire and your name are never linked directly. Your questionnaire return will remain anonymous. The survey has been approved by the Research Ethics Committee of the University of Sheffield.

I really appreciate your time to assist me in my research. This survey is funded entirely from my PhD research grant. But I am happy to offer three £50 cash prizes for you to win by completing this survey. You are also welcome to receive the results after November this year. If you are interested in joining the prize draw, and / or receiving the research results, please fill in your contact details on the separate sheet provided and enclose it in the questionnaire return. The sheet will be detached from the questionnaire when the return envelope is opened. Please keep this covering letter for your records.

If you have any queries or comments regarding this survey, please feel free to contact the principal investigator Ms Fei Qu by email: fei.qu@sheffield.ac.uk, or the investigator's supervisor Prof Aki Tsuchiya by email a.tsuchiya@sheffield.ac.uk.

Yours Sincerely,

Fei Qu
23 June 2014

Cover letter (Variant 2)

The University Of Sheffield.

Fei Qu (PhD student)
School of Architecture
University of Sheffield
Western Bank
S10 2TN, Sheffield
Contact: fei.qu@sheffield.ac.uk

Dear Sir/Madam,

I am a PhD student at the University of Sheffield and am writing to invite you to participate in a short questionnaire survey with a focus on well-being and the living environment. You are selected from thousands of residents in your area. I hope you are able to help my research by completing the enclosed questionnaire and returning it before 7th July 2014 using the pre-addressed envelope (there is no need to attach a postage stamp).

The questionnaire should not take longer than 15 minutes of your time to complete. It covers topics such as your health and well-being, your living environment, and your views on environmental issues. We do not expect there are any risks to you from participating in this survey. However, if you have any related concerns, you can email the principal investigator at the email address provided below to ask for further advice. Your participation in this survey is voluntary and you are free to end your participation at any time. Completion and return of the questionnaire implies your consent to participate. Your participation is of utmost importance to my PhD study.

The information you provide will be strictly confidential. Your name and address are not on the returned questionnaire, and they will not be used in any process of the research or reporting. For the analysis, we need to be able to work out the physical environment around your home. This is done through the code on your questionnaire (e.g. A9999), which locates your dwelling on the site map. The code on your questionnaire and your name are never linked directly. Your questionnaire return will remain anonymous. The survey has been approved by the Research Ethics Committee of the University of Sheffield.

I really appreciate your time to assist me in my research. This survey is funded entirely from my PhD research grant. But I am happy to offer three £50 cash prizes for you to win by completing this survey. You are also welcome to receive the results after November this year. If you are interested in joining the prize draw, and/or receiving the research results, please fill in your contact details on the separate sheet provided and enclose it in the questionnaire return. The sheet will be detached from the questionnaire when the return envelope is opened. Please keep this covering letter for your records.

If you have any queries or comments regarding this survey, please feel free to contact the principal investigator Ms Fei Qu by email: fei.qu@sheffield.ac.uk or the investigator's supervisor Prof Aki Tsuchiya by email a.tsuchiya@sheffield.ac.uk.

Yours Sincerely,

Fei Qu
23 June 2014

Contact sheet (for additional comments and prize draw, only showing Variant 1 here for example)

Main Questionnaire, WindNet Research Network, University of Sheffield.

** This separate sheet will be detached from the questionnaire when the return envelope is opened.*

If there is anything else you would like to tell us about living near wind turbines, or anything about this survey, please feel free to write them down in the following box and send it back with the questionnaire. You can also email us at fei.qu@sheffield.ac.uk

(Optional)

If you are interested in joining the prize draw, and/or receiving the research results, please compete the contact sheet below and enclose it in the questionnaire return. (*You can cut off the sheet if you don't want your comments to be associated with your contact details.)*

Contact Details

Name: ____________________

Postal address: ____________________

____

Email: ____________________

Phone number: ____________________

☐ Tick this box to enter the prize draw of £50

☐ Tick this box to receive the survey results by email

Appendix III. Sites, sample and respondents

Table 5A.1 Short listed wind farm sites

Wind farm site			**Mechanical Factors**			**Affecting factors of surrounding residential areas**				**Other notes**
ID	*Name*	*Year of operation*	*Turbine model*	*Power Per Turbine (MW)*	*No. Of Turbines*	*Description (urbanisation, residential/industrial, etc.)*	*Distance (meters) to residence*	*Density of residence*	*Other major noise sources*	*Reason for exclusion*
1	***Site A***	2014	Nordex N100	3.4	1	Suburban - near three high density residential areas	350	high	none	
2	***Site B***	2006	Enercon E70	2	2	Suburban - Inside factory site, community around	300	high	industrial noise	
3	***Site C***	2005	Vestas2 NM923	2.75	1	Suburban/urban - In the town of Lowestoft, at seaside	>350	high	none	
4	**Derby Sewage Treatment Works**	2014		2.5	2	Urban/industrial - inside industrial area, near motor way,	600	high	motor way	large noise from motor way
5	**Bradwell on Sea**	2013		2.05	10	Rural - very low density	1000-1500	very low	none	community size too small
6	**HMP Standford Hill**	2013		2.3	2	Rural - communities on north and south	>1500		none	far away from residents
7	**Port of Tilbury**	2013		2.3	4	Suburban/industrial - at sea side	>1500		industrial noise	completely industrial area, near river
8	**Greencroft Estate**	2012		2	2	Rural-suburban - on south of a community	>800	medium	none	small community size
9	**Africa Alive**	2011		2.05	2	Rural-suburban - on the west of a community	>1200	medium	none	rural area, wind turbine far away from nearby communities
10	**Lindhurst Wind Farm**	2010	Vestas V90	1.8	5	Suburban	>600	medium	none	small community size
11	**Dagenham**	2010	Enercon E66	1.8 2.3	2 1	Urban/industrial - Inside a industrial area, surrounded by communities	>700	high	industrial noise	in industrial area, near River Thames
12	**Toddleburn**	2010	Siemens SWT-1.3	2.3	12	Rural - on north-west side of a small community	100-600	very very low	none	low density of community

