DETERMINING THE POTENTIAL FOR ENHANCED VENTILATION USING WIND-DRIVEN ROOF TURBINES IN REDUCING RISK PROBABILITY FOR TUBERCULOSIS TRANSMISSION IN HOUSEHOLDS IN DIEPSLOOT, SOUTH AFRICA, 2019

By

EUNICE MUTAVA

Student number: 468692

Research report submitted to University of the Witwatersrand, School of Public Health in partial fulfillment of the requirements for the Master's degree in Public Health (Occupational Hygiene)

Supervisor:	Professor Derk Brouwer
Co – Supervisor:	Dr Tanusha Singh

Johannesburg, South Africa, March 2021

DECLARATION

I, Eunice Mutava, hereby declare that this whole research report is my own work except as indicated in the references and acknowledgements. The report is submitted in partial fulfillment of the requirements for the degree of Master of Public Health (MPH) in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in this or any other university.

Signature

Signed at ALBERTON

On the 17th day of March of 2021.

ACKNOWLEDGEMENTS

I would like to acknowledge the important role that the following individuals played in my life in so far as completing this research report:

- My academic supervisors Professor Derk Brouwer and Dr. Tanusha Singh, for their support and guidance throughout the research process. Your input and motivation have been invaluable in helping me to learn how to do research in the occupational hygiene field, and to navigate some of the more emotionally challenging aspects of this project.

- It is with immense gratitude that I acknowledge the participants of this study, without whose participation this research report would not have been possible.

- I would also like to extend my sincere gratitude to the National Institute for Occupational Health (NIOH) for the measurement instruments and to Thabo Jafta and Njabulo Xulu at the Institute for assistance with the measurement strategy and for the many interesting and good-spirited discussions on ventilation techniques.

- The Anglo American Endowed Chair in Occupational Hygiene at the Wits School of Public Health for financing my studies and making required study resources available when I needed them most.

- My husband, Tapiwa David Mutava, and my mothers Nelda and Enika for their understanding and support during my absence from many family commitments, for stepping in when such commitments needed my presence and for their faith in my capabilities.

DEDICATION

This study is dedicated to my late father, Carson “Ndinatse” Matingo. I am grateful you for the solid foundation that he laid for me and the wisdom which he shared during the times he was with us. This has undoubtedly enriched my life and my world. May his dear soul continue to rest in eternal peace.

ABSTRACT

Introduction

The scarcity of appropriate long-stay and palliative care facilities in South Africa, shortage of beds in designated hospitals as well as patient intolerance to prolonged hospital stay, compels a decision to release patients with drug-resistant forms of tuberculosis into the community before they have finished treatment. Environmental containment strategies that are cheap, consume less energy and are easy to install, such a wind-driven roof turbine ventilators, have thus been suggested as alternatives to enforced hospitalization to curb the risk of ongoing community transmission of tuberculosis.

Research aim

The aim of this study was to determine the potential that enhanced ventilation using wind-driven roof turbines in domestic homes has on the risk probability for TB transmission in Diepsloot, a resource-limited community in the Gauteng province within South Africa.

Research objectives

The objectives of this research were

- To describe the physical and social characteristics of the participating households in Diepsloot, South Africa.
- To assess the impact of wind-driven roof turbines on indoor temperature, indoor moisture levels, CO_2 concentration, room ventilation and air exchange rate in eight households (four intervention households, four control households) using a CO_2 tracer gas decay technique for measuring air changes per hour over a three-month period in Diepsloot, South Africa in 2019.
- To estimate, using the Wells-Riley mathematical model, the potential effect of wind-driven roof turbines to reduce the probability of TB transmission.

Methods

Two South African seasons (winter and spring) and time of day (day and evening) were covered in the duration of the study. A baseline survey that evaluated the similarities in characteristics of the households identified in the Diepsloot Township was conducted. Using results from this survey, eight households were purposively sampled and then assigned to intervention and control groups using a pairwise comparison method, which paired a single household from the control group with a specific household in the intervention group. The pairwise comparison method determined whether households were significantly different from one another against criteria such as residential density, size of rooms, quality of structure, presence of outbuildings and occupant behaviour. Pre-intervention air monitoring was conducted to determine how similar the households were in terms of air exchange rates as these vary with activities that occur in each household. The wind-driven roof turbines were directly installed, without any ducting, in rooms in the four houses assigned to the intervention group. A carbon-dioxide (CO_2) tracer gas technique, where a CO_2 gas was injected in the house and its concentration decay recorded over time, was conducted. This was done under one condition – all windows and doors were shut. This standardized natural ventilation from open windows and doors among intervention and control houses. To establish the air exchange rate in air changes per hour (ACH), a natural logarithm of CO_2 decay concentrations was calculated. A multivariate analysis utilising mixed effects regression modelling using repeated measures was then performed to assess the impact of the wind-driven roof turbine on the ventilation rate. In addition, the Wells-Riley equation was used to determine the potential effect of the wind-driven roof turbines to reduce the probability of TB transmission. All data analysis was done using Microsoft Excel 2016 and Stata version 15 (StataCorp, 2017) with a cut-off of 0.05 used to interpret the significance of the p-values of all analyses ($p \leq 0.05$).

Results

Turbine households were noticeably cooler on average and had higher indoor-outdoor temperature ($t = 4.5$, $p < 0.001$) and humidity ($t = -7.4$, $p < 0.001$) differentials than the control households. In addition, the presence of a wind-driven roof turbine resulted in a strongly

significant ($z = 2.62$, $p < 0.01$) CO_2 concentration decay than in the control household group. The average ventilation rates in turbine households ranged from 0.75 – 1.08 $m^3/h.m^2$ compared to 0.37 – 0.53 $m^3/h.m^2$ of the control households. Furthermore, for maximum occupancy, the highest ventilation rate per occupant was estimated at 6.4 L/s.person in the turbine households compared to 0.5 L/s.person for control households. The Wells-Riley model determined that approximately 65 – 79% of susceptible individuals would become infected with tuberculosis (TB) following and 8-hour exposure to an infected person in a control household. This risk was shown to nearly halve in the turbine households.

Conclusion

These results suggest a positive correlation between the presence of the wind-driven roof turbine and improved household air exchange rates. The study further supports the idea for harnessing natural ventilation using low-cost and low- maintenance wind-driven ventilation technologies on a wider scale as this presents the first steps to achieving effective ventilation for airborne infection control particularly for resource-limited communities that face facility limitations and financial constraints.

Key words

Wind-driven roof turbine; air exchange rate; carbon dioxide decay method; resource-limited setting; infection risk; Wells-Riley model

TABLE OF CONTENTS

1. DECLARATION ii
2. ACKNOWLEDGEMENTS iii
3. DEDICATION iv
4. ABSTRACT v
5. TABLE OF CONTENTS viii
1. LIST OF FIGURES xiv
2. LIST OF TABLES xvi
1. LIST OF APPENDICES xvii
2. LIST OF EQUATIONS xviii
3. CHAPTER 1 1

INTRODUCTION 1

1.1 Background 1

1.2 Statement of the problem 5

1.3 Justification of the research 5

1.4 Research question, aims and objectives 7

1.4.1 Research question 7

1.4.2 Aim of the research 7

1.4.3 Specific objectives 7

1.5 Research assumptions 8

1.6 Operational definitions 8

1.6.1 Enhanced ventilation 8

1.6.2 Wind-driven roof turbine 8

1.6.3 Risk probability for TB transmission 9

1.6.4 Household 9

1.7 Structure of the research report 9

1.8 Summary of chapter 10

4. CHAPTER 2 12

LITERATURE REVIEW 12

2.1 Introduction 12

2.2 Policy framework for tuberculosis control in South Africa 12

2.3 Tuberculosis infection prevention control measures ... 14
  2.3.1 Environmental control in tuberculosis infection prevention and control ... 16
  2.3.2 Ventilation rates ... 17
  2.3.3 Ventilation in TB control ... 23
2.4 Techniques for studying building air exchange ... 27
2.5 Wind-driven turbine ventilator ... 32
2.6 Mathematical modelling of risks of airborne infectious diseases ... 34
2.6 Summary of chapter ... 39
5. CHAPTER 3 ... 41
METHODOLOGY ... 41
3.1 Introduction ... 41
3.2 Setting – Sampling site description ... 42
3.3 Study approach ... 43
3.4 Study design ... 44
3.5 Baseline survey ... 44
3.6 Household selection ... 45
  3.6.1 Assignment to intervention and control groups ... 46
3.7 Measurement period ... 46
3.8 Pre-intervention air monitoring ... 47
3.9 Sample size ... 47
3.10 Data collection ... 48
  3.10.1 Objective measurements ... 48
  3.10.2 Subjective measurements ... 53
3.11 Pilot study ... 54
3.12 Validity and reliability of data collection instruments ... 55
3.13 Data management ... 55
3.14 Data analysis ... 56
3.15 Ethical considerations ... 60
3.16 Summary of chapter ... 60
6. CHAPTER 4 ... 62
RESULTS ... 62
4.1 Introduction ... 62
4.2 Participating households ... 62

4.2.1 Pre-intervention results 63
4.3 Physical and social characteristics of the participating households 64
4.3.1 Physical characteristics 65
4.3.2 Social household characteristics 67
4.4 Final roof turbine installation 68
4.5 Weather conditions prevailing at time of study 69
4.6 Indoor air quality and comfort parameters 70
4.7 Roof turbine airflow 71
4.8 Carbon dioxide concentration decay 73
4.9 Air exchange rates........ 76
4.10 Risk for TB infection 80
7. CHAPTER 5........ 83
DISCUSSION........ 83
5.1 Introduction 83
5.2 The physical and social characteristics of the participating households in Diepsloot, South Africa 84
5.3 Impact of wind-driven roof turbines on temperature, moisture levels, CO_2 concentration, room ventilation and air exchange rate 86
5.4 Estimating the potential effect of wind-driven roof turbines to reduce the probability of TB transmission........ 91
5.5 Acceptability of the intervention 93
5.6 Limitations of the study 93
5.6 Summary of chapter 95
8. CHAPTER 6........ 96
SUMMARY, CONCLUSIONS AND RECOMMENDATIONS 96
6.1 Introduction 96
6.2 Summary 96
6.2.1 Major findings and contribution to knowledge 97
6.3 Recommendations 100
6.4 Indications for further research 100
6.5 Concluding remarks 101
9. REFERENCES........ 103
10. PLAGIARISM DECLARATION 142
11. APPENDIX A – BASELINE ENVIRONMENTAL SURVEY 143

12. APPENDIX B – PARTICIPANT INFORMATION SHEET AND CONSENT FORM (INTERVENTION GROUP) 146
13. APPENDIX C – PARTICIPANT INFORMATION SHEET AND CONSENT FORM (CONTROL GROUP) . 148
14. APPENDIX D - INTERVIEW SCHEDULE 150
15. APPENDIX E - INSTITUTIONAL ETHICS LETTER 153

1. CHAPTER 1........ 1
INTRODUCTION........ 1
1.1 Background 1
1.2 Statement of the problem 5
1.3 Justification of the research........ 5
1.4 Research question, aims and objectives........ 6
1.4.1 Research question........ 7
1.4.2 Aim of the research........ 7
1.4.3 Specific objectives........ 7
1.5 Research assumptions 8
1.6 Operational definitions........ 8
1.6.1 Enhanced ventilation 8
1.6.2 Wind-driven roof turbine........ 8
1.6.3 Risk probability for TB transmission 9
1.6.4 Household........ 9
1.7 Structure of the research report........ 9
1.8 Summary of chapter 10
2. CHAPTER 2........ 12
LITERATURE REVIEW........ 12
2.1 Introduction 12
2.2 Policy framework for tuberculosis control in South Africa 12
2.3 Tuberculosis infection prevention control measures 14
2.3.1 Environmental control in tuberculosis infection prevention and control 16
2.3.2 Ventilation rates........ 17
2.3.3 Ventilation in TB control 23
2.4 Techniques for studying building air exchange 27
2.5 Wind-driven turbine ventilator........ 32

