Evaluation of Noise Levels of Micro-Wind Turbines Using a Randomised Experiment

by

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Abstract

One of the biggest environmental concerns of a wind turbine is the wind turbine noise (Prospathopoulos and Voutsinas, 2007). This study assesses the noise impacts of wind turbines on the environment by comparing the micro-wind turbine noise to traditional accepted surrounding sounds. The collection of the sound level data was done by using a randomised experiment. The sound level data was then fitted to a General Linear Model to determine the relationship between the sound levels generated at a given site to the time of day, wind speed, wind direction and distance from the sound source.

An additional study was conducted to determine the relationship between wind speed and the sound levels of wind turbines. The distribution of frequency components of wind turbine sound was also determined.

Keywords: *Micro-wind turbine noise, randomised experiment, General Linear Model, wind speed, frequency.*

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Contents

List of Figures

List of Tables

Chapter 1

Introduction

Energy is an important aspect of social and economic development in South Africa. The demand for electricity has increased over the years and the challenge is to promote renewable energy in South Africa (Winkler, 2005).

Eskom, the predominant supplier of electricity in South Africa, has implemented a number of price increases over the past few years causing a concern in the country. In light of the current electricity shortage there is a need to consider alternative energy sources. Solar, water, wind and nuclear power are generating interest as future sustainable sources of power.

One of the most developed and cost effective renewable energy source has been shown to be wind energy (Prospathopoulos and Voutsinas, 2007). Wind turbines are one of the cleanest energy production machines (Islam, 2010). Tommaso, Miceli and Rando (2010) refer to a study conducted by Greenpeace where it was estimated that in the year 2020, 12% of the world's energy will be covered by means of wind energy.

One of the biggest environmental concerns of a wind turbine is the wind turbine noise (Prospathopoulos and Voutsinas, 2007). When there is excessive exposure to noise it has been shown to cause health problems. The most common health problems are hearing loss, headaches, and fatigue (caused by sleep disturbance) (Alberts, 2006). Extremely high noise exposure may even cause constricted arteries and a weakened immune system (Alberts, 2006). This study assesses the noise impacts of wind turbines on the environment by comparing the wind turbine noise to traditionally accepted surrounding sounds.

Sound is a complex phenomenon with temporal and psychological dimensions (Howe, Gastmeier and McCabe, 2007). Noise is defined as unwanted sound (Alberts, 2006). The Nelson Mandela Metropolitan Municipality (NMMM) uses the 7 dBA rule when assessing a sound source. This rule states that when a sound source is louder than 7 dBA of the ambient sound of that environment the sound source is defined as being noisy. This study uses the 7 dBA rule to identify whether a wind turbine is too noisy for a certain environment.

Pedersen and Waye (2007) claim that noise associated with wind turbines may just be a perception. Factors that add to noise perception are visibility, economic benefit from wind turbine farms and place of residence. Pedersen and Waye (2007) showed that respondents of a survey indicate that there is an increase in the irritability of noise when they can see the wind turbines. Furthermore Pedersen and Waye (2007) showed that one in two respondents were positive towards wind turbines, but only one in every five were positive towards their impact on the landscape scenery. Bolin, Nilsson and Khan (2010) investigated whether natural sounds were able to mask wind turbine noise. Their results showed that there was a reduction in the perceived loudness of wind turbines due to the masking of natural sounds. Wind turbine farms are normally placed in rural areas with low ambient noise. This may contribute to the perception that wind turbines are noisy.

Most studies conducted internationally on the noise emission of wind turbines have been survey studies. These types of studies deal with the perception of noise and focus on large scale wind turbine farms near residential areas. Since there are no operational wind turbine farms near residential areas in South Africa a survey study was not possible. However, micro-wind turbines are a growing area of interest in the Port Elizabeth (PE) region. There has been an increase in the installation of micro-wind turbines and solar panels in households. As such, this study evaluates actual noise measurements from operational micro-wind turbines in PE.

This study was partitioned into two parts. The first part involved collecting noise data from several sites (including a horizontal axis micro-wind turbine and a vertical axis micro-wind turbine) in the Summerstrand region of PE. The study assesses the sound levels of the wind turbines by comparing the mean sound pressure levels (SPL) of the micro-wind turbines to traditionally accepted surrounding sounds.

The second part of the study involved evaluating the noise emission of several micro-wind turbine systems in the Eastern Cape region. Sound measurements were taken over time to determine the average acoustic power of the wind turbine. Noise readings were recorded concurrently with wind speed and a frequency analysis was conducted in order to determine the dominant frequency components of the wind turbine.

The study had the following objectives:

- To propose a method for comparison of wind turbine noise to traditional surrounding sounds.
- To identify the factors influencing the sound levels of micro-wind turbines by comparing the sound levels at different sites.
- To determine whether wind turbines are noisy by looking at the following:

    - Comparing wind turbine sound to traditionally accepted surrounding sounds.
    - Using the NMMM 7 dBA rule to identify whether a sound source is noisy.
- To evaluate the frequency components of the wind turbines for the Nelson Mandela Metropolitan University (NMMU) Centre of Energy Research.
- To evaluate the influence of the wind speed on the noise levels of the two micro-wind turbines.

Chapter 1 provides an introduction to the research and presents the basic outline for the project. Chapter 2 provides a literature review including the theory of sound, wind turbine noise and the theoretical background of experimental design. Chapter 3 discusses the methodology of the study and details of the experimental setups for both experiments. Chapter 4 gives the results of the randomised experiment and Chapter 5 discusses results for the evaluation of the different micro-wind turbines. Chapter 6 discusses the results obtained, and gives an insight into any future research opportunities in the field.

Chapter 2

Literature Review

Chapter 2 gives a summary of the theory needed for the analysis of wind turbine sound. It provides a brief summary of wind, wind turbines, focussing on micro-wind turbines. Chapter 2 gives the theory of sound, noise, noise perception and characteristics of the sounds of wind turbines. Previous studies done internationally are discussed and a motivation for the study is provided. This chapter also provides insight into the statistical theory behind experimental design.

2.1 Wind

Wind is caused by pressure fluctuations across the earth’s surface due to uneven heating of the earth by solar radiation. Wind is a form of solar energy. The mechanism of the wind motion is controlled by four main forces, pressure forces, coriolis forces (caused by the rotation of the earth), inertial forces (due to the large-scale circular motion) and frictional forces (vegetation and water) at the earth’s surface (Manwell, McGowan and Rogers, 2007).

Wind speed ranges in velocity from a gentle breeze to gale force. Wind is referred to as a horizontal air motion and is seldom steady as it fluctuates in both speed and direction. Changes in direction of wind are due to short-periods of acceleration and deceleration of wind speeds (Tyson and Preston-Whyte, 1988). Turbulence is a response to rapid accelerations in wind speed. Acceleration of air is the rate of change of wind speed with respect to time. Turbulence is generated by two main causes: friction at the earth’s surface and thermal effects. Steady wind motion is defined when these sudden accelerations are not present.

Horizontal variations in temperature gradients affect the variation of wind speed with respect to height. The wind profile states that wind speed increases as the height increases (Tyson and Preston-Whyte, 1988).

The term wind power is used to describe the process in which kinetic energy of wind is converted to mechanical energy. In a wind turbine this mechanical energy is converted to electricity by a generator (Tyson and Preston-Whyte, 1988).

2.2 Wind turbines

The first wind powered machine (windmill) recorded in history was in 900AD. This machine was built by the Persians and was used for tasks such as water pumping, grinding grain, sawing wood and powering tools. These machines were unable to withstand high wind speeds and were inherently inefficient (Burton, Sharpe, Jenkins and Bossanyi, 2008). After the industrial revolution, most European countries lost interest in using wind as an energy resource. Coal and other fossil fuels had many more advantages which wind did not possess (Manwell et al, 2007).

The re-emergence of wind energy began in 1960 after scientists became aware of the detrimental effects of burning fossil fuels. When the idea for using wind for electrical generation was proposed, a substantial amount of money was invested into development and research. During the years of 1891 to 1918, more than 100 turbine-generators ranging in power output from 20-35 kW were built in Denmark. The largest wind turbine in the 1930's had a diameter of 53.3 m with a power rating of 1.25 MW (Burton et al, 2008). Over the last 25 years large scale commercial wind turbines have been developed ranging from 50 kW to 5 MW.

Figure 2.1 illustrates the sizes of the current commercially available wind turbines (Manwell et al, 2007).

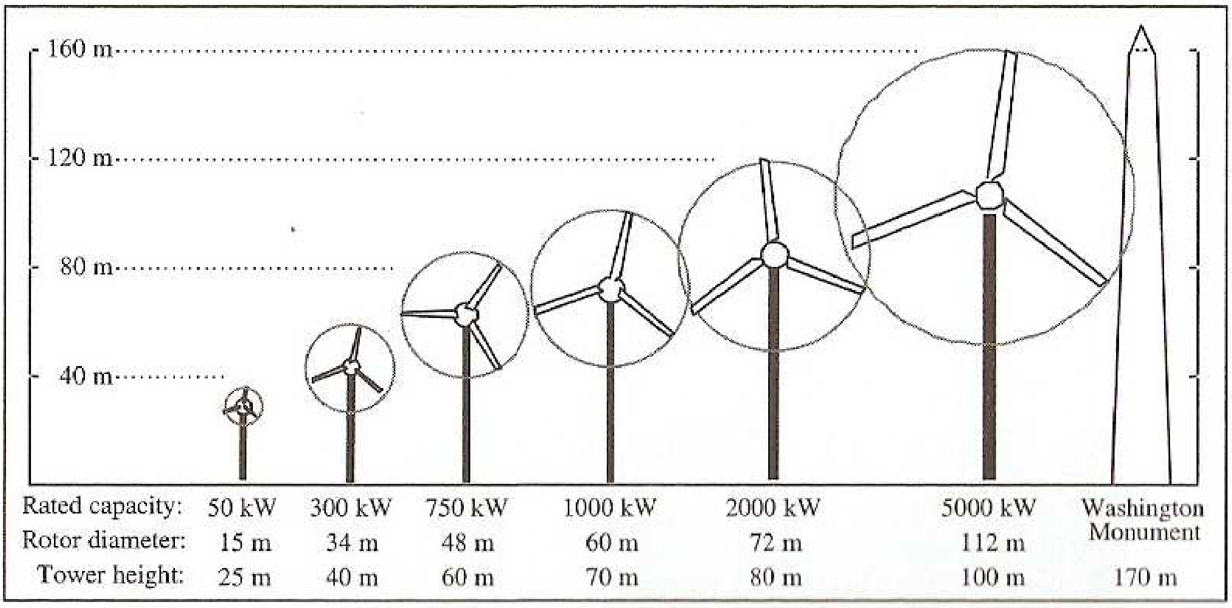


Figure 2.1: Representative size, height, and diameter of wind turbines (Manwell et al, 2007).

In the last few years wind turbines have improved tremendously in design and power generation. This study focuses on micro-wind turbine applications for the vertical axis and horizontal axis micro-wind turbines.

2.2.1 Micro-wind turbines

Individual small-scaled wind turbines are generally used for off grid applications in South Africa and are very different to large scale wind farms.

Micro-wind turbines are predominantly used for household applications in South Africa. Often the small scale wind turbines are used in conjunction with photovoltaic (PV) modules to form a hybrid system. This study focuses on these small scale wind turbines. The reason for this study is that these wind turbines are often used for household applications and can potentially cause disturbances to residences. If the turbines are found to be noisy this could adversely influence their use in residential areas.

Vertical axis micro-wind turbines are seldom used on large scale applications due to their low power efficiency. Shown in Figure 2.2 is a vertical axis micro-wind turbine.

Figure 2.2: Vertical axis micro-wind turbine.

Vertical axis micro-wind turbines represent a valid alternative to horizontal axis micro-wind turbines particularly for household applications. According to Tommaso et al (2010) the advantages of using vertical axis micro-wind turbines are:

- Continuous power generation in both low and high wind intensity conditions.

- Functions well in turbulent conditions.
- Simple design which allows for easy access and maintenance.
- No yawing system.
- Allows for less environmental impacts on its surroundings.

The disadvantages of the vertical axis micro-wind turbines are that they have a low tip-speed ratio (tip-speed ratio is the ratio between the rotational speed of the tip of a blade and the actual velocity of the wind) and as a result low efficiency, the self start ability of the vertical blades is low and the power generated cannot be controlled by pitching the rotor blades (Islam, 2010).

A traditional horizontal axis micro-wind turbine is designed with a long tail, which houses the generator, and a number of aerodynamic blades. The three bladed horizontal wind turbines are the most common due to their aerodynamic efficiency. Other factors such as component cost, system reliability and aesthetics influence the design of a horizontal axis micro-wind turbine. The tail of the horizontal axis micro-wind turbine is designed to work as a rudder to the turbine, which means it directs the blades of the turbine to face the oncoming wind. The tail of the turbine may have many shapes, sizes and designs. Shown in Figure 2.3 is a horizontal axis micro-wind turbine.

Figure 2.3: Horizontal axis micro-wind turbine.

The advantage of using a horizontal axis micro-wind turbine is that the efficiency compared to a vertical axis wind turbine is more.

2.3 Sound fundamentals

2.3.1 Sound

In order to understand sound propagation it is important to identify the nature of sound. Sound can be defined as rapid fluctuations of air pressure. These pressure fluctuations are repeating cycles of compressed and expanding air. Sound is a travelling pressure wave which is characterised by its amplitude, wavelength (λ) and frequency (f).

The sound wave is an example of a longitudinal wave. As a wave travels through a medium, the elements of the medium vibrate which produces a change in the density and pressure of the medium (Serway and Jewett, 2004). These pressure fluctuations produce sensations in the human ear which are then registered as a sound. These pressure waves might be generated in several ways, for example the vibration of vocal chords or the membrane of a loud speaker (Szasz and Fuchs, 2008).

The speed of sound is a function of the medium through which it travels. Sound waves travel through air at the speed of 340 m/s and through water at the speed of 1500 m/s (Serway and Jewett, 2004).

The human ear is a sensitive detector of sound between 20 Hz to 20 kHz. The function of the ear is to efficiently transform the vibration energy of waves into electrical signals which are carried to the brain via the nerves.

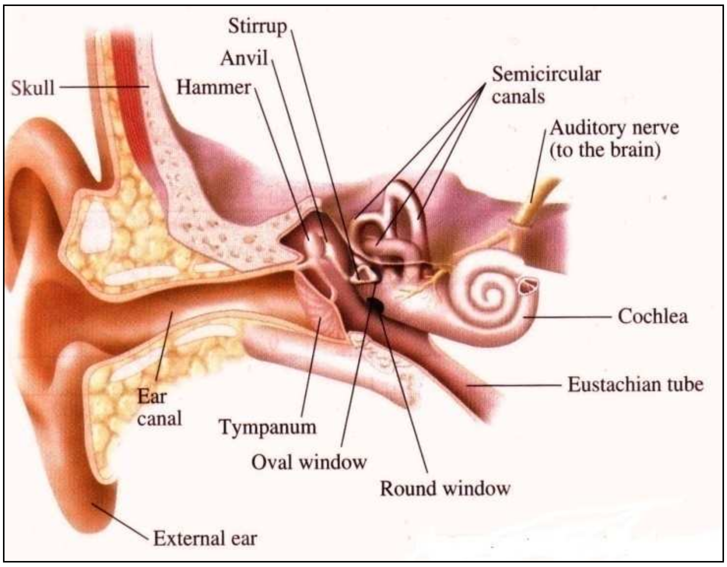


Figure 2.4: The human ear (Giancoli, 1980).

Figure 2.4 is a diagram of the human ear. The ear is conventionally divided into three parts: outer ear, middle ear and inner ear. The function of the outer ear is to channel sound waves from the outside down the ear canal to the eardrum (tympanum). The eardrum then vibrates in response to the impinging sound waves. The middle ear consists of three small bones, hammer, anvil and stirrup. These three bones are responsible for transferring vibrations of the eardrum to the inner ear at the oval window. The inner ear consist of semicircular canals, these canals are responsible for the transformation of vibrational energy of the sound waves into electrical energy. These electrical impulses are then sent to the brain (Giancoli, 1980).

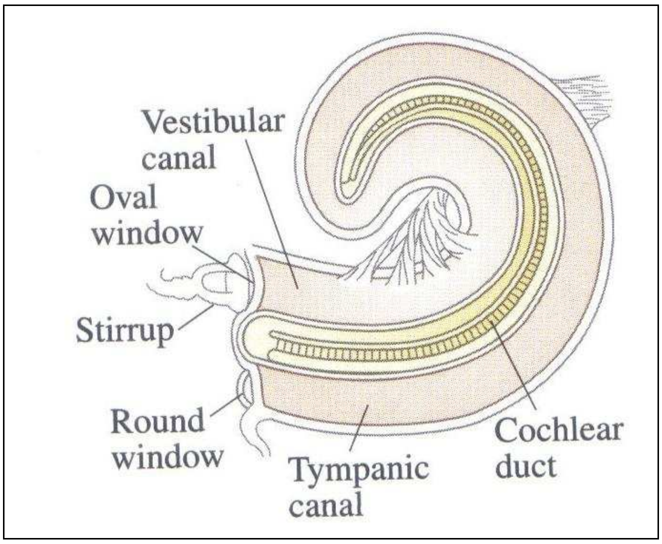


Figure 2.5: The cochlea (Giancoli, 1980).

Figure 2.5 is a diagrammatic representation of the cochlea. The cochlea is liquid filled. The sound vibration travels from the oval window down the vestibular canal and back up the tympanic canal because of the viscosity of the liquid in the cochlea. Remaining energy from this interaction is dissipated at the round window at the end of the tympanic canal. Between these two canals there is a third canal known as the cochlear duct. On the basilar membrane, the membrane separating the cochlear duct from the tympanic canal is the Corti which contains 30 000 nerve endings. As the pressure passes the tympanic canal, it causes ripples in the basilar member and the attached Corti. This energy is transformed into electrical pulses and sent to the brain by the auditory nerves. The thicker, less taut, basicular membrane will be more sensitive to low frequency sounds. A tighter, thinner membrane will be more sensitive to higher frequencies (Giancoli, 1980).

There are two aspects of sound that are evident to a human listener, “loudness” and “pitch”. Loudness is related to the energy of a sound wave. Pitch refers to whether the frequency of the sound is high (like the sound of a violin) or low (like the sound of a bass drum). Pitch is a perceptual attribute and plays a role in the organisation, segregation and identification of a sound (Thorne, 2007). The physical quantity that determines pitch is frequency and is defined as the number of oscillations per unit time. Acoustical frequency is expressed in Hertz (Hz). Hertz is a measure of one wave cycle per second.

Pure tones are tones that consist of a single frequency. These types of tones are rarely found. Sounds heard on a daily basis are often not just a single frequency (Szasz and Fuchs, 2008). The human ear responds to frequencies in the range of about 20 - 20 000 Hz (Rogers, Manwell and Wright, 2006). The notion of frequency is essential for acoustic evaluations. Different sounds have different combinations of frequencies and amplitudes giving them different properties. Depending on these properties, a certain type of sound will be produced.

Sound waves can be divided into four categories according to their frequencies. These categories are audible waves, infrasonic waves, low frequency waves and ultrasonic waves. Audible waves are waves that lie in the range of human sensitivity. The frequency range of human hearing is 20 - 20 000 Hz. Infrasonic waves are waves that are below 20 Hz. Infrasonic waves are present in the environment and other sources such as ambient air turbulence, ventilation units, waves on a seashore, traffic, aircraft and other machinery (Rogers et al, 2006). Low frequency sounds are categorised as low frequency pressure vibrations. This range is heard at the bottom of human perception, 10 – 200 Hz. Ultrasonic waves refer to waves with frequencies that are above the audible frequency range (Serway and Jewett, 2004).

The frequency spectrum of acoustic pressure has to be determined in order to characterise sound. There are three types of commonly used spectra. These include the narrowband, the 1/3 octave band and the 1/1 octave band. The band, in this case, refers to a given frequency interval over which the amplitudes are averaged. For an octave band the upper limiting frequency is double the lower limiting frequency. For narrowband frequencies the width of the bands are constant. The narrowband frequency is also “small” enough to capture pure tones and therefore provides detail about the spectrum. Shown in Figure 2.6 is an example of the narrowband, 1/3 octave band and the 1/1 octave band spectra of the same acoustic pressure signal (Szasz and Fuchs, 2008).

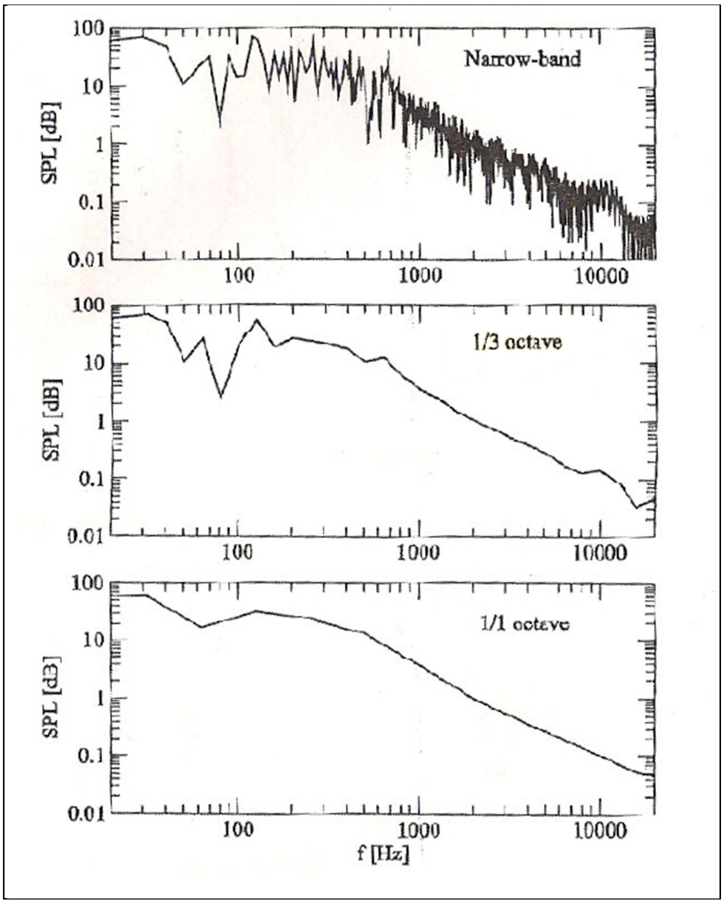


Figure 2.6: Narrowband, 1/3 octave band and 1/1 octave band of the same acoustic pressure signal (Szasz and Fuchs, 2008).

Loudness is related to a physically measurable quantity, the intensity of the wave. The intensity is defined as the energy transported by the wave per unit time across unit area and is proportional to the square of the wave amplitude. Since energy per unit time is power, intensity has units of power per unit area (W/m^2) (Giancoli, 1980).

The human ear can detect sounds with an intensity as low as 10^{-12} W/m^2 and as high as 1 W/m^2 (even higher, although above this is painful). This is an incredibly wide range and because of this range what humans perceive as loudness is not directly proportional to the intensity. To produce a sound that sounds about twice as loud requires a sound wave that has about 10 times the intensity. This is roughly valid at any sound level for frequencies near the middle of the audible range (Giancoli, 1980).

Because of this relationship between the subjective sensation of loudness and physically measureable quantity “intensity”, it is usual to specify Sound Pressure Level (SPL) using a logarithmic scale. SPL refers to the instantaneous difference between the actual pressure created by the wave and the average pressure given at a point in space. SPL is measured on a logarithmic scale in units known as decibels (dB). A decibel scale (Figure 2.7) is a measure of the sound energy contained in the pressure changes (Giancoli, 1980).

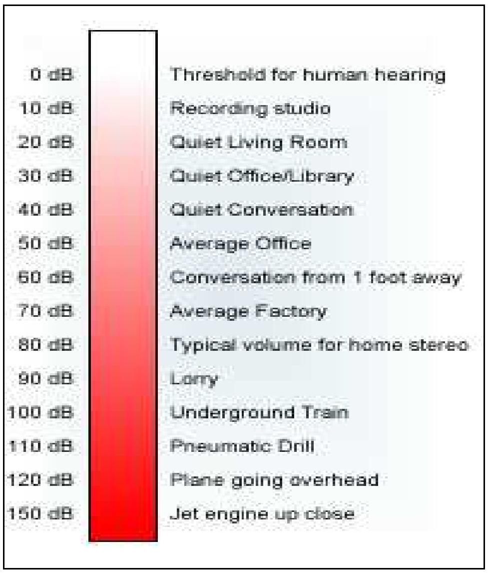


Figure 2.7: Example of a decibel scale (Brown, 2010).

The SPL, β, of any sound is defined in terms of its intensity, I, as follows (Ranft, Ameri, Alexander and Eniva, 2010):

$$\beta = 10\log\left(\frac{-I}{I_0}\right)$$

Where I_0 is the reference intensity which is the threshold of hearing at 1000 Hz,

$I_0 = 10^{-12}$ W/m^2. The intensities and SPL’s for a number of common sounds are listed in Table 2.1.

Table 2.1: Intensity of various sounds (Giancoli, 1980).

Source of Sound	**SPL (dB)**	**Intensity (W/m^2)**
Jet plane at 30 m	140	100
Threshold of pain	120	1
Loud indoor rock concert	120	1
Siren at 30 m	100	$1\text{x}10^{-2}$
Busy street traffic	70	$1\text{x}10^{-5}$
Ordinary conversation, at 50 cm	65	$3\text{x}10^{-6}$
Quiet radio	40	$1\text{x}10^{-8}$
Whisper	20	$1\text{x}10^{-10}$
Threshold of human hearing	0	$1\text{x}10^{-12}$

Human sensitivity to sound is frequency dependent. For frequencies of 3000 – 4000 Hz the sensitivity is the highest and the threshold of hearing is 0 dB. Weighting scales have been created to reflect the human perception of sound while taking into account the uneven sensitivity of the ear. The most common scale used in assessing environmental and occupational noise is A-weighting. It approximates the human response to sounds of medium intensity. B-weighting, which is not as common as A-weighting, approximates the human response to medium to loud intensity (around 70 dB). C-weighting is the human response to loud intensity sounds. This type of weighting can also be used for low frequency sounds. G-weighting is designed for infrasound. Figure 2.8 illustrates a weighting scale and the frequency properties (Pantazopoulou, 2007).

To determine the response of human hearing to changes in sound, sound level meters are equipped with filters that give less weighting to lower frequencies (Ranft, et al, 2010).