Table 5A.1 Short listed wind farm sites

Wind farm site			Mechanical Factors			Affecting factors of surrounding residential areas				Other notes
ID	*Name*	*Year of operation*	*Turbine model*	*Power Per Turbine (MW)*	*No. Of Turbines*	*Description (urbanisation, residential/industrial, etc.)*	*Distance (meters) to residence*	*Density of residence*	*Other major noise sources*	*Reason for exclusion*
13	**Wem Ddu**	2010	Enercon E70	2.3	4	Rural - community linearly distributed on both sides	100-500	low	none	complex terrain, low density of community
14	**Broom Hill**	2009	REpower MM82s	2	4	Rural - on the northeast of Tow Law, on both side of B6301	>1000	very very low	none	rural area, community size too small
15	**Trimdon Grange**	2008	Nordex N60	1.3	4	Rural - on the northwest of Trimdon Grange village	>1200	medium	none	far away from community, has been studied (reported TV signal deprived)
16	**Langley Park**	2008	REpower 2.0	2	4	Rural - a small town of Burnhope on northwest	1000-1500	very low	none	density too low
17	**The Hollies**	2008	Nordex N60	1.3	2	Rural - on the south of small village Burgh Le Marsh	>1500	low	none	density too low
18	**Bilbster**	2008	Nordex N60	1.3	3	Rural - on west side of a small community	200-800	low	none	in Highland, low density
19	**Bristol Port**	2007	Enercon E82	2	3	Suburban/industrial - at sea side, in the town of Avonmouth	>600	high	moterway & industrial	near motorway, only few residence nearby, others on the other side of the motorway
20	**Bin Mountain**	2007	GE 1.5s	1.5	6	Rural - Community on both sides, beside river	200-1000	low	none	In Northern Ireland, no detailed map source
21	**Wardlaw Wood (Darly)**	2006	Vestas V90	3	6	Rural - far away from residence	>1800	high	none	far away from community
22	**Glass Moor**	2006	REpower MM82	2	8	Rural - on the east of Pondersbridge	400	very very low	none	very low density of community
23	**North Pickenham**	2006	Vestas V90	1.8	8	Rural - community dispersedly around	>1500	low		far away from community, low density

Source: UKWED

Table 5A.2 Sample size in each noise strata of each site

		Variant 1					Variant 2					Total
		Group No.4 >45	Group No. 3 40-45	Group No.2 35-40	Group No.1 <35	Total	Group No.4 >45	Group No. 3 40-45	Group No.2 35-40	Group No. 1 <35	Total	
Site A	Target sample size	214	214	214	157	799	72	72	70	52	266	1065
	Available Individuals	109	1159	2028	3305	6601	109	1159	2028	3305	6601	13202
	Out for delivery	52	215	215	186	668	15	85	75	68	243	911
	Unreachable	2	3	12	5	22	0	6	10	9	25	47
	Delivered	50	212	203	181	646	15	79	65	59	218	864
Site B	Target sample size	214	214	214	157	799	72	72	70	52	266	1065
	Available Individuals	762	3191	3383	11643	18979	762	3191	3383	11643	18979	37958
	Out for delivery	310	225	140	195	870	100	100	50	55	305	1175
	Unreachable	17	14	18	0	49	4	7	10	0	21	70
	Delivered	293	211	122	195	821	96	93	40	55	284	1105
Site C	Target sample size	214	214	214	157	799	72	72	70	52	266	1065
	Available Individuals	304	724	2222	127	3377	304	724	2222	127	3377	6754
	Out for delivery	164	285	285	63	797	55	95	95	17	262	1059
	Unreachable	7	5	4	10	26	6	17	3	5	31	57
	Delivered	157	280	281	53	771	49	78	92	12	231	1002
	Target sample size	640	640	640	470	2390	215	215	210	155	795	3185
Total	Out for delivery	526	725	640	444	2335	170	280	220	140	810	3145
	Unreachable	26	22	34	15	97	10	30	23	14	77	174
	Delivered	500	703	606	429	2238	160	250	197	117	733	2971