2.6 Mathematical modelling of risks of airborne infectious diseases 34
2.6 Summary of chapter 39
3. CHAPTER 3........ 41
METHODOLOGY 41
3.1 Introduction 41
3.2 Setting – Sampling site description........ 42
3.3 Study approach 43
3.4 Study design........ 44
3.5 Baseline survey........ 44
3.6 Household selection........ 45
3.6.1 Assignment to intervention and control groups........ 46
3.7 Measurement period 46
3.8 Pre-intervention air monitoring........ 47
3.9 Sample size........ 47
3.10 Data collection 48
3.10.1 Objective measurements........ 48
3.10.2 Subjective measurements........ 53
3.11 Pilot study 54
3.12 Validity and reliability of data collection instruments........ 55
3.13 Data management 55
3.14 Data analysis 56
3.15 Study limitations .... **Error! Bookmark not defined.**
3.16 Ethical considerations........ 60
3.17 Summary of chapter 60
4. CHAPTER 4........ 62
RESULTS 62
4.1 Introduction 62
4.2 Participating households........ 62
4.2.1 Pre-intervention results 63
4.3 Physical and social characteristics of the participating households........ 64
4.3.1 Physical characteristics 65
4.3.2 Social household characteristics........ 67
4.4 Final roof turbine installation 68

4.5 Weather conditions prevailing at time of study 69
4.6 Indoor air quality and comfort parameters 70
4.7 Roof turbine airflow 71
4.8 Carbon dioxide concentration decay 73
4.9 Air exchange rates 76
4.10 Risk for TB infection 80
5. CHAPTER 5 83
DISCUSSION 83
5.1 Introduction 83
5.2 The physical and social characteristics of the participating households in Diepsloot, South Africa 84
5.3 Impact of wind-driven roof turbines on temperature, moisture levels, CO_2 concentration, room ventilation and air exchange rate 86
5.4 Estimating the potential effect of wind-driven roof turbines to reduce the probability of TB transmission 91
5.5 Limitations of the study 93
5.6 Summary of chapter 95
6. CHAPTER 6 96
SUMMARY, CONCLUSIONS AND RECOMMENDATIONS 96
6.1 Introduction 96
6.2 Summary 96
6.2.1 Major findings and contribution to knowledge 97
6.3 Recommendations 100
6.4 Indications for further research 100
6.5 Concluding remarks 101
7. REFERENCES 103
8. PLAGIARISM DECLARATION REPORT 141
9. TURNITIN REPORT 142
10. APPENDIX A – BASELINE ENVIRONMENTAL SURVEY 1433
11. APPENDIX B – PARTICIPANT INFORMATION SHEET AND CONSENT FORM (INTERVENTION) 146
12. APPENDIX C – PARTICIPANT INFORMATION SHEET AND CONSENT FORM (CONTROL) 148
13. APPENDIX D - INTERVIEW SCHEDULE 150
14. APPENDIX E - INSTITUTIONAL ETHICS LETTER 153

LIST OF FIGURES

Figure 1.1: Types of wind-driven roof turbine ventilators……………………………………………………….4

Figure 2.1: Schematic presentation of air exchange rate in a closed space………………………………18

Figure 2.2: Mixing versus displacement ventilation………………………………………………………………..22

Figure 2.3: Example of CO_2 decay curves in a bedroom equipped with double box window and located in a building built in 1908……………………………………………………………………………………………..28

Figure 2.4: CO_2 decay curves in 6 rooms of different air tightness – non-linear regression and linear regression……29

Figure 2.5: CO_2 decay curve for measuring ventilation……………………………………………………………29

Figure 2.6 Stack effect (passive) and wind-induction (active) strategies of the wind-driven roof turbine………31

Figure 3.1: Informal settlement alongside formal housing units in Diepsloot……………………………41

Figure 3.2: Power calculations…………………………………………………………………………………………….46

Figure 3.3: Fan and CO_2 gas tank connected to a gas regulator………………………………………………..48

Figure 3.4: TSI's IAQ-Calc^{TM} Indoor Air Quality Meter Model 7525……………………………………………49

Figure 3.5: VelociCalc^{R} 9545 Model…………………………………………………………………………………….51

Figure 4.1: 'Pyramid on cube' shape of the studied house……………………………………………………63

Figure 4.2: An example of the physical structure of the house under study……………………………..64

Figure 4.3: Configuration of the house……………………………………………………………………………….65

Figure 4.4: Representation of the floor plan of the house……………………………………………………..66

Figure 4.5: Installed wind-driven roof turbine………………………………………………………………………67

Figure 4.6: The inside of the wind-driven roof turbine as viewed from inside the house…………..68

Figure 4.7: Mean airflow through the wind-driven roof turbine over the study period…………….71

Figure 4.8: Bar graphs showing exponential characteristics of the CO_2 concentration decay……73

Figure 4.9: CO_2 decay in turbine versus control households according to time of day……………..73

Figure 4.10: CO_2 decay in turbine versus control households according to season…………………..74

Figure 4.11: Logarithmic curve showing mean CO_2 decay in turbine households during the day in winter………77

Figure 4.12: Logarithmic curve showing mean CO_2 decay in turbine households during the evening in winter……….78

Figure 4.13: Logarithmic curve showing mean CO_2 decay in control households during the day in winter………78

Figure 4.14: Logarithmic curve showing mean CO_2 decay in control households during the evening in winter……….79

Figure 4:15: Variation of risk rates for infection with ventilation…………………………………………....81

LIST OF TABLES

Table 2.1: Air change per hour and removal efficiencies……………………………………………………….16

Table 2.2: Typical air exchange rates per hour for well-insulated spaces……………………………….18

Table 2.3: Values assigned to the Wells-Riley model variables……………………………………………35

Table 4.1: Key attributes of participating households used for pairwise comparison………………62

Table 4.2: Physical house characteristics……………………………………………………………………64

Table 4.3: On-site climatic conditions………………………………………………………………………69

Table 4.4: Indoor air quality and comfort parameters during the intervention period……………..69

Table 4.5: Mean air velocity flowing through the turbine…………………………………………………71

Table 4.6: Significance of predictor variables on CO_2 decay…………………………………………….74

Table 4.7: Mean air exchange rates in turbine versus control households as influenced by time of day and season……………………………………………………………………………………………75

Table 4.8: House ventilation rates……………………………………………………………………………76

Table 4.9: Estimated ventilation rate (L/s per person) for average household occupancy………..79

Table 4.10: Infection risk for tuberculosis infection in turbine households……………………………. 79

Table 4.11: Infection risk for tuberculosis infection in control households…………………………….80

Table 4.12: Comparison of the ratio of risk between turbine and control households……………..81

LIST OF APPENDICES

Plagiarism declaration……………………………………………………………………………………………………140
Turnitin report……….141
Appendix A: Baseline environmental survey…………………………………………………………………………..146
Appendix B: Participant information sheet……………………………………………………………………… 149
Appendix C: Participant informed consent form………………………………………………………………….151
Appendix D: Occupant interview schedule……………………………………………………………………….153
Appendix E: Institutional ethics letter………………………………………………………………………………….156

LIST OF EQUATIONS

Equation 1: Air change rate……………………………………………………………………………………………………17

Equation 2: Ventilation rate…………………………………………………………………………………………………..17

Equation 3: Wells-Riley Equation (Noakes, 2008) ……………………………………………………………………….34

Equation 4: Multivariate regression analysis equation…………………………………………………………………..56

CHAPTER 1

INTRODUCTION

1.1 Background

South Africa is among the countries with the highest burden of tuberculosis (TB). The Health Systems Trust (2017) reported a peak of the national TB incidence rate in 2009 at 832 per 100 000 (Health Systems Trust, 2017), but reported that this figure has since declined. Meanwhile, the World Health Organization (WHO) statistics give an estimated incidence of 322,000 cases of active TB in South Africa in 2017 (WHO, 2018). This compares with an estimated incidence of 520 000 in 2015, of 593 000 in 2014 or of 649 000 in 2013 (TBfacts.org, 2019; WHO, 2018). Despite the safety and relative efficacy of the standard TB drugs (first line of treatment for drug sensitive TB) used for treatment (Ershova et al., 2014), South Africa still reports a high burden of multi-drug resistant TB (MDR-TB), a resistance to this standard treatment. According to the CDC (2006), the standard care for TB treatment comprises a four-drug regimen. This is because treatment with a single drug therapy can lead to the development of a bacterial population resistant to that drug. This multiple treatment therapy can prove difficult, as far as patient adherence is concerned, to ensure as patients may be reluctant or unable to take the treatment. Where there is inadequate treatment, there may be treatment failure, relapse, ongoing transmission and development of drug resistance (CDC, 2006).

It was in 2008 that South Africa implemented an inpatient model of care (Health Systems Trust, 2017) for persons diagnosed with MDR-TB and other forms of resistant TB. In this model, persons suffering from resistant forms of tuberculosis were to be admitted and receive TB treatment in the first six months. This initial treatment was to be administered at nominated, centralized and specialized treatment facilities such as at a tertiary hospital like Chris Hani Baragwanath. These designated facilities are referred to as "Provincial Centres of Excellence" (Department of Health [DoH], 2019). With this compulsory admission the expectation was that it will not only facilitate daily injections and allow close monitoring of adverse events and adherence, but prevent population transmission (Health Systems Trust, 2017). After this six-month compulsory admission and with a negative sputum smear result, when the patient was discharged they were expected to complete their treatment (for a period of 18 months or longer) at their local healthcare facility and return to the centralised, specialist hospital for monthly outpatient visits. For some, this proved to be quite expensive as it meant travelling up to 500km to reach designated hospitals (Health Systems Trust, 2017).

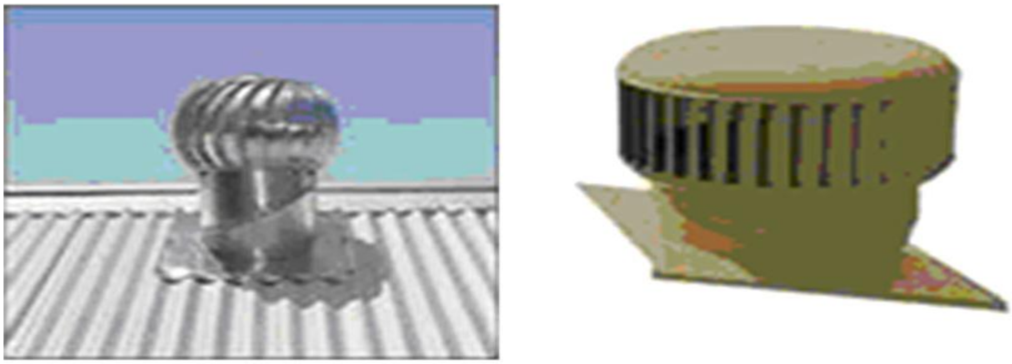
Critics of this model purported by the policy for resistant TB management that requires that all drug-resistant TB be treated as inpatients at designated hospitals have highlighted two unfortunate consequences. Firstly, they have argued that compulsory confinement is not sustainable for an already overburdened healthcare system. Scarcity of appropriate long-stay or palliative care facilities in the country, and shortage of beds in the designated hospitals, compels a decision to release the patients into the community before they had finished treatment. Evidence from research by Dheda et al., (2017), Fokazi (2014) and Pietersen et al. (2014) demonstrated that 40% of patients with drug-resistant TB who had failed treatment and had positive sputum cultures were discharged from hospital into communities that have inadequate resources to support proper home-based care when required (The Lung Institute, SA, 2018).