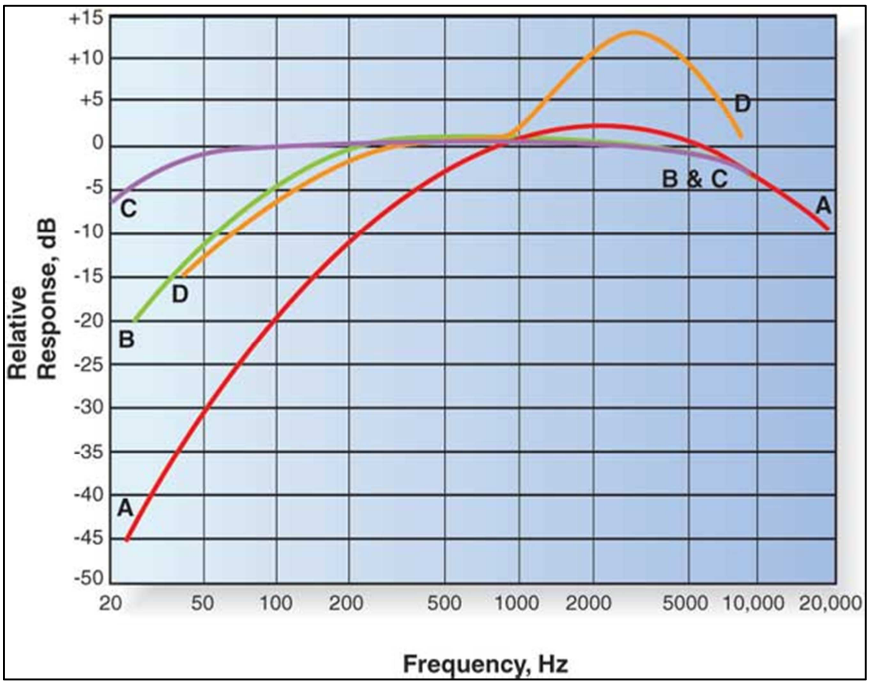


Figure 2.8: Acoustic Weighting Curve (Retrieved on the 13th of November 2011 from www.extron.com).

Human response to sounds measured in decibels have the following properties:

- A change in a sound level of 1 dB cannot be perceived.
- Doubling energy of a source corresponds to a 3 dB increase in a sound.
- A 3 dB change is not typically considered a discernable difference.

- A change in 5 dB is a noticeable difference in sound pressure level.
- A 6 dB increase is equivalent to halving the distance to the source of sound. 10 dB increase, is subjectively heard as doubling the loudness.
- The threshold of pain is a SPL of 140 dB.

These properties just mentioned provide a better understanding of sound and perception of sounds depending on the frequency. Using these characteristics, a framework can be developed to determine whether a sound source is to be defined as being irritating according to the noise levels (Rogers, et al, 2006).

2.3.2 Equal loudness level contours

Figure 2.9 shows equal-loudness contours that illustrates how human hearing, specifically perception of loudness, varies with frequency.

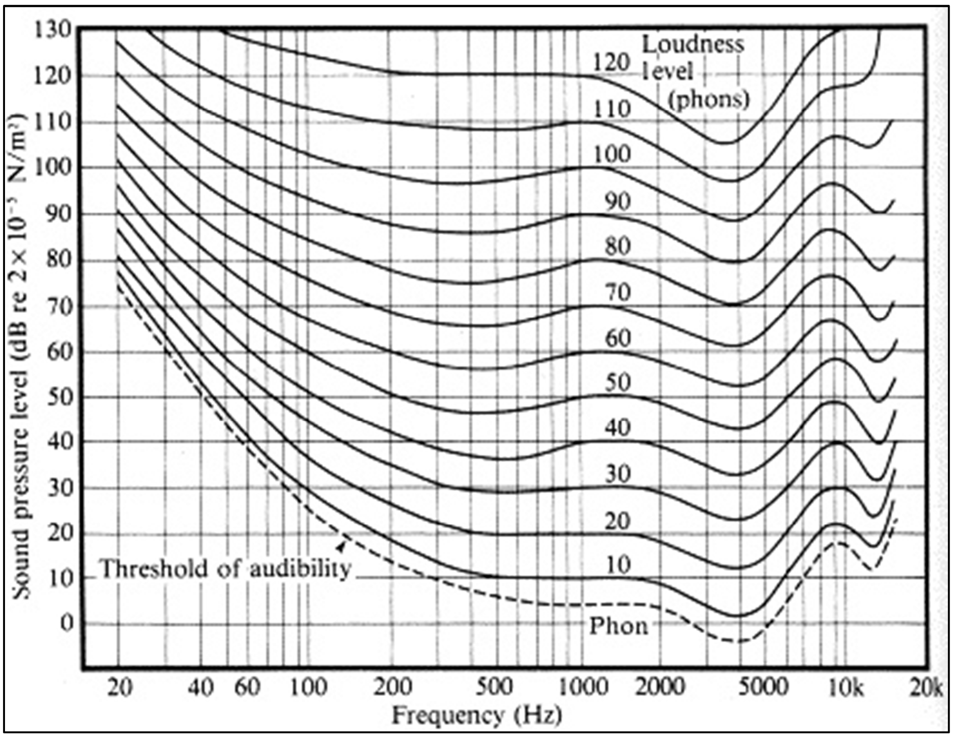


Figure 2.9: Equal loudness contours (Retrieved on the 13th of November 2011 from www.offbeatband.com).

These equal-loudness contours are often referred to as phon lines. These lines show what a sound level will be heard as at a certain frequency. For example, a sound at a SPL of 40 dB will only be perceived as 40 dB at a frequency of 1000 Hz. At other frequencies, for example 300 Hz, the sound will be perceived as 10 dB. The phon line at the bottom of the graph shows the minimum audible field and signifies the threshold of hearing. Figure 2.9 also illustrates that loudness increases for decreasing frequencies.

Assessments should be done in order to determine whether low frequency sounds are present. Low frequency properties might give an indication of why the wind turbine sound might be perceived as being noisy (Davidsen, 2009 and Thorne, 2007).

2.3.3 Human response to low frequency sound

Low frequency noise refers to noise within the frequency range of 20 - 200Hz. Low frequency sound has a longer wave length than high frequency sound. Because of this longer wave length, low frequency noise has the following characteristics:

- Is less attenuated by walls and enclosures.
- Can rattle walls and objects.
- Can mask higher frequency sound more than higher frequency sound can mask lower frequency sound.
- Can cross large distances without significant energy loss from atmospheric and ground attenuation.
- Can cause subjective reactions in humans.

There are a number of sources that produce low frequency noise. These include engines, compressors, ventilation systems, traffic noise, thunder, ocean waves, earthquakes and wind turbines (Davidsen, 2009).

Infrasounds that are found below 20Hz may not be audible but the pressure that is created by the sound may still be perceived at the eardrum and cause an irritation (Leventhall, 2006).

Low frequency sound may be perceived as being more irritating due to its characteristics (Davidsen, 2009). It is important to determine the frequency components when conducting a noise evaluation. This is done in order to help determine what effects a noise source could have on its environment. A sound having these low frequency characteristics may have a negative impact on an environment.

2.3.4 Noise

Noise is defined as unwanted sound. The significant difference between sound and noise is the emotional response to noise. The perception of sound as noise depends on the duration and amplitude of the sound (Kamperman and James, 2008). This is a major characteristic when defining noise. For sound to become noise it possess characteristics that are not solely dependent on the “loudness” of the sound (Thorne, 2007). These characteristics could include temporal, cultural and social factors, as well as an individual’s response to noise and the individuals living environment.

Temporal factors include the duration of the noise. This is an important factor to consider in noise assessments, as duration gives an indication on how long the noise is present in an environment. The longer a sound is present in an environment, the greater the chance that the sound will be perceived as being irritating or noisy (Thorne, 2007).

Cultural and social factors as well as the physical properties of a sound have an effect on the perception of noise. These factors influence a person’s response towards a sound. The acceptance of a sound has a strong correlation to environmental, social and economic factors. People with different standards of living have different expectations of the noise of an environment. Studies have shown that people living in a noisy environment find it hard to adjust to relatively quiet environments (Thorne, 2007).

2.4 Wind turbine acoustics

2.4.1 Types of wind turbine sounds

Wind turbine sounds are characterised according to their frequency components. These include: tonal, broadband, low frequency and impulsive sounds. Tonal is a sound at discrete frequencies. It is caused by the meshing of the gears and non-aerodynamic instabilities interacting with the rotor blade. Broadband sounds are characterised by a continuous distribution of sound pressures with frequencies greater than 100 Hz. The interaction of the wind turbine blades with the surrounding air flow is an example of broadband sound. Figure 2.10 illustrates this interaction.

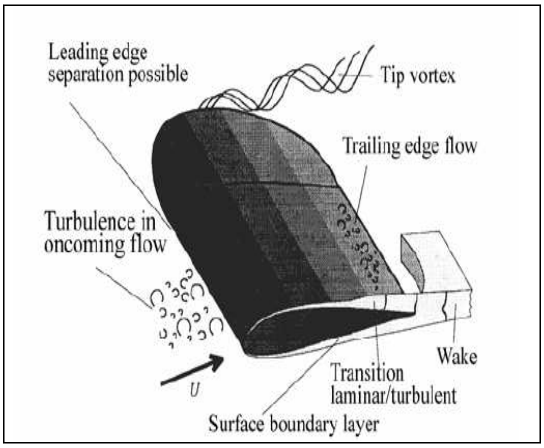


Figure 2.10: Air flow across the blade section (Brown, 2010).

Low frequency sound is described as a sound in the frequency range of 20 - 200 Hz. This type of frequency is caused when the turbine blade encounters localised flow deficiencies due to the flow around the tower. Lastly, impulsive sounds are described as short acoustic impulses or thumping sounds that vary in amplitude. This is caused by the interaction between air flow, the wind turbine tower and the blades of the wind turbine (Rogers et al, 2006 and Dutilleux and Gabriel, 2008).

There are two sources of sound from operating wind turbines, mechanical sounds and aerodynamic sounds.

2.4.2 Mechanical sound

Mechanical noise originates from the relative motion of the mechanical components. The main source of mechanical noise is generated from the machinery in the nacelle. This includes the gearbox, generator, yaw drives, cooling fans and auxiliary equipment. One of the main sources of mechanical noise in the nacelle is the gearbox. Emitted sounds from the mechanical components are associated with rotation of the mechanical and electrical equipment. This type of sound contains tonal sound components but it also has the broadband sound components (Rogers et al, 2006 and Howe et al, 2007).

In addition the hub, rotor and tower may act as ‘loudspeakers’. This means that these components transmit and radiate the mechanical sounds. The transmission path of sound can be air-borne or structure-borne. Air-borne implies that sound is directly propagated from the component or interior into the air. While structure-borne indicates that sound is transmitted along other structure components before the sound is radiated into the air. Figure 2.11

illustrates the transmission path and sound power levels for the individual components of a 2 MW wind turbine. Figure 2.11 shows that the main source of mechanical noise is the gearbox, which radiates noise from the nacelle surface and the machinery enclosure (Rogers et al, 2006).

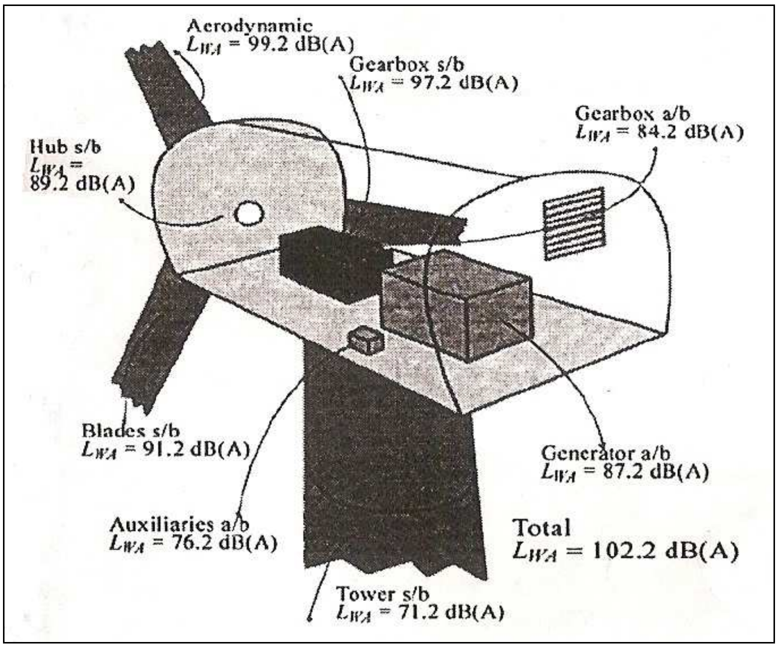


Figure 2.11: Components and total Sound Power Levels of a 2 MW wind turbine, showing the structure-borne and air-borne transmission paths (Rogers et al, 2006).

2.4.3 Aerodynamic sound

Aerodynamic noise is described as the noise caused by the interaction of the wind turbine blades and the air flow around the blades (Minnesota Department of Health, 2009). Aerodynamic noise produced by wind turbines is often described as a “swishing” sound. Depending on the wind turbine and wind speed, aerodynamic noise is also described as a “buzzing”, “whooshing”, “pulsing” or even a “sizzling” sound (Alberts, 2006). The sound power of aerodynamic noise is related to the ratio of the blade tip speed to the wind speed.

Aerodynamic noise is affected by the shape of the blade, the interaction of the air flow (wind speeds) with the blades and the tower, the shape of the blades trailing edge and the tip of the blade. Turbines with their blades downwind of the tower are known to cause a thumping sound as each blade passes the tower. Most noise is radiated perpendicular to the blades rotation. Since wind turbines rotate to face the incoming wind, the noise is radiated in different directions depending on the wind direction. Turbulent wind conditions cause unsteady forces on the blades which results in aerodynamic noise.

Table 2.2 provides an example of the relationship of SPL to wind speed of two small wind turbines (Alberts, 2006).

Table 2.2: Sound power of small wind turbines (Alberts,2006).

Model	**Turbine size**	**Wind speed (m/s)**	**Estimated sound pressure (dBA)**
Southwest Windpower Whisper H400	900 W	5	83.8
		10	91
Bergey Excel BW03	10 kW	5	87.2
		7	96.1
		10	105.4

Aerodynamic noise tends to increase with rotation speed of the wind turbine blade. For this reason, some wind turbines are designed to operate at lower rotation speeds when wind speeds are low. Wind turbines operating at lower rotation speed tend to minimise the noise problem in low wind conditions (Boyle, 2009).

2.4.4 Noise propagation model

Sound generated by wind turbines involves three stages: sound generation, propagation and reception. Sound generation, in the form of mechanical and aerodynamic noise, has been discussed in section 2.4.2 and 2.4.3. The other two stages will be discussed in this section.

Noise generated by a wind turbine is propagated through the air. This propagated sound is affected by the air properties, the landscape, vegetation and presence of different obstacles. Increasing the distance from a sound source to the receiver, increases the amount of acoustic energy that is lost. This is due to the larger area over which the sound is spread which decreases the SPL. Furthermore, the absorption of sound due to air viscosity converts acoustic energy into heat, and therefore the sound energy is lost.

Reflections and diffraction of sound waves occur when the ground and surrounding objects influence the sound propagation path. For high frequencies a shadow zone occurs behind the object. This shadow zone decreases with decreasing frequencies. Figure 2.12 shows the shadow zone created by obstacles causing the diffraction of high and low frequency waves (Szasz and Fuchs, 2008).

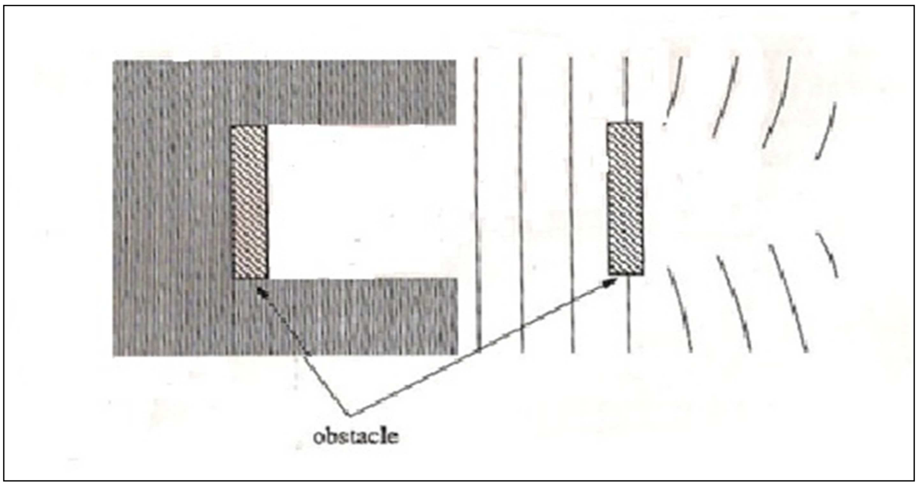


Figure 2.12: Diffraction behind obstacles high-frequency (left) and low-frequency (right) waves (Szasz and Fuchs, 2008).

Refraction is caused by temperature gradients. These temperature gradients cause different densities in different layers of the air. As a consequence these gradients impose different propagation speeds on the sound waves. Wind speeds and wind direction also influence the direction of the noise propagation.

The influence of temperature, wind speed and wind direction on sound waves are shown in Figure 2.13. Figure 2.13 (a) indicates that when there is no wind and no temperature gradient, the sound waves propagate in straight lines. Figure 2.13 (b) shows that in windy conditions the noise propagation paths are curved towards the wind direction. Negative temperature gradients cause lower temperature regions at higher altitudes and therefore lower propagation speeds for noise. As a result, the noise propagation paths will be curved upwards (Figure 2.13 (c)). Illustrated in Figure 2.13 (d) is what happens for positive pressure gradients. Figure 2.13 shows certain shadow zones, which illustrate where noise will not be propagated.

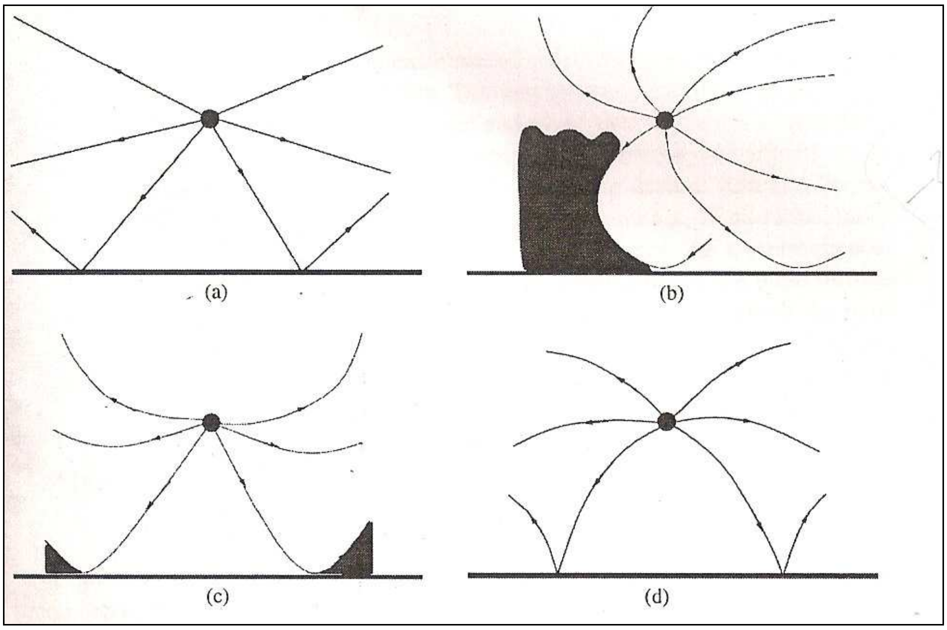


Figure 2.13: Influence of temperature, wind speed and wind direction on sound waves (Szasz and Fuchs, 2008).

Compared to other industrial noise sources, wind turbines have two distinctive features. Firstly, the source is located at elevated level which tends to reduce screening and ground attenuation effects. Secondly, in windy conditions sound propagation is difficult to predict.

The third stage of the noise propagation model is the sound reception. This is the perception of sound from the position of an observer. Other than the SPL there are a number of factors that influence the perception of sound of a wind turbine as being acceptable or annoying. The odds of perceiving a sound and being annoyed by the sound increases with SPL's. The visual impact also plays a role in wind turbine noise evaluation. It has been shown in previous studies that wind turbines have been considered as ugly structures in contrast to their surroundings (Pederson and Waye, 2007). This emotional response adds to the negative feeling towards wind turbine structures. Studies have also shown that the visual angle of the turbine, the perception of the blinking shadows and attitude towards wind turbines play a role in people's perception of wind turbine noise.

Field studies have also shown that there is an increase in noise annoyance when wind turbines can be seen. This is due to the rotational movement of the wind turbine as it attracts the eye. The multimodal sensory effect or aesthetic response could increase the risk of annoyance (Pederson and Waye, 2007). Annoyance response can also be explained by psycho-acoustic parameters. These include the sharpness, loudness, roughness, fluctuation strength and modulation of a sound.

The ambient noise level effects the perception of sound (Pederson and Waye, 2007). In regions with high background noise levels, wind turbine noise is considered to be less disturbing. Wind turbine noise is said to be more disturbing during the night than during the day due to the decreased ambient noise levels.

All the factors mentioned in section 2.4.4 play a role in wind turbine noise evaluations and should be considered when determining whether a wind turbine is classified as being noisy. The characteristics also give a deeper understanding of wind turbine acoustics and the reasons why wind turbines are perceived as being noisy.

2.5 Day and night noise measurements

In a study van den Berg (2003), claims that wind speed at hub height in the evening is 2.6 times the expected speed. This increased wind speed causes higher rotational speed of wind turbines and consequentially an increase in sound levels of up to 15 dB relative to the same reference wind speed during the day for large scaled wind turbines.

Day and night measurements are assumed to have an audible difference at some distance from the wind turbine. Van den Berg (2003) showed that on a summers day or even during strong winds the turbines may only be heard within a few hundred metres. But at night a wind park can be heard from distances up to several kilometres when wind turbines rotate at high wind speeds. The study showed that it is important to monitor the difference of sound levels between day and night as there could be a large scale difference.

2.6 Health effects

One of the biggest concerns relating to environmental impacts of wind turbines is the apparent health effects that are caused by extremely high exposure. Studies have shown that wind turbine noise is a part of daily community noise in European countries. This noise is mixed with various other noise sources such as road, rail and aviation traffic. It is difficult to establish health effects due to wind turbine noise specifically. Although, exposure to extremely high noise levels can cause headaches, irritability, fatigue, constricted arteries, and a weakend immune system.

The Minnesota Department of Health (2009) claims that there is no evidence that wind turbines generate the level of noise to create these problems.

Despite having never been shown to cause these health effects in European conditions, the potential ability of the noise pollution still causes a concern among residents near potential or actual wind turbine farms.

The World Health Organisation (WHO) (2010) recognized that low frequency noise is an environmental issue. The WHO (2010) claimed that noise pollution health effects due to low frequency noise include:

- Noise-induced hearing impairment.
- Interference with speech communication.
- Sleep disturbance.
- Mental health.
- Effects on residential behaviour and creates annoyance.

A study on micro-wind turbines is particularly relevant as these turbines are generally located in residential areas.

There have been a number of articles discussing the noise irritation of the large scaled wind turbines in the local Eastern Cape Herald. The articles appeared in the Herald on April 6th, 13th and 27th April 2010. These articles gave the opinions of locals towards the wind turbine farms. There was positive and negative feedback regarding the wind turbine farms. One of the concerns expressed were the apparent noise levels of the wind turbines. This lends practical significance to the study as the perception of the noise effects may be a cause of the negative response towards wind turbines.

2.7 Previous wind turbine noise studies

Bolin et al (2010) investigated whether natural sounds were able to mask wind turbine noise. The main objective of the study was to determine detection thresholds and the reduction of the perceived loudness of wind turbine noise in the presence of natural ambient sound sources. The second objective was to compare the empirical results with predictions from two existing models of partial loudness. The results were achieved by setting up two experiments. Each experiment had two wind turbines with three masking sounds. These masking sounds were wind in coniferous trees and deciduous trees and sound from sea waves. The first experiment included thirty listeners. These listeners determined the detection thresholds of wind turbine noise in the presence of the natural sounds. This was achieved by using a threshold tracking method. The second experiment included the same group of listeners. In this case the listeners matched the loudness of partially masked wind turbine noise with the loudness of unmasked wind turbine noise. The results of this study showed that wind turbine noise may be completely masked by natural sounds of trees and sea waves at S/N ratios of -8 to -12 dB. An S/N ratio is the difference between the A-weighted sound level of a wind turbine and the A-weighted sound level of the background sound. Bolin et al (2010) also found that there was a reduction in perceived loudness of wind turbine noise for an S/N ratio of up to 2 dB. It was concluded that existing models for predicting partial loudness do not work well for predicting masking of wind turbine noise by natural sounds. The results showed that it is important to look at ambient noise levels in an environment where a wind turbine noise assessment is taking place. This gives an indication of whether the wind turbine noise is been masked by the natural ambient noise.

Pederson and Waye (2004) did a study to evaluate the prevalence of noise perception and annoyance due to wind turbine sound among people living near a wind turbine farm. Another study done by Pederson (2007) was conducted in order to evaluate the relationship between noise annoyance and perception due to the influence of different environments. Their research was conducted in Europe via a questionnaire study with 754 respondents. The results showed that the odds of perceiving and being annoyed by wind turbine noise increased with increasing SPL. These studies also showed that noise perception and annoyance were associated with terrain and urbanisation. In rural areas there was an increased risk of perception and annoyance compared to an urban area. Furthermore rural areas are often situated on hilly or rocky terrain and this increases the risk of annoyance associated with the wind turbine visibility factor. These studies showed that it was important to evaluate the site to identify other factors that can influence noise perception of wind turbines (Pederson and Waye 2007 and Pederson, van den Berg, Bakker and Bouma, 2009).

In another study by Pederson (2007*)* it was showed that wind turbine noise was more annoying than transportation and industrial noise. It was suggested that this was because of the “swishing” sound quality and the lack of night time abatement of the wind turbines. The study also concluded that having a high visibility of wind turbines enhances negative response and increases the risk of annoyance. The study also demonstrated that there was a significant decrease in annoyance when people benefit economically from the wind turbines, despite the exposure to similar sound levels.

An evaluation of the relationship between long term measurements of ambient noise levels and wind speed and wind direction conditions at two fixed sites was conducted by Mckenzie, Bullmore and Flindell (2002). From the study it was concluded that ambient noise levels were much less affected by wind speed and direction, while wind turbines were affected by these factors. Other factors such as rainfall, temperature and humidity were also investigated. However, the range of variation in each of these variables was insufficient to yield any conclusive results.