Table 6A.1 Study sample, number of respondents, and response rate

Table 6A.1. Study sample, number of respondents, and response rate according to predicted 5-dB(A) sound level interval

		Variant 1					Variant 2					Total of two variants
		Sampling Group No.4	Sampling Group No.3	Sampling Group No.2	Sampling Group No.1	Total	Sampling Group No.4	Sampling Group No.3	Sampling Group No.2	Sampling Group No.1	Total	
Site A	Study sample	50	212	203	181	646	15	79	65	59	218	864
	No. of respondents	7	37	26	28	98	3	16	15	17	51	149
	Response rate	14.0%	17.5%	12.8%	15.5%	15.2%	20.0%	20.3%	23.1%	28.8%	23.4%[b]	17.2%[c]
Site B	Study sample	293	211	122	195	821	96	93	40	55	284	1105
	No. of respondents	43	19	11	13	86	5	12	10	2	29	115
	Response rate	14.7%	9.0%	9.0%	6.7%	10.5%	5.2%	12.9%	25.0%	3.6%	10.2%	10.4%
Site C	Study sample	157	280	281	53	771	49	78	92	12	231	1002
	No. of respondents	23	28	22	4	77	6	8	2	0	16	93
	Response rate	14.6%	10.0%	7.8%	7.5%	10.0%	12.2%	10.3%	2.2%	0.0%	6.9%	9.3%
Total of three sites	Study sample	500	703	606	429	2238	160	250	197	117	733	2971
	No. of respondents	73	84	59	45	261	14	36	27	19	96	357
	Response rate	14.6%	11.9%	9.7%	10.5%	11.7%	8.8%	14.4%	13.7%	16.2%	13.1%[a]	12.0%

a: The overall response rate of Variant 2 using door-drop delivery was 10.7% (study sample=682, No. of respondents=73).
b: The response rate of Variant 2 using door-drop delivery in Site A was 16.8% (study sample=167, No. of respondents=28).
c: The response rate in Site A using door-drop delivery was 15.5% (study sample=813, No. of respondents=126).

Appendix IV. Additional tables on questionnaire results

Table 6A.2. Reliability analysis on questions related to wind turbine noise annoyance

	Valid n	Missing	Corrected Item- Total Correlation	Cronbach's Alpha if item deleted
Q5 WTN Annoyance	252	9	0.572	0.882
Q9 WTN Annoyance overall	258	3	0.813	0.850
Q10 WTN annoyance outside	259	2	0.771	0.859
Q10 WTN annoyance inside	250	11	0.721	0.863
Q13 Annoyed when windy	246	15	0.801	0.851
Q13 Annoyed when inside with window closed	248	13	0.474	0.888
Q13 Annoyed when heavy traffic outside	246	15	0.591	0.879
Q13 Annoyed when at night	246	15	0.698	0.864

Cronbach's Alpha = 0.883. Valid *n*=220, excluded=41, Total 261.

Table 6A.3. Association between noticing wind turbine noise, sound pressure levels (SPLs), and covariates, expressed as odds ratio (OR) with 95% confidence intervals (CIs)

Model		**SPL (dBA)**		**Covariates of interest**		
No.	R^2	OR	(95%CI)		OR	(95%CI)
1	0.220	**1.21**	**(1.13-1.30)**			
				Variant and site factors:		
2	0.224	**1.22**	**(1.14-1.30)**	Questionnaire variant (Variant 2)	1.12	(0.56-2.25)
3	0.239	**1.18**	**(1.11-1.27)**	*Site (ref: Site C)*		
				- Site A	1.18	(0.47-2.96)
				- Site B	**2.23**	**(1.03-4.81)**
				Demographic and socioeconomic factors		
4	0.257	**1.24**	**(1.16-1.32)**	Age	**1.15**	**(1.03-1.28)**
				Age squared	**0.88**	**(0.79-0.97)**
5	0.224	**1.22**	**(1.14-1.30)**	Sex (female)	1.02	(0.56-1.88)
6	0.248	**1.22**	**(1.14-1.30)**	*Highest qualification (ref: O-level)*		
				- No qualification	0.60	(0.27-1.31)
				- A-level	0.65	(0.24-1.78)

Table 6A.3. Association between noticing wind turbine noise, sound pressure levels (SPLs), and covariates, expressed as odds ratio (OR) with 95% confidence intervals (CIs)