Furthermore, continued confinement has been associated with frequent escapes by the patients (London, 2008). In addition, critics have identified the distance (some up to 500km) that patients have to travel post-discharge from the centralised health facilities as deterring compliance to treatment, resulting in high mortality.

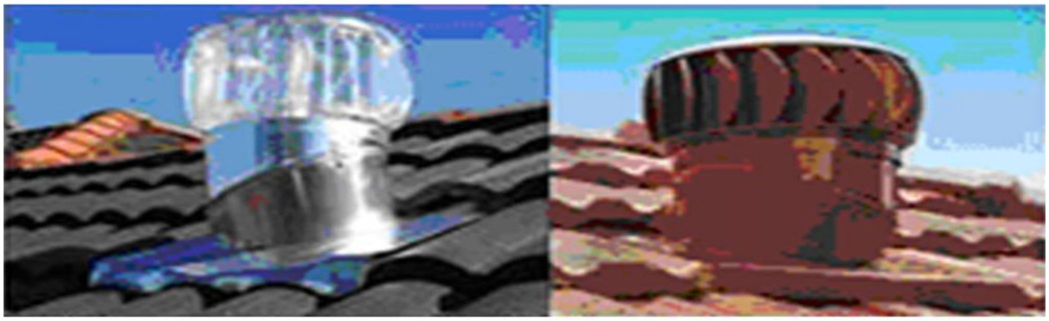
There are issues that are posed by these early discharges, the frequent patient escapes and the deterrence from seeking healthcare. Of considerable importance is the risk they carry for increasing the TB disease burden. Recent research evidence shows that a third of these early discharged patients were at a high risk of transmitting the disease into the wider community (Dheda et al. 2017; Fokazi, 2014; Pietersen et al., 2014). Fears arose that lead to the incurable TB strain spreading and an increase in the number of people diagnosed with the incurable TB. Some statistics indicate that there are patients being diagnosed with the drug-resistant strain of TB, who have never had TB before, meaning they could have been infected by those discharged patients (Dheda et al., 2017). London (2008) cautions not to blame early discharges for this incidence in the community. He reasons that patients with drug-resistant TB will probably have infected their close contacts by the time they reach diagnosis, thus making it reasonable to make the inference that the burden of disease transmission would have occurred even before detection. These findings outline the critical need for urgent action to curb the airborne transmission of this disease to the wider community, including appropriate environmental containment strategies.

Considering the consequences of the drug-resistant TB management policy in the country, a different solution, aside from compulsory hospital admission, is proposed to prevent transmission to third parties – home confinement. Goamaere et al., (2007) suggested that home confinement was a practical alternative, particularly if combined with barrier measures and health services support (Goemaere et al., 2007). This has been hailed as a less restrictive alternative that achieves the same objective as enforcing hospitalisation of drug-resistant TB patients to protect others' health. From a policy perspective, London (2008) reminds us that should policy guidelines for home confinement be drafted, awareness needs to be raised on the magnitude of the hygiene precautions that could be taken at home and their likely success. London (2008) further suggests that certain factors would need to be considered such as residential density, size of rooms, quality of the structure, presence of outbuildings and other factors.

Much of the current literature, especially where identification and follow-up of TB cases has been demonstrated to be difficult, has focused on the provision of ventilation systems as an extra measure of protection (Kalliomaki et al., 2016; Nardell, 2016; Cox et al., 2012; Bolashikov & Melikov, 2009; WHO, 2007). Collectively, these studies agree on the significant implications of room ventilation diluting and removing infectious aerosols, such as TB. Cox et al., (2012) determined that harnessing natural ventilation using simple technology driven by natural forces, such as wind, or the sun, might play a fundamental role in providing this promising alternative (Cox et al., 2012). One such measure, which Cox et al. (2012) suggest is the installation of wind-driven roof turbines ducted through the roof and powered by the wind (Cox et al., 2012) to remove potentially contaminated air. These devices, shown in Figure 1.1, are used mostly for ventilating roof spaces and industrial buildings.



(A) 300 mm curved vane turbine (B) 300 mm straight vane turbine



(C) 250 mm straight vane turbine (D) 250 mm straight vane turbine

Figure 1.1 Types of wind-driven roof turbine ventilators **(Source:** Khan, Su & Riffat, 2008**).**

The wind-driven turbine ventilators consist of a number of vertical vanes, which are either straight or curved blades that are mounted on a frame in a spherical or cylindrical form (Khan, Su & Riffat, 2008). In their study to assess the efficacy of wind-driven turbines to achieve recommended ventilation rates in a healthcare setting, Cox et al. (2012) demonstrated that there is a potential for these devices to assist in improving airflow and ventilation and contribute to the control of TB transmission (Cox et al., 2012). What would make this control measure attractive for a community or household set-up is that they are a low-cost and low-maintenance technology that does not require electricity (Cox et al., 2012).

This study, thus, considered evaluating the potential of an enhanced ventilation system using this low-cost, easy to implement and low-maintenance technology ventilation control system (wind—driven turbines) in reducing risk of third-party infection in resource-limited communities into which terminally ill drug-resistant TB patients and those that are in the recovery phase are released or escape into.

1.2 Statement of the problem

South Africa's drug-resistant TB policy's objectives of implementing treatment and protecting third parties from infection is no longer served by compulsory hospital admission (London, 2008). Due to an overburdened healthcare system, incurable TB patients are released into communities. Furthermore, confinement deters patients from seeking healthcare and there have been reports of frequent patient escapes from confinement. This then poses a risk of ongoing community transmission of the disease. While home confinement has been suggested as a promising alternative (London, 2008; Goemaere et al., 2007) to enforced hospitalisation, one area that has received insufficient attention is the issue of environmental TB control in household settings. Increasing room ventilation is the mainstay of environmental controls (Cox et al., 2012). However, there is insufficient data to prescribe minimum ventilation rates for household settings (Li et al., 2007). Most evidence is largely from hospitals and clinical settings (Chamie, et al., 2013; Shenoi et al., 2010; WHO, 2009; Joshi et al., 2006; Jensen et al., 2005) whose characteristics differ from community ones. In South Africa, the IUSSNS Task team (2014) drafted minimum definitive ventilation guidelines for odour control and airborne cross infection in primary care facilities. These guidelines could be used to model and develop customised airborne infection control policies for the community into which drug-resistant TB patients are discharged or escape into.

1.3 Justification of the research

Patients who are still infectious but with some prospects of cure after prolonged therapy from resistant forms of TB are being released into the community. While some evidence show that this is due to scarce bed space in designated hospitals (Dheda et al., 2017; Pietersen et al., 2014), the incurability nature of the disease, poor response to treatment and prohibitive costs of treatment for drug-resistant TB (Moll, 2007; Centres for Disease Control and Prevention, 2006) which are unsustainable in the low-income and middle-income countries like South Africa where TB is most prevalent, from a social perspective, the patient intolerability of prolonged hospital stay can also be seen as a contributory factor towards this early release. Despite drug-resistant TB comprising less than 3% of the total case load in South Africa (The Lung Institute, South Africa, 2018), in 2010, MDR/XDR TB utilised almost 45% of the national TB budget of about US$280 million (Dheda et al., 2017; Medecins Sans Frontieres, 2011). Such disproportionate and prohibitive costs pose a threat to the stability of TB control programmes in South Africa and other countries with similar resource constraints making the disease significant to public health. The fact that costs are so high may result in greater rationing of who gets treatment and for how long to the extent that it may lead to policies that results in earlier termination of treatment than might have been the case and result in untreated cases returning to the community. Less restrictive alternatives such as home confinement coupled with barrier measures and health service support have been suggested in place of enforced hospitalisation.

As such, evidence needs to be collected that would inform decisions that need to be made of the appropriate type of barrier measures to be implemented as part of containment strategies to curb community-based TB transmission. The Cox et al. (2012) study from which this study springs from was done in a healthcare setting in the Western Cape where wind speed may be different (higher) compared to the inland which is the setting for this study. As such, an intervention like a turbine ventilator, should be pragmatic, based on local conditions, the climate and taking cognisance of available resources (Verkuji & Middelkoop, 2016). That way, such interventions can inform future/potential programmes that will aim to connect designated inpatient health facilities where patients are first treated with home-based and/or community care when patients who are still infectious but with some prospects of cure are released to enable continued care and minimising continuing transmission (The Lung Institute, SA, 2018).

A study conducted by Abney (2011) on the significance of TB-related stigma and stigmatizing acts in areas of Khayelitsha Township in Cape Town, South Africa provides an important link of human behaviour to technologies such as the one in this study. Abney (2011) found an association between perceptions of TB as a disease of dirtiness with certain occupant behaviour such as closing windows. This finding makes the findings that emerged from this study more applicable.

1.4 Research question, aims and objectives

1.4.1 Research question

The central question in this research report asks:

To what extent is the risk probability for TB transmission impacted upon when enhanced ventilation using wind-driven roof turbines is applied in domestic homes?

1.4.2 Aim of the research

The aim of this research is to determine the potential that enhanced ventilation using wind-driven roof turbines in domestic homes has on the risk probability for TB transmission in Diepsloot, a resource-limited community in the Gauteng province within South Africa.

1.4.3 Specific objectives

The objectives of this research are:

- To describe the physical and social characteristics of the participating households in Diepsloot, South Africa.
- To assess the impact of wind-driven roof turbines on indoor temperature, indoor moisture levels, CO_2 concentration, room ventilation and air exchange rate in eight households (four intervention households, four control households) using a CO_2 tracer gas decay technique for measuring air changes per hour over a three-month period in Diepsloot, South Africa in 2019.

- To estimate, using the Wells-Riley mathematical model, the potential effect of wind-driven roof turbines to reduce the probability of TB transmission.

1.5 Research assumptions

The study works under the assumptions of equal host susceptibility, uniform sizes of droplets, uniform ventilation, homogeneous mixing of air, and minimal elimination of infective particles other than by removal by ventilation.

1.6 Operational definitions

1.6.1 Enhanced ventilation

Ventilation is a technique to provide outdoor air into a building or a room and the resulting distribution of that air within the building (WHO, 2009). Thus, ventilation has three basic elements which are ventilation rate, airflow direction and air distribution. Ventilation can be achieved through natural, mechanical and mixed mode (hybrid) means, depending on the driving force. The mixed mode ventilation relies on natural driving forces to provide the desired (design) flow rate. It uses mechanical ventilation when the natural ventilation flow rate is too low (WHO, 2009). Throughout this research report, the term enhanced ventilation falls under the hybrid (mixed methods) ventilation and refers to the harnessing of outdoor air to remove moisture and pollutants emitted from indoor sources within a building (Batterman, 2017) using a simple technology (roof turbine) that utilizes wind forces, providing a roof-exhaust system that increases airflow in a building.

1.6.2 Wind-driven roof turbine

The term whirly bird is a relatively common name used for wind-driven roof turbines. According to Turbovent (2019), a wind-driven roof turbine is a cylindrical metal vent with blades which are either curved or straight, usually mounted on a roof. In this study, all wind-driven roof turbines installed are constructed of aluminium material, are spherical in shape and comprise a 240mm curved vane.

1.6.3 Risk probability for TB transmission

The assessment of the risk, using a mathematical model, for TB transmission in a household setting. While a variety of mathematical models have been suggested for the determination of risk probability for TB transmission, this research report used a modified mathematical model based on the Wells-Riley equation that was first suggested by Wells and Riley in 1955 (Lyzigos et al., 2013; Noakes et al., 2008).