Pantazopoulou (2007) discussed methods for the reduction of wind turbine noise. These methods related to the location of a wind turbine farm, obstacles breaking sound waves and the design of the wind turbine blades. The paper focussed on ambient sound levels that were of the same magnitude of sound of wind turbines. Factors that were thought to influence sound levels were evaluated. The factors were:

- Sound characteristics (directivity, height).
- Distance from the source to the observer.
- Air absorption.
- Ground effects (reflection and absorption).
- Weather effects (wind speed, temperature, humidity).
- Land topology.

A study in the UK (Eltham, Harrrison and Allen, 2007) showed that 84$\pm$7.2% of the population were positive about including wind energy in the UK. Results also showed that 10$\pm$5.9% of the population thought that the visual intrusion of wind turbines was greater after the wind farm was constructed while 11$\pm$6.1% believed that the noise factor was more intrusive than expected.

These survey type studies were not recommended for this research. Most people in South Africa have never heard of or seen a wind turbine, survey studies would have had limited benefits. Micro-wind turbines are a new area of focus in renewable energy in South Africa. Therefore this study looked at actual sound levels from operational micro-wind turbines.

2.8 Different sound sources

The experiment of this study compared the sounds of different sites to the noise of two micro-wind turbines. Section 2.8 gives a brief description of each site under evaluation.

2.8.1 Traffic noise

Traffic noise is expected to provide a good comparison to wind turbine sound as it is a common sound and the sound varies depending on the time of the day.

Excessive traffic noise is one of the most common noise complaints among residents that live near a vicinity of constant traffic, for example busy highways, industrial areas, shopping malls or even areas of large businesses. Traffic noise can affect the ability to work, learn or sleep (Retrieved on the 30th May 2011 from trafficnoise.org).

Traffic noise depends on the vehicle type. Noise from an automobile is primarily sourced from the interaction between the tires of the vehicle and the road. These type of vehicles produce sounds from 72 to 74 dBA when travelling at 80 km/hr and at a distance of 15 m. Medium to large vehicles are said to generate sounds from the engine and exhaust. Medium trucks produce 80 to 84 dBA when travelling at 80 km/hr at a distance of 15 m. Large heavier trucks produce 84 to 86 dBA at the same distance and speed (Retrieved on the 30th May 2011 from trafficnoise.org).

2.8.2 Rural

A rural site was included in the experimental design as it provides a good measure of an environment with low ambient noise and could be used as a lower bound of a sound level created in a very quiet environment.

A rural area is defined as an area outside of towns or cities. It is an environment that is large and isolated with low population density. A rural area is an environment with low ambient noise. Excessive noise created in this type of environment will cause a disturbance to residents that live in this area (Retrieved on the 30th May 2011 from acoustics.com).

2.8.3 Residential

A residential area is a good site for comparison as many micro-wind turbines are designed for use in residential areas. Hence this site is expected to show whether micro-wind turbines will cause a disturbance in this type of environment.

Residential sound may be caused by a number of sources. The most common sources involve loud amplified music, televisions, barking dogs, washing machines or household appliances.

Car alarms, traffic in the residential area and even burglar alarms can increase the ambient noise in an residential area (Retrieved on the 10th June 2011 from tunbridgewells.gov.uk).

A residential environment is believed to have low ambient noise and the noise levels are believed to decrease in the night.

2.8.4 Sea

The ocean is a useful comparison with wind turbine noise as the ocean sounds are believed to have a "calming effect" on people. This site provides sound levels that are acceptable at certain frequencies.

The ocean is filled with different types of sounds. The underwater sound is generated by a variety of natural sources, such as breaking waves, rain and marine life. The background sound of the ocean is known as the ambient noise. The ambient noise is mostly due to the spray and the bubbles associated with the breaking of waves. The sound levels of the sea increases with increasing wind speeds (Retrieved on the 6th of June 2011 from dosits.org).

2.9 Experimental design

Experimental design originated in the early 1900's by R.A Fisher. It was associated with agricultural research. This type of study was formulated in order to save time and money by obtaining more information about a sample in a shorter period of time.

An *experiment* is a process of collecting data. The dependent variable observed during an experiment is known as the *response variable*. The *design* of an experiment is planning of the sampling procedure for an experiment. It refers to the choice of *treatments* and a manner in which the experimental units are assigned to *treatments*. Since the purpose of an experiment is to reveal the response of one variable to changes in other variables, it is important to make a distinction between *explanatory* and the *response variables*. A response variable is the variable that is measured in an *experiment*. The *explanatory variable* in an experiment is often referred to as a *factor*. *Factors* are the independent variables, quantitative or qualitative, that are related to a response variable. A *treatment* is a combination of levels of the factors involved in an experiment. An advantage of an experimental design is that it can observe the effects of several factors simultaneously. The interaction of several factors can also show effects that might not have been observed when each factor was tested on its own (Mendenhall and Sincich, 2006).

There are three basic principles to experimental design; *control*, *randomisation* and *replication*. Randomisation is the experimental procedure that will be covered in this research study therefore an explanation of the basic principles of this procedure is required.

Randomisation is the manner in which treatments are assigned to the experimental units. According to Mendenhall and Sincich (2006) the formal definition of randomisation is *"A completely randomised design to compare p treatments is one in which the treatments are randomly assigned to the experimental units."*

2.10 Conclusion

Chapter 2 summarises the theory behind sound, wind turbines, wind turbine noise and experimental design. It gives a description of different type of sounds produced in different environments and highlights previous studies done in wind turbine acoustics.

Chapter 3

Methodology

The aim of the study was to determine whether wind turbines are noisy and cause disturbance to humans. This is done by comparing the sound of micro-wind turbines to traditionally accepted sounds in the community. The sound data was collected using a randomised experiment. Seven sites and four different times of the day were selected. The sequence in which the measurements were taken was randomised. A General Linear Model (GLM) was then used to determine the relationship between the sound generated at each site versus the time of day, wind speed, distance and wind direction.

In addition to this evaluation, a separate sound evaluation was conducted. This evaluation involved observing several wind turbine systems in the Eastern Cape Region. This was done in accordance to the IEC Internal standards[1]. The IEC provides a uniform methodology that will ensure consistency and accuracy in noise measurements. The IEC standards provides guidance in measurement, analysis and reporting of complex acoustic emissions from wind turbine generator systems. The IEC provided a noise evaluation that was required by the NMMU physics department.

This chapter explains the experimental setups of both experiments and the evaluation techniques used to analyse the sound readings. This chapter also gives detailed descriptions of the sites under evaluation in order to determine the differences between sound sources at each site.

3.1 Equipment and sites

3.1.1 Equipment

During the randomised experiment the following equipment was used: MT975 sound level meter, WSD-100 Wind Speed and Direction Sensor and a HP Probook 4520 laptop.

The MT975 sound level meter has the followings specifications which are displayed in Table 3.1.

[1] IEC 61400-11 International standards: Wind turbine generator systems Part11: Acoustic noise measurement techniques.

Table 3.1: MT975 Sound levels meter specifications.

Standard applied:	IEC61672-1 Class2
Frequency range:	+/-1.4 dB
Dynamic range:	31.5 Hz - 8 KHz
Level Ranges:	LOW: 30 dB – 80 dB
	MEDIUM: 50 dB – 100 dB
	HIGH: 80 dB – 130 dB
	AUTO: 30 dB – 130 dB
Frequency weightings:	A/C
Time Weighting:	Fast (125ms), Slow (1s)
Microphone:	½ inch electrets condenser
Analog output:	AC/DC outputs from earphone outlet. AC=1 Vrms, DC=10 mV/dB
Image:	

The sound level meter was set to take measurements at A-weighting with a fast time weighting setup. The sound level meter was connected to a HP Probook 4520 laptop during the measurement process. This was done in order to export measurements to an MS Excel spreadsheet.

A WSD-100 Wind Speed and Direction Sensor were used to record average wind speed measurements in km/h and average wind direction for each measurement. The WSD-100 can withstand hurricane-force winds, yet is sensitive to a very light breeze. It features a hand-balanced wind direction vane for optimal stability and accuracy. Wind speeds and wind direction were logged instantaneously every five minutes.

Figure 3.1: WSD-100 Wind Speed and Direction Sensor.

The WSD-100 Wind Speed and Direction Sensor were set up at the Centre of Energy Research (CER) on the NMMU South Campus. Wind speeds and wind direction measurements that were used for the experiment were obtained using the WSD-100 Wind Speed and Direction Sensor. It was assumed that this measurement was an accurate average measurement for wind speed and wind direction for the Summerstrand region in Port Elizabeth, where all measurements were recorded.

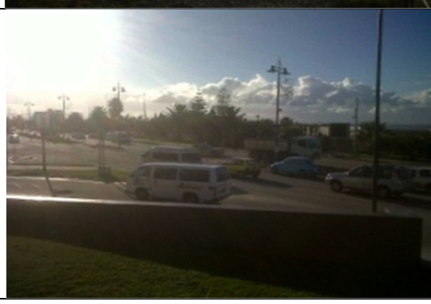
3.1.2 Sites

The seven sites under evaluation are shown in Figure 3.2. The seven sites that were used in the study were a rural environment (green), a residential area (yellow), a beachfront (red), a busy road (orange), a horizontal axis micro-wind turbine (purple), a vertical axis micro-wind turbine (blue) and the ambient noise measurement from the vertical axis micro-wind turbine site (blue). Unfortunately the horizontal axis wind turbine could not be switched off during the experiment. This meant that an ambient measurement for this site was not included.

Figure 3.2: Sites under evaluation (Retrieved on the 17th July 2011 from maps.google.com).

A short description of each site is given in Table 3.2.

Table 3.2: Site description.

Site	Image
Horizontal Axis Wind Turbine e300[1] (1kW): Hobie Beach, Summerstrand, Port Elizabeth. Co-ordinates: 33°S 58.88` 25°E 39.53` This wind turbine was situated approximately 50 m away from the sea and 10 m away from a road. Although the sound source was placed in an area of high ambient noise a sound clip of the wind turbine was captured and it was found that the wind turbine sound was clear.	
Vertical Axis Wind Turbine: NMMU South Campus, Outdoor Research Facility Summerstrand, Port Elizabeth. Co-ordinates: 34°S 0.51` 25°E 39.91` The vertical axis wind turbine was set up at the CER. The centre is situated on a nature reserve on the NMMU campus. The nature reserve is believed to be a quiet environment with low ambient noise.	
Residential Area: Cathcart Road, Humewood, Port Elizabeth. Co-ordinates: 33°S 58.81` 25°E 38.45` The residential area is a quiet neighbourhood with minimal noise interference from outside sources.	
Beach Front: Pollock Beach, Summerstrand, Port Elizabeth. Co-ordinates: 33°S 59.07` 25°E 40.29` The first measurement position was taken 5 m away from the sea water. The sites sounds levels could have been influenced by people talking, children playing, dogs or wild life.	
Rural environment: NMMU South Campus (nature reserve) Summerstrand, Port Elizabeth. Co-ordinates: 34°S 0.51` 25°E 39.75` This environment was found on the nature reserve on the NMMU South campus. This is a quiet environment with low ambient noise.	
Street: Beach road, Humewood, Port Elizabeth. Co-ordinates: 33°S 58.60` 25°E 38.87` This site was found close to a busy road with constant traffic during the day and night. Large and small car use this road.	

3.2 Data collecting

Readings were taken over a 70 day period. The site and time for each reading were selected randomly and four measurements were taken at each site and time. The reason that only four sets of measurements were taken at each site and time was due to the time constraints. Five sets of measurements at each site and time would have taken 108 days. The randomised selection process of each site and time was created in R 2.11.1. The randomised selection process is given in Appendix A.

Measurements were taken at 08h00, 12h00, 17h00 and 22h00. The reasons for the choice of these four times were that they were believed to include a typical day's activity. The 08h00 and 17h00 times include the usual busy community activity. The12h00 time included the midday relaxation activity while 22h00 time included the quiet period.

For each treatment level two separate readings were taken. These recordings were related to the distance from the sound source. The first measurement was read close to the sound source and the second measurement was taken approximately 10 m away from the first measurement position.

The measurement position for the wind turbine was calculated in accordance to the dimensions of the wind turbine. The formula used for this calculation is shown in section 3.4.2. All other measurement positions used this calculated value as the reference position.

Sound measurements were recorded in decibels with an A-weighting over a period of two minutes. Measurements were taken at a height of one meter above ground level. This was done to reduce the influence of atmospheric conditions and terrain effects. In the two minute period decibel measurements were recorded every half a second making a sample size of 240. This was a large enough sample to obtain an accurate decibel recording for each measurement. According to the IEC document at least 30 measurements are required in a one minute period to determine an accurate average decibel reading for a wind turbine evaluation.

The following information was collected concurrently with the sound measurements at each site:

- Wind speed (km/hr).
- Wind direction.

Once sound data was collected the average decibel over the 240 measurements was calculated in MS Excel 2007. The 25% trimmed means were calculated in the same manner. The trimmed mean is a measure of central tendency which disregards a given percentage of the sample when the mean is calculated. The trimmed mean is a useful estimator as it is less sensitive to outliers and gives a robust estimate of the central measure.

The average wind speed and average wind direction were calculated within a 15 minute period of the time that the sound measurements were taken. This was done logistically as the wind speed and wind direction could not be calculated at the exact time the sound measurements were taken. Instead the wind speed and wind direction data were recorded instantaneously every five minutes. The wind direction was defined as a qualitative variable as it came in the followings format North (N), North North East (NNE), North East (NE), East North East (ENE), East (E), East South East (ESE), South East (SE), South South East (SSE), South (S), South South West (SSW), South West (SW), West South West (WSW), West (W), West North West (WNW), North West (NW) and North North West (NNW). Due to the small sample of measurements in some directions, wind direction measurements were grouped into 4 categories, North, South, East and West. If a direction was found between N and NE (including NE) it was categorised as N. If a direction was found between N and NW (including NW) it was categorised as N. If a measurement was found between S and SE (including SE) it was found to be S and if the direction was found between S and SW it was categorised as S. If a direction was found between NW and SW it was categorised as W and if the direction was found between NE and SE the direction was categorised as E.

From the 14th April 2011 to the 28th April 2011 the wind speed and wind direction measurements were not recorded due to an electrical fault at the CER. This lost information would have adversely affected the model. The wind speed and wind direction for this period was obtained from the PE weather station situated at the PE airport. It was assumed that measurements from the PE weather station would give a reasonable estimate for the Summerstrand region as it is located within 10 km of the region.

The data received from the PE weather station contained wind speed in m/s. All wind speed data that was collected during the experiment was thus converted to m/s.

3.3 Statistical methods

3.3.1 Descriptive statistics

Numerical and graphical statistical methods were used to describe the quantitative and qualitative data collected during the experiment. This was achieved by using the basic descriptive functions in STATISTICA 10. The measures calculated in the descriptive summary give an indication of the central tendency of the data, the spread of the data set and graphical illustration of the distribution of the data. The data summaries also give an indication of errors that might have occurred during data input.

The following measures were included in the descriptive statistic summary: mean, median, the minimum and maximum value, variance, standard deviation, skewness and kurtosis.

The most common measure of central tendency is the sample mean. The sample mean is defined as follows:

The mean of the sample of *n* measurements $x_1, x_2, ..., x_n$ is $\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}$.

The median is defined as the midpoint of a data set. This measure gives a value such that half the observations are below the value and half the observations are above it. For an odd number of observations, arranging data in ascending order, the median is the $\left(\frac{n+1}{2}\right)th$ observation. For an even data set the median is the average of the pair of observations occupying the central position of the ordered data (Wackerly, Mendenhall and Scheaffer, 2002).

The variation (spread) of the data can be described by the following descriptive statistics: the range, the variance and the standard deviation (Kele, Lombard, Mouton and van der Merve, 2010).

The range of a sample is defined as the difference between the largest and smallest measurement and gives an indication of the spread of the data.

The variance of a data set is defined as the average of the squares of the deviation of the measurements from the mean. The variance of the sample of *n* measurements $x_1, x_2, ..., x_n$ is

$s^2 = \frac{\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2}{n-1} = \frac{\sum_{i=1}^{n} x_i^2 - n\bar{x}^2}{n-1}$. The square root of the variance is defined as the standard deviation of the sample and is similarly $s = \sqrt{s^2}$.

The coefficient of skewness of a random variable is defined as the ratio of the third central moment to the cube of the standard deviation. This is defined for the population under study as $\gamma_1 = \frac{E(X-\mu)^3}{\sigma^3}$. The coefficient of skewness gives an indication of the skewness of a distribution. When $\gamma_1 = 0$ implies that the distribution of the random variable is symmetric, when $\gamma_1 < 0$, it implies that the distribution is skewed to the left (negatively skewed) and when $\gamma_1 > 0$, it implies that the distribution of the random variable is skewed to the right (positively skewed).

The coefficient of kurtosis is a measure of the peak or the flatness of the curve of the distribution. The coefficient of kurtosis is defined as the ratio of the fourth central moment to the square of the variance. This is defined for the population under study as $\beta_2 = \frac{E(X-\mu)^4}{\sigma^4}$. Positive kurtosis indicates that there is more weight applied to the tails of the distribution, while negative kurtosis implies that there is less weight given to the tails of the distribution (Mendenhall and Sincich, 2006).

3.3.2 Linear models

In a complex analysis with more than one independent variable multiple regression models are often used to predict the response variable. The aim of this study was to determine the relationship between the site, time, distance, wind speed and wind direction on the average sound level generated at a given site. A GLM was used to make a comparison between the response variable, the sounds generated by wind turbines and sounds generated at sites without turbines.

If we represent *k* predictor (independent) variables $x_1, x_2, ..., x_k$ and a response (dependent) variable *Y* then the GLM has the following form

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + ... + \beta_k x_k + \varepsilon$$

The parameters $\beta_1, \beta_2, ..., \beta_k$ of the model determine the contribution of the independent variables x_i to the response variable *Y*. These parameters are constants (weights) with values which need to be estimated from a sample. The common method used for the estimation of these parameters is known as least squares (Bowerman and O'Connell, 1990).

The term ε denotes the random error. It is assumed that the random error term is an independent and identically normally distributed random variable with a mean of zero and a constant variance (σ_ε^2). The random error term is included to account for the lack of fit of a model, random fluctuations of responses or a combination of these two factors (Mendenhall and Sincich, 2006).

Two types of independent variables were considered during this study, these variables were quantitative and qualitative in nature. Quantitative variables assume numerical values corresponding to points on a line. A variable that is non-numerical and is classified into different categories is defined as a qualitative variable. The quantitative variable that was included in the experimental design was the wind speed as it took on continuous numerical values. While site (rural, ambient, vertical wind turbine, horizontal wind turbine, residential area, road, beach front), time (08h00, 12h00, 17h00, 22h00) and wind direction (N, S, E, W) were all categorised therefore giving them a qualitative property (Mendenhall and Sincich, 2006).

The parameters $\beta_0, \beta_1, \beta_2, ..., \beta_k$ are estimated such that the sum of square errors is a minimum. The least squares prediction line is one that satisfies the following two properties:

- $SE = \sum (y_i - \hat{y}_i) = 0$, the sum of the residuals is 0.
- $SSE = \sum (y_i - \hat{y}_i)^2$, the sum of squared residuals is a minimum for any other linear model with $SE = 0$.

The estimates of the parameters $\beta_0, \beta_1, \beta_2, ..., \beta_k$ which minimise the SSE in the study were determined using the statistical software package STATISTICA 10.

The following assumptions are made about the general form of the probability distribution of the error term ε:

- The mean of the probability distribution of ε is 0. This assumption implies that the mean value of y for a given value of x is $E[y] = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + ... + \beta_n x_k$.
- The variance of ε is constant.
- ε is normally distributed.
- The errors associated with any two different observations are independent.

These assumptions allow for the development of reliable least squares estimators for $\beta_0, \beta_1, \beta_2, ..., \beta_k$. The assumptions also allow for hypothesis tests to be performed testing the utility of the model. Various techniques are used to check the validity of the assumptions made about the error term.

Residual analysis is required to determine how well the data fits the model. A residual, $\hat{\varepsilon}$, is defined as the observed value minus the predicted value. Residual plots indicate whether the assumptions made about the error terms are satisfied. Partial residuals measure the influence of a variable on the dependent variable after the affects of other variables have been removed or accounted for.

An outlier is defined as an *"observation that is far removed from the rest of the data set"* (Mendenhall and Sincich, 2006). An outlier describes a value that does not fit the pattern of the data points. An outlier is an observation that has an extremely large residual value. The presence of outliers in a data set can affect the residual variance and the estimates of the regression parameters as well as the accuracy of a model's prediction (Mendenhall and Sincich, 2006).

Several factors contribute to the presence of outliers in the data set. These include sampling errors, such as malfunctioning of equipment and not sampling from the target population, errors in data measurements, recording or entering of data. Also errors could be caused by extreme variation in the data set owing to biological or environmental variations such as temperature, humidity, gust or turbulence of wind (Mickey, Dunn and Clark, 2004).

Graphical residual plots give an indication of outliers that may be present in the data. Cook's distance is a numerical measure that is used to determine whether a residual is an outlier. Cook's distance is defined by the equation

$$D_i = \frac{(y_i - \hat{y}_i)^2}{(k+1)MSE}\left[\frac{h_i}{(1-h_i)^2}\right].$$

where h_i is defined as the leverage, and $k + 1$ is defined as the number of β parameters in the GLM. The leverage value h_i is defined as a measure of the influence of y_i on its predicted value.

The multiple coefficient of determination denoted by R^2 is a measure of how well a model fits a data set. The multiple coefficient of determination is defined by the equation

$$R^2 = 1 - \frac{SSE}{SS_{yy}} \text{ where } 0 \le R^2 \le 1,$$

and where $SSE = \sum (y_i - \hat{y}_i)^2$, $SS_{yy} = \sum (y_i - \bar{y})^2$ and $\hat{y}_i$ is the predicted value of y_i. An alternative measure of the model adequacy is the adjusted multiple coefficient of determination R_a^2. The formula for R_a^2 is given by the equation

$$R_a^2 = 1 - \left[\frac{(n-1)}{n-(k+1)}\right]\left(\frac{SSE}{SS_{yy}}\right),$$

where n is the sample size and k is the number of β parameters in the model. R^2 and R_a^2 have similar interpretations. However the adjusted multiple coefficient of determination, R_a^2, takes into account the sample size and the number of β parameters in the model.

A method that can be used for identifying the significance of a variable is backwards stepwise regression. To use this method, the linear model is fitted to the potential predictor variables. If k predictor variables are fitted to the data the model is given by the equation

$$E[y] = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k .$$

The parameter with the highest p-value for the hypothesis test $H_0 : \beta_i = 0$ and $H_1 : \beta_i \neq 0$ identifies a potential insignificant variable x_i. Provided the p-value falls above a certain critical significant level (5%) this variable is omitted from the model as the variable is considered as insignificant.

Two models are nested if one model contains all the terms of the second model. The more complex of the two models is called the complete model and the simpler of the two models is called the reduced model. A nested F-Test is used to obtain the most parsimonious model.

The Nested *F*-Test is given as follows:

Reduced model:

$$E[Y] = \beta_0 + \beta_1 x_1 + \ldots + \beta_g x_g ,$$

Complete model:

$$E[Y] = \beta_0 + \beta_1 x_1 + \ldots + \beta_g x_g + \beta_{g+1} x_{g+1} + \ldots + \beta_k x_k .$$

The significance of the variables omitted from the reduced model is tested with the hypothesis

$$H_0 : \beta_{g+1} = \beta_{g+2} = \ldots = \beta_k = 0$$
$$H_1 : \textit{At least one of the } \beta \textit{ parameters being tested is nonzero.}$$

The test statistic for this hypothesis is given by

$$F = \frac{(SSE_r - SSE_c)/(k-g)}{(SSE_c)/(n-(k+1))}.$$

Where SSE_r is the sum of squared errors for the reduced model, SSE_c is the sum of squared errors for the complete model; k-g is the number of β parameters specified in H_0, $k+1$ is the number of β parameters in the complete model. The decision reached is that H_0 is rejected if the test statistic is greater than some predetermined critical value of the *F* distribution.

3.4 Wind turbine evaluation

3.4.1 Frequency analysis

The frequency analysis included the evaluation of several wind turbine systems in the Eastern Cape region according to the IEC. The IEC states that it is important to give full detailed description of the wind turbine including the manufacturer, rotor details, and the physical environment where the wind turbine is placed and the acoustic data recorded from the wind turbine.

This following information is provided in Table 3.3 with accompanying figures:

Table 3.3: Wind turbine description.

Wind Turbine	Image
Horizontal Axis Wind Turbine e300[1] (1kW): **Site:** Hobie Beach, Summerstrand, Port Elizabeth. **Co-ordinates:** 33°S 58.88` 25°E 39.53` **Description of site:** 10m away from a busy road, 50m away from the beach. **Manufacturer:** Kestrel **Type**: One horizontal, three bladed micro-wind turbine. **Power:** 1kW **Volts:** 48 V	
Vertical Axis Wind Turbine: **Site:** NMMU South Campus, Outdoor Research Facility Summerstrand, Port Elizabeth. **Co-ordinates:** 34°S 0.51` 25°E 39.91` **Description of site**: Rural environment. **Manufacturer:** Russel Phillips. **Type**: One vertical micro-wind turbine. **Power:** 1kW **Volts:** 48 V	
Horizontal Axis Wind Turbine e300[1] (1kW): **Site:** Walmer Park Shopping centre **Co-ordinates:** 33°S 58.87` 25°E 33.60` **Description of site:** Shopping complex, 30m away from busy road. **Manufacturer:** Kestrel **Type**: Three horizontal, three bladed micro-wind. turbines **Power:** 1kW **Volts:** 48V	

3.4.2 Experimental setup

Sound clips were recorded at a location close to the wind turbine. This was done in order to minimise the influence of terrain effects, atmospheric conditions or wind induced noise. A microphone was mounted at the centre of a flat hard board. The microphone diaphragm was normal in the plane to the hard board with the axis of the microphone pointing towards the wind turbine facing the oncoming wind. The board was made of hard chip wood and had a diameter of 1 m and was 12 mm thick. Provided in Figure 3.3 is an illustration of the mounted microphone placed on the hard chip wood board as per the IEC requirements.