Model		SPL (dBA)		Covariates of interest		
No.	R^2	OR	(95%CI)		OR	(95%CI)
				- Higher education below degree	0.40	(0.13-1.25)
				- Degree level	**0.25**	**(0.07-0.83)**
				- Other professional/certification	0.80	(0.19-3.45)
7	0.201	**1.19**	**(1.11-1.27)**	Household income (low to high)	0.79	(0.54-1.14)
				Susceptible groups:		
8	0.222	**1.22**	**(1.14-1.30)**	Having long-standing illness	0.93	(0.50-1.73)
9	0.226	**1.22**	**(1.15-1.30)**	Retired	0.82	(0.44-1.53)
10	0.230	**1.22**	**(1.15-1.30)**	On maternity leave	2.27	(0.61-8.45)
				Situational factors:		
11	0.224	**1.22**	**(1.14-1.30)**	Owned (v.s. rent)	1.09	(0.58-2.05)
12	0.224	**1.22**	**(1.14-1.30)**	Moved in after wind turbine launched	0.89	(0.43-1.83)
				Attitudinal factors		
13	0.220	**1.21**	**(1.14-1.29)**	Sensitivity to noise (1-6)	1.01	(0.82-1.24)
14	0.251	**1.22**	**(1.15-1.31)**	Sustainability is low priority (1-6)	**0.72**	**(0.57-0.91)**
15	0.229	**1.21**	**(1.14-1.29)**	Environmental friendly (1-6)	0.85	(0.69-1.06)
				Attitude to WT (only in Variant1)		
16	0.200	**1.19**	**(1.11-1.28)**	Factor 1 (Positive to the utility)	0.53	(0.24-1.20)
17	0.190	**1.19**	**(1.11-1.28)**	Factor 2 (Positive to the appearance)	0.32	(0.07-1.42)
18	0.191	**1.19**	**(1.11-1.28)**	Factor 3 (Negative to the necessity)	1.34	(0.54-3.33)
19	0.197	**1.20**	**(1.12-1.28)**	Factor 4 (Negative to the efficiency)	0.51	(0.18-1.50)
20	0.235	**1.19**	**(1.11-1.28)**	Factor 5 (Negative to the environmental impact)	**2.86**	**(1.41-5.83)**
				Architectural and visual factors		
21	0.204	**1.20**	**(1.13-1.28)**	Number of bedrooms	0.98	(0.70-1.38)
22	0.277	**1.25**	**(1.16-1.34)**	*Housing type (ref: semi-detached)*		
				- Detached house	0.90	(0.35-2.28)
				- Mid-terraced house	0.76	(0.35-1.64)
				- End-terraced house	**0.13**	**(0.27-0.65)**
				- Flat	**0.29**	**(0.10-0.80)**
23	0.253	**1.24**	**(1.16-1.32)**	*Orientation (ref: rooms facing both sides)*		
				- All rooms facing front	0.23	(0.03-1.87)
				- All rooms facing back	0.51	(0.10-2.70)
				- Rooms facing three sides or more	2.51	(0.98-6.39)

Table 6A.3. Association between noticing wind turbine noise, sound pressure levels (SPLs), and covariates, expressed as odds ratio (OR) with 95% confidence intervals (CIs)

Model		SPL (dBA)		Covariates of interest		
No.	R^2	OR	(95%CI)		OR	(95%CI)
24	0.249	**1.15**	**(1.07-1.24)**	*Visibility of the WT (ref: can't see any) (only in Variant 1)*		
				- See WT from window	1.41	(0.44-4.49)
				- See WT from garden	1.20	(0.28-5.10)
				- See WT from both window & garden	**4.09**	**(1.35-12.43)**

Statistically significant correlations in boldface.

Table 6A.4. Association between annoyance with wind turbine noise, sound pressure levels (SPLs), and covariates, expressed as odds ratio (OR) with 95% confidence intervals (CIs)

Model		SPL (dBA)	Covariates of interest	
No.	R^2	OR (95%CI)		OR (95%CI)
1	0.134	**1.17 (1.09-1.25)**		
			Variant and site factors:	
2	0.137	**1.17 (1.09-1.25)**	Questionnaire variant (Variant 2)	1.11 (0.50-2.44)
3	0.146	**1.15 (1.06-1.24)**	*Site (ref: Site C)*	
			- Site A	1.21 (0.42-3.47)
			- Site B	1.91 (0.78-4.69)
			Demographic and socioeconomic factors	
4	0.213	**1.20 (1.11-1.29)**	Age	**1.27 (1.08-1.29)**
			Age squared	**0.79 (0.68-0.92)**
5	0.137	**1.17 (1.09-1.25)**	Sex (female)	0.96 (0.48-1.92)
6	0.185	**1.18 (1.10-1.26)**	*Highest qualification (ref: O-level)*	
			- No qualification	**0.26 (0.15-0.88)**
			- A-level	0.27 (0.07-1.02)
			- Higher education below degree	0.41 (0.12-1.40)
			- Degree level	**0.24 (0.06-0.90)**
			- Other professional/certification	1.05 (0.25-4.46)
7	0.139	**1.17 (1.09-1.27)**	Household income (low to high)	0.98 (0.66-1.44)
			Susceptible groups:	
8	0.157	**1.19 (1.11-1.27)**	Having long-standing illness	0.75 (0.36-1.56)
9	0.157	**1.19 (1.11-1.27)**	Retired	0.75 (0.36-1.56)
10	0.138	**1.17 (1.09-1.26)**	On maternity leave	1.37 (0.28-6.77)
			Situational factors:	
11	0.137	**1.17 (1.09-1.26)**	Owned (v.s. rent)	1.12 (0.54-2.33)
12	0.139	**1.17 (1.09-1.25)**	Moved in after wind turbine launched	1.27 (0.58-2.80)
			Attitudinal factors	
13	0.135	**1.17 (1.09-1.25)**	Sensitivity to noise (1-6)	1.05 (0.83-1.34)
14	0.141	**1.17 (1.09-1.25)**	Sustainability is low priority (1-6)	0.86 (0.66-1.12)
15	0.137	**1.17 (1.09-1.25)**	Environmental friendly	1.09 (0.85-1.38)
			Attitude to WT (only in Variant1)	
16	0.122	**1.14 (1.06-1.23)**	Factor 1 (Positive to the utility)	0.47 (0.19-1.13)
17	0.119	**1.14 (1.06-1.23)**	Factor 2 (Positive to the appearance)	0.37 (0.08-1.65)