1.6.4 Household

Throughout this research report, the term household is used interchangeable to refer to the social structure and the physical housing of a group of associated/related occupants of a Reconstruction and Development Programme (RDP) house, a formal stand-alone housing unit in Extension 8 of the Diepsloot Township in the Gauteng province, South Africa.

1.7 Structure of the research report

The overall structure of this study takes the form of six chapters, including this introductory chapter that reflects on the context of the research. It highlights the background of the study, clarification of concepts under study, a brief introduction of the literature, the statement of the research problem, which describes the rationale for doing this research. Subsequently the chapter highlights the research objectives and the questions that this research addressed as well as the significance of the study. In the last section of the chapter, a discussion is presented on the research delimitations and research assumptions.

Chapter Two deals with the literature review, whose purpose is to highlight the reviews, opinions and arguments made by other researchers on different aspects of ventilation for different settings. This includes a discussion on airborne microbial transmission with a focus on TB, different TB infection control interventions, ventilation in TB infection control, air quality measurements and TB risk assessment.

The Third chapter is concerned with the methodology used to carry out this study. The chapter discusses the research approach, sampling procedures, data collection methods and elucidates the data analysis approach. The last section of the chapter discusses the reliability, validity and ethical standards pertinent to this particular research.

The Fourth chapter presents the key findings of the study. Chapter Five provides an interpretation of the study's findings and discusses the findings against the research objectives envisaged at the start of the research.

Chapter Six is a synopsis of the conclusions drawn from the analysis and interpretation of the study results. The chapter draws upon the entire research report, tying up the various first hand findings in order to answer the central question that drove this study. It identifies the contribution to knowledge made by the study and proposes recommendations for future research.

1.8 Summary of chapter

The main objective of this study is to determine the potential for enhanced ventilation using a wind-driven turbine technique in reducing third party TB infection in a household set-up in a resource-limited community the Gauteng province. This chapter outlines the general background to the study and the rationale for conducting the research by highlighting the challenges that hinder some aspects of TB control in SA. Furthermore, the problem statement of the research is outlined indicating the scarcity of literature that prescribes minimum ventilation rates for household settings in the SA context that will enable the implementation of home confinement as a practical, less restrictive alternative to enforced hospitalization for drug-resistant TB management. The aim and objectives of the research, the research questions and assumptions were clarified in this chapter.

The following chapter presents an exploration on the literature review done by the researcher that lays out the theoretical dimensions of this study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, the researcher compares, analyses, contrasts and reviews the arguments advanced towards the control of tuberculosis (TB) infection using ventilation in different settings. The literature reviewed examines five main areas of discussion. This starts with the policy framework in place in South Africa to control TB and the challenges of this model in containing transmission. Various TB infection prevention control (IPC) interventions are reviewed with an argument provided on how ventilation, though a traditional primary prevention measure has gradually become an overseen intervention in TB infection control, particularly where contemporary building designs lean more towards air tightness and energy consumption. Furthermore, a discussion on the different ventilation techniques follows, highlighting the impending debate on what constitutes ventilation best practice in an effort to determine the pertinent criteria that can be used for household settings. In addition, air quality measurements with a focus on the different air quality models used to assess the capability of a ventilation effort is evaluated. Following on this one, a review of infection risk assessment with a focus on an adapted Wells-Riley mathematical model of respiratory infection is made. The chapter concludes by highlighting the critical air change measurements to determine whether a unique set of success criteria can be identified for all settings including households.

2.2 Policy framework for tuberculosis control in South Africa

After adjusting for population size, South Africa is identified as having the highest prevalence and incidence of TB and the second largest number of diagnosed multi-drug resistant TB cases among the 22 high burden countries (WHO, 2013).

Of the 500 000 cases of multidrug resistant TB reported globally in 2014, roughly 8% of these cases, which constitutes 40 000 of the global cases, were reported to be cases of rifampicin-resistant TB (RR-TB) or multidrug-resistant (MDR-TB) in South Africa (Dheda et al., 2017; Falzon et al., 2013; WHO, 2012). In 2015, 19 613 patients were reported to have been diagnosed with RR-TB in South Africa (WHO, 2016). The fact that these figures are primarily based on a combination of results of a national survey that was conducted in 2001 and routinely reported case numbers is seen as problematic. Until recent and reliable evidence becomes available, it is believed that this is an under-estimate of the situation in South Africa (Dheda et al., 2017; Cox et al., 2012). As Weyer et al., (2004) points out, since the prevalence of drug-resistant TB is considered a measure of the effectiveness of existing TB control programmes, the highlighted statistics either emphasise grave inadequacies in current treatment and management strategies for TB in South Africa or highlight an ailing health system.

The previous national TB guidelines for drug-resistant TB placed emphasis on a standardised treatment regimen for MDR-TB and XDR-TB that called for mandatory hospitalisation in centralised specialist TB hospitals (National Department of Health [NDoH], 2019) until the patient had two consecutive negative TB cultures taken at least 30 days apart (Schnippel, Firnhaber, Conradie, Ndjeka & Sinanovic, 2018). These guidelines have been fraught with many challenges, such as, insufficient numbers of hospital beds to provide for mandatory hospitalisation for all MDR-TB patients (Medecins Sans Frontieres, 2018), the cost of lengthy hospitalisation (Hughes & Osman, 2014; Pietersen et al., 2014; Schnippel et al., 2013; Cox et al., 2010; Centres for Disease Control, 2006), and the consequent long waiting lists at most major provincial specialist TB hospitals (NDoH, 2019). The other consequences not foreseen by the policy makers were unidentified cases (Medecins Sans Frontieres, 2018), poor cure rate (Jaksuwan et al., 2018; O'Donnell et al., 2009; Keshavjee et al., 2008), poor treatment adherence (NDoH, 2016), abscondment and early release into the community (Dheda et al., 2017). Three previously published South African studies highlight the role of transmission of XDR-TB in communities and health facilities in driving the drug-resistant TB epidemic in South Africa (Auld et al., 2018; Shah et al., 2017; Gandhi et al., 2006). This possibility of transmission of drug-resistant TB triggers responses to evaluate IPC measures to minimise transmission of TB in community and household settings.

In 2011, further revisions were made to the guidelines for MDR-TB treatment and these revisions highlighted strategies for decentralisation and de-institutionalisation of MDR-TB treatment (Cox et al., 2010). However, an observation from Medecins Sans Frontieres (2018) is that there has been slow decentralisation, which has led to delays in commencing patients on treatment. This further puts a delay in efforts to curb the infectiousness of the disease and its transmission in the general population.

2.3 Tuberculosis infection prevention control measures

TB is transmitted from person to person by tiny airborne particles, called 'droplet nuclei' containing tubercle bacilli (Centres for Disease Control and Prevention, 2006). After release of these particles through being coughed up by persons with untreated or inadequately treated, clinically-active pulmonary or laryngeal TB (Kalliomaki et al., 2016), the droplets undergo evaporative water loss in the air to become droplet nuclei (Tang, 2016). The duration of contact with someone who has active pulmonary or laryngeal TB while in a similar air space increases the chances of a susceptible person inhaling airborne TB bacilli.

According to a report by the Department of Health (2017), the top four contributors by risk group to the TB epidemic in South Africa are clinic attendees, HIV infected, informal settlements and household contacts. In this instance, the Department of Health (2017) reiterates that in terms of these TB statistics in South Africa, 92% of the prevalence information is derived from clinic attendees followed by information gathered from the HIV infected (contributing 80% to the prevalence statistics), with information gathered from informal settlements and household contacts contributing 36% and 14% respectively to the epidemic statistics. For this reason, TB transmission in community/congregate settings and among household contacts of drug susceptible, MDR- and XDR-TB patients has been receiving increased attention (Brouwer et al., 2015; Buregyeya et al., 2013; Naidoo, Seevnarain & Nordstrom, 2012).

It is the ease of spread of TB transmission by airborne droplet nuclei, which makes the control of TB transmission important (Kuyinu et al., 2016). Thus, the incorporation of IPC practices may interrupt the transmission of TB in different settings (Farley et al., 2012). The WHO and Centres for Disease Control and Prevention guidelines suggest a three-level hierarchy of controls that includes administrative control, environmental control, and personal protection (Cain, Nelson & Cegielski, 2010; Nathanson et al., 2010) which have been adapted to address resource-limited settings.

Administrative control measures decrease TB exposure risk by rapid detection, isolation, treatment of TB patients and prevention of active disease in those infected through isoniazid prevention therapy (INH). INH reduces the risk of a first episode of TB occurring in people exposed to infection or with latent infection as well as recurrent episodes of TB (WHO, 2008). At both individual and population levels, risk assessment using mathematical models in settings with a high burden of both HIV and TB suggest that the INH strategy contributes to a reduction in the incidence of TB (WHO, 2008).

Environmental control reduces the concentration of infectious droplet nuclei in the air and controls the direction of contaminated airflow. While effective ventilation is necessary for infection control, facility limitations and financial constraints impose challenges especially in resource-limited settings (Kompala, Shenoi & Friedland, 2013). Personal respiratory protection includes the use of respirators to prevent inhaling contaminated air (Farley et al., 2012; Cain, Nelson & Cegielski, 2010; Gandhi et al., 2010; WHO, 2009; Jensen et al., 2005). An additional challenge that resource-limited settings face is the cost associated with the regular use of disposable respirators. While these personal protection devices are essential, Kompala, Shenoi and Friedland (2013) found that respirator prices are prohibitively expensive, ranging from US$1 to $2 each (Kompala, Shenoi & Friedland, 2013). This is equivalent to between R17 to R34 in South Africa, where 55.5% of the population (30.4 million people) live below the upper-bound poverty line (StatsSA, 2017).

When these highlighted IPC strategies are combined, they show high efficacy in interrupting the transmission of TB, with the synergistic combination of these IPC strategies alleged to prevent nearly half of extensively drug-resistant (XDR)-TB cases, even in a resource-limited setting (Basu et al., 2007).

2.3.1 Environmental control in tuberculosis infection prevention and control

Environmental control is the second level of the TB IPC hierarchy. The purpose of environmental controls is to prevent spreading TB by reducing the concentration of infectious airborne droplet nuclei (Farley et al., 2012). Environmental measures are categorised into two: primary and secondary controls. The central focus for primary environmental controls includes infection source control and contaminated air removal through infiltration, using local exhaust ventilation (LEV) and general ventilation. Secondary environmental controls include two types of infection control. Firstly, airflow control for preventing contamination of air near the infection source. Secondly, purification of the air using air-cleaning methods like high efficiency particulate air (HEPA) filtration or ultraviolet germicidal irradiation (UVGI) (Jafari et al., 2014; Jensen et al., 2005; Luksamijarulk et al., 2004; Geshwiler et al., 2003; Beggs et al., 2002; Coker et al., 2001; Centres for Disease Control and Prevention, 1994).

Infiltration is the uncontrolled leakage of air through the building envelope (Nazaroff, 2014) and natural ventilation occurs by thermal, wind or diffusion effects through windows, doors and other designed openings in the building (Breen et al., 2010; Bouhamra et al., 1998). Both infiltration and natural ventilation are non-powered airflows that come about because of pressure differences that result from differences between wind and indoor-outdoor temperature differences (Shiraz and Penell, 2017; Bouhamra et al., 1998). Mechanical ventilation consists of intentional powered air-exchange that is induced by mechanically powered equipment such as motor-driven fans or blowers (Nazaroff, 2016) and intake and/or exhaust vents (Wargocki, 2002) that have been specifically designed and installed for ventilation (Bouhamra et al., 1998).

Air treatment involves “purifying the re-circulated air through the ozone-based oxidation process and air scrubbing devices” (Cui et al., 2017) such as air conditioning systems (Fisk, 2013), room air cleaners or air purifiers such as HEPA filters (Vijayan et al., 2015).