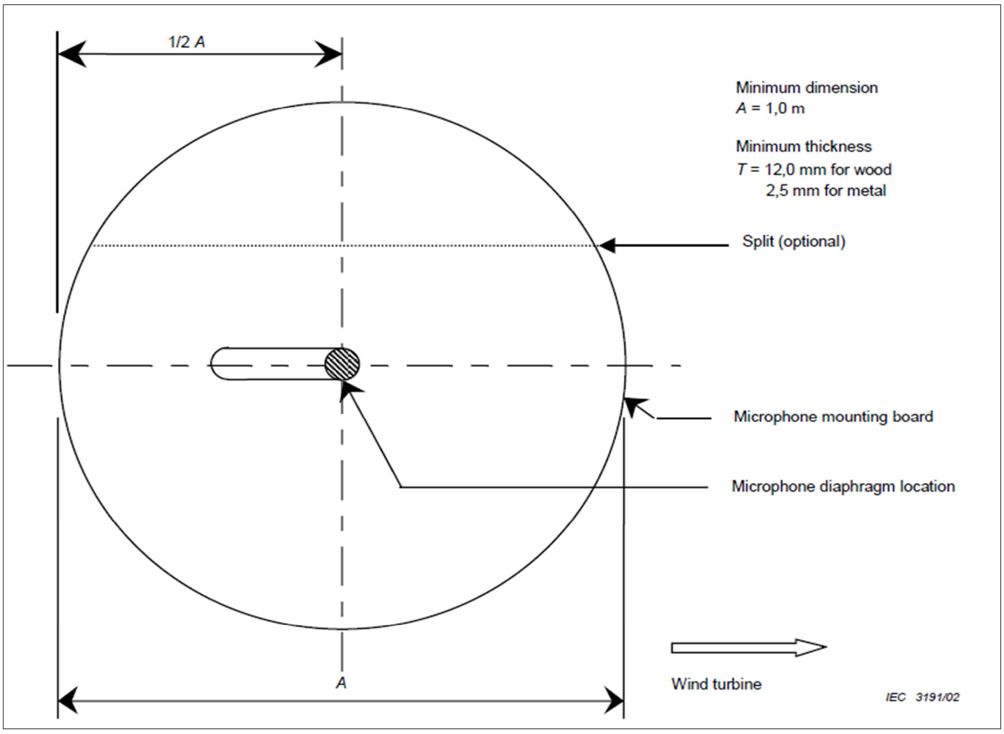


Figure 3.3: Mounting of the microphone-plan view (IEC 61400-11.2002).

The microphone that was used during this experiment was a Philips SBC3070 condenser microphone. The specifications on the SBC3070 condenser microphone are shown in Table 3.4.

Table 3.4: Technical specifications of the Philips SBC3070 condenser microphone.

Type:	Electret Condenser
Polar Pattern	Super-Uni-Directional (Cardioid) for long and Short distances
Frequency Range	60-14000 Hz
Impendence	>2.3 kΩ
Input sound pressure level	120 dB Max
Signal-to-noise ratio	40 dB or more
Type of plug	3.5 mm L-shaped type, mono
Dimensions	257 x 24 mm (length x diameter)

The microphone was placed on a board at a reference distance R_0 from the wind turbine. The downwind measurement position R_0 is identified as the reference position shown on Figure 3.4. R_0 for a horizontal axis wind turbine is calculated in accordance to the wind turbine dimensions and was determined by the equation $R_0 = H + \frac{D}{2}$, where H is the vertical distance from the ground to the rotor equatorial plane and D is the equatorial diameter of the horizontal axis wind turbine.

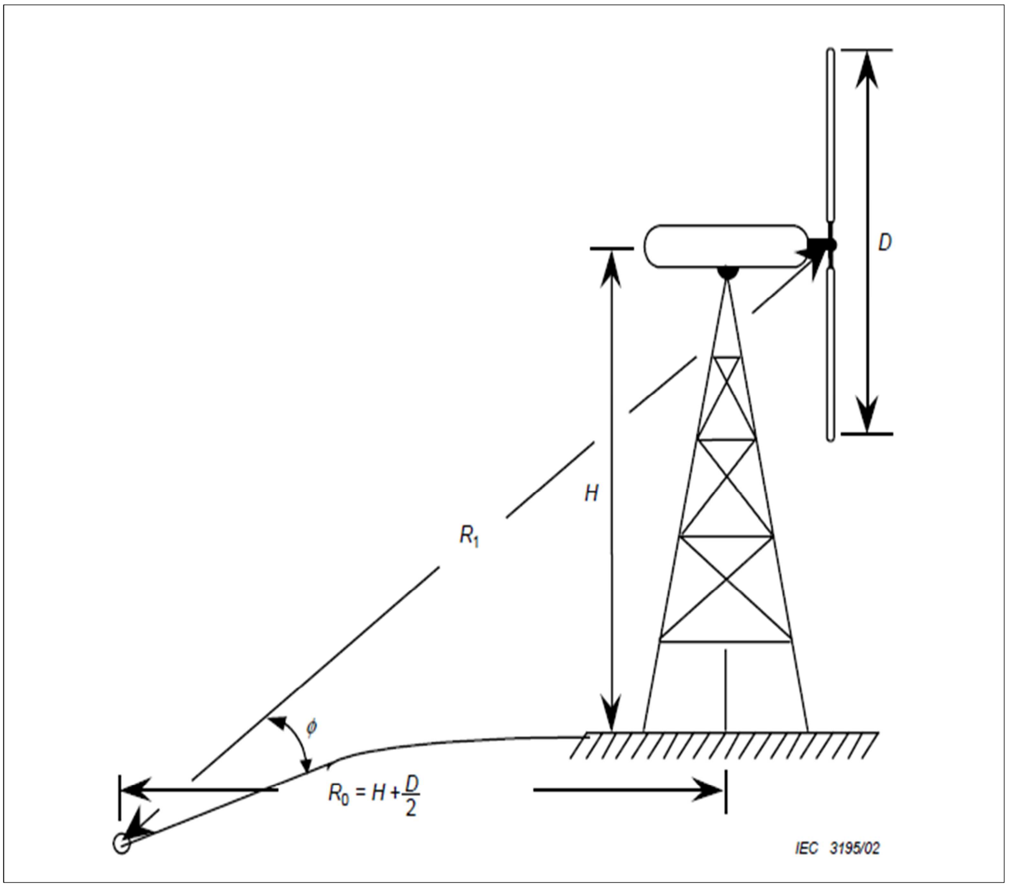


Figure 3.4: Reference position R_0 (IEC 61400-11.2002).

R_0 for a vertical axis wind turbine is calculated with accordance to the wind turbine dimensions and is determined by the equation $R_0 = H + D$, where H is the vertical distance from the ground to the rotor equatorial plane and D is the equatorial diameter.

Figure 3.5 shows the downwind measurement position for a vertical axis wind turbine.

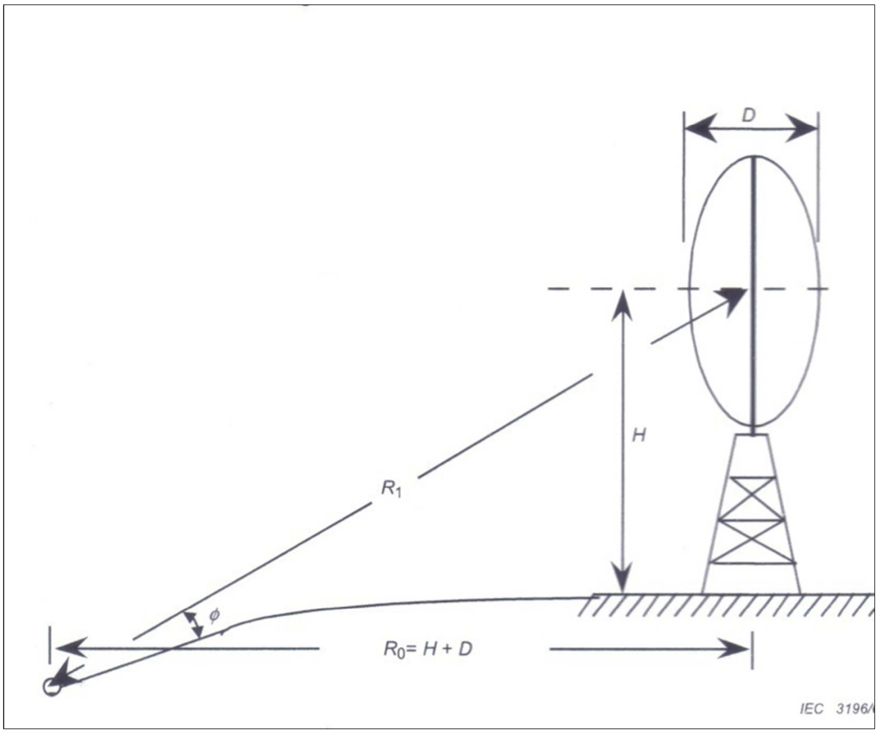


Figure 3.5: Reference position R_0 (IEC 61400-11.2002).

To minimise the influence of the edges of the reflecting board on the noise readings, the board was placed flat on the ground. This was done by levelling the gaps under the board with soil. The inclination angle ϕ shown on Figure 3.4 and Figure 3.5 must be between $25°$ and $40°$ according to the IEC requirements.

Sounds clips were recorded over a 40 second period using the Phillips SBC3070 condenser microphone which was plugged into a HP Probook 4520 laptop. Sounds clips were saved in Audacity 1.3, audio software package. This software package is available for Windows 98 and later, Mac OS X, Linux and other Unix-like systems. Sound clips were recorded at Stereo 44100 Hz 32 bit rate. Audacity 1.3 was used for the spectral analysis of the wind turbine sound clips. The advantage of using Audacity is that it is a free audio software package and can be downloaded off the site http://audacity.sourceforge.net/download/.

The spectral analysis was run in the Plot Spectrum function in Audacity. A certain portion (30 seconds) of the sound clip was selected. This selected section was checked for interference from other sources; hence the whole sound clip was not used. The power spectrum for the selected proportion of audio region was calculated. The selected proportion of the audio file (which is a set of sound pressure values at points in time) was converted to a graph of frequencies against amplitudes. This was done using a mathematical algorithm known as a Fast Fourier Transform (FFT). This gives a value for each narrow band of frequencies that represents how much of those frequencies are present in the sound. All the values are then interpolated to create the graph. Shown in Figure 3.6 is an example of the plot spectrum in Audacity.

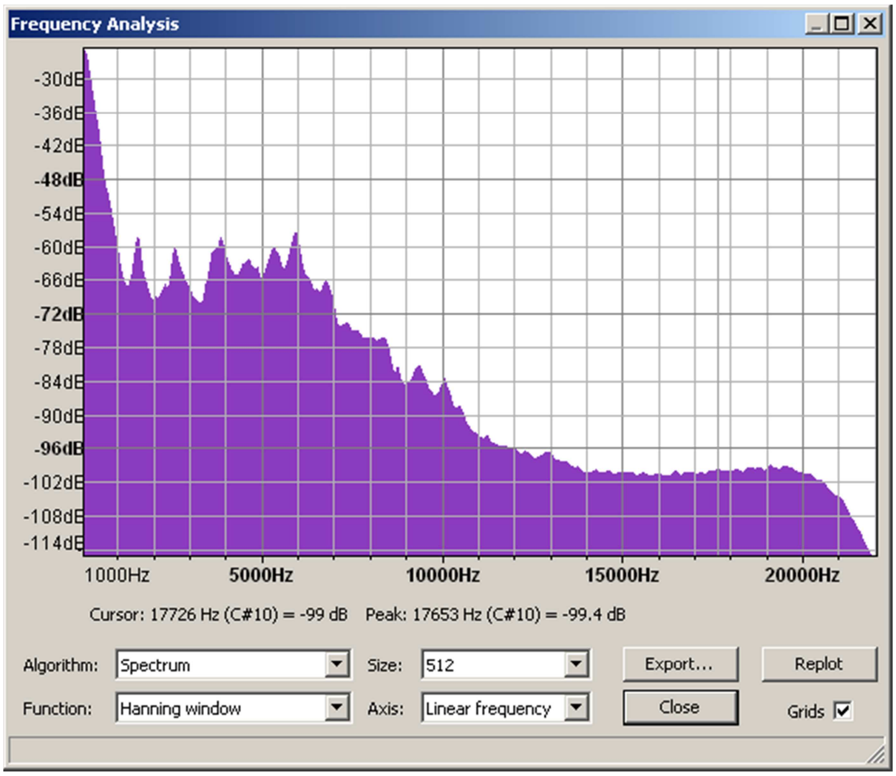


Figure 3.6: Example of the Power Spectrum in Audacity.

A total of 4096 sampling frequency sampling bins were chosen. This was done in order to obtain a range of frequencies from 0 Hz.

Once the frequency spectrum had been obtain from Audacity, the frequency and SPL were exported to MS Excel. Plots of the relative SPL as a function of frequency were obtained for each wind turbine. During each sound recording the wind speed, temperature and time of day were collected. These measures were recorded using the Kestrel 4500 Pocket Weather Tracker.

Additional analysis included in this study was the fitting of the yearly wind speed data to a Weibull distribution. Weibull distribution is the most commonly used distribution that is fitted to wind speed data. This analysis was done to determine the distribution of wind speeds found at the CER. A wind rose plot will be used to demonstrate the wind direction in the PE region.

3.5 Conclusion

This chapter discusses the methodology for the experimental design and the frequency analysis. This chapter also gives detailed descriptions of the sites under evaluation in order to determine the differences between sound sources at each site. Also included are the techniques used for the statistical analysis.

Chapter 4

Results and Discussion

The results in Chapter 4 refer to the data that was collected during the randomised experiment. The methodologies discussed in Chapter 3 were used to analyse the data. The descriptive statistical analysis is given in Section 4.1 with results presented in tabular and graphical form followed by discussion. The analysis and discussion of the results from the GLM's that were fitted to the average sound level data are presented in Section 4.2.

4.1 Descriptive statistics

A basic descriptive analysis of the quantitative variables was done in STATISTICA 10. The analysis was presented numerically and graphically. The variables defined as quantitative measures were:

- The average decibel (dBA) measurement.
- Wind speed (m/s).

All descriptive statistics results are for the distance one data. A similar pattern for distance two results were observed hence it was not reported. Presented in Table 4.1 are the descriptive analysis results of decibel measurements at the seven sites under evaluation.

Table 4.1: Descriptive statistics.

	Street	**Horizontal wind turbine**	**Beach front**	**Residential area**	**Rural**	**Vertical wind turbine**	**Ambient site of the vertical wind turbine**
Mean (dBA)	65.99	62.39	60.49	50.91	48.37	46.12	43.80
Trimmed Mean (25%) (dBA)	65.97	62.25	60.33	50.93	47.58	45.52	43.94
Median (dBA)	66.91	62.62	60.00	50.24	46.33	44.60	43.15
Sample Size (n)	16	16	16	16	16	15	16

Table 4.1 indicates that the street had the highest average decibel reading of 65.99 dBA. The sound levels from the traffic were influenced by heavy trucks using the street, the speed of vehicles travelling in the vicinity and the change in engine speeds for traffic lights, hills and intersecting roads. This street is used by heavy trucks during the day and has a busy traffic intersection with traffic lights. These factors influence the average sound levels present at the site.

The horizontal axis wind turbine had an average decibel reading of 62.39 dBA. This was the second highest average sound level found across the sites. Although the microphone was in close proximity to the wind turbine, the surrounding sounds of traffic, pedestrians and beach activity could have contributed to the readings. However it was noted that the wind turbine made sounds that can be described as a “whoosing” and “swishing” sound. This type of sound can be characterised as an aerodynamic sound. Aerodynamic sounds are produced by the interaction between the blades of the wind turbine and the air flow around the blades. These sounds would have also been captured when taking the measurements.

The lowest average decibel reading was the ambient sound level at the vertical axis wind turbine site. This result was surprising as the rural site was expected to have the lowest sound level readings. However, the rural site measurement position was situated near several trees and bushes. An increase in wind speeds could have increased the noise levels due to the moving of the leaves of the trees and bushes. Also the ambient measurement for the vertical axis wind turbine was situated at the CER which consists of buildings and other structures. These buildings and structures influenced noise propagation paths and most likely dampened the sound levels recorded.

The second lowest average decibel reading was found at the vertical axis wind turbine with an estimated sound level of 46.12 dBA. The ambient reading at this site had the lowest average decibel estimate overall. The vertical axis wind turbine mean estimate of 46.12 dBA indicates a 2.32 dBA increase in sound levels at this site. This increase was less than the 7 dBA upper limit of the NMMM noise regulations. This result lends support to the installation of vertical axis wind turbines as the noise level increase is less than the allowed increase.

The beach front site had the third highest average sound level of 60.49 dBA. This estimate of the mean sound level is similar to the estimated mean sound level at the horizontal axis wind turbine and the street. This implies that the noise generated by the horizontal axis wind turbine could be masked by the beachfront noise if placed in close proximity to the shore line.

The residential site had an average sound level of 50.91 dBA. This average sound level was similar to the estimated mean sound levels at the rural, vertical and ambient sites implying that installing horizontal axis wind turbines could increase the noise levels in residential areas. The vertical axis wind turbine indicated an increase of 2.32 dBA in a relatively quiet environment. Therefore, ambient sound levels of a residential area may be able to mask the noise levels generated by a vertical axis wind turbine. This is a useful result for those advocating the installation of micro-wind turbines in residential areas.

Table 4.2 shows the variance and standard deviation of sound levels recorded at the seven sites under evaluation.

Table 4.2: Variance and standard deviation of the decibel measurements at the seven sites under evaluation.

	Street	**Horizontal wind turbine**	**Beach front**	**Residential area**	**Rural**	**Vertical wind turbine**	**Ambient site of the vertical wind turbine**
Variance $(dBA)^2$	14.10	17.77	25.61	17.24	60.79	36.21	23.16
Standard Deviation (dBA)	3.75	4.22	5.06	4.15	7.80	6.02	4.81

The estimated variance of the sound readings at the rural site is 60.79 $(dBA)^2$. This value is considerably greater than the next highest estimated variance of 36.21 $(dBA)^2$ at the vertical axis wind turbine site. This result was not surprising as the rural site is quiet and any external sound in the environment has a big influence on the recordings. The outside influences that could have affected the readings are high wind speeds, moving of the decibel reader or even moving trees or bushes. The 25 % trimmed mean of 47.58 dBA did not differ much from the mean sound level of the rural site. This indicates that although there may have been external influences, these influences did not affect the average decibel level a great deal.

The street site had the lowest variability estimate of 14.10 $(dBA)^2$ which indicated that the sound levels at the street remains constant and relatively loud at 65.99 dBA. Both the horizontal axis wind turbine and residential site had relatively low variability of 17.77 $(dBA)^2$

and 17.24 $(dBA)^2$ respectively, indicating that the average sound levels at these sites were relatively constant. This observation is supported by the 25% trimmed mean for both sites. The trimmed means differ negligibly from the estimated average sound level obtained.

The vertical axis wind turbine had a large variance of 36.21 $(dBA)^2$. Wind turbine sounds vary with wind speeds. Therefore any changes in wind speeds would affect the noise of the wind turbine causing variability in noise recordings. Given that the mean decibel recording of the vertical axis wind turbine is one of the lowest, it is likely that the volatile wind speeds adversely affect the variability of the measurements. In addition the changes were amplified because of the low mean decibel level.

The beach front had a moderately high variance of 25.61 $(dBA)^2$. This site has sound levels that are most likely affected by wind speeds and beach visitors. The data set had one missing observation. This is seen on Table 4.1, under the vertical axis wind turbine column. The missing sample measurement occurred at 08h00. The reason a measurement was not obtained was a malfunction of the vertical axis wind turbine.

Figure 4.1 is a graphical representation of the mean decibel recordings for the seven sites at the four different times. The graph indicates that the sound levels at the residential site, ambient site of the vertical axis wind turbine, the vertical axis wind turbine site and the rural environment are lower than the other three sites. Figure 4.1 shows that the average sound levels at the vertical axis wind turbine were lower than the residential area. This is a very interesting result. This indicates that the existing noise in the residential areas is sufficiently noisy to potentially mask any noise created by the vertical axis wind turbine. This means installing a vertical axis wind turbine in a residential area may not increase the noise pollution, as is often argued.

As discussed in the literature review, environments with high sound levels may have the ability to mask wind turbine noise. This masking may decrease the perception of noise irritability of wind turbines. The sites with the highest sound levels are the street and the beachfront. This suggests these sites are potentially good environments in which to place horizontal axis wind turbines.

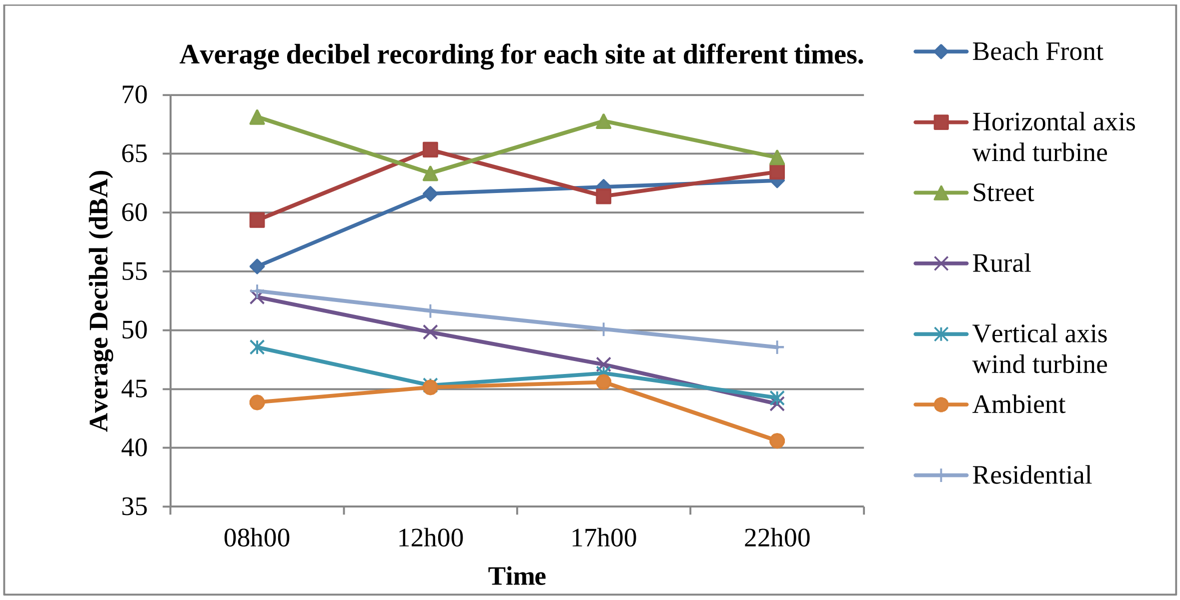


Figure 4.1: The average decibel recordings for each site across the four different times.

Figure 4.2 is a graphical representation of the mean decibel recordings for the four different time periods. Figure 4.2 shows that the average sound levels are the lowest in the evenings at 22h00. This is not surprising as there is a decrease in traffic noise, construction noise, wind speed and human activity at this time. The average sound levels across the remaining three time periods are very similar.

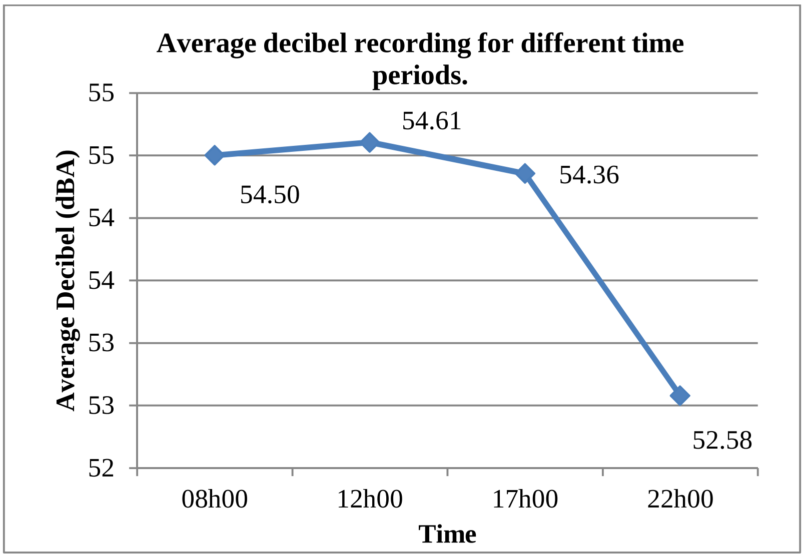


Figure 4.2: The average decibel recording for the different time periods.

Figure 4.3 is a graphical representation of the mean decibel recordings for the different wind directions. It is observed that the lowest sound level occurs when wind direction is in the Northerly direction. The 95% confidence intervals for the means are illustrated with vertical bars. These intervals demonstrate that there is overlap in mean decibel recordings for three of the four wind directions. In particular West, South and East have intervals which cover their respective mean estimates.

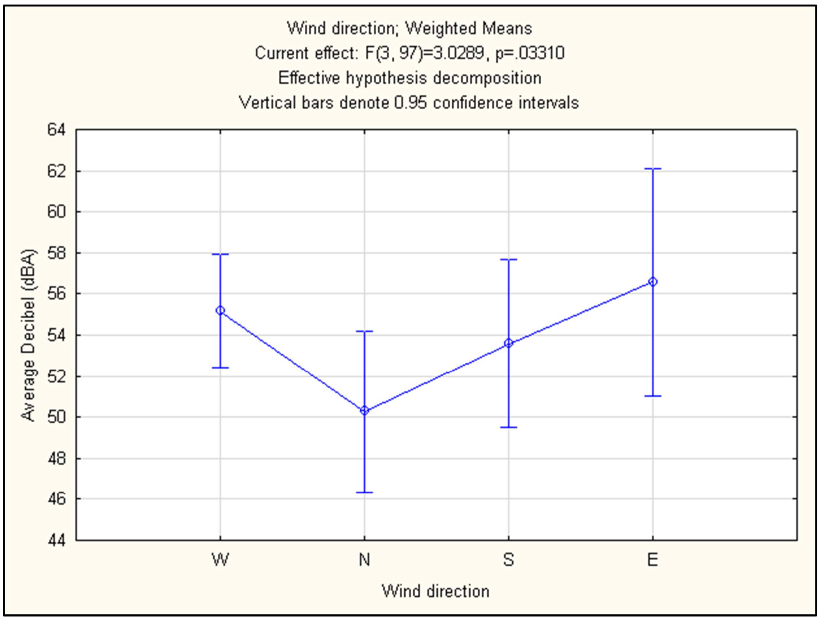


Figure 4.3: The average decibel recording for the different wind directions.

Figure 4.4 shows a pie chart representing the percentage distribution of wind direction data collected during the experiment. Approximately 44 % of the time the wind direction was found to be coming from the Westerly direction. The highest sound levels were found for winds coming from the Easterly direction (Figure 4.3). Figure 4.4 shows that during the experiment wind direction from the East occurred 14 % of the time.