Table 6A.4. Association between annoyance with wind turbine noise, sound pressure levels (SPLs), and covariates, expressed as odds ratio (OR) with 95% confidence intervals (CIs)

Model		**SPL (dBA)**	**Covariates of interest**	
No.	R^2	OR (95%CI)		OR (95%CI)
18	0.126	**1.14 (1.06-1.23)**	Factor 3 (Negative to the necessity)	2.73 (0.96-7.82)
19	0.103	**1.14 (1.06-1.23)**	Factor 4 (Negative to the efficiency)	1.03 (0.35-2.99)
20	0.167	**1.14 (1.06-1.23)**	Factor 5 (Negative to the environmental impact)	**3.44 (1.52-7.77)**
			Architectural and visual factors	
21	0.127	**1.16 (1.08-1.25)**	Number of bedrooms	0.99 (0.67-1.46)
22	0.203	**1.20 (1.11-1.29)**	*Housing type (ref: semi-detached)*	
			- Detached house	1.03 (0.37-2.88)
			- Mid-terraced house	0.71 (0.30-1.71)
			- End-terraced house	0.00 0.00
			- Flat	0.44 (0.15-1.33)
23	0.145	**1.17 (1.09-1.26)**	*Orientation (ref: rooms facing both sides)*	
			- All rooms facing front	0.43 (0.05-3.45)
			- All rooms facing back	1.01 (0.20-5.19)
			- Rooms facing three sides or more	1.60 (0.55-4.69)
24	0.156	**1.10 (1.01-1.20)**	*Visibility of the WT (ref: can't see any) (only in Variant 1)*	
			- See WT from window	2.08 (0.52-8.37)
			- See WT from garden	1.13 (0.17-7.46)
			- See WT from both window & garden	**4.40 (1.11-17.38)**

Statistically significant correlations in boldface.

Table 7A.1. Association between sleep and annoyance of other environmental noise tested with logistic regression controlling for WTN and other covariates.

	Annoyance with neighbourhood noise (among other nuisances) (1-5)		Annoyance with traffic noise (among other nuisances) (1-5)	
Dependent variable:	Exp(B)	95%CI	Exp(B)	95%CI
a) sleep not disturbed	**0.66****	**(0.45-0.97)**	0.83	(0.58-1.20)
b) hard to fall asleep	1.10	(0.86-1.40)	1.13	(0.86-1.47)
c) sleep less deeply	**1.29****	**(1.04–1.60)**	1.01	(0.80-1.28)
d) lie awake for a while	**1.34*****	**(1.08-1.66)**	1.20	(0.96-1.51)
e) take sleeping pills to fall asleep	1.27	(0.85-1.89)	**1.41***	**(0.95-2.11)**

Adjusted for maximum SPLs, age, sex, longstanding illness, noise sensitivity, site and questionnaire variants. N=329-330

*** P<0.01 level; ** p<0.05 level; *p<0.1. Statistically significant level below 0.1 in boldface.

Table 7A.2. OLS regressions showing the association between general health, WTN, and covariates

Model (sample)	Variables	*p*-value	B
1	***General Health*** *(1 excellent – 5 poor) (n=136, R^2=0.084)*		
(Variant 1+2,	Maximum SPL	0.179	-0.121
Had LSID)	Age	0.768	0.147
	Age square	0.750	-0.158
	Female	0.159	0.129

	Household income (ref: < £20,000)		
	£20,000 - £29,999	0.665	0.039
	£30,000 - £49,999	0.015	**-0.224**
	more than £50,000	0.886	-0.013
	I don't know / missing	0.204	-0.262
	Variant 2	0.854	0.016
2	***General Health*** *(1 excellent – 5 poor (n=209, R^2=0.137)*		
(Variant 1+2,	Maximum SPL	0.395	0.058
Had ***no*** LSID)	Age	0.215	0.491
	Age square	0.243	-0.472
	Female	0.004	**-0.196**
	Household income (ref: < £20,000)		
	£20,000 - £29,999	0.331	-0.077
	£30,000 - £49,999	0.001	**-0.269**
	more than £50,000	0.012	**-0.462**
	I don't know / missing	0.925	0.015
	Variant 2	0.166	-0.167

Statistically significant correlations in boldface.

Table 7A.3. OLS regressions showing the association between happiness, WTN, and covariates.