While cost effective first steps for the control of TB include maximising natural ventilation, any decision made on the type of environmental TB IPC measures to implement should consider factors such as available resources, local conditions and climate. Furthermore, the monetary issues associated with environmental measures such as UVGI or air filtration should be considered when advocating for their usage as part of a TB IPC package (Verkuijl & Middelkoop, 2016). This further highlights the importance of evaluating the cost-effectiveness of implementing the TB IPC measures for household settings.

2.3.2 Ventilation rates

Yamamoto, Shendell, Winer and Zhang (2010) find that in order to characterize human exposure to airborne contaminants, to evaluate the energy consumption of a building and to determine the appropriate size of mechanical heating and air conditioning equipment, the residential air exchange rate (AER) or ventilation rate is an important factor to demarcate and properly define. The AER or ventilation rate of a building is defined as the rate at which external air (fresh air) flows into the building and replaces indoor air in a given time period (Brouwer et al., 2017; Reichman et al., 2017; Nazaroff, 2014; Bouhmra, Elkilani & Abdul-Raheem, 1998).

The AER is measured in units of air changes per hour (ACH), which is equivalent to the ratio of the hourly indoor air volume replaced by outdoor air to the total indoor volume (Jensen et al., 2005). Therefore, a high ACH means a large volume of outdoor air comes in and replaces the indoor air over time (Bouhmra, Elkilani & Abdul-Raheem, 1998). Other ventilation metrics include ventilation rate (m^3 per hour) and ventilation rate per person (liters per second per person [L/s/person]) (Batterman, 2017). The ACH easily estimates flow rates in simple building layouts, with openings on opposites sides based on wind-driven and stack-driven (temperature differences) effects. As building designs have become complex there has been more building air tightness, with continued reliance on mechanical ventilation of spaces and a need for energy conservation to avoid penalties. There is thus a need for metrics which not only account for this but account for contaminants other than human bio-effluents, such as building materials and furnishings.

Table 2.1 illustrates the airborne contaminant removal efficacy, measured over an hour, for the removal of airborne contaminants.

Table 2.1 ACH and removal efficiencies.

ACH	**Airborne contaminant removal efficacy at 1 hour (%)**	**Minutes required for removal efficacy**	
		99%	99.9%
2	86.5	138	207
4	98.2	69	104
6	99.75	46	69
12	99.9994	23	35
20	99.99999	14	21

Source. Jensen et al. (2005).

Table 2.1 shows that in health care facilities, the ACH with the highest removal efficiency is 20, which takes 21 minutes to successfully remove 99.9% of airborne contaminants. These ventilation values are in line with the minimum averaged ventilation rates recommended by the WHO guidelines for infection control in health care settings (WHO, 2009). Etheridge (2012) recapitulates that considering that changes occur in wind speed, wind direction and external and internal temperatures with time, the magnitude of the AER or ventilation rate is expected to vary over a wide range in quite short time intervals.

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 62 stipulates that in order to provide adequate indoor air quality for conditioned spaces, minimum ventilation rates or AERs should be determined in terms of building use and occupancy. This means that the amount of air specified for a dwelling considers the size of that dwelling and the number of occupants, which is typically determined from the number of bedrooms (ASHRAE, 2013). However, the ASHRAE (2013), provide no clarity on what type of ventilation system is acceptable to attain these specifications nor do they make reference to the health standards related to these specifications. What the ASHRAE (2013) has done is recommend minimum ventilation rates according to the air space occupied per person. They argue that these rates are intended to provide adequate fresh air to remove water vapour resulting from perspiration, to reduce body odours to a level where they are not noticeable and to deal with the smoking pollution problem (ASHRAE, 2013). Where other domestic contaminants are produced such as during cooking, in toilets and bathrooms the rates specified are higher. The rates for industrial situations, which produce artificial contaminants from work processes are specified based on the severity of the released airborne contaminants.

The ventilation flow rate is referred to as "either an absolute ventilation flow rate in L/s or m^3/s, or an air-change rate relative to the volume of the space (ACH)" (WHO, 2009). The relationship between ventilation rate in L/s and air-change rate is:

$$\text{Air-change rate} = [\text{ventilation rate (L/s)} \times 3600\ (\text{s/hr})] \times 0.001\ (m^3/s)]/[\text{room volume}\ (m^3)] \qquad \textit{Equation 1}$$

or,

$$\text{Ventilation rate (L/s)} = \text{air-change rate} \times \text{room volume}\ (m^3) \times 1000\ (l/m^3)/3600\ (\text{s/hr}) \qquad \textit{Equation 2}$$

Source. WHO (2009).

In terms of Equation 1, for example, if AER =1 ACH, this means that all the inside air of the space is replaced by outside once in one hour; if AER= 0.5 ACH, the air is replaced by every two hours etc. (Figure 2.1).

The WHO has provided guidelines on the minimum averaged ventilation rates for health care settings. For household settings, in order to ensure adequate ventilation, the ASHRAE (2013) says that the living area of a home should be ventilated at a rate of 0.35 air changes per hour or 15 cubic feet per minute (cfm) per person, whichever is greater. Ventilation rates of between 10 and 18 ACH are expected for night cooling for household settings according to Engineering Toolbox (2019). Table 2.2 below shows typical air exchange rates per hour for well-insulated spaces:

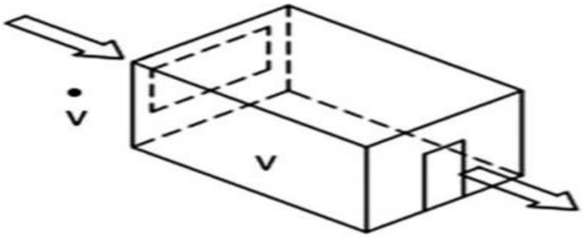


Figure 2.1 Schematic presentation of air exchange in a closed space **Source**: Afonso (2015).

Table 2.2 Typical air exchange rates per hour for well-insulated household spaces.

	Typical ACH
No windows or exterior doors	0.33
Windows or exterior doors on one side	0.67
Windows or exterior doors on two sides	1
Window or exterior doors on three sides	1.33

Source. Engineering Toolbox (2019).

It should be noted, however, that these values are determined having made the assumption of residences being single-zone areas. A single zone, for tracer gas studies of ventilation, assumes homogeneity, isolation and perfect mixing. A key aspect of homogeneity is that at every point within a single zone, the density and concentration of the tracer gas are the same. The assumption that there are no buffer zones and thus the zone is only communicating with the outside areas whose concentration of tracer gas is unaffected is at the heart of our understanding of the isolation aspect of single zones. Central to perfect mixing is the assumption that any tracer gas that is injected in the zone becomes uniformly distributed within the zone (Sherman, 1990).

However, these assumptions have received some critical attention. The use of single zone models has been criticised as having substantial limitations such as inadequately representing pollutant concentrations and exposures in other rooms in the dwelling where people spend a substantial fraction of time. Furthermore, the issue of infiltration is unaccounted for and should not be overlooked in these interpretations. Findings suggest that infiltration has become the common mode of ventilation in homes nowadays, mainly because of availability of central heating and cooling techniques and the need for privacy, which deter the use of windows. The South African Residential Ventilation Building Code (SANS 10400, 2011, South Africa) recommends an average natural infiltration rate of 0.35 m^3/h per m^2. ASHRAE (2013) find that a home's natural infiltration rate is unpredictable and uncontrollable because it depends on the home's airtightness, outdoor temperatures, wind, and other factors. Thus, during mild weather, some homes may lack sufficient ventilation for pollutant removal. This is in agreement with findings from an early study (Brundett & Poulney, 1985 cited in Hayati, 2017) that demonstrated that window and door cracks only present a much smaller source (< 30%) of air leaks than was commonly believed. In contrast to these findings, Yoshino et al. (2006), after studying household dwellings in 15 developed countries, concluded that the ventilation requirements of the households could be met by casual infiltration through cracks without opening windows. They found that the ventilation requirements in housing can be satisfied in most cases with 25 m^3/h of fresh air per person or 1.26 m^3/h per square metre of floor area. These are equivalent to about 0.5 ACH for a $100m^2$ house (Yoshino et al., 2006).

Wargowki (2016), after conducting an extensive review of published scientific literature that investigated the association between measured ventilation rates and the measured and observed health problems found that it seemed likely that health risks may occur when ventilation rates are below 0.4 air changes per hour in households. In Kampala, Uganda, Chamie et al. (2013) reported that in homes at high risk for TB transmission, ventilation rates were significantly lower in homes reporting TB in a contact (12 vs. 17 ACH). Their study demonstrated that opening a window resulted in a mean increase of 7 ACH (Chamie et al., 2013).

A study conducted by Liuliu et al. (2012) took seasons into consideration and showed that in living areas, AERs were highest in winter and lowest in spring, bedroom AERs were highest in summer and lowest in spring. Comparably, a study by Eskola et al. (2007) on Finnish houses showed an average actual air change rate in the summer period was 0.40 L/h in houses with mechanical supply and exhaust ventilation and 0.37 L/h in houses with mechanical exhaust ventilation. Winter period values were 0.41 L/h and 0.34 L/h for houses with mechanical supply exhaust ventilation and mechanical exhaust ventilation respectively, and 0.30 L/h in naturally ventilated houses. In the United States of America (USA), Yamamoto et al. (2010) demonstrated a median AER across urban areas and seasons of 0.71. In an area such as Texas, which is typically hot and humid during the summer, the measured AERs were lower in the summer cooling season (median = 0.37 ACH) than in the winter heating season (median = 0.63 ACH). This area tended to use room air conditioners. Where the summer season was less humid such as Los Angeles, they observed that natural ventilation through open windows and screened doors could have resulted in increased measured AER in California study homes. Winter and autumn ventilation rates were similar, but the rates were slightly higher in spring and much higher in summer (Yamamoto et al., 2010). According to Pandian, Ott and Behar (1993), multi-level residences have higher air exchange rates than single-level residences (Pandian, Ott & Behar, 1993).

In South Africa, Lygizos et al. (2013) showed that when windows are closed, mean ACH of 3 were achieved compared to ACH of 20 when windows are opened. While in Zimbabwe, Mushayabasa (2013) found that a prison cell of volume 195 m^3 with 40 adult inmates comprising of 90% TB susceptibles and 10% TB infectives, requires a ventilation rate of 8 ACH to maintain the reproductive number less than unity.

Cox et al. (2012) took it a step further and harnessed natural ventilation using wind-driven roof turbines. With this technique, they demonstrated that high room ventilation rates of 6.9, 7.8, 8.1 and 6.3 ACH, meeting WHO recommended thresholds, may be achieved using wind-driven roof turbines and grates, even at low wind speeds. They showed that higher median ACH were recorded with open roof turbines and grates (and larger diameter of installed turbine), compared to open windows across all wind speed quartiles.

Although the air changes per hour (ACH) is the common metric used to model air exchange in indoor rooms (Nazaroff, 2014; Aliabadi, 2011; Laussmann and Helm, 2011), there may be a strong dispute for using this metric. Some authors have argued that the ventilation per person or per unit of surface area, i.e. L/s.person, L/s.m^2, are better measures (Salehi et al., 2016; Whyte et al., 2014; Liao et al., 2013; Liao et al., 2008) for characterising air quality for buildings compared to the ACH, which is deemed a weaker and poorer metric for the determination of the ideal indoor air quality. The ACH determination relies on an air exchange rate that has been achieved through ventilation that is dependent on the natural forces (infiltration, air leakage, and temperature and humidity differences). Mudarri (2010) reiterates this one of the reasons the ACH is not referenced as a metric in the current USA and European indoor air quality standards. He clarifies that it is because of building codes that foster energy conservation which have in turn led to the tightening of building envelopes and reduced air infiltration and leakages resulting in significantly reduced air exchange (Mudarri, 2010).