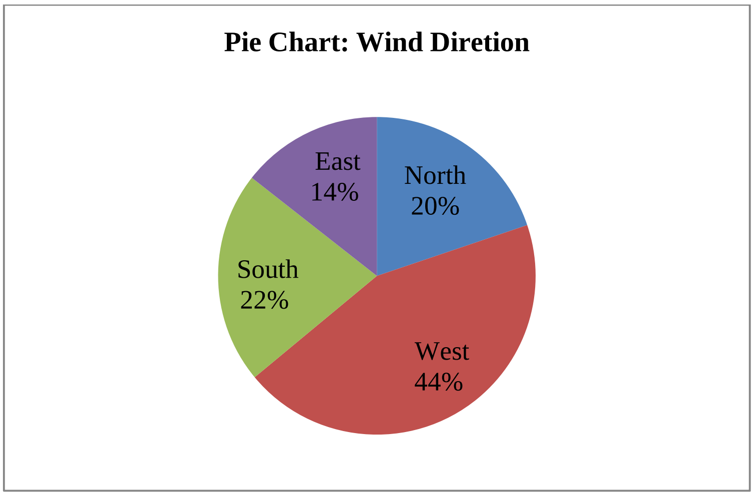


Figure 4.4: Pie chart of percentage distribution of average wind direction.

The summarised statistics in Table 4.3 included measures of central location and variability. The table provides numerical descriptive statistics for wind speeds (m/s) measured during the course of the experiment.

Table 4.3: Descriptive statistics for wind speed data.

	Wind Speed
Sample size (n)	111
Mean (m/s)	3.98
Median (m/s)	3.58
Min (m/s)	0.45
Max (m/s)	10.73
Variance $(m/s)^2$	5.77
Standard Deviation (m/s)	2.40
Standard Error (m/s)	0.23
Skewness	0.55
Kurtosis	-0.34

The average wind speed recorded was 3.98 m/s. Most micro-wind turbines cut-in wind speed is between 1 m/s to 3 m/s. This implies that most micro-wind turbine blades start turning at wind speeds found in this range. The mean wind speed for a site is critical to the feasibility of wind turbine development at a site. This is because the power of the wind varies with the cube of the wind speed. For example, a 6 % increase in wind speed would result in an increase of 20 % in power available in the wind. Therefore, the average wind speed calculated during the experiment shows that the wind speeds are sufficient for micro-wind turbine applications in the Summerstrand, PE region. It is important to note that these results are based on the experimental data, for a more reliable average wind speed estimate it is recommend that the average wind speed is calculated over a year.

The estimated variance of the average wind speeds was found to be 5.77 $(m/s)^2$. This value is believed to be significantly high. This large variance in wind speeds is also observed by the large range of wind speeds, found to be between 0.45 m/s and 10.73 m/s.

The positive skewness of 0.55 for the average wind speed indicates that the distribution is skewed to the right. This is also graphically illustrated in the frequency response histogram in Figure 4.5. Figure 4.5 is a histogram which represents the mean wind speeds that were recorded during the experiment. The coefficient of kurtosis is a measure of the weight given to the tails of a distribution. The measure of kurtosis for the wind speed was found to be - 0.34. This value indicates that there is a slight weight given to the tails of the distribution. This weight given in the tails of the distribution also shows that the spread of wind speeds found across the 70 days is large.

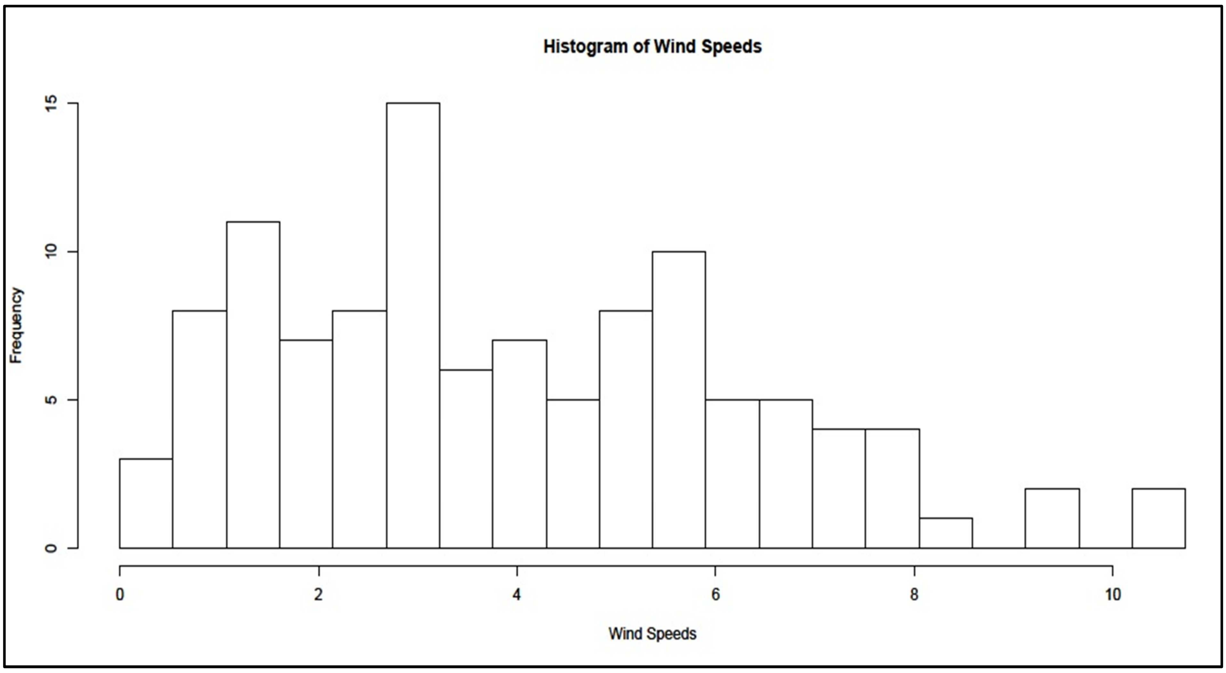


Figure 4.5: Frequency response histogram of the average wind speeds.

In summary, the descriptive statistics lend support to groups advocating the installation of micro-wind turbines. In particular, installation of vertical axis micro-wind turbines does not increase noise pollution excessively. This is potentially the case in quiet residential areas or well as noisy areas. Horizontal axis micro-wind turbines could potentially be masked in more noisy environments such as busy streets and busy beach front areas.

4.2 General linear model

To assess the noise level of wind turbines, general linear models were used. The models compare the response variable, the average sound measurement, at the different sites and the results are interpreted as noise comparisons. The linear models were also used to identify which variables influence the sound levels. The coding displayed in Appendix B, Table B.1 was assigned to the qualitative variables used in the model.

The flow chart in Figure 4.6 provides a simple schematic representation of the analysis route followed in the experiment.

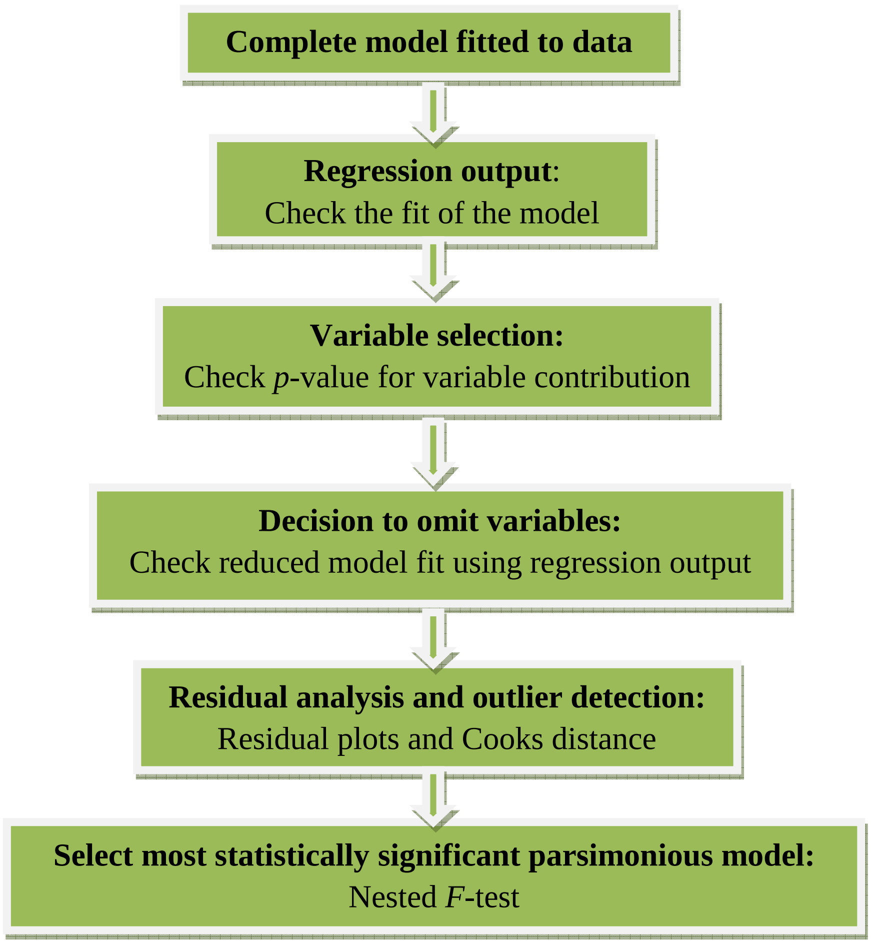


Figure 4.6: Analysis route for the experiment.

4.2.1 Model one

The following model was fitted to the sound level data:

$$y = \beta_0 + \underbrace{\beta_1 x_1}_{windspeed} + \underbrace{\beta_2 x_2 + \ldots + \beta_7 x_7}_{site} + \underbrace{\beta_8 x_8 + \ldots + \beta_{10} x_{10}}_{time} + \underbrace{\beta_{11} x_{11}}_{distance}$$
$$+ \underbrace{\beta_{12} x_{12} + \ldots + \beta_{14} x_{14}}_{direction} + \varepsilon$$

with y, the response variable, the average decibel measurement (dBA). The independent quantitative variable, x_1 = wind speed (m/s), and the independent qualitative variables site, time, wind direction and distance coded as binary response variables. The seven sites are coded as

$$x_2 = \begin{cases} 1 & if \quad Beach\ Front \\ 0 & otherwise \end{cases}, \quad x_3 = \begin{cases} 1 & if \quad Horizontal\ axis\ wind\ turbine \\ 0 & otherwise \end{cases},$$

$$x_4 = \begin{cases} 1 & if \quad Ambient\ site \\ 0 & otherwise \end{cases}, \quad x_5 = \begin{cases} 1 & if \quad Vertical\ axis\ wind\ turbine \\ 0 & otherwise \end{cases},$$

$$x_6 = \begin{cases} 1 & if \quad Rural\ site \\ 0 & otherwise \end{cases}, \text{ and } x_7 = \begin{cases} 1 & if \quad Street \\ 0 & otherwise \end{cases}$$

with the residential site used as the base level.

The four time periods are coded as

$$x_8 = \begin{cases} 1 & if \quad 08h00 \\ 0 & otherwise \end{cases}, \quad x_9 = \begin{cases} 1 & if \quad 12h00 \\ 0 & otherwise \end{cases}, \text{ and } x_{10} = \begin{cases} 1 & if \quad 17h00 \\ 0 & otherwise \end{cases}$$

with 22h00 used as the base level.

The two distance measures are coded as

$$x_{11} = \begin{cases} 1 & if \quad Distance\ one \\ 0 & otherwise \end{cases}$$

with distance two used as the base level.

The four directions are coded as

$$x_{12} = \begin{cases} 1 & if \quad West \\ 0 & otherwise \end{cases}, \quad x_{13} = \begin{cases} 1 & if \quad North \\ 0 & otherwise \end{cases}, \text{ and } x_{14} = \begin{cases} 1 & if \quad South \\ 0 & otherwise \end{cases}$$

with East used as the base level.

This model was fitted to 222 data points using the statistical software package STATISTICA 10. The complete results of the fitted model are given in Appendix B, Table B.2, with selective results shown in the accompanying tables. In Table 4.4 are the goodness-of-fit measures of model one, as well as the significance level of the models’ overall fit.

Table 4.4: Goodness-of-fit statistics for model one.

Multiple R	**Multiple R^2**	**Adjusted R^2_a**	**F**	**p**
0.8707	0.7582	0.7418	46.3555	0.0000

The coefficient of correlation (R), coefficient of determination (R^2) and adjusted coefficient of determination (R^2_a) are 0.8707, 0.7582 and 0.7418 respectively. These statistics all indicate a good fit for the model. The *F*-test to determine the utility of the model had a statistically significant *p*-value of 0.00. This small *p*-value indicated that the model was useful for predicting the average sound level based on the independent variables used.

The effects of the individual factors are shown in Table 4.5. The significance of the factor was shown by the *p*-value in the table. Commonly used levels of significance are 1 %, 5 % and 10 %. These are typically referred to as strong significance, significant and weakly significant respectively. The results in Table 4.5 indicate that wind speed, site and wind direction are statistically significant at the 1 % level whilst time and distance are statistically insignificant at the 10 % level.

Table 4.5: Effects of individual factors for model one.

Effect	**SS**	**df**	**MS**	**F**	**p**
Intercept	111572.60	1	111572.60	5012.97	0.0000
Wind Speed (m/s)	1244.50	1	1244.50	55.91	0.0000
Site	11035.80	6	1839.30	82.64	0.0000
Time	91.90	3	30.60	1.37	0.2511
Distance	34.50	1	34.50	1.55	0.2145
Wind Direction	329.50	3	109.80	4.93	0.0024
Error	4607.20	207	22.30		

We use these results to reduce the size of the model by omitting the insignificant factors whilst simultaneously cautioning researchers to the fact that the model used did not contain interaction terms. Interaction terms can influence factor levels in such a way that a factor appears to be statistically significant yet it is the interaction between factors that create the significance. Likewise it is also possible that a factor appears to be statically insignificant yet it is an important predictor of a response variable. The reason for not including interaction terms at this stage is that the variable, wind direction is uncontrolled, which resulted in an incomplete data set hence estimation problems occurred. Logically distance from the wind turbine should be an important predictor but in this case it was found to be statistically insignificant.

The reduced model estimated for the 222 data points is given by the equation

$$y = \beta_0 + \underbrace{\beta_1 x_1}_{windspeed} + \underbrace{\beta_2 x_2 + \ldots + \beta_7 x_7}_{site} + \underbrace{\beta_{12} x_{12} + \ldots + \beta_{14} x_{14}}_{direction} + \varepsilon ,$$

with variables as previously defined.

The complete results of the fitted reduced model are given in Appendix B, Table B.3 with selected results shown in the accompanying tables. In Table 4.6 is the summary of goodness-of-fit measures of the reduced model one, as well as the significance level of the overall models' fit.

Table 4.6: Goodness-of-fit statistics for reduced model one.

Multiple R	**Multiple R^2**	**Adjusted R^2_a**	**F**	**p**
0.8669	0.7515	0.7398	63.8219	0.0000

Although there was a slight decrease in the R, R^2 and R^2_a the model still had a good fit to the average sound level data. This decrease was due to the decrease in the number of variables used in the estimated model. The *F*-test had a statistically significant *p*-value of 0.00 which indicated a good fit for the model. This small *p*-value indicated that the model was useful in predicting the average sound level based on the independent variables used.

Table 4.7: Effects of individual factors for reduced model one.

Effect	**SS**	**df**	**MS**	**F**	**p**
Intercept	125026.10	1	125026.10	5573.08	0.0000
Wind Speed (m/s)	1387.60	1	1387.60	61.85	0.0000
Site	11386.50	6	1897.80	84.59	0.0000
Wind Direction	351.60	3	117.20	5.22	0.0017
Error	4733.60	211	22.40		

The effects of the individual factors are shown in Table 4.7. The results in Table 4.7 indicate that wind speed, site and direction are all statistically significant at the 1 % level.

Although the goodness-of-fit statistics are useful when comparing models, a commonly used inferential method is the significance test of a complete model versus a reduced model. The Nested *F*-Test was used to compare the complete model to the reduced model (time and distance omitted). The following hypotheses were tested for the contribution of the time and distance variables x_8, x_9, x_{10} and x_{11}.

H_0: $\beta_8 = \beta_9 = \beta_{10} = \beta_{11} = 0$

H_1: At least one of the β parameters being tested is nonzero.

With the test statistic calculated as follows

$$F = \frac{(SSE_r - SSE_c)/(k-g)}{(SSE_c)/(n-(k+1))} = \frac{(4733.56 - 4607.15)/(14-10)}{4607.15/(222-15)} = 1.40.$$

The critical value *F* for $\alpha = 0.05$, $v_1 = 4$, and $v_2 = 207$, was calculated in Microsoft excel 2007 as $F_{0.05} = 2.42$. Since the test statistic value *F*=1.40 does not exceed 2.42, we do not reject H_0 and conclude that the reduced model, with factors site and wind direction and covariate wind speed, contribute best to the prediction of *y*, the average decibel.

Throughout the experimental period it was noticed that when collecting recordings, irregular external noises were common. As an example, when capturing sound measurements at the street site, taxi hooting was not uncommon. To counter these occurrences it was considered prudent to test for outliers in the data.

A residual plot was used to observe whether outliers were present in the sound level data. The residual plot for the reduced model is given in Figure 4.7. Two residuals were identified as potential outliers and these observations were then tested using Cooks distance.

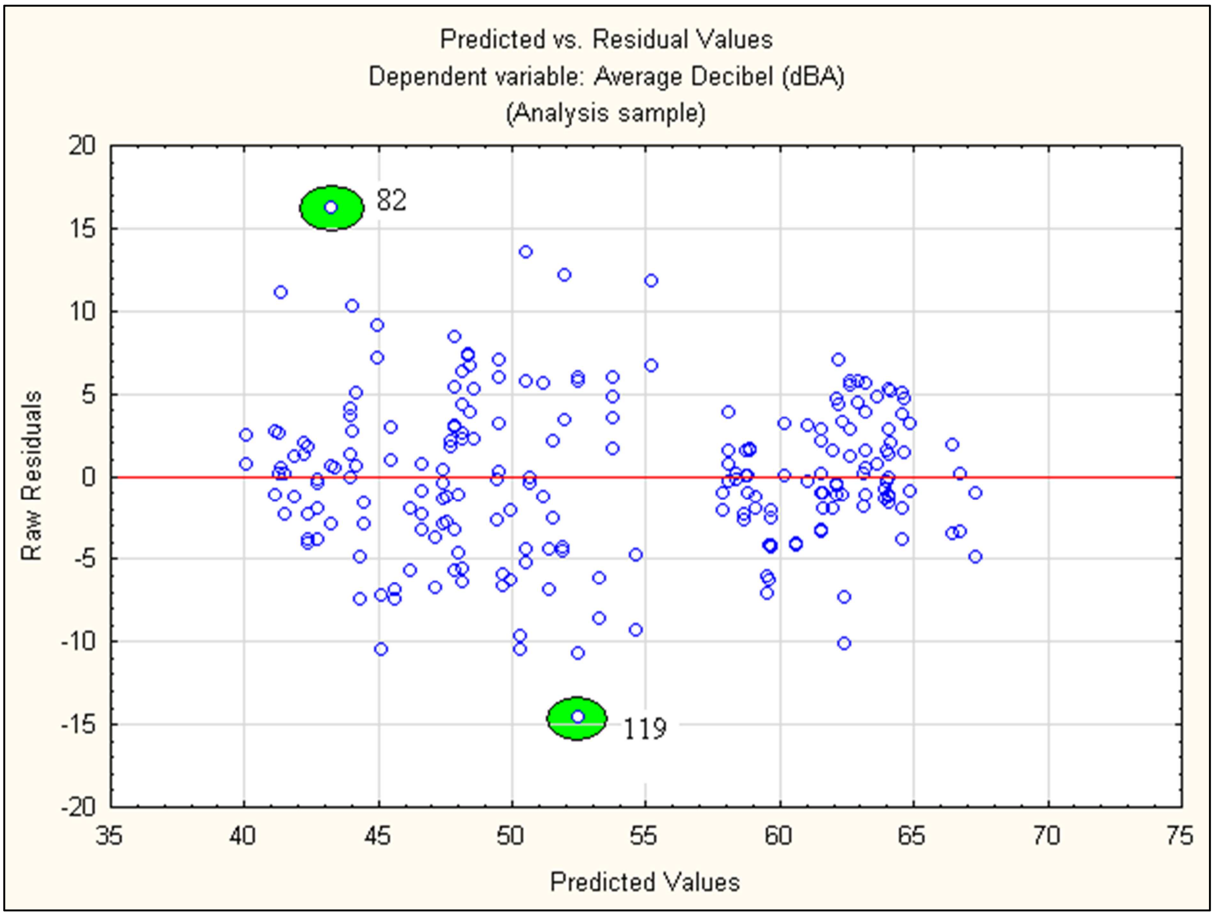


Figure 4.7: Residual plot for potential outlier detection.

The values for Cooks distance for the two data points are given in Table 4.8.

Table 4.8: Cooks distance for potential outliers.

Case number	Cooks distance
119	0.0843
82	0.0574

Mendenhall and Sincich (2006) suggested a cut off identification of 1.0 when trying to identify outliers using Cooks distance. The values for Cooks distance showed that the identified observations were not outliers as the Cooks distance values were smaller than the cut off value of 1.0.

To check the assumptions made about the error term (Section 3.3.2) a residual plot and normal probability plot were used. Residual plots are used to check the assumption made about the error term having constant variance and mean value of zero. Figure 4.7 indicates no clear pattern in the residual plot. This indicates that the assumption made about the error term having constant variance is satisfied. The residuals are evenly spread around zero, supporting the assumption of zero mean.

The normal probability plot was used to check the assumption made about the error term being normally distributed. In the normality plot, the residuals were graphed against the expected values of the residuals under the assumption of normality. If a linear trend on the normal probability plot is observed, it suggests that the normality assumption is satisfied. Appendix B, Figure B.1 shows the normality probability plot of the reduced model. This plot shows that the normality assumption about the error term was met.

Given we have reduced our model to the most parsimonious case and that no outliers are detected it is now opportune to consider the parameter estimation for each variable. The individual parameter estimates for the reduced model are given in Table 4.9.

Table 4.9: Parameter estimates for reduced model one.

	Average Decibel (dBA) Parameter Estimates	**Average Decibel (dBA) Std Error**	**Average Decibel (dBA) t**	**Average Decibel (dBA) p**	**- 95% Conf Lim**	**+95% Conf Lim**
Intercept	49.27	0.66	74.65	0.0000	47.97	50.57
x_1 **Wind speed**	1.21	0.15	7.87	0.0000	0.91	1.51
x_2 **Beach front**	7.45	0.79	9.45	0.0000	5.89	9.01
x_3 **Horizontal axis wind turbine**	7.39	0.79	9.39	0.0000	5.83	8.93
x_4 **Ambient site**	-8.18	0.79	-10.37	0.0000	-9.73	-6.62
x_5 **Vertical axis wind turbine**	-7.45	0.81	-9.10	0.0000	-9.04	-5.85
x_6 **Rural site**	-5.51	0.78	-7.06	0.0000	-7.04	-3.97
x_7 **Street**	9.83	0.78	12.53	0.0000	8.29	11.38
x_{12} **West**	-1.55	0.53	-2.94	0.0037	-2.59	-0.51
x_{13} **North**	1.26	0.667	1.89	0.0607	-0.05	2.57
x_{14} **South**	-1.38	0.61	-2.25	0.0254	-2.59	-0.17

The intercept represents the average sound level response for the base level variables. The estimated parameter for wind speed indicates that for every 1 m/s increase of wind speed there will be 1.21 increase in the average sound level if all other variables are fixed. To interpret the parameter estimates, two examples will be discussed.

The parameter estimate for variable x_4 is -8.18. This is the smallest estimate for all the parameters. This estimate is the difference between the estimated mean sound level for the ambient site and the mean base level when all other factors are fixed. The negative value indicates a site of low sound levels. This estimate (-8.18) is interpreted as follows: the mean sound level recording at the ambient site is 8.18 dBA less than the residential site when all other factors are fixed. This mean response for the ambient measurement for the vertical axis micro-wind turbine site confirms what has already been shown in section 4.1; that the site has very low sound levels compared to the other six sites.

Variable x_7 had a parameter estimate of 9.83. This is the largest estimate of all the parameters. This estimate is the difference between the estimated mean sound level for the street and the mean base level for when all other factors are fixed. The positive value indicates a site of high sound levels. This estimate (9.83) is interpreted as follows: the mean sound level recording at the street is 9.83 dBA higher than the residential site when all other factors are fixed. This mean response for the street confirms what has already been shown in section 4.1; that the site has very high sound levels compared to the other six sites.

The *p*-values for the parameter estimates indicated that all but one of the variables in the model is statistically significant at the 5 % level. Variable x_{13} has a *p*-value slightly higher than 0.05. However the overall factor contribution was statistically significant and wind direction was found to be a useful predictor.

The conclusion of the statistical analysis is that the reduced model is preferred to the complete model. The factors wind speed, site and wind direction were found to be significant predictors of the average sound level. Surprisingly, the factors time and distance were found to be statistically insignificant, however as discussed earlier this could be a result of interaction effects.

To determine the statistical significance between the average sound level for the different times and distances, Bonferroni statistics were calculated for the complete model. The Bonferroni *p*-values of the statistics are shown in Table 4.10.

Table 4.10: Bonferroni *p*-values for time comparisons.

Time:	**08h00** **Avg Dec.** **54.72 dBA**	**12h00** **Avg Dec.** **54.61 dBA**	**17h00** **Avg Dec.** **54.36 dBA**	**22h00** **Avg Dec.** **52.58 dBA**
08h00		1.0000	1.0000	0.2432
12h00	1.0000		1.0000	0.0429
17h00	1.0000	1.0000		0.5825
22h00	0.2432	0.0429	0.5825	

The *p*-values for the Bonferroni statistics indicated that there was a statistically significant difference between the average sound levels for times 22h00 and 12h00. This observation is supported by the descriptive statistics of Figure 4.2 in section 4.1.

The *p*-values for the Bonferroni statistics for distance are shown in Table 4.11.

Table 4.11: Bonferroni *p*-values for distance comparisons.

Distance	**Distance 1** **Avg Dec.** **54.06 dBA**	**Distance 2** **Avg Dec.** **53.27 dBA**
1		0.2145
2	0.2145	

The *p*-value for the Bonferroni statistics indicated that there is no statistical significant difference between the average sound level for distance one and distance two.

The problem now investigated is the case of interaction effects as previously highlighted. Interaction terms can influence factor levels in such a way that a factor appears to be statistically significant and/or insignificant. The analysis approach for factorial experiments advocated in standard texts such as Mendenhall and Sincich (2006), Devore and Peck(1993) and Steyn, Smit, du Toit and Strasheim (2007) is first to test for interaction. If interaction is present then tests for individual factors are avoided and instead individual treatment tests are conducted. The problem with this experiment is the uncontrolled variable wind speed (and hence wind direction) which theory and results from model one indicate are important predictors of the response variable.

In model one, this study avoided interaction terms, however, it is important to determine whether or not interaction is present in the experiment. The following analysis takes cognisance of the importance of interaction and provides qualified assessment on the data.