Model (sample)	Variables	*p*-value	B
1	***Happiness*** *(0 very unhappy - 10 very happy) (n=336, R2=0.185)*		
(Variant 1+2)	SPL(maximum)	0.408	-0.015
	Age	0.004	**-0.103**
	Age square	0.002	**0.107**
	Female	0.621	0.113
	Household income (ref: < £20,000)		
	£20,000 - £29,999	0.401	0.305
	£30,000 - £49,999	0.904	-0.044
	more than £50,000	0.911	-0.055
	I don't know / missing	0.188	0.430
	Employment (ref: in employment)		
	unemployed	0.056	-1.091
	retired	0.477	-0.256
	other	0.251	-0.463
	Marital status (ref: married / in civil partnership / cohabiting)		
	single	0.000	**-1.433**
	separated / divorced	0.405	-0.331
	widowed	0.016	**-1.002**
	Longstanding illness (no/yes)	0.000	**-1.008**
	Variant 2	0.808	-0.062

Statistically significant correlations in boldface.

Table 7A.4. OLS regressions showing the association between life satisfaction, WTN, and covariates.

Model (sample)	Variables	*p*-value	B
1	***Life satisfaction*** *(1 not satisfied at all - 7 completely satisfied) (n=342, R2=0.215)*		
(Variant 1+2)	SPL (maximum)	0.854	-0.002
	Age	0.031	**-0.049**
	Age square	0.060	0.041

Table 7A.4. OLS regressions showing the association between life satisfaction, WTN, and covariates.

Model (sample)	Variables	*p*-value	B
	Female	0.185	0.191
	Household income (ref: < £20,000)		
	£20,000 - £29,999	0.405	0.190
	£30,000 - £49,999	0.344	0.216
	more than £50,000	0.707	**0.118**
	I don't know / missing	0.994	0.002
	Employment (ref: in employment)		
	unemployed	0.058	-0.704
	retired	0.047	**0.450**
	other	0.369	-0.230
	Marital status (ref: married / in civil partnership / cohabiting)		
	single	0.000	**-0.913**
	separated / divorced	0.077	-0.436
	widowed	0.049	**-0.515**
	Longstanding illness (no/yes)	0.000	-0.771
	Variant 2	0.457	0.119

Statistically significant associations in boldface.

Table 7A.5. Regression modelling self-reported general health using the dataset of Understanding Society wave 6.

Variables	*p*-value	B	Std. Error
(Constant)	0.000	1.385	0.037
Age	0.000	0.018	0.002
$Age^2/100$	0.000	-0.011	0.002
Female	0.000	0.046	0.009
Income			
Upper half	0.001	-0.038	0.011
I don't know / missing	0.000	0.103	0.019
Employment (ref: in employment)			
Unemployed	0.000	0.664	0.019
Retired	0.000	0.102	0.019
Other	0.000	0.174	0.016
Highest qualification (ref: degree level)			
No qualification	0.000	0.370	0.018
O-level or equivalent	0.000	0.175	0.014
A-level or equivalent	0.000	0.152	0.014
Higher education below degree	0.000	0.087	0.016
Other	0.000	0.211	0.019
Marital status (ref: married / in civil partnership / cohabiting)			
Single	0.000	-0.146	0.022
Separated / Divorced	0.001	0.160	0.048
Widowed	0.000	0.334	0.084
Longstanding illness (no/yes)	0.000	0.994	0.011

Dependent variable: General health (1 Excellent – 5 Poor), Sample: Understanding Society wave-6 (2014), n=39844, R^2=0.322

Table 7A.6. Descriptive statistics of the observed and predicted level of general health

Respondents [n(%valid)]	Observed in Understanding Society	Predicted for current study	Predicted for US (2014)	Observed in current study

Mean		2.52	2.72	2.54	2.92
In general, would you say your health is…	1 (Excellent)	7379 (18.5%)	1 (0.3%)	7 (0.0%)	17 (4.8%)
	2 (Very good)	14003 (35.1%)	171 (47.6%)	27533 (60.9%)	108 (30.4%)
	3 (Good)	10969 (27.5%)	118 (32.9%)	13302 (29.4%)	141 (39.7%)
	4 (Fair)	5319 (13.3%)	69 (19.2%)	4358 (9.6%)	63 (17.7%)
	5 (Poor)	2174 (5.5%)	0	2 (0.0%)	26 (7.3%)
	Total	39844 (100%)	359 (100%)	45202 (100%)	355 (100%)
Missing		5446	0	88	4