The use of the WHO recommended rate of between 6 to 12 ACH for an airborne precaution room is equivalent to 80 L/s per patient in a 4 x 2 x 3 m^3 room, with an hourly averaged ventilation rate of 160 L/s per patient being recommended (Atkinson, Chartier & Pessoa-Silva, 2009) for high risk areas. When ACH is used to measure ventilation performance, the volume of the enclosed room is clearly an important parameter. For a given ACH, a ward with a larger volume can provide a larger airflow rate (m^3/h or L/s) than a room with a smaller volume.

2.3.3 Ventilation in TB control

Ventilation techniques are found to be the most effective choice among all current available IPC methods for reducing and diluting airborne pathogens (Malangu & Mngomezulu, 2015; Jafari et al., 2014). Findings from a study by Tang (2016) show that large particles of the droplet nuclei, with a diameter >20 µm, are found to rapidly deposit onto wall surfaces because the force of gravity is more significant than ventilation induced effects. Smaller particles (with a diameter of 0.1-10 µm) are usually suspended for a long time (Tang, 2016; Knibbs et al., 2011; Xie et al., 2007) increasing their likelihood to transmit pathogens over great distances (Tang, 2016; Knibbs et al., 2011; Xie et al., 2007). This means that fine particles and pathogens present in a gas cloud are significantly influenced by ventilation and airflow patterns (Kalliomaki et al., 2016; Tang, 2016; Hang et al., 2015). The two modes for air distribution by which this is achieved within buildings is mixing and displaced ventilation (Figure 2.1).

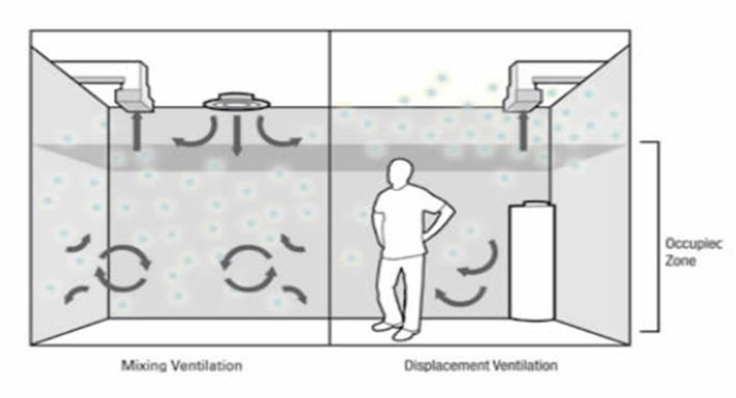


Figure 2.2 Mixing versus Displacement ventilation **(Source:** Hardy, 2015**).**

Displacement ventilation has been increasingly shown to result in better air quality as it removes air impurities and provides only clean air to an occupied zone than mixing ventilation where air is supplied to ventilated spaces (Figure 2.2) (Qian, 2006; Bjarne et al., n.d.). Harnessing natural ventilation using wind-driven roof turbines is a form of displacement ventilation, which in addition to ensuring the quality of indoor air, results in good thermal comfort, requires less initial investment and has low maintenance costs (Ren, Tian & Meng, 2015). Some of the demerits of this type of ventilation is the need to have a larger air output and for effective control of indoor humidity since the temperature of supply air is high (Ren, Tian & Meng, 2015).

Thus, an environmental TB IPC intervention, related to ventilation and airflow patterns, is needed to curb disease transmission (Hang et al., 2015) as its goal is to prevent the spread of TB by protecting susceptible people from inhaling airborne particles generated by infectious individuals. However, an evaluation of different low-cost ventilation systems in resource-limited settings, is lacking.

Ventilation of a space can be achieved through two means – natural and mechanical. It may be natural, by simply opening windows and/or doors, or mechanical, with air extraction and/or supply fans (Cox et al., 2012). When a decision whether to use mechanical or natural ventilation for infection control is made, factors such as needs, the availability of the resources and the cost of the system to provide the best control to counteract the risks should be considered (WHO, 2009). Since natural ventilation depends on the movement of air through open windows and doors and can also be achieved by infiltration, is the cheapest practicable measure to ensure sufficient air changes per hour (WHO, 2009). It is for this reason that the option is found particularly attractive for tropical and temperate climates as well as resource-limited healthcare systems (Escombe, 2007). The additional use of exhaust and mixing fans further assists in the distribution of air and the direction of airflow (TB Coalition for Technical Assistance, 2010; WHO, 2009). A study by Cox et al. (2012) showed that high room ventilation rates can be achieved by using wind-driven roof turbines and air-intake grates, even at low wind speeds (Cox et al., 2012).

In rooms in which airborne droplet nuclei are present, the WHO currently recommends that natural ventilation should be no less than 60 litres/second/patient (WHO, 2012). The US Centre for Disease Control and Prevention (Centres for Disease Control and Prevention, 2006), which use a different ventilation measure, recommends between 6 and 12 air changes per hour (ACH) for such rooms (Centres for Disease Control and Prevention, 2006). Similarly, the American Institute of Architects (2001) recommends minimum ventilation rates of two ACH in patient rooms, six in patient corridors and 12 ACH in protective environment rooms, bronchoscopy rooms and emergency department waiting areas. However, an acceptable level of transmission has not yet been defined which would make modelling appropriate ventilation rates for whatever setting easy.

Even though natural ventilation has been found to be the cheapest indoor air option in resource-limited settings compared to mechanical ventilation, it is highly effective provided the buildings are well-designed and under optimal outside condition (Malangu and Mngomezulu, 2015). However, poor building designs and in addition to a cold weather climate such as at night, and the closure of windows for thermal comfort, security and pest control, natural ventilation is demonstrated to be an inadequate, unreliably unpractical option (Malangu and Mngomezulu, 2015; Nardell et al., 1991). Moreover, since natural ventilation is climate dependent, control over direction of airflow is difficult and there is no easy-to-use tool for measuring ACH (Lee, 2016; WHO, 2009).

Unaffordable installation and maintenance costs limit mechanical ventilation use in resource-limited settings (WHO, 2009). On the other hand, mechanical ventilation is a costly disinfection alternative. This is because it requires careful design, strict equipment maintenance, adoption of rigorous standards, and design guidelines that take into consideration all aspects of indoor environmental quality and energy efficiency (Lee, 2016; WHO, 2009). Such observations underscore the need to explore the potential of low-cost, easy to implement ventilation systems such as wind-driven turbines to reduce the risk probability for TB transmission in resource-limited communities where the prevalence of airborne disease transmission is especially high.

Several studies that have been conducted on TB IPC implementation have tended to evaluate the use of natural ventilation in healthcare settings (Brouwer et al., 2015; Ogbonnaya et al., 2014; Buregyeya et al., 2013; Cox et al., 2012; Naidoo, Seevnarain & Nordstrom, 2012). Only a few evaluated this alternative in different contexts in Africa, such as traditional Zulu homes (Lygizos et al., 2013), public places such as a tavern, a bank, the waiting room in a social security office, a clinic waiting room, a large shop in the town, a small rural shop, a small rural church, a high school classroom, a post office and a fast-food restaurant (Taylor et al., 2016) and urban households in Uganda (Chamie et al., 2013; Whalen et al., 2011). In South Africa, a study by Naidoo et al. (2012) underlined the importance of keeping windows and doors open to ensure adequate number of air changes per hour. Similarly, Chamie et al. (2013) and Lygizos et al. (2013) found opening windows and doors significantly improves ventilation and air quality within a room, achieving a mean ACH of 14 and 20 respectively. Lygizos et al. (2013) also demonstrated that ventilation improved incrementally as the area contributing to ventilation increased (Lygizos et al., 2013). In their modelling study, Basu et al. (2007) showed that an average of 33% of XDR-TB cases were reduced by improvements in natural ventilation. Likewise, ventilation rates of less than 2 ACH (which is equivalent to 13 L/s for a 4 × 2 × 3 m^3 room) were demonstrated to be associated with higher tuberculin skin test conversion rates by Menzies et al. (2000). To assess the adequacy of natural ventilation using window-to-floor surface area in Uganda, Buregyeya et al. (2013) reported inadequate ventilation in almost 50% of facilities, whereas studies from Mozambique (Brouwer et al., 2015) and Nigeria (Ogbonnaya et al. (2014) reported recommended ventilation rates in the majority of facilities assessed. However, these studies were conducted in healthcare facilities and there has been far too little attention paid to household settings.

Escombe et al. (2007) conducted a comparative analysis of mechanical and natural ventilation systems in healthcare settings in Peru and found that opening windows and doors provided a median ventilation of 28 ACH. This was more than double the recommended 12 ACH in mechanically ventilated, negative-pressure rooms (WHO, 2009; Centres for Disease Control and Prevention, 2006). Jiamjarasrangsi et al. (2009) in Thailand and Friedland et al. (2012) in South Africa report similar findings. The authors, however, cautioned that such associated natural disinfection is achievable provided there is correct door and window operation (Escombe et al., 2007). They also point out another important factor that should be considered - the age of the facilities (Escombe et al., 2007). Facilities built more than 50 years ago are largely characterised by large windows and high ceilings. The observation is that such facilities show greater ventilation of 40 ACH than modern, naturally ventilated rooms (17 ACH) with windows and doors open (Escombe et al., 2007). This is in contrast to the observation by Bouhmra, Elkilani & Abdul-Raheem (1998) whose findings point out that the air exchange rate of a building cannot be estimated based on the building' construction or age or from a simple visual inspection. The authors deem it possible only when a detailed quantification of the leakage sites and their magnitude area are made (Bouhmra, Elkilani & Abdul-Raheem, 1998).

The WHO (2009) highlights other factors to consider and which should be detailed when results of implementation of natural ventilation as an IPC measure are reported. These factors are inclusive of climatic conditions such as wind velocity and direction, the carbon dioxide measurement device and the type of building in which measurements were done, as multiple, interconnected rooms affect the mixing conditions within the measured space (WHO, 2009) as well as human behaviour, attitudes and, cultural beliefs. The last factor on the social aspects is very important as it has an influence on the likely adoption of new technologies such as the wind-driven roof turbine. While establishing the efficacy of the intervention in reducing TB risk is the first step, before it can be considered for roll out there has to be an evaluation of how likely the technology will be acceptable. To reiterate on this, a study conducted by Abney (2011) identified how people's perceptions of TB as a disease of dirtiness would lead them to keep their windows shut at night (besides crime and odours). Establishing this link of human behaviour to techonologies would make the finidings emerging from this study more applicable.

2.4 Techniques for studying building air exchange

While there are many methods that have been established to characterise the performance of ventilation systems, tracer gas methods are widely used to measure air exchange rates (Laussmann & Helm, 2013). Tracer gas methods are based on assumptions, including one, which is hardly suitable for natural ventilation, which is steady airflows (Remion, Moujalled & Mankibi, 2018). Two other assumptions made when tracer gas is used are the homogeneity of the tracer gas (room air is well mixed) and that the tracer gas is chemically inert with room objects neither absorbing nor releasing the tracer gas. Furthermore, it is assumed that the external and internal exchange of air occurs in places with direct contact with the outside (e.g. windows) and that the room is a single zone system (Sundell et al., 2011). The last assumption is made to cater for differences in room temperature, which may lead to stratification, ineffective mixing and the presence of dead-zones within a room (Van Buggenhout et al., 2009).