To test whether interaction was present between factors the following model was fitted to the sound level data

$$y = \beta_0 + \underbrace{\beta_1 x_1}_{wind\ speed} + \underbrace{\beta_2 x_2 + \ldots + \beta_7 x_7}_{site} + \underbrace{\beta_8 x_8 + \ldots + \beta_{10} x_{10}}_{time} + \underbrace{\beta_{11} x_{11}}_{distance} + \underbrace{\beta_{12} x_{12} + \ldots + \beta_{14} x_{14}}_{direction}$$

$$+ \underbrace{\beta_{15} x_2 x_8 + \ldots + \beta_{71} x_{11} x_{14}}_{two-way-interaction} + \underbrace{\beta_{72} x_2 x_8 x_{11} + \ldots + \beta_{170} x_2 x_8 x_{11}}_{three-way-interaction}$$

$$+ \underbrace{\beta_{170} x_2 x_8 x_{11} x_{12} + \ldots + \beta_{224} x_7 x_{10} x_{11} x_{14} + \varepsilon}_{four-way-interaction},$$

with variables as previously defined.

This model was fitted to 222 data points using the statistical software package STATISTICA 10. This model included both two-way, three-way and four-way interaction terms. STATISTICA gave an incomplete fit to the model, due to the lack of sample data. This model was ill conditioned because of insufficient data for some interactions. Upon investigation it was noticed that there was no data for the interactions between a number of variables and the wind direction variables. To continue it was necessary to omit the wind direction variable from the model.

The reduced model estimated for the 222 data points is given by the equation

$$y = \beta_0 + \underbrace{\beta_1 x_1}_{windspeed} + \underbrace{\beta_2 x_2 + \ldots + \beta_7 x_7}_{site} + \underbrace{\beta_8 x_8 + \ldots + \beta_{10} x_{10}}_{time} + \underbrace{\beta_{11} x_{11}}_{distance}$$

$$+ \underbrace{\beta_{15} x_2 x_8 + \ldots + \beta_{40} x_{10} x_{11}}_{two-way-interaction} + \underbrace{\beta_{41} x_2 x_8 x_{11} + \ldots + \beta_{58} x_7 x_{10} x_{11}}_{three-way-interaction} + \varepsilon,$$

with variables as previously defined.

The results of the fitted reduced model are given in Appendix B, Table B.4 with selective results shown in the accompanying table. In Table 4.12 is the summary of the goodness-of-fit measures for reduced model one including interaction terms, as well as the significance level of the models' overall fit.

Table 4.12: Goodness-of-fit statistics for reduced model one with interaction terms.

Multiple R	**Multiple R^2**	**Adjusted R^2_a**	**F**	**p**
0.8937	0.7987	0.7304	11.6929	0.0000

The coefficient of correlation (R), coefficient of determination (R^2) and adjusted coefficient of determination (R^2_a) are 0.8937, 0.7987 and 0.7304 respectively. These statistics all indicate a good fit for the model. The *F*-test to determine the utility of the model had a statistically significant *p*-value of 0.00. This small *p*-value indicated that the model was useful for predicting the average sound level based on the independent variables used.

The effects of the individual factors are shown in Table 4.13. The significance of the factor is shown by the *p*-value in the table. The results in Table 4.13 indicate that distance and interaction terms including distance were statistically insignificant. We use this result to reduce the size of the model by omitting distance as a factor.

Table 4.13: Effects of individual factors for reduced model one with interaction terms.

Effect	**SS**	**df**	**MS**	**F**	**p**
Intercept	90472.90	1	90472.90	3893.18	0.0000
Wind Speed (m/s)	1101.07	1	1101.07	47.38	0.0000
Site	10607.26	6	1767.88	76.07	0.0000
Time	156.60	3	52.20	2.24	0.0848
Distance	37.06	1	37.06	1.60	0.2084
Site*Time	828.14	18	46.01	1.98	0.0133
Site*Distance	126.59	6	21.10	0.908	0.4907
Time*Distance	18.95	3	6.32	0.272	0.8456
Site*Time*Distance	129.99	18	7.22	0.311	0.9971
Error	3834.40	165	23.24		

The reduced model (excluding wind direction and distance) estimated for the 222 data points is given by the equation

$$Y = \beta_0 + \underbrace{\beta_1 x_1}_{windspeed} + \underbrace{\beta_2 x_2 + \ldots + \beta_7 x_7}_{site} + \underbrace{\beta_8 x_8 + \ldots + \beta_{10} x_{10}}_{time} + \underbrace{\beta_{15} x_2 x_8 + \ldots + \beta_{28} x_7 x_{10}}_{two-way-interaction} + \varepsilon$$

with variables as previously defined.

The complete results of the fitted reduced model are given in Appendix B, Table B.5 with selected results shown in the accompanying table. In Table 4.14 is the summary of goodness-of-fit measures for the reduced model one including interaction, as well as the significance level of the models overall fit.

Table 4.14: Goodness-of-fit statistics for reduced model one including interaction terms.

Multiple R	**Multiple R^2**	**Adjusted R^2_a**	**F**	**p**
0.8846	0.7825	0.7509	24.8034	0.0000

Although there was a slight decrease in the R and R^2 and an increase in the R^2_a the model still indicated a good fit to the average sound level data. The decrease was due to the decrease in the number of variables used in the estimated model whilst the increase was due to the penalty term for additional variables. The *F*-test had a statistically significant *p*-value of 0.00 which indicated a good fit for the model. This small *p*-value indicated that the model was useful in predicting the average sound level for the various independent variables.

The effects of the individual factors are shown in Table 4.15. The significance of the factor is shown by the *p*-value in the table.

The results in Table 4.15 indicate that wind speed, site and site*time interactions are all statistically significant at the 1 % level. While the time factor was statistically significant at the 10 % level only. Time was not removed from the model; as if time were removed there would be no interaction present in the model.

Table 4.15: Effects of individual factors for reduced model one including interaction terms.

Effect	SS	df	MS	F	p
Intercept	90472.90	1	90472.90	4214.66	0.0000
Wind Speed (m/s)	1101.07	1	1101.07	51.29	0.0000
Site	10607.26	6	1767.88	82.36	0.0000
Time	156.60	3	52.20	2.43	0.0664
Site*Time	828.14	18	46.01	2.14	0.0059
Error	4143.01	193	21.47		

Although the goodness-of-fit statistics are useful when comparing models, the Nested *F*-Test was used to compare the complete model to the reduced model (distance omitted). The model including distance (omitted wind direction variable) was compared to the model excluding distance (with omitted wind direction variable). The following hypotheses were tested for the contribution of the distance variables.

H_0: All parameters containing the distance variable = 0

H_1: At least one of the parameters being tested is nonzero

With the test statistic calculated as follows

$$F = \frac{(SSE_r - SSE_c)/(k-g)}{(SSE_c)/(n-(k+1))} = \frac{(4143.01 - 3834.40)/(28)}{3834.40/(222-57)} = 0.47$$

The critical value F for $\alpha = 0.05$, $v_1 = 28$, and $v_2 = 207$, was calculated in Microsoft excel 2007 as $F_{0.05} = 1.6$. Since the test statistic value F=0.47 does not exceed 1.6, we do not reject H_0 and conclude that the reduced model with factors site, wind speed and time including interactions between site and time, contributes best to the prediction of y, the average decibel.

A residual plot was again used to observe whether outliers were present in the sound level data and to check the assumptions made about the error term. The residual plot for the reduced model is given in Figure 4.8. Two residuals were identified as potential outliers and these observations were then tested using Cooks distance.

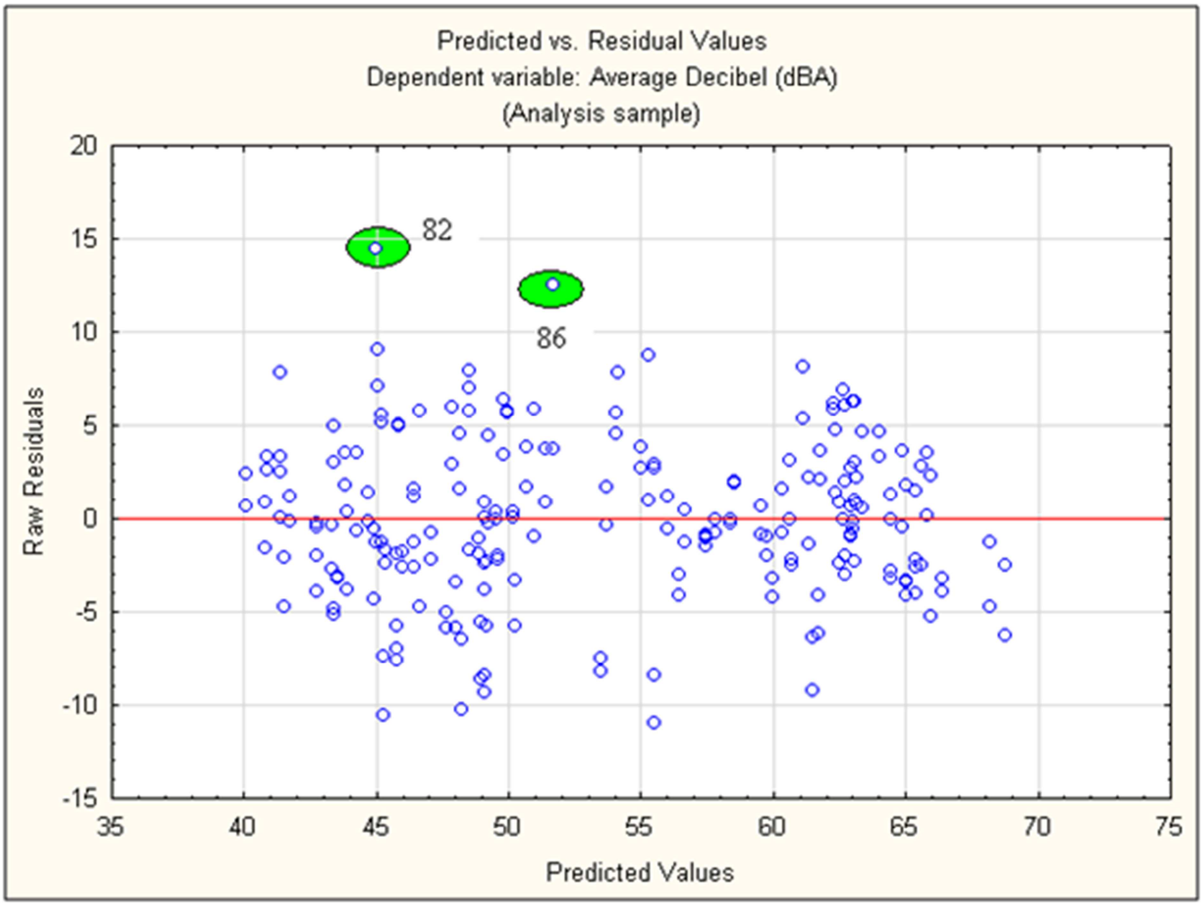


Figure 4.8: Residual plot for potential outlier detection.

The values for Cooks distance for the two data points are given in Table 4.16.

Table 4.16: Cooks distance for potential outliers.

Case number	Cooks distance
82	0.0553
86	0.0513

The values for Cooks distance showed that the identified observations were not outliers as the Cooks distance values were smaller than the cut off value of 1.0.

To check the assumptions made about the error term (Section 3.3.2) a residual plot and a normal probability plot was used. Figure 4.8 indicates no clear pattern in the residual plot. This indicates that the assumption made about the error term having constant variance is satisfied. The residuals are evenly spread around zero, supporting the assumption of zero mean.

The normal probability plot was used to check the assumption made about the error term being normally distributed. In the normality plot, the residuals were graphed against the expected values of the residuals under the assumption of normality. Appendix B, Figure B.2 shows the normality probability plot of the reduced model. The plot indicates that the normality assumption about the error term is met.

Given the reduced model is the most parsimonious case and that no outliers are detected it is now opportune to consider the parameter estimation for each variable. The individual parameter estimates for the reduced model are given in Table 4.17.

Table 4.17: Parameter estimates for reduced model one.

	Average Decibel (dBA) Parameter Estimates	**Average Decibel (dBA) Std Error**	**Average Decibel (dBA) t**	**Average Decibel (dBA) p**	**- 95% Conf Lim**	**+95% Conf Lim**
Intercept	48.71	0.75	64.92	0.0000	47.23	50.19
x_1 Wind speed	1.24	0.17	7.16	0.0000	0.89	1.57
x_2 Beach front	6.97	0.76	9.16	0.0000	5.47	8.47
x_3 Horizontal axis wind turbine	7.25	0.77	9.44	0.0000	5.73	8.76
x_4 Ambient site	-7.90	0.77	-10.28	0.0000	-9.41	-6.38
x_5 Vertical axis wind turbine	-7.08	0.79	-8.92	0.0000	-8.64	-5.51
x_6 Rural site	-5.65	0.76	-7.45	0.0000	-7.15	-4.16
x_7 Street	9.72	0.77	12.61	0.0000	8.20	11.24
x_8 08h00	1.55	0.58	2.68	0.0078	0.41	2.68
x_9 12h00	-0.60	0.58	-1.03	0.3021	-1.75	0.54
x_{10} 17h00	-0.73	0.55	-1.32	0.1867	-1.81	0.35
x_2 Beach front x_8 08h00	-5.19	1.32	-3.94	0.0001	-7.79	-2.59
x_2 Beach front x_9 12h00	0.97	1.32	0.75	0.4553	-1.61	3.58
x_2 Beach front x_{10} 17h00	2.29	1.31	1.75	0.0823	-0.29	4.88
x_3 Horizontal axis wind turbine x_8 08h00	-2.84	1.32	-2.16	0.0324	-5.43	-0.24
x_3 Horizontal axis wind turbine x_9 12h00	2.49	1.32	1.88	0.0608	-0.11	5.09

x_3 Horizontal axis wind turbine x_{10} 17h00	-1.28	1.31	-0.97	0.3360	-3.85	1.32
x_4 Ambient site x_8 08h00	1.73	1.32	1.31	0.1906	-0.86	4.33
x_4 Ambient site x_9 12h00	-1.23	1.34	-0.92	0.3599	-3.87	1.41
x_4 Ambient site x_{10} 17h00	0.57	1.31	0.43	0.6658	-2.02	3.15
x_5 Vertical axis wind turbine x_8 08h00	2.35	1.47	1.60	0.1107	-0.54	5.24
x_5 Vertical axis wind turbine x_9 12h00	-0.76	1.34	-0.57	0.5698	-3.39	1.87
x_5 Vertical axis wind turbine x_{10} 17h00	-1.84	1.35	-1.36	0.1752	-4.51	0.83
x_6 Rural site x_8 08h00	2.17	1.32	1.64	0.1009	-0.43	4.77
x_6 Rural site x_9 12h00	-1.61	1.38	-1.16	0.2451	-4.34	1.11
x_6 Rural site x_{10} 17h00	0.10	1.32	0.07	0.9404	-2.51	2.70
x_7 Street x_8 08h00	-1.20	1.36	-0.88	0.3794	-3.89	1.48
x_7 Street x_9 12h00	-1.32	1.32	-0.99	0.3219	-3.93	1.29
x_7 Street x_{10} 17h00	1.07	1.31	0.81	0.4167	-1.52	3.66

The intercept represents the average sound level response for the base level variables. The estimated parameter for wind speed indicates that for every 1 m/s increase of wind speed there will be 1.24 increase in the average sound level if all other parameters are fixed. To interpret the parameters estimates, three examples will be discussed.

The parameter estimate for variable x_4 is -7.90. This is the smallest estimate of all the parameters. This estimate is the difference between the estimated mean sound level for the ambient site and the mean base level with all other factors are fixed. The negative value indicates a site of low sound levels. This estimate (-7.90) is interpreted as follows: the mean sound level recording at the ambient site is 7.90 dBA less than the residential site when all other factors are fixed. This mean response for the ambient measurement site for the vertical axis micro-wind turbine has already been shown in section 4.1 to have very low sound levels compared to the other six sites.

Variable x_7 had a parameter estimate of 9.72. This is the largest estimate of all the parameters. This estimate is the difference between the estimated mean sound level for the street and the mean base level for when all other factors are fixed. The positive value indicates a site of high sound levels. This estimate (9.72) is interpreted as follows: the mean sound level recording at the street is 9.72 dBA higher than the residential site when all other factors are fixed. This mean response for the street has already been shown in section 4.1 to have very high sound levels compared to the other six sites.

The third example that will be discussed will be the interaction between the beach front and 08h00. This interaction had a parameter estimate of -5.19. This estimate is the difference between the difference between the estimated mean sound level for the beach front and the difference for the mean sound levels at time 08h00 for all other factors fixed. The interaction between site and time indicate that omitting the time factor from model one may have been an error. However as argued previously, its removal was necessary in the main effect models as there was insufficient data for the uncontrolled variables.

The analysis from the main effects models and the interaction included effects models give confounding results. These are not surprising results as when interaction effects are present the statistical interpretations become difficult. However, the models have shown that several factors evaluated are important predictors of the response variable. As this study is a first attempt at investigating the noise of wind turbines it provides a useful starting point for future evaluations.

4.2.2 Model two: Assessment of data at distance one

Model two was used to check the results of model one. Sound level data at distance one was fitted to the following model.

$$y = \beta_0 + \underbrace{\beta_1 x_1}_{windspeed} + \underbrace{\beta_2 x_2 + \ldots + \beta_7 x_7}_{site} + \underbrace{\beta_8 x_8 + \ldots + \beta_{10} x_{10}}_{time} + \underbrace{\beta_{11} x_{11} + \ldots + \beta_{13} x_{13}}_{direction} + \varepsilon$$

with y, the response variable, the average decibel measurement (dBA). The independent quantitative variable x_1 = wind speed (m/s), and the independent qualitative variables site, time and direction coded as binary response variables. The seven sites are coded as

$$x_2 = \begin{cases} 1 & if \quad Beach\ Front \\ 0 & otherwise \end{cases}, \quad x_3 = \begin{cases} 1 & if \quad Horizontal\ axis\ wind\ turbine \\ 0 & otherwise \end{cases},$$

$$x_4 = \begin{cases} 1 & if \quad Ambient\ site \\ 0 & otherwise \end{cases}, \quad x_5 = \begin{cases} 1 & if \quad Vertical\ axis\ wind\ turbine \\ 0 & otherwise \end{cases},$$

$$x_6 = \begin{cases} 1 & if \quad Rural\ site \\ 0 & otherwise \end{cases}, \text{ and } x_7 = \begin{cases} 1 & if \quad Street \\ 0 & otherwise \end{cases}$$

with the residential site used as the base level.

The four time periods are coded as

$$x_8 = \begin{cases} 1 & if \quad 08h00 \\ 0 & otherwise \end{cases}, \ x_9 = \begin{cases} 1 & if \quad 12h00 \\ 0 & otherwise \end{cases}, \text{ and } x_{10} = \begin{cases} 1 & if \quad 17h00 \\ 0 & otherwise \end{cases}$$

with 22h00 used as the base level.

The four wind directions are coded as

$$x_{11} = \begin{cases} 1 & if \quad West \\ 0 & otherwise \end{cases}, \ x_{12} = \begin{cases} 1 & if \quad North \\ 0 & otherwise \end{cases}, \text{ and } x_{13} = \begin{cases} 1 & if \quad South \\ 0 & otherwise \end{cases}$$

with East used as the base level.

This model was fitted to 111 data points using the statistical software package STATISTICA 10. Again results showed that the time factor was statistically insignificant. This factor was omitted from the model. The results of goodness-of-fit and significance measures of both the complete and reduced (time omitted) models are shown in Table 4.18 with complete results for both models given in Appendix B, Table B.6. The effects of the individual factors for the complete model are also given in Appendix B, Table B.7.

Table 4.18: Goodness of fit statistics for model two for both complete and reduced model.

	Multiple R	**Multiple R^2**	**Adjusted R^2_a**	**F**	**p**
Complete model	0.8956	0.8021	0.7756	30.2513	0.0000
Reduced model	0.8911	0.7940	0.7734	38.5483	0.0000

The coefficient of correlation (R), coefficient of determination (R^2) and adjusted coefficient of determination (R^2_a) for the complete model was 0.8956, 0.8021 and 0.7756 respectively. These statistics all indicated a good fit for the model. The *F*-test to determine the utility of the model had a statistically significant *p*-value of 0.00. This small *p*-value indicated that the model was useful for predicting the average sound level based on the independent variables used.

Although there was a very slight decrease in the R, R^2 and R^2_a for the reduced model the model still indicated a good fit to the average sound level data. This decrease was due to the decrease in the number of variables used in the estimated model. The *F*-test had a statistically significant *p*-value of 0.00 which indicated a good fit for the model. This small *p*-value indicated that the model was useful in predicting the average sound level for the various independent variables.

The reduced model estimated for 111 data points is given by the equation

$$y = \beta_0 + \underbrace{\beta_1 x_1}_{windspeed} + \underbrace{\beta_2 x_2 + \ldots + \beta_7 x_7}_{site} + \underbrace{\beta_{11} x_{11} + \ldots + \beta_{13} x_{13}}_{direction} + \varepsilon .$$

The effects of the individual factors for the reduced model are shown in Table 4.19. The significance of the factor is shown by the *p*-value in the table. The results in Table 4.19 indicated that wind speed and site are statistically significant at the 1 % level. While wind direction is shown to be statistically significant at a 5 % level.

Table 4.19: Effects of individual factors for reduced model two.

Effect	**SS**	**df**	**MS**	**F**	**p**
Intercept	64000.00	1	64000.00	3022.70	0.00
Wind Speed (m/s)	640.23	1	640.23	30.24	0.00
Site	6497.92	6	1082.99	51.14	0.00
Direction	192.27	3	64.09	3.02	0.03
Error	2117.31	100	21.17		

The Nested *F*-Test was used to compare the complete model to the reduced model (time omitted). The following hypotheses were tested for the contribution of the time variables x_8, x_9 and x_{10}.

H_0: $\beta_8 = \beta_9 = \beta_{10} = 0$

H_1: At least one of the β parameters being tested is nonzero.

With the test statistic calculated as follows

$$F = \frac{\left(SSE_r - SSE_c\right)/(k-g)}{(SSE_c)/(n-(k+1))} = \frac{(2117.31-2033.75)/(13-10)}{2033.75/(111-14)} = 1.329.$$

The critical value *F* for $\alpha = 0.05$, $v_1 = 3$, and $v_2 = 97$ was calculated in Microsoft excel 2007 as $F_{0.05} = 2.7$. Since the test statistic value *F*=1.329 does not exceed 2.7, we do not reject H_0 and conclude that the reduced model with factors site, wind speeds and wind direction, contributes best to the prediction of *y*, the average decibel.

Just like in the previous section model one, a residual analysis and Cooks distance values were used to test whether outliers were present in the data. Again residual analysis and Cooks distance values showed no outliers present in the data. These results are shown in Appendix B, Figure B.3 and Table B.8. The residual plot and normality plot showed that assumptions made about the error term were satisfactory. These plots are also given in Appendix B, Figure B.3 and Figure B.4 respectively.

Parameters estimates for model two are given in Appendix B, Table B.8, with similar interpretations as in model one.

Model two confirmed that time was statistically insignificant, however again as discussed in the previous section this could be a result of interaction affects.

4.3 Conclusion

In conclusion, model one fitted the sound level data well. The time factor was removed from the model due to the interaction. The recommendation for improving the analysis is to increase the sample size. For this study, sample size was restricted as the installation of the wind turbine at the CER had taken longer than expected. The distance factor was found to be insignificant. Increasing the distance from the wind turbine at which distance two is measured could show that the factor does influence the response variable.

Chapter 5

Wind Turbine Analysis

The results provided in Chapter 5 refer to the data collected during the wind turbine analysis. Section 5.1 briefly discusses the climate characteristics in the Summerstrand region of Port Elizabeth (PE). These climate characteristics relate particularly to wind speed and wind direction. Section 5.2 relates to the sound analysis of three micro-wind turbine systems in PE.

5.1 Wind speed and wind direction for Port Elizabeth

For wind turbine construction it is important to have an idea of the wind speed and wind direction distributions in that region. If wind speeds are found to be too low or have too much variability then wind turbine operation would be inadequate for energy generation. Knowledge of prevailing wind direction is important since wind turbines need to be placed such that structures or geographical features do not interfere with their operation.

The distribution of wind speeds and wind direction data in the Summerstrand region of PE was required by the CER. This information was used by the CER for other research applications. Wind speed and wind direction data were collected using the Wind Speed and Direction Sensor. This sensor was set up at the CER (discussed in section 3.1.1). Wind speed and wind direction data were logged instantaneously every five minutes. Wind speed data was recorded in km/h but was then converted to m/s for the fitting of the Weibull distribution. Wind speed and wind direction data was recorded from the beginning of January 2011 to the end of October 2011. All data recorded during this time period was used for the fitting of the Weibull distribution and the wind rose plot.

The Weibull distribution is often used to represent wind speed data (Manwell et al, 2007) and is also used as a statistical model to represent the frequency distribution of wind speeds.

The two parameter distribution is expressed mathematically as

$$f(u) = \frac{k}{A}\left(\frac{u}{A}\right)^{k-1} \exp\left(-\left(\frac{u}{A}\right)^{k}\right) ,$$

where $f(u)$ is the frequency occurrence of the wind speed u. The two parameters of the Weibull distributions are often referred to as the scale parameter A and the shape parameter k.

The Weibull distribution was used to demonstrate the frequency distribution of wind speed data found in Summerstrand, PE. The scale and shape parameters where estimated in R. These parameters were estimated using the maximum likelihood estimation procedure. Given the properties of the Weibull distribution all wind speed data having a value of 0 m/s was converted to the lowest wind speed that can be recorded with the WSD-100 sensor which was 0.4 m/s. The shape parameter was estimated as 1.62 and the scale parameter was estimated as 4.03. Figure 5.1 provides a graphical representation of the Weibull distribution that was plotted in R.