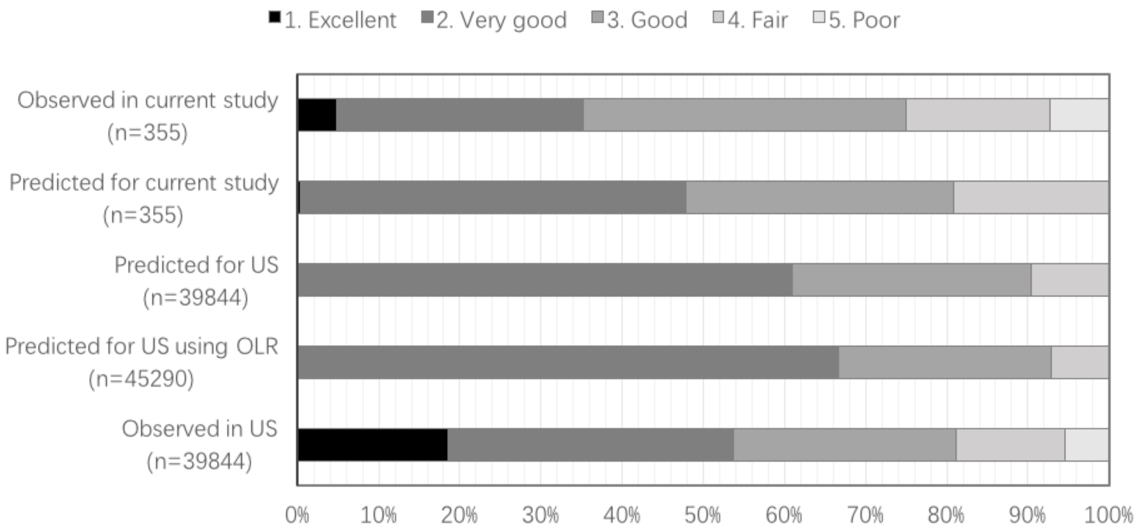


Figure 7A.1. Cluster stack bar charts showing the percentage of respondents in each score of general health with ordered logistic regression (OLR) used for within-sample prediction.

The 4th bar chart in the figure illustrates that ordered logistic predictions still underestimated the extreme values of general health. The results using US and OLR are not qualitatively different.

Table 7A.7. Regression modelling self-reported life satisfaction using the dataset of Understanding Society wave 6.

Variables	*p*-value	B	Std. Error
(Constant)	0.000	5.930	0.057
Age	0.000	-0.026	0.002
$Age^2/100$	0.000	0.029	0.003
Female	0.032	0.033	0.015

Income			
Upper half	0.000	0.077	0.017
Employment (ref: in employment)			
Unemployed	0.000	-0.833	0.031
Retired	0.000	0.280	0.030
Other	0.978	-0.001	0.027
Highest qualification (ref: degree level)			
No qualification	0.000	-0.247	0.029
O-level or equivalent	0.000	-0.139	0.022
A-level or equivalent	0.000	-0.135	0.022
Higher education below degree	0.003	-0.078	0.026
Other	0.000	-0.219	0.030
Longstanding illness (no/yes)	0.000	-0.443	0.017

Dependent variable: Satisfaction of your life overall & satisfaction of health (1 Not satisfied at all – 7 Completely Satisfied), Sample: Understanding Society wave-6 (2014); n=35807, R^2=0.074.

Table 7A.8. Descriptive statistics of the observed and predicted level of life satisfaction

Respondents [n(%valid)]		Observed	Predicted for current study	Predicted for US (2014)	In Understanding Society wave 6 (2014)
Mean		5.13	5.23	5.24	5.24
How satisfied you are with your life overall	1 (Not satisfied at all)	10 (2.8%)	0	0	691 (2.0%)
	2	10 (2.8%)	0	0	1916 (5.4%)
	3	20 (5.6%)	0	0	2636 (7.4%)
	4	56 (15.8%)	16 (4.5%)	2831 (6.3)	3171 (8.9%)
	5	97 (27.3%)	246 (68.5%)	34905 (78.1)	6291 (17.6%)
	6	112 (31.5%)	97 (27.0%)	6974 (15.6)	16808 (47.0%)
	7 (Completely satisfied)	50 (14.1%)	0	0	4294 (12.0%)
	Total	355	359	44710	35807
Missing		4	0	580	9483

Table 7A.9. Regression modelling self-reported happiness levels using the dataset of HSE 2011 and 2010.

Variables	*p*-value	B	Std.Error
***Happiness in HSE 2011** (n=6889, R^2=0.081)*			
(Constant)	0.000	9.236	0.196
Age	0.000	-0.057	0.008
$Age^2/100$	0.000	0.061	0.008
Female	0.000	0.171	0.043
Income (ref: < £20,000)			
£20,000 - £29,999	0.271	0.081	0.074
£30,000 - £49,999	0.094	0.103	0.061
more than £50,000	0.000	0.319	0.066

I don't know / missing	0.098	-0.134	0.081
Economic status (ref: in employment)			
Unemployed	0.000	-0.375	0.106
Retired	0.047	0.162	0.081
Other	0.000	0.502	0.068
Highest qualification (ref: degree level)			
No qualification	0.073	0.129	0.072
O-level or equivalent	0.091	0.108	0.064
A-level or equivalent	0.169	0.096	0.070
Higher education below degree	0.034	0.160	0.076
Other	0.521	0.062	0.097
Marital status (ref: married / in civil partnership / cohabiting)			
Single	0.000	-0.516	0.068
Separated / Divorced	0.000	-0.574	0.074
Widowed	0.000	-0.653	0.094
Longstanding illness (no/yes)	0.000	-0.629	0.046

Dependent variable: Happiness (0 Very unhappy – 10 Very happy), Sample: Health Survey for England 2010, 2011.