An ideal tracer gas is expected to fulfill certain criteria in order to measure AERs (Laussmann & Helm, 2011; Sherman, 1990). Shin, Lee, Ahn et al. (2004) identified criteria related to an indeal tracer gas that focus on its constituency relative to the environment in which it will be used, toxicity, reactivity, flammability and measurability. Firstly, the gas should not be a normal constituent of the environment to be investigated. Secondly, it should be easily measurable, non-toxic and non-allergenic to permit its use in occupied spaces. Thirdly, it should be non-reactive and non-flammable so that its movement is easily traced. Lastly, it should be economical to use (Laussmann & Helm, 2011). However, no single tracer gas fulfills all these requirements mentioned. As such, a wide variety of gases have been employed and chosen to exploit a specific characteristic. Some studies reported AERs using perfluorocarbon tracer (PFT) compounds [Bady et al., 2010; Barlow & Coceal, 2009; Chao, Wan & Law, 2004; Asimakopoulos et al., 2001). The most commonly used methods are sulfur hexafluoride (SF_6), nitrous oxide, isobutene and carbon dioxide (Hori, Soma & Mizoguchi, 2005).

Carbon dioxide (CO_2) fulfils the second and third of the above-mentioned specifications of an ideal tracer gas (Laussmann & Helm, 2011). Although CO_2 is one of the gaseous organic compounds always detectable in the indoor air, it is often used to assess the air quality of occupied rooms. In addition to CO_2 gas being low-cost, it meets safety requirements (Laussmann & Helm, 2011). Furthermore, since humans exhale metabolic CO_2 in considerable quantities, its concentration can increase to several thousand ppm (ml/m^3 room air) within a short time, which means it can be easily generated for utilisation (Zhang et al., 2015; Li, Li & Qi, 2014). A room with environmental CO_2 concentration has about 400 ppm (Issarow, Mulder & Wood, 2015), but as people occupy it, the concentration of exhaled air starts to increase, depending on the ventilation rate per person, room volume, and the number of people in the room (Emmerich and Persily, 2001 cited in Laussman & Helm, 2011, Lygizos et al., 2013; Persily, 1997). This is because people in the room contribute to the increase of CO_2 concentration by their exhaled air depending on their oxygen consumption, respiratory quotient and physical activities (Emmerich and Persily, 2001 cited in Laussman & Helm, 2011; Persily, 1997). Therefore, in this study, only commercially acquired CO_2 will be injected in unoccupied households.

Laussman and Helm (2011) report that the results of Dols and Persily (1992), Nabinger et al. (1994), and Persily (1997) have, demonstrated that AER cannot be reliably determined from spot, peak or average values of the CO_2 concentration inside buildings. The reasons for this are that these values are strongly influenced by the number of occupants in the rooms, their times of stay, and, hence, the incessantly changing carbon dioxide supply rates. Therefore, the authors observed that depending on the amount of natural ventilation the AER is sometimes over-estimated up to two-fold of the real value. They explain this to be as a result of the air-tightness of modern buildings and the usual residence times of the occupants that prevent the equilibrium concentration from being approached.

There are three main types of tracer gas methods that are commonly used: constant injection used in a study by Warren & Parkins, (1985) cited in Laussman & Helm (2011); constant concentration used in a study by Chao, Wan & Law, (2004) and concentration decay used in a study by Cui et al., (2015) and Lygizos et al., (2013). In the constant injection method, a defined amount of tracer gas is constantly emitted over a certain period of time. Thus, the tracer gas concentration increases with time and reaches a stable value (equilibrium concentration) which depends on the room volume, the air change rate and the emission rate (Laussmann &Helm, 2011). In the constant concentration method, tracer gas is released in the room until a predefined concentration is reached. During the entire measurement the tracer gas concentration is kept constant with an automated dosing and control system (Laussmann & Helm, 2011). The drawback of the constant concentration method is that it requires expensive equipment and technical support for the automatic adjustment of the supply rate (International Organization for Standardization, 2007).

The simplest tracer gas technique used in evaluating ventilation performance (WHO, 2009) is the concentration decay method known as the step-down method. In this method, tracer gas is injected into the room for a short period of time, either from a gas bottle with pressure reducer or manually from filled gas tanks. After mixing with the room air, the tracer gas concentration is measured at regular time intervals (Laussman & Helm, 2011). Thus, the decay method requires the injection of the gas before the measurement, and the evolution of the concentration of the gas provides the AER (Remion, Moujalled & Mankibi, 2018; Iizuka et al., 2010). Figures 2.3, 2.4 and 2.5 show examples of the resulting CO_2 decay curves that can be plotted to determine AER or the ventilation rate. The overarching principle for all the types of gas methods is that all require that the tracer gas concentration in a space be as uniform as possible if the ventilation rate is to be measured accurately (Shinohara et al., 2010).

Due to its simplicity and its requirement for the least amount of tracer gas, the decay method is the most common in single zones. One limitation of assuming homogeneity of the tracer gas in a single zone is that there is always a difference between the densities of the zone tracer gas from that of the indoor air. This may lead to stratification of the gas, which then make it impossible to obtain a uniform concentration within the space. To avoid this problem, it is usual to place small fans inside the space to disperse the gas (Laussman & Helm, 2011).

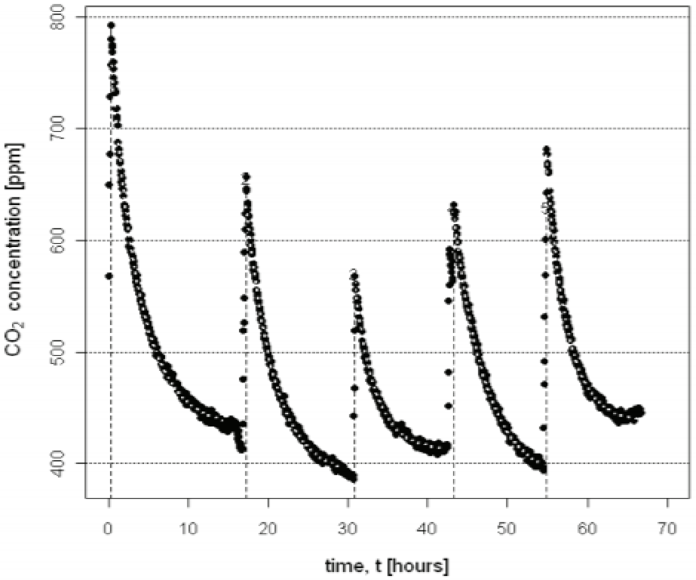


Figure 2.3 Example of CO_2 decay curves in a bedroom equipped with double box window and located in a building built in 1908. **Source:** Laussmann & Helm (2011).

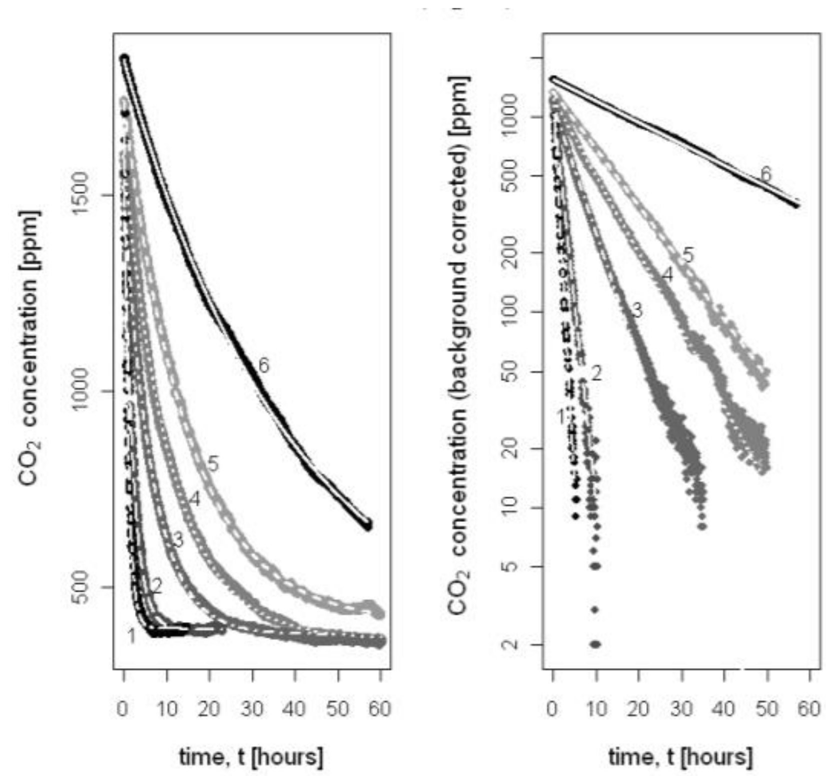


Figure 2.4 CO_2 decay curves in 6 rooms of different air tightness – non-linear regression and linear regression. **Source:** Laussman & Helm, (2011)

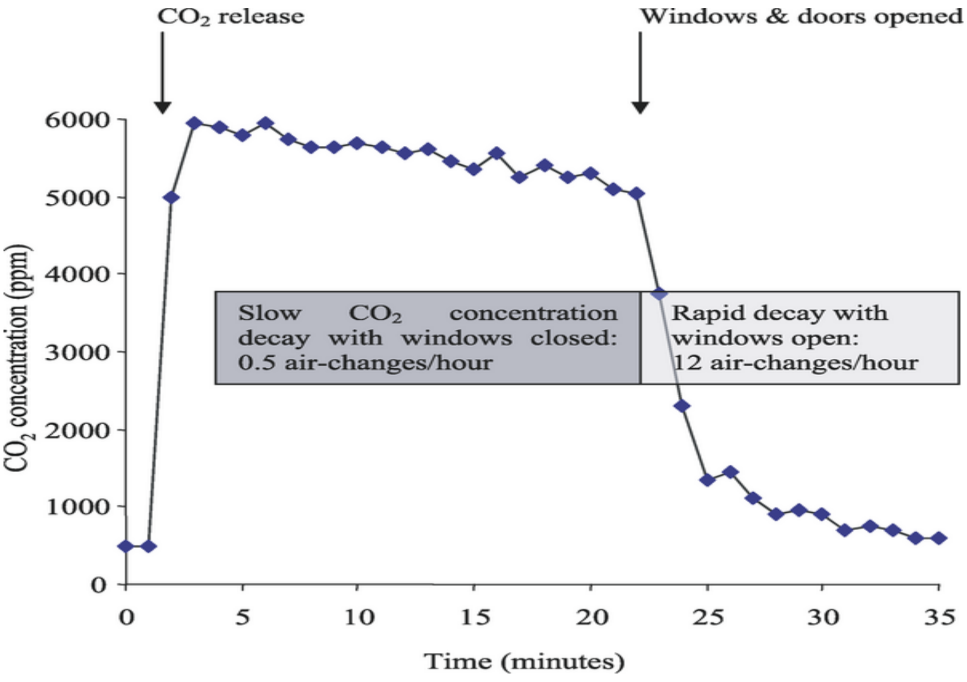


Figure 2.5 CO_2 decay curve for measuring ventilation. **Source:** Escombe et al. (2007).

Laussmann and Helm (2011) showed that under stable weather conditions, CO_2 decay curves can decrease exponentially over a period of 50 hours and longer (Figure 2.4). They argued that this was an indication that tracer gas and room air can remain homogeneously mixed over such long periods without the need of a fan (Laussmann & Helm, 2011). Figure 2.5 shows that during initial release of CO_2 to a peak of 6000 parts/million (ppm), there is demonstrable rise in the concentration followed by a slow decay with a calculated ventilation rate of 0.5 ACH. When natural ventilation was introduced, through opening windows and doors, the CO_2 concentration is shown to have fallen rapidly with a calculated ventilation rate of 12 ACH (Escombe et al., 2007). The current study aims to determine the impact of the ventilation rates created by a wind-driven roof turbine on how rapidly the CO_2 generated decays.