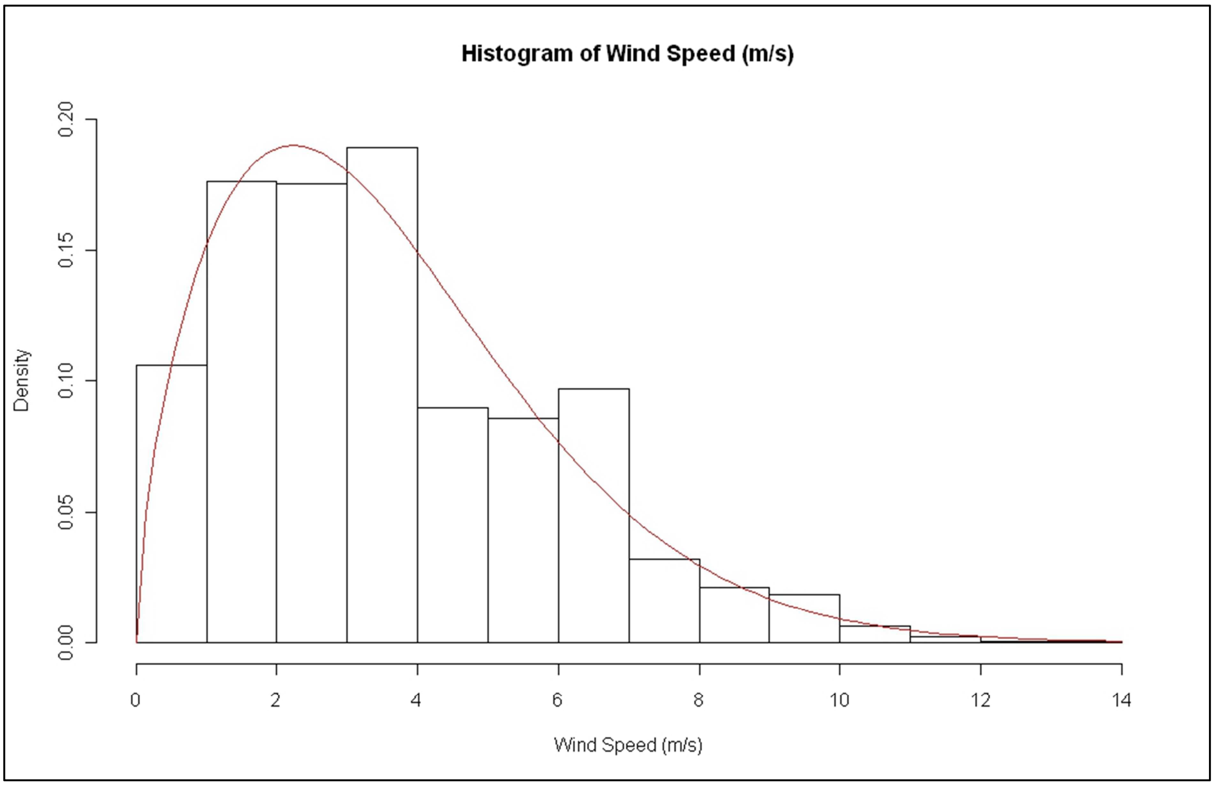


Figure 5.1: Weibull relative distribution plot for the Summerstrand, PE region for wind speed data from January 2011 to October 2011.

The prominent wind speeds in the Summerstrand region were found to be between 1 and 4 m/s. This upper region was high indicating that the Summerstrand region maybe a good site for micro-wind turbine applications. These results correlate with the results in Chapter 4

Figure 4.5. However, these results came from a much larger sample size that provides a better indication of the true wind speeds found in the Summerstrand region.

Although not a primary objective of the study, the Weibull distribution appears to fit the wind speed data well. The tails of the distribution seem to fit the high wind speeds found in the region.

Shown in Figure 5.2 is the wind rose indicating the frequency of wind direction in the Summerstrand region of PE.

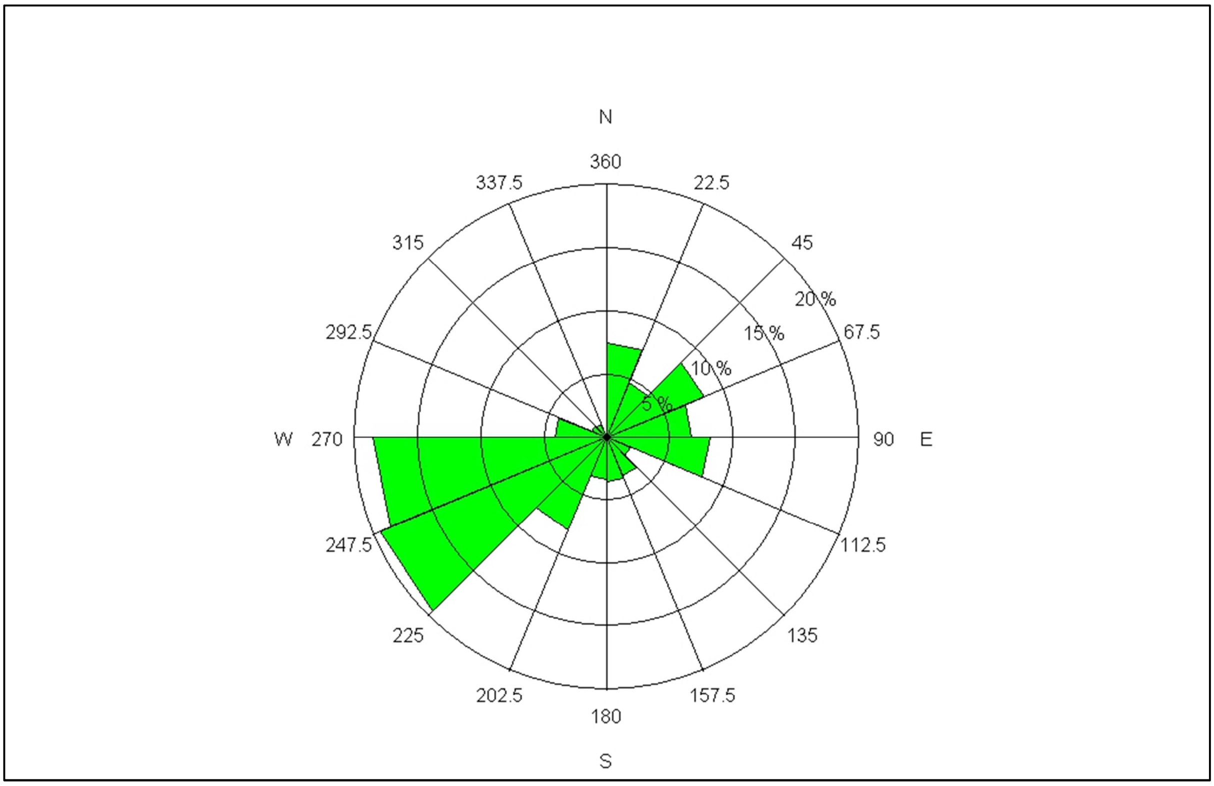


Figure 5.2: Wind rose plot for the Summerstrand, PE region for wind direction data from January 2011 to October 2011.

The wind rose showed that the most common wind direction is from the West-South-West direction. This is the same result found in Chapter 4, Figure 4.4.

5.2 Sound analysis

The sound analysis performed on each individual wind turbine system included a comparison between the SPL and wind speed and a comparison between sound levels at different distances away from the wind turbine. Data for this analysis was collected using a Kestrel 4500 Pocket Weather Tracker that recorded wind speed and temperature. Sound measurements were recorded using the MT975 sound level meter with an A-weighting setup. Measurements were recorded every five seconds over a two-minute period. An average SPL and average wind speed measurement was calculated. Measurements were taken at a height of one meter above ground level.

The measurement position was calculated in accordance with the dimensions of the wind turbine. This calculation was discussed in section 3.4.1 for both the horizontal axis micro-wind turbine and the vertical axis micro-wind turbine. Measurements were recorded on different days at several different wind speeds.

The comparisons of measurements at different distances were recorded in the same manner as discussed in the previous paragraph. The second measurement position was 10 m away from the first measurement position (position one was discussed in section 3.4.1).

A frequency analysis was conducted to determine the frequency distribution of a sound clip of a wind turbine under high wind speeds. The reason for the frequency analysis was to determine whether low frequencies are present in wind turbine sound due to the human response characteristics of low frequency noise mentioned in section 2.3.3.

5.2.1 Horizontal axis micro-wind turbine e300i (1 kW)

Figure 5.3 shows the relationship between the average wind speed and the average SPL for the horizontal axis Kestral e300i 1kW micro-wind turbine. Figure 5.3 lends support to the claim that the sound levels of a wind turbine are a function of wind speed. Already discussed in Chapter 2, sound generated from a wind turbine is a function of wind speed. The results in Figure 5.3 support this relationship for the horizontal axis micro-wind turbine. This was also the findings in Chapter 4, as wind speed was found to have a significant influence on the average sound levels. There appears to be a large variability in the sound levels recorded at the horizontal axis micro-wind turbine. This variability could have been caused by external influences in the environment. Due to the location of the horizontal axis wind turbine this is highly possible. These external influences could have been caused by large vehicles’ using the road near the wind turbine or even pedestrians walking past.

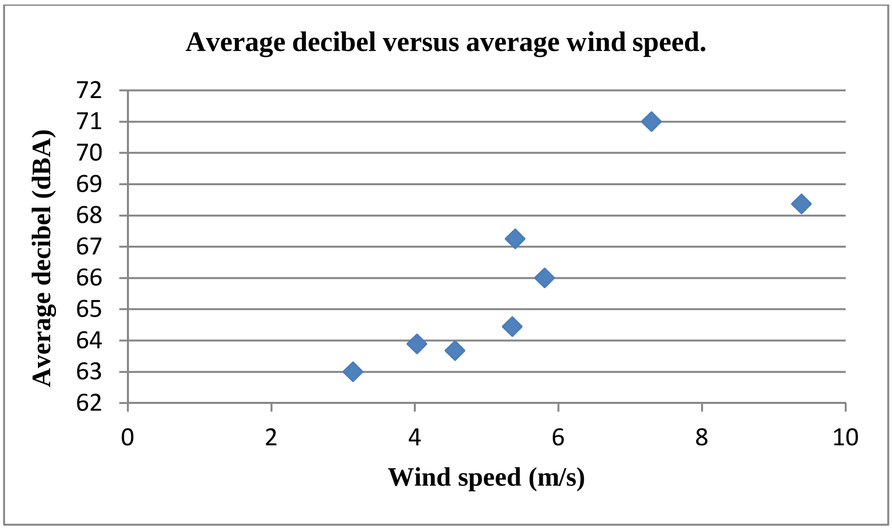


Figure 5.3: A plot of wind speed versus the average SPL reading for the horizontal axis micro-wind turbine.

The increase in the average SPL is probably due to the mechanical stresses and increased forces on the aerodynamic components. The horizontal axis wind turbine appeared to make “buzzing” and “whoosing” sounds as each blade passed the wind turbine tower. These sounds relate to the interaction of the air flow with the wind turbine blades and the wind turbine tower (aerodynamic sounds).

An individual analysis was conducted to determine the relationship between the average SPL and different distances away from the wind turbine. Distance one was taken at the measurement position calculated in accordance with the dimensions of the wind turbine. Distance two was taken 10 m away from the first measurement position.

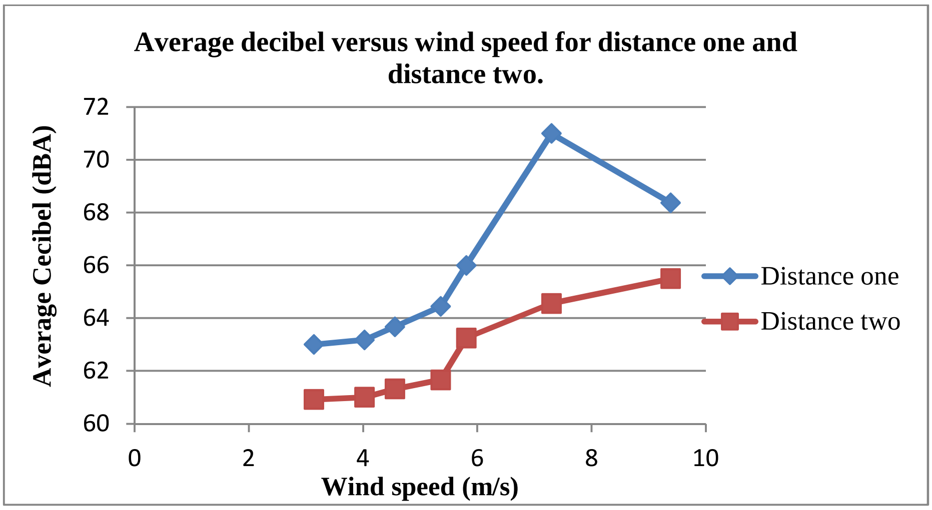
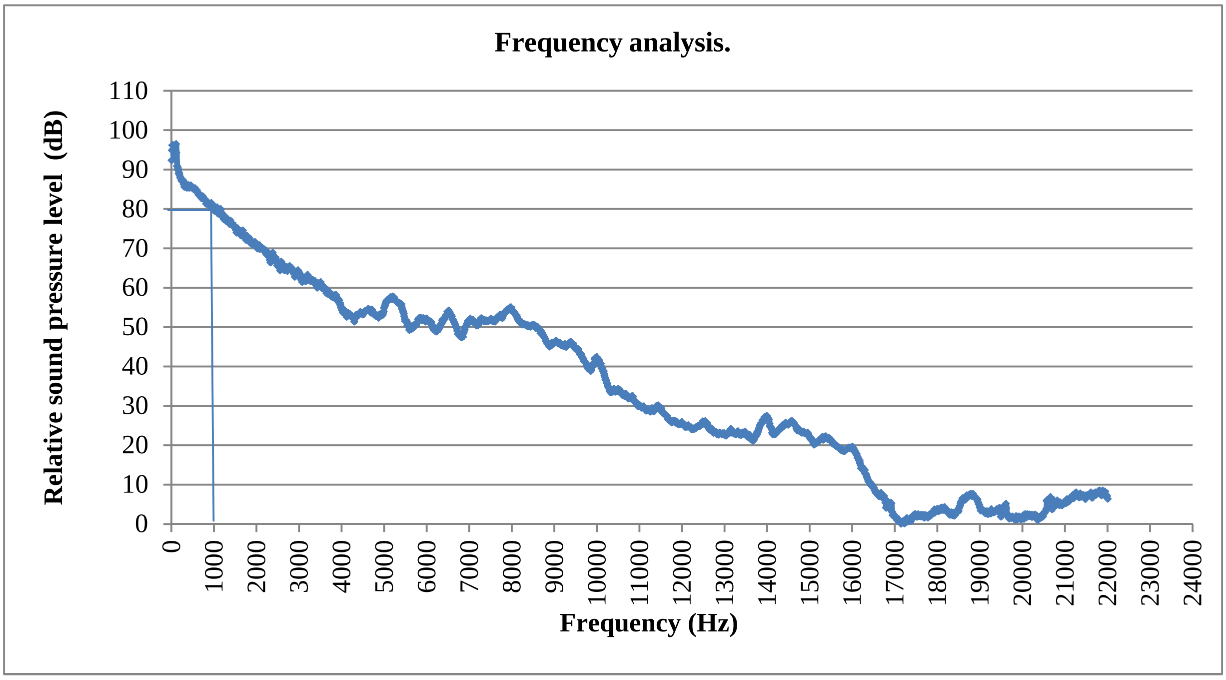


Figure 5.4: A plot of wind speed versus the average SPL for the horizontal axis micro-wind turbine for two different distances.

Figure 5.4 shows that there is difference in sound level readings at different distances away from the wind turbine. This difference was approximately two decibels, except for the second last measurement. This could be due to the increased ambient sound levels due to the high wind speeds or any external influences in the environment. The relationship between the average SPL and distance was not observed in the GLM. However this could be due to the lack of sample data collected during the randomised experiment and the influence of other sites relationship with distance. As mentioned in Chapter 4, distance may also have no influence in the GLM due to interaction effects.

The frequency sound data collection process was discussed in section 3.4.1. The frequency components were used to determine the shape of the distribution of frequencies present in a sound recording of the wind turbine at a reasonably high wind speed. The frequency distribution showed that lower frequencies are present at higher sound levels.

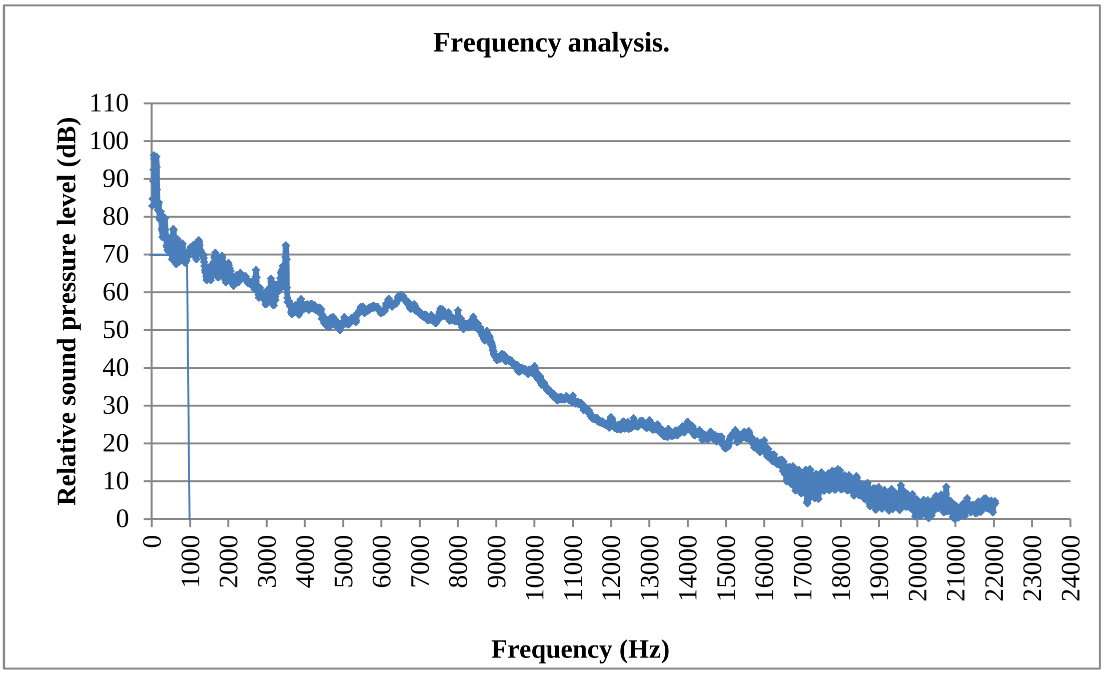


Site	Hobie Beach
Type	Micro-Horizontal axis
Model	Kestral e300i 1kW
Wind Speed	7 m/s
Average Decibel	71.3 dBA
Temperature	16.5 °C

Figure 5.5: Frequency distribution of a sound recording of the horizontal axis micro-wind turbine.

Referring to section 2.3.2, phons lines represent the perception of loudness at a certain frequency. Figure 5.5 refers to the raw frequency data without phons lines present. At 1000 Hz a sound will be perceived as approximately ± 78 dBA. When recording the sound clip ambient sounds influenced the recording of the frequency components of the wind turbine. Therefore the frequency distribution was only used to determine when low frequency components will be present in that environment. The best method for evaluating the frequency components of a wind turbine model is a wind tunnel.

Figure 5.6 shows the frequency distribution of the combination of three horizontal axis Kestral e300[i] 1kW micro-wind turbines. Figure 5.6 shows that lower frequencies are present at higher sound levels for this environment.



Site	Walmer Park Shopping Centre
Type	Micro-Horizontal axis
Model	Kestral e300[i] 1kW
Wind Speed	4 m/s
Average Decibel	67.3 dBA
Temperature	18 °C

Figure 5.6: Frequency distribution of a sound recording of the horizontal axis micro-wind turbine

5.2.2 Vertical Axis Wind Turbine (1 kW)

Figure 5.7 shows the relationship between the average wind speed and the average SPL recorded for the vertical axis 1kW micro-wind turbine. The vertical axis wind turbine appears to be much quieter compared to the horizontal axis wind turbine. This is the same result that was obtained in the descriptive statistics section in Chapter 4.

From an observational study the vertical wind turbine made a “thumping” sound. This sound was due to the bearings and was categorised as a mechanical sound.

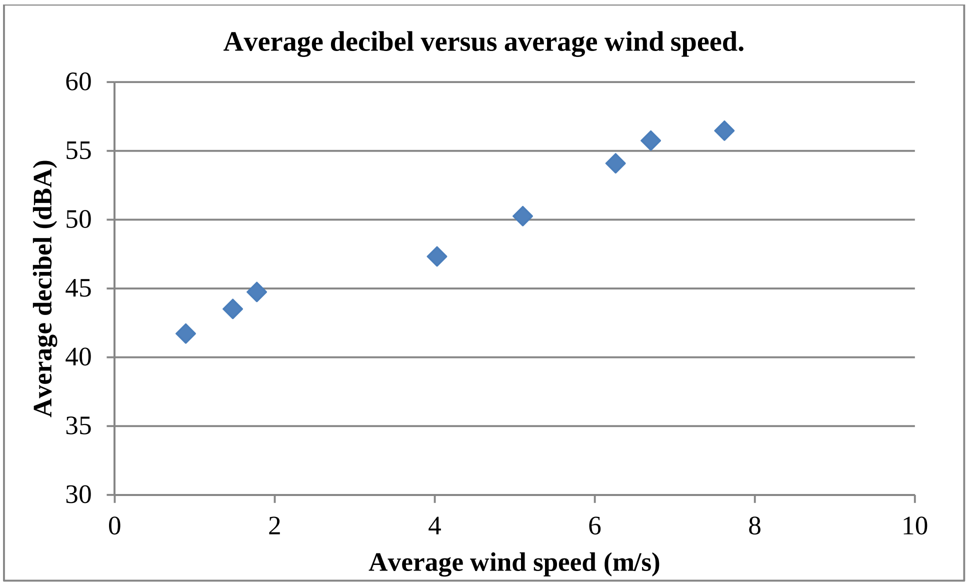


Figure 5.7: Affects of Wind Speed on Average SPL for the vertical axis micro-wind turbine.

An individual analysis was conducted to determine the relationship between the average SPL and different distances away from the wind turbine. Distance one was taken at the measurement position calculated in accordance to the dimensions of the wind turbine. This was discussed in section 3.4.1. Distance two was taken 10 m away from the first measurement position.

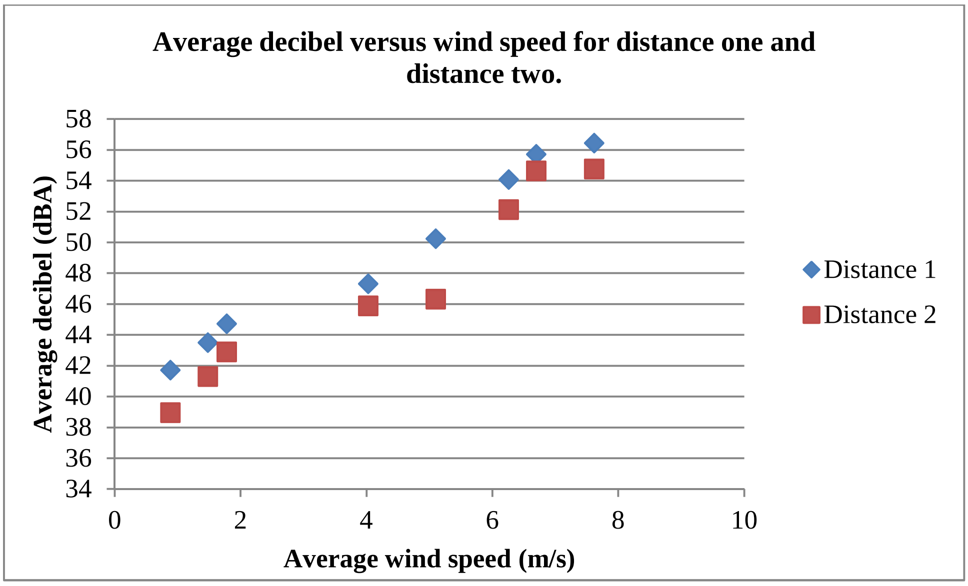
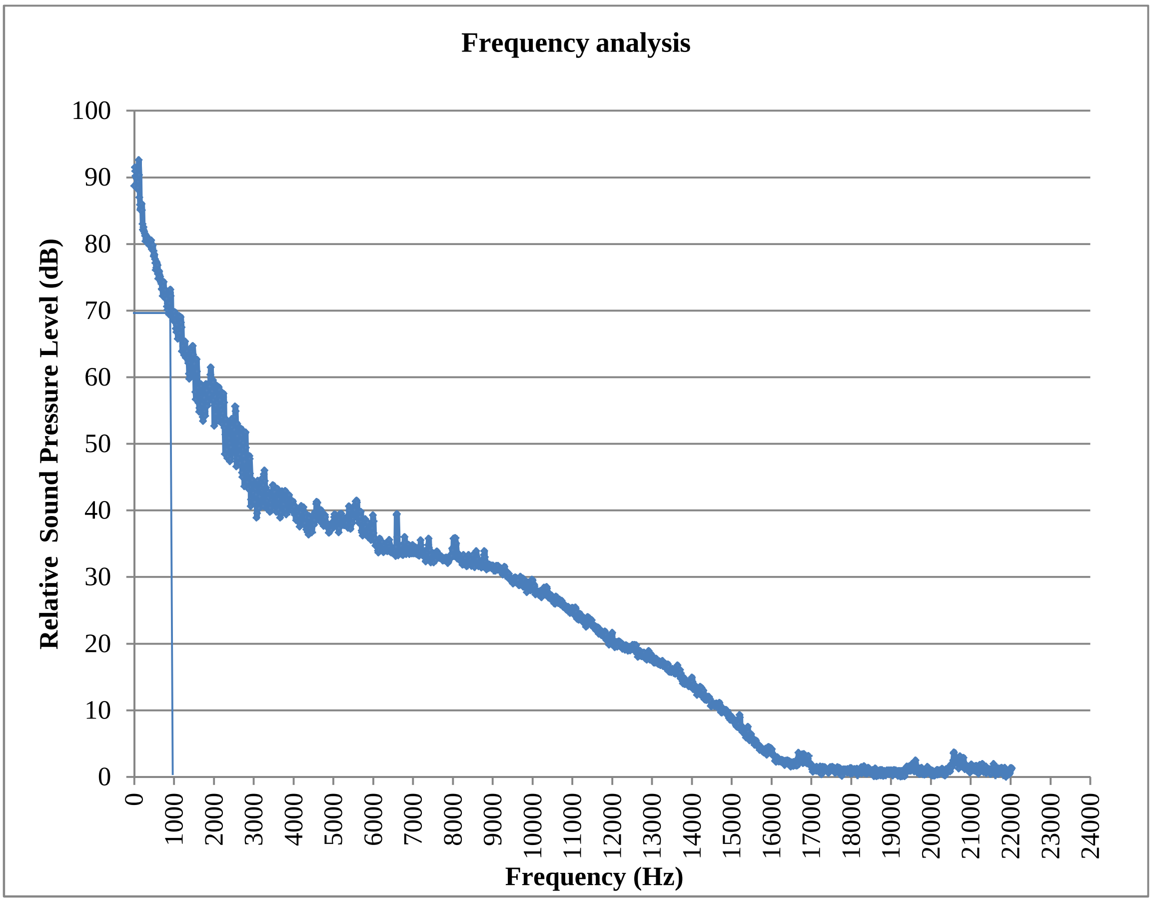


Figure 5.8: A plot of wind speed versus the average SPL for the horizontal axis micro-wind turbine for two different distances.