Table 7A.10. Descriptive statistics of the observed and predicted level of happiness

Respondents [n(%valid)]		Observed (in this survey)	Predicted for current study	Predicted for HSE 2011	Observed In HSE 2011
Mean		7.25	7.89	7.85	7.85
How happy would you say you are?	0 (very unhappy)	2 (0.6%)	0	0	37 (0.5%)
	1	4 (1.1%)	0	0	16 (0.2%)
	2	11 (3.2%)	0	0	59 (0.8%)
	3	9 (2.6%)	0	0	83 (1.2%)
	4	10 (2.9%)	0	0	131 (1.8%)
	5	34 (9.7%)	0	0	477 (6.7%)
	6	21 (6.0%)	7 (1.9%)	120 (1.5%)	483 (6.8%)
	7	72 (20.6%)	74 (20.6%)	1661 (20.4%)	969 (13.6%)
	8	89 (25.5%)	237 (66.0%)	5684 (69.7%)	2189 (30.7%)
	9	46 (13.2%)	41 (11.4)	692 (8.5%)	1345 (18.9%)
	10 (very happy)	51 (14.6%)	0	0	1331 (18.7%)
	Total	349 (100%)	359 (100%)	8157 (100%)	7120 (100%)
Missing		10	0	2460	3497

Table 8A.1. Binary logistic regressions modelling noticeability (models 1 & 2) of and annoyance (models 3 & 4) with wind turbine noise (WTN) for two sub-samples of different night-time road traffic noise (RTN) levels (Ln>41 or ≤41dBA) using WTN levels and RTN levels controlling for sites and questionnaire variants.

Model (sample)	Variables	B	*p*-value	Odds Ratio
1	***Notice WTN*** *[n=204, R2=0.301, p(H-L)=0.660]*			
(Group 1:	Ld (Day-time traffic noise)	0.069	0.470	1.071
Ln≤41dBA)	Maximum SPL (Wind turbine noise)	0.209	**0.000**	1.233
	Site A	-0.826	0.213	0.438
	Site B	-0.230	0.695	0.795
	Variant 2	0.615	0.208	1.849
2	***Notice WTN*** *[n=204, R2=0.300, p(H-L)=0.946]*			
(Group 1:	Ln (Night-time traffic noise)	0.060	0.528	1.062
Ln≤41dBA)	Maximum SPL (Wind turbine noise)	0.209	**0.000**	1.233

Table 8A.1. Binary logistic regressions modelling noticeability (models 1 & 2) of and annoyance (models 3 & 4) with wind turbine noise (WTN) for two sub-samples of different night-time road traffic noise (RTN) levels (Ln>41 or ≤41dBA) using WTN levels and RTN levels controlling for sites and questionnaire variants.

Model (sample)	Variables	B	*p*-value	Odds Ratio
	Site A	-0.766	0.238	0.465
	Site B	-0.137	0.818	0.872
	Variant 2	0.619	0.205	1.858
3	***Annoyed by WTN*** *[n=204, R2=0.194, p(H-L)=0.917]*			
(Group 1:	Ld (Day-time traffic noise)	-0.109	0.312	0.897
Ln≤41dBA)	Maximum SPL (Wind turbine noise)	0.200	**0.001**	1.221
	Site A	-0.500	0.508	0.606
	Site B	-0.451	0.492	0.637
	Variant 2	0.406	0.470	1.501
4	***Annoyed by WTN*** *[n=204, R2=0.192, p(H-L)=0.300]*			
(Group 1:	Ln (Night-time traffic noise)	-0.100	0.349	0.905
Ln≤41dBA)	Maximum SPL (Wind turbine noise)	0.200	**0.000**	1.222
	Site A	-0.596	0.420	0.551
	Site B	-0.605	0.371	0.546
	Variant 2	0.407	0.469	1.502

Appendix V. Publications of the candidate

The following is a list of journal articles and conference proceedings written by the candidate during the course of the research in this thesis.

Journal articles:

Qu, F., and Kang, J. (2017) Effects of built environment morphology on wind turbine noise exposure at building façades. *Renewable Energy*, 107, 629-638.

Jones, C.R., Lange, E., Kang, J., Tsuchiya, A., Howell, R., Crisp, R.J., Steel, J., Meade, K., **Qu, F.**, Sturge, D., Bray, A. (2014) "WindNet: Improving the impact assessment of wind power projects", *AIMS Energy,* Volume 2, Issue 4, 461-484.

Conference papers:

Qu, F., Tsuchiya, A. and Kang, J. (2017) Impact of noise from suburban wind turbines on human well-being. *Proceedings of 7th International Conference on Wind Turbine Noise*, Rotterdam, the Netherlands.

Qu, F., Kang, J. and Tsuchiya, A. (2015) Effects of built environment morphology in residential areas on resisting wind turbine noise on building façades. *Proceedings of 6th International Meeting on Wind Turbine Noise*, Glasgow, UK.

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

Qu, F. and Kang, J. (2013) Modelling spatial distribution of wind turbine noise in sub-urban environments. *Proceedings of the AIA-DAGA 2013 Annual Conference on Acoustics*, Merano, Italy.