Figure 5.8 shows that there is a difference in sound level readings at different distances away from the wind turbine. There appears to be approximately a 2 dBA difference between measurement recorded at distance one and distance two. Although the measurement taken at approximately 5.5 m/s appears to have a much larger difference. This observation maybe an outlier in the data set. The relationship between the average decibel and distance was not observed in the GLM. However this could be due to the lack of sample data and interaction effects.

The frequency sound data collection process was discussed in section 3.4.1. The frequency components were used to determine the distribution of frequencies present in a sound recording of the wind turbine at a reasonably high wind speed. The frequency distribution showed that lower frequencies are present at higher sound levels.



Site	CER
Type	Micro-Vertical axis
Model	NMMU: 1kW
Wind Speed	6m/s
Average Decibel	54.3 dBA
Temperature	20°C

Figure 5.9: Frequency distribution of a sound recording of the vertical axis micro-wind turbine.

5.3 Conclusion

Chapter 5 briefly explains some characteristics of wind turbine sound with focus on the relationship between wind turbine sound, wind speed and downwind distance from the turbine. Chapter 5 also showed the frequency distribution of wind turbine sounds.

Chapter 5 showed that there was a relationship between wind speed and SPL. Results showed that if there was an increase in wind speed there will be an increase in SPL. This result was the same for both the horizontal axis micro-wind turbine and the vertical axis micro-wind turbine. These results correlated with research done by Mckenzie, et al (2002). Although

Mckenzie et al (2002) focused on large wind turbines it appears that the same relationship is present between wind speed and SPL for the micro-wind turbines.

The evaluation on distance showed that SPL appeared to decrease the further away from the wind turbine. As mentioned in section 2.4.4, increasing the distance away from a sound source to a receiver, increases the amount of acoustics energy lost. This is due to the larger area over which the sound wave is propagated. Furthermore, the absorption of sound due to air viscosity converts acoustic energy into heat energy, and therefore the sound energy is lost. There appears to be an approximately 2 dBA decrease in SPL for the horizontal axis micro-wind turbine and for the vertical axis micro-wind turbine.

The frequency analysis showed that high SPL are present at low frequencies. Due to external sources of sound, a frequency analysis could not get the frequency components of the wind turbine itself. To isolate sounds from a micro-wind turbine, the frequency analysis should be done in a wind tunnel.

Chapter 6

Conclusion and Future Work

The aim of the study was to provide a comparison between wind turbine noise and traditionally accepted surrounding sounds. The collection of sound level data was done using a randomised experiment. Seven sites and four different times were selected. A General Linear Model was used to determine the relationship between the noise generated at a given site and the time of day, wind speed, wind direction and distance from the sound source.

The statistical analysis summary showed that reduced model one was preferred to the complete model. Reduced model one was a good fitting model according to the coefficient of correlation (R), coefficient of determination (R^2) and adjusted coefficient of determination (R^2_a). A Nested *F*-test showed, at a significance level of 5 %, that the reduced model was the best fitting model to the sound level data. The factors; wind speed, site and wind direction were found to be significant predictors of the average sound level. Surprisingly, the factors time and distance were found to be statistically insignificant. Interaction terms can influence factor levels in such a way that a factor appears to be statistically significant and/or insignificant. The analysis from the main effects models and interaction models gave confounding results. This is not a surprising result as when interaction is present the statistical interpretations become difficult. However, the models show that several factors are important predictors of the response variable. As this study is the first attempt at investigating the noise of micro-wind turbines it provides a useful starting point for future evaluations.

Pitfalls in the study included the inability to assess the ambient noise measurement of the horizontal axis micro-wind turbine. This data would have given an indication of how the sound levels of the environment changed. It would also have been useful in the comparison of the different sites. Another pitfall was the missing sound measurement of the vertical axis wind turbine at 08h00.

Improvements in the model would have been to increase the sample size and increase the distance two measurement from the wind turbine. Distance showed to be an insignificant predictor for the average sound level. Increasing the distance from the wind turbine may show the relationship between distance and average sound level in the model. Time was found to be insignificant in the model, this could have been caused by the interaction affect.

Chapter 5 gave individual wind turbine analysis on three micro-wind turbine applications. This analysis was required by the NMMU, CER. A Weibull distribution of wind speed in the Summerstrand, PE region was fitted. This plot showed good potential wind speeds for micro-wind turbine applications in the region. The wind rose plot showed that wind direction in the region was predominantly from the Westerly direction. Wind turbine noise increased with wind speeds for both wind turbine systems. Results also showed wind turbine noise decreases with distance away from the wind turbine. Pitfalls in the study related to the frequency analysis conducted in Chapter 5 included: outside influences such as traffic, people talking and sea noise allowed for inconclusive results. A wind tunnel may be the optimal solution for the frequency analysis of wind turbine sound. Although the frequency response curves gave an indication of the combined frequencies found in the environment, the distribution showed that low frequency sounds will be present at high sound levels.

The following is a list of noise reduction strategies that are given in theory:

- *Masking*. Bolin et al (2010) has shown that the masking of wind turbine noise by adding "positive" noise from natural sources (trees, waves) can reduce the perception of the wind turbine sound. Placing a wind turbine in an environment with high sound levels may increase the acceptance of wind turbines. From this study the sound levels of the sea provide a natural accepted sound source with high levels which has the ability to mask the horizontal axis wind turbine noise.
- *Blade speed*. A method for reducing the emitted sound levels is to decrease the angular speed of the rotor. Applying this method will decrease the aerodynamic sound by decreasing the "buzzing", "swishing" and "sizzling" sounds. Although the drawback from this method involves reducing the production of generated electrical power.
- *Shape of the blade*. Increasing the angle of attack and thick airfoils lead to increased sound levels. Decreasing this angle may provide a quieter wind turbine model.

This is an area for extensive future research, both in the field of wind turbine acoustics and experimental design. From this study increasing the sample size might improve the fit of the General Linear Model. Adding more variables such as rainfall, topography, height, ambient noise, temperature and other distance measures to the randomised experiment may allow for a more accurate and informative model to be developed. Increasing the number of micro-wind turbine models in the experiment may provide more information about the wind turbine acoustics.

In conclusion, a new methodology for collecting of sound level data was developed. This methodology allowed for good accurate modelling of sound level data. Site, wind speed and wind direction were identified as factors influencing the sound levels in an environment. Therefore this study added to the body of knowledge in the field of wind turbine acoustics.

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SOFT WARE USED:

Audacity 1.3

Microsoft Excel 2007

R 2.11.1

STATISTICA 10

Appendix A

Randomised Selection Process

The following coding in Table A.1 was given to the different sites and times:

Table A.1: Randomised coding for R 2.11.1.

Name	Value
Site: Beach Front	1
Site: Horizontal Wind Turbine	2
Site: Ambient	3
Site: Vertical Wind Turbine	4
Site: Rural	5
Site: Street	6
Site: Residential	7
Time: 8:00	1
Time: 12:00	2
Time: 17:00	3
Time: 22:00	4

Randomised selection process is given in Table A.2.

Table A.2: Randomised selection process.

Location	**Time**	**Distance**	**Random Sample**	**Day**
7	1	1	1	1
6	2	1	2	1
1	4	1	3	1
3	4	1	4	2
3	3	1	5	3
5	2	1	6	4
1	3	1	7	4
1	1	1	8	5
5	4	1	9	5
6	4	1	10	6
6	1	1	11	7
3	2	1	12	7
4	4	1	13	7
4	3	1	14	8
2	1	1	15	9
3	3	1	16	9

7	3	1	17	10
4	1	1	18	11
4	3	1	19	11
3	2	1	20	12
7	4	1	21	12
5	1	1	22	13
6	1	1	23	14
5	2	1	24	14
5	4	1	25	14
5	1	1	26	15
1	4	1	27	15
7	2	1	28	16
2	3	1	29	16
7	2	1	30	17
2	1	1	31	18
1	3	1	32	18
6	2	1	33	19
2	3	1	34	19
7	3	1	35	20
2	1	1	36	21
1	4	1	37	21
7	4	1	38	22
5	3	1	39	23
2	2	1	40	24
4	4	1	41	24
2	1	1	42	25
6	2	1	43	25
7	4	1	44	25
5	1	1	45	26
2	3	1	46	26
3	2	1	47	27
4	2	1	48	28
4	1	1	49	29
5	2	1	50	29
6	3	1	51	29
3	1	1	52	30
7	3	1	53	30
3	3	1	54	31
4	1	1	55	32
1	3	1	56	32
1	2	1	57	33
4	2	1	58	34
3	1	1	59	35
2	4	1	60	35

1	2	1	61	36
2	4	1	62	36
3	2	1	63	37
6	4	1	64	37
6	1	1	65	38
7	1	1	66	39
6	1	1	67	40
1	4	1	68	40
7	3	1	69	41
5	2	1	70	42
1	1	1	71	43
5	3	1	72	43
3	4	1	73	44
2	4	1	74	45
7	4	1	75	46
4	2	1	76	47
3	3	1	77	47
1	1	1	78	48
7	2	1	79	48
6	4	1	80	48
7	2	1	81	49
6	3	1	82	49
5	1	1	83	50
3	4	1	84	50
7	1	1	85	51
7	1	1	86	52
4	4	1	87	52
1	2	1	88	53
6	3	1	89	53
5	4	1	90	54
4	4	1	91	55
5	4	1	92	56
3	1	1	93	57
1	3	1	94	57
3	1	1	95	58
6	4	1	96	58
6	2	1	97	59
2	2	1	98	60
2	2	1	99	61
4	2	1	100	62
5	3	1	101	62
2	3	1	102	63
4	3	1	103	64
6	3	1	104	65

4	1	1	105	66
2	4	1	106	66
5	3	1	107	67
2	2	1	108	68
4	3	1	109	68
1	2	1	110	69
3	4	1	111	69
1	1	1	112	70

Randomised R coding:

```
random.test <- function(a,b,c,d){
        y <- c()
        g <- a*b*c*d
            for(i in 1:a){
                    for(j in 1:b){
                    for(k in 1:c){
                    for(l in 1:d){
        y <- c(y,i,j,k*l^0)
        }}}}
        y <- matrix(y, ncol = 3, byrow = T)
            r <- seq(1,g,1)
            k <- matrix(sample(r,length(r),replace = F), nrow = length(r),byrow = T)
            y <- cbind(y,k)
            y <- y[order(y[,4]),]
            e <- array(1,dim = g)
                for(p in 2:g){
                    e[p] <- ifelse(y[p-1,2] == 3, e[p-1] +1,(ifelse(y[(p-1),2]>=y[p,2],e[p-
1]+1,e[p-1])))
                    }
            e <- matrix(e, ncol = 1, byrow = T)
            y <- cbind(y,e)
        return(y)
    }
```

Appendix B

Regression Analysis

The results in Appendix B are pertaining to the general linear models discussed in Chapter 4.

Table B.1: Qualitative Variable coding for STATISTICA.

Name	Value
Site: Beach Front	1
Site: Horizontal Wind Turbine	2
Site: Ambient	3
Site: Vertical Wind Turbine	4
Site: Rural	5
Site: Street	6
Site: Residential	7
Time: 08:00	1
Time: 12:00	2
Time: 17:00	3
Time: 22:00	4
Direction: North	N
Direction: South	S
Direction: West	W
Direction: East	E
Distance: 1	1
Distance: 2	2

Table B.2: Goodness-of-fit statistics for model one.

Multiple R	0.8707
Multiple R^2	0.7582
Adjusted R^2_a	0.7452
SS Model	14444.15
df Model	14
MS Model	1031.72
SS Residual	4607.15
df Residual	207
MS Residual	22.26
F	46.3555
p	0.0000

Table B.3: Goodness-of-fit statistics for reduced model one.

Multiple R	0.8669
Multiple R^2	0.7515
Adjusted R^2_a	0.7398
SS Model	14317.75
df Model	10
MS Model	1431.77
SS Residual	4733.56
df Residual	211
MS Residual	22.43
F	63.8218
p	0.0000

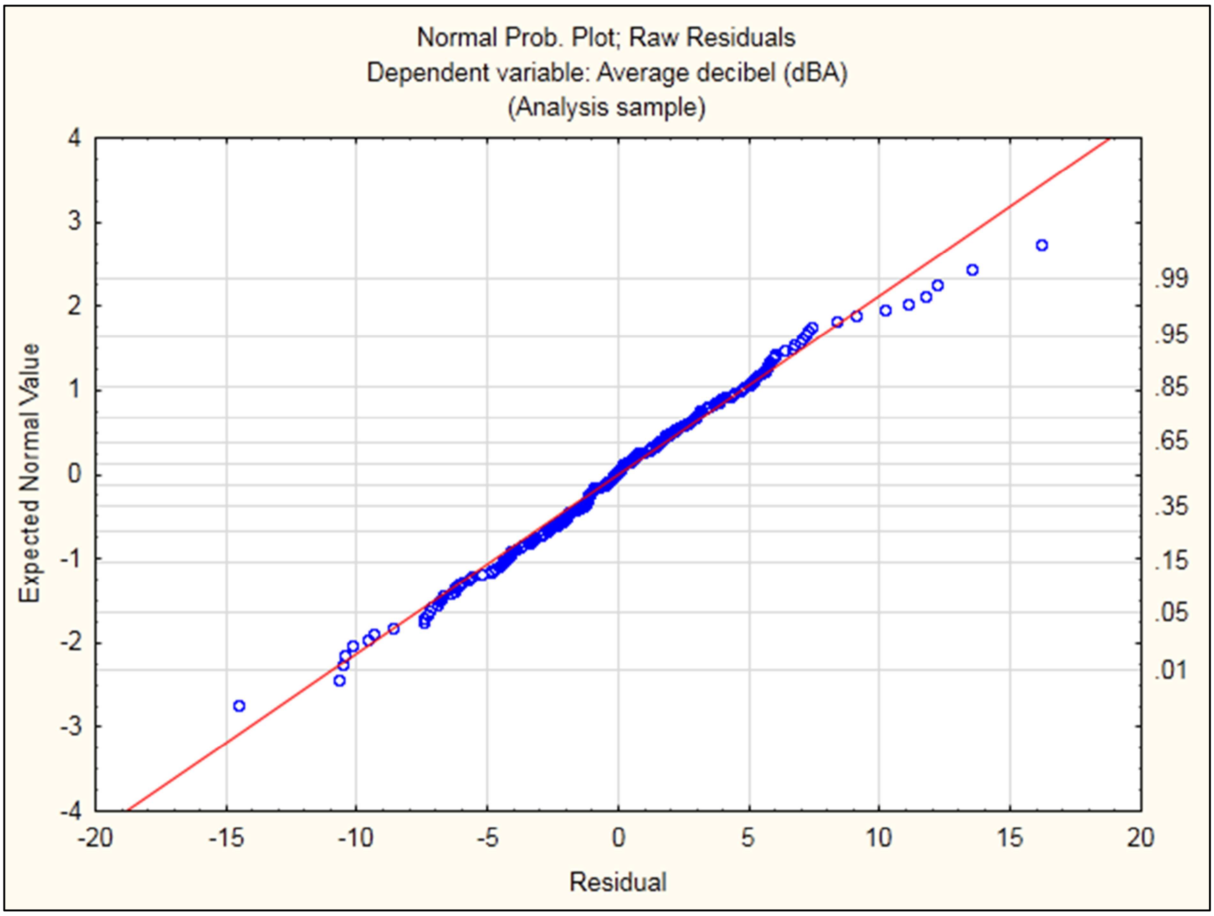

Figure B.1: Normal probability plot of the residuals of reduced model one.

Table B.4: Goodness-of-fit statistics for reduced model one with interaction terms.

Multiple R	0.8937
Multiple R^2	0.7987
Adjusted R^2_a	0.7304
SS Model	15216.90
df Model	56
MS Model	271.73
SS Residual	3834.40
df Residual	165
MS Residual	23.24
F	11.6929
p	0.0000

Table B.5: Goodness-of-fit statistics for reduced model one with interaction terms.

Multiple R	0.8846
Multiple R^2	0.7825
Adjusted R^2_a	0.7509
SS Model	14908.29
df Model	28
MS Model	532.44
SS Residual	4143.01
df Residual	193
MS Residual	21.47
F	24.8034
p	0.0000

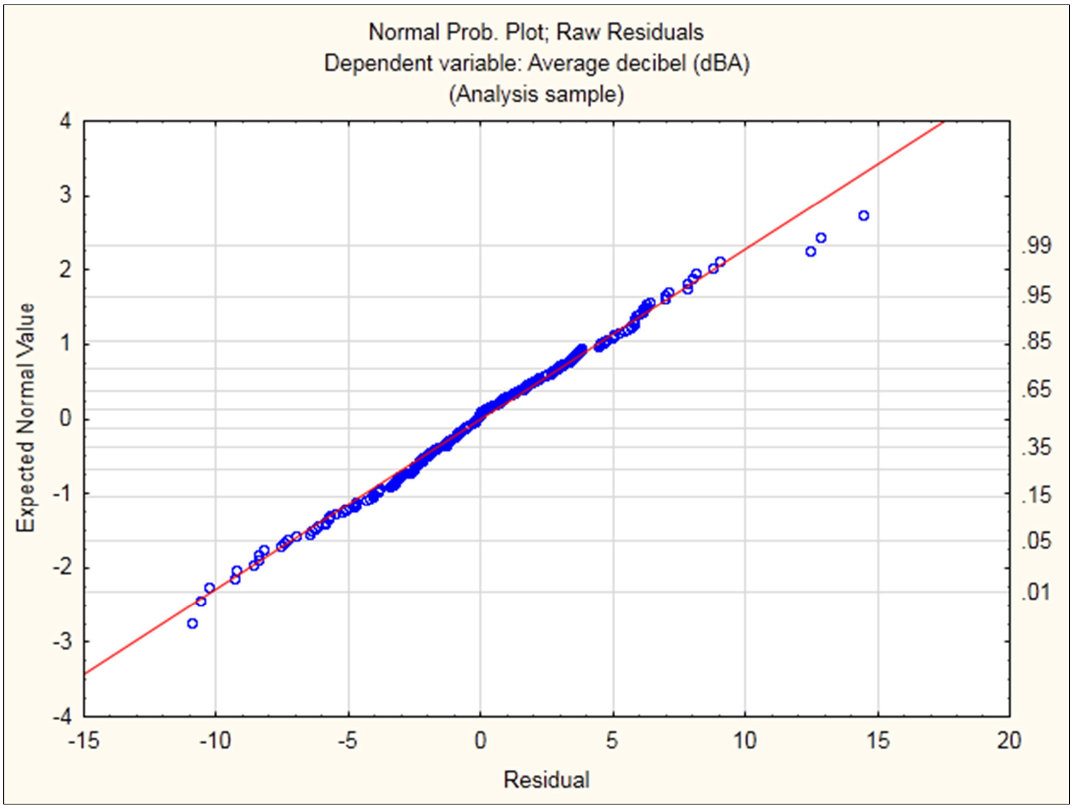

Figure B.2: Normal probability plot of the residuals of reduced model one including interaction.

Table B.6: Goodness-of-fit statistics for model two for both complete and reduced models.

	Complete model	Reduced model
Multiple R	0.8956	0.8911
Multiple R^2	0.8021	0.7940
Adjusted R^2_a	0.7756	0.7734
SS Model	8245.42	8161.86
df Model	13	10
MS Model	634.26	816.18
SS Residual	2033.75	2117.31
df Residual	97	100
MS Residual	20.97	21.17
F	30.2513	38.5483
p	0.0000	0.0000

Table B.7: Effects of individual factors for complete model two.

Effect	SS	df	MS	F	p
Intercept	56784.98	1	56784.98	2708.369	0.0000
Wind Speed (m/s)	607.79	1	607.79	28.989	0.0000
Site	6255.35	6	1042.56	49.725	0.0000
Time	83.56	3	27.85	1.329	0.2696
Wind Direction	190.52	3	63.51	3.029	0.0331
Error	2033.75	97	20.97		

Table B.8: Cooks distance for potential outlier.

Case number	Cooks distance
56	0.1254
64	0.0645

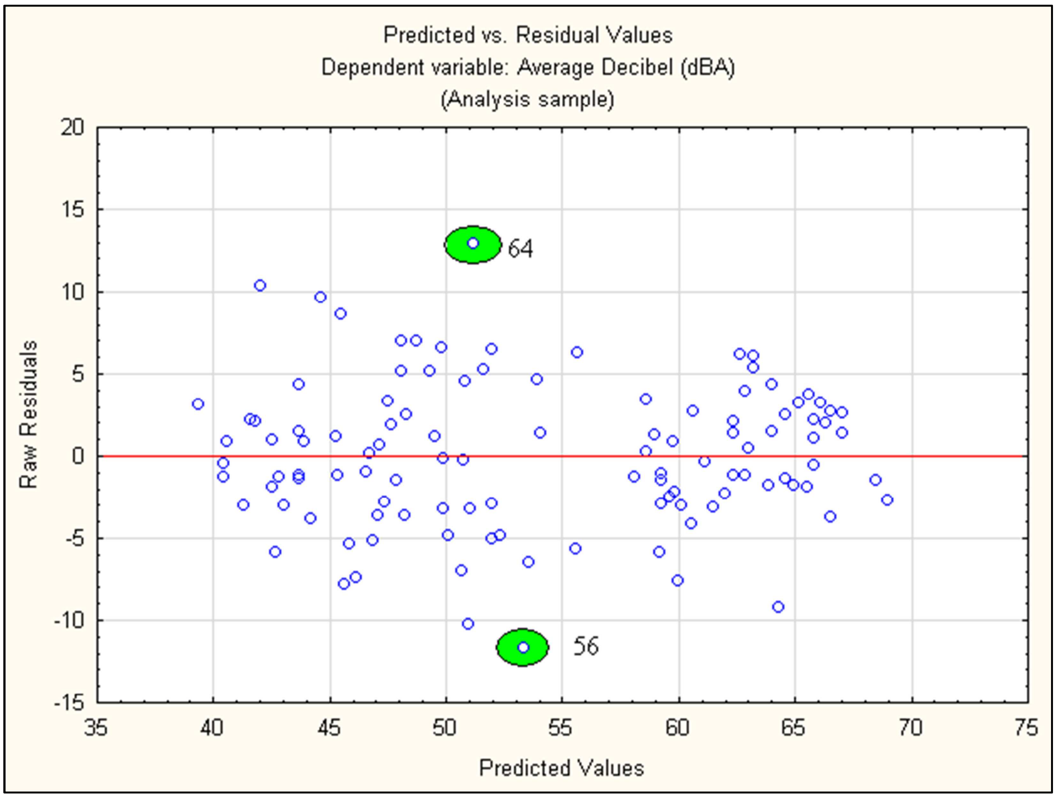

Figure B.3: Residual plot for potential outlier detection.

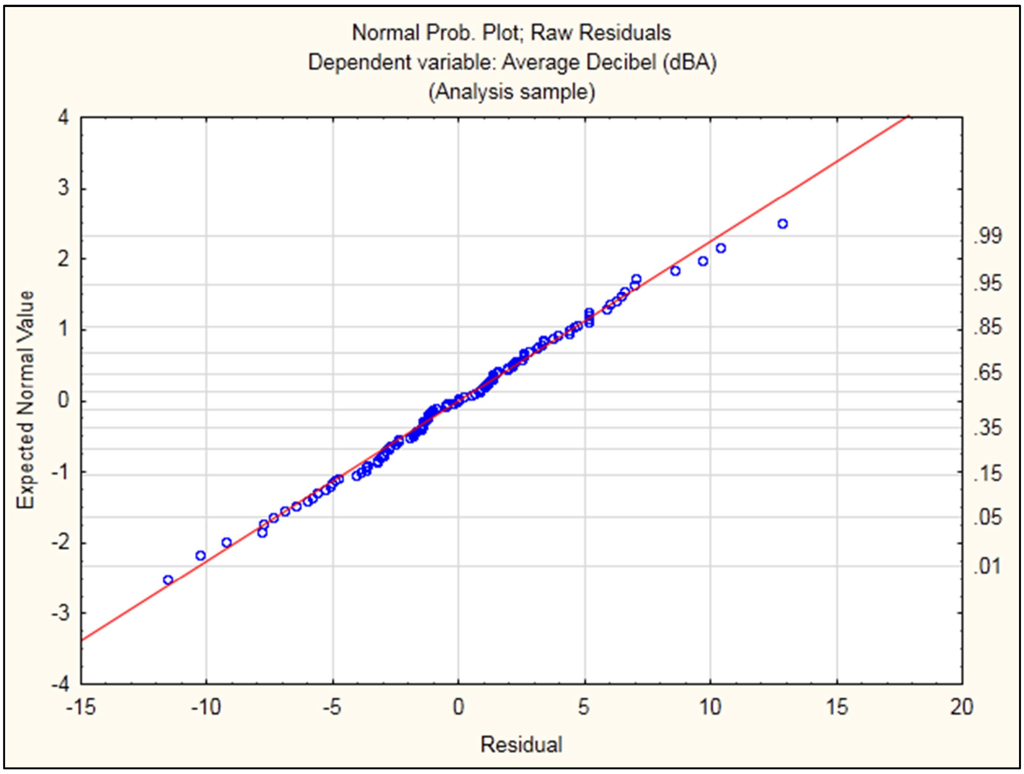

Figure B.4: Normal probability plot of the residuals of reduced model two.

Table B.9: Effects of individual factors for reduced model two.

	Average Decibel (dBA) Parameter Estimates	**Average Decibel (dBA) Std Error**	**Average Decibel (dBA) t**	**Average Decibel (dBA) p**	**- 95% Conf Lim**	**+95% Conf Lim**
Intercept	49.852	0.91	54.80	0.0000	48.05	51.65
x_1 Wind speed	1.16	0.21	5.498	0.0000	0.74	1.58
x_2 Beach front	7.31	1.08	6.74	0.0000	5.15	9.46
x_3 Horizontal axis wind turbine	7.62	1.08	7.05	0.0000	5.47	9.75
x_4 Ambient site	-9.60	1.08	-8.85	0.0000	-11.75	-7.44
x_5 Vertical axis wind turbine	-7.50	1.11	-6.74	0.0000	-9.71	-5.29
x_6 Rural site	-5.32	1.07	-4.97	0.0000	-7.45	-3.12
x_7 Street	11.12	1.08	10.31	0.0000	8.9789	13.26
x_{11} West	-1.38	0.727	-1.90	0.0697	-2.82	0.06
x_{12} North	0.505	0.92	0.54	0.5847	-1.30	2.32
x_{13} South	-1.52	0.84	-1.80607	0.0739	-3.19	0.15