In general, the outdoor air concentration of CO_2 is between 350 and 450 ppm or even higher, depending on the season and the intensity of anthropogenic activities. Thus, the CO_2 decay curve will not decline to zero. Instead, the CO_2 concentration decreases to values, which are near to that of the outdoor air. This must be taken into account when analysing CO_2 decay curves (Laussmann & Helm, 2011).

Despite the importance of the positioning of the CO_2 sensor during measurements (International Organization for Standardization [ISO], 2004), few guidelines are available (Mahyuddin & Awbi, 2012). Van Buggenhout et al. (2009) recommend siting at the ventilation outlet, while acknowledging wind speed, thermal effects and wind direction may make this impractical. This lack of guidance combined with other experimental aspects can make comparison of results difficult (Mahyuddin & Awbi, 2012). This difficulty in making comparisons is offset by ensuring that certain methodological factors, including measurement method, application details, instrumentation and their calibrations, timings, number of measurements, meteorological conditions and building conditions, are comprehensively described (Persily & Levin, 2011).

2.5 Wind-driven turbine ventilator

The ASHRAE (2001) defines a wind-driven turbine ventilator as “a heat escape port located high in a building and properly enclosed for weather tightness with the primary motive forces being stack effect and wind induction". Thus, while the wind-driven turbine ventilators have predominantly been classified as an active technology even though it does not use electricity (Khan et al., 2008), they have also been categorized as a passive ventilation strategy.

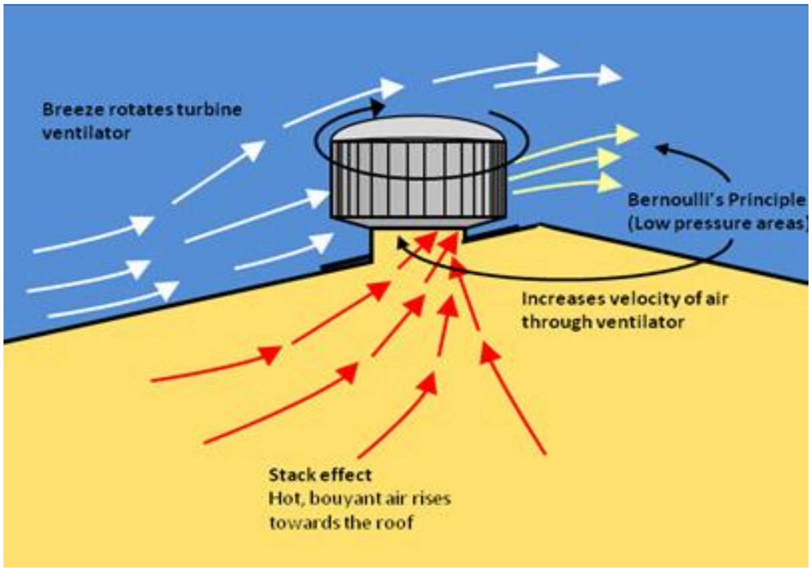


Figure 2.6 Stack effect (passive) and wind induction (active) strategies of the wind-driven roof turbine. **Source:** https://roofwhirlys4africa.co.za/about-wind-turbine-ventilation/.

When the ventilator rotates in its vertical axis, it creates an updraft inside the turbine which then extracts air from the interior of the house. The categorization into active or passive strategy depends largely on the prevailing winds (Figure 2.6). A wind-driven turbine is active when its constantly spinning blades, driven by outdoor wind force, creates a centrifugal force in the turbine which then extracts air from the interior of a building (Khan et al., 2008). The ventilator utilises a passive ventilation strategy in the absence of wind. The openings between blades induce a stack effect when indoor air is warmer than outdoor air. As the warm air moves upward in the building, it reduces the pressure at the bottom of the building, forcing cooler air to be drawn into the building.

Studies which have investigated the turbine ventilator's performance (hot and stale air exhaustion from a building) have suggested that it is significantly influenced by blade design, construction material, make, model, size, wind speed and roof inclination (Khan et al., 2008;

West, 2008). The outcome results of the ventilators have been discussed in terms of ventilation rate (measured in ACH, L/s or m^3/hour), air velocity (in m/s) and air temperature reduction (in ^{o}C). Studies have shown the performance of the turbine ventilator to lead reducing temperature and increased ventilation rates. Dale and Ackerman (1999) demonstrated a reduction in temperature by 0.56^{o}C and a 15% increase in ventilation rate from 5.3 ACH to 6.1 ACH. This was in a temperate climate and windy condition. Furthermore, Porfirio (2004) demonstrated in a study in Brazil an increase in ventilation rate from 0 to 5 ACH if wind-driven turbine ventilators were driven only by natural wind. Size, for instance, has been demonstrated to affect ventilation rates with bigger sizes producing higher rates. According to energycut.com (2020), given wind speeds of 5.4 m/s (19km/hour), standard wind-driven turbines have the ability to move 8 – 15 m^3/hour (2- 4 L/s). It is also reported that inclined rooftops enable more efficiency of the turbine ventilators even at higher speeds. This is because with no inclined rooftops, higher wind speeds tended to cause larger flow separation at the blades, reinforcing a need for blade design optimisation (Tien & Ahmed, 2011). Based on these findings, best practice guidelines recommend that one turbine be installed per 80m^3 of building to achieve a ventilation rate of 12 ACH or 1 per 160m^3 for 6ACH. The recommended roof incline is between 0 – 45^{o}.

Wind driven roof turbines are popular because of their affordability. While the cost of turbine is relatively low and economical (costing less than R1 700 per unit), the turbine may not be as effective given its dependency on wind. Solar Whiz (2015) also note a probability of the turbine to malfunction once they catch leaves or other debris thereby decreasing the turbine's spinning capacity.

2.6 Mathematical modelling of risks of airborne infectious diseases

For TB to progress from infection to disease there are a number of internal factors that are involved, including the state of the host immune system, host genetics, and the virulence of the infecting strain of *Mycobacterium tuberculosis* (MTB) (Smith, 2003). One other important, yet overlooked, external factor is ventilation. The premise is that when the concentration of exhaled air increases in the room with infectors present, the probability of susceptible individuals acquiring airborne infectious diseases also increases (Richardson et al., 2014). This is because exhaled air from infectious individuals usually contains infectious particles (i.e. 'quanta'), within droplet nuclei that may remain airborne for prolonged periods and when inhaled may result in new infection of a susceptible individual (Buonanno et al., 2020; Issarow, 2015; Wells, 1955). Having knowledge of this has enabled the modelling of the transmission risk for TB, based on the premise that the higher the ventilation rate, the more rapid the decay of aerosolised infectious particles within a room's air.

In recent years, there has been an increasing interest in mathematical modelling of respiratory infection and control measure effects (Fennelly and Nardell, 2015; Liao et al., 2013; Bolashikov and Melikov, 2009; Liao et al, 2008; Li et al., 2007; Wan and Chao, 2005). This is as a way to determine and extrapolate the potential impact of public health interventions especially where population-level empirical data is hugely lacking or has proven to be expensive, time consuming or unethical to acquire (Houben et al., 2014). These mathematical models are mechanistic representations of how the disease burden is established (Houben et al., 2014). The South African context is largely characterised by constrained resources and these mechanistic representations can become important tools to assist in the understanding of disease burden (Houben et al., 2004). Furthermore, the results of modelling can be used to support policy for implementing those strategies that are most likely to be beneficial for public health and the broader economy (Houben et al., 2014; Azimi and Stephens, 2013).

Literature abounds with earlier studies that have utilised mathematical models which have strongly suggested that airborne transmission can be reduced by increasing the supply of fresh air (Fennelly and Nardell, 2015; Issarow et al., 2015; Lygizos et al., 2013; Bolashikov and Melikov, 2009; Furuya et al., 2009; Li et al., 2007; Wan and Chao, 2005). These findings are significant especially where there is a lack of biological proof to demonstrate definitively the impact of ventilation on TB transmission. Several epidemiologic investigations have underscored the significant role that room ventilation plays in determining airborne transmission of TB (Chamie et al., 2013; Myatt et al., 2004; Menzies et al., 2000). This is because the modelling studies, which include ventilation as a determinant, have demonstrated that improving ventilation, particularly when used in conjunction with other interventions, helps to reduce the risk of airborne infection.

One such mechanistic representation, which is often used to quantify the risks associated with airborne transmission of respiratory diseases, is the Wells-Riley model (Riley et al., 1978). The model is used for predicting the risk for transmitting respiratory infectious diseases in indoor premises (To, 2010). The model requires an analysis of ventilation strategy and its association to airborne infections. The model is based on a concept of 'quantum of infection' (infectivity) where transmission risk in a defined space over time is modelled as a Poisson process (Escombe et al., 2007). Here the rate of generation of infectious airborne particles (referred to as quanta) q, is used to predict the likelihood of new individuals (N_C) in an indoor environment, which is ventilated at a constant rate (Q), being exposed to the infectious particles, over a period of time (t), succumbing to infection (Azimi and Stephens, 2013; Noakes, 2008). This is demonstrated by Equation 3.

$$N_C = S\left(1 - e^{-\frac{Iqpt}{Q}}\right)$$

Equation 3

Source: Noakes (2008)

where,

N_C = number of new infections

S = number of susceptible individuals

I = number of infector individuals

p = pulmonary ventilation rate of a person (m^3/hour)

q = quanta generation rate (1/hour)

t = exposure time (hour)

Q = room ventilation rate with clean air (m^3/hour)

In this study, the model is applied stochastically, whereby the assumption is that at any intake dose, the host will have a probability of getting infected. This means the host must intake a dose containing at least one pathogen and this pathogen has to reach the infection site and survive until they give rise to symptoms in the host (To, 2010). The values assigned to the model's equation are expected (Table 2.3) and not exact values as the stochastic model considers the randomness in the distribution of pathogens in a space. In the model, S and I are taken to represent 1 person, for instance, and what is varied is the room ventilation rate (Q).

The model premises that the probability of infection from an airborne infection is inversely correlated to the room ventilation rate (Escombe et al., 2007). Based on this model, in situations of high quanta production (e.g. high-risk, aerosol generating procedures), the estimated probability of infection with 15 minutes of exposure in a room with 12 ACH would be below 5% (Atkinson, Chartier & Pesso-Silva, 2009). The Wells-Riley model has important limitations. One limitation is the assumption that air in the building space is fully mixed and there is homogeneity in either infectiousness or susceptibility to infection (Yates et al., 2016). Another limitation is that of the assumption that the quantum generation rate and outdoor air supply rate remain steady with time. For the latter, the model therefore, requires measurement of outdoor air supply rates, which are frequently difficult to measure and often vary with time (Rudnick & Milton, 2003).

Wood et al., (2010) used the Wells Riley equation to model household and community infection risks and found that the maximal household annual risk of tuberculosis infection was 3%, which was primarily determined by the number of resident adults. They postulated that transmission risk outside the home increased with increasing number of households visited and that transmission probabilities were sensitive to exposure time, ventilation, and period of adult infectivity (Wood et al., 2010).

Lygizos et al. (2013) applied the Wells-Riley equation in their study and utilised previously established values for variables to facilitate comparison between their study and other studies' results. Table 2.3 below shows the values, which they designated.

Table 2.3 Values assigned to Well-Riley model variables. **Source**: Lygizos et al. (2013).

Variable/parameter	**Value designated**	
Number of infectious quanta (q)	13	Wood et al.,(2011); Furuya et al., (2009) & Riley et al., (1978) set this value at 1 per hour
Number of infectors (I)	1	Presumed to be per household
Pulmonary ventilation rate of susceptible individuals	0.6 m^3/h	This was previously established by the authors. According to Pinna et al., (2006) this value is set at 360 litres/hour which equates to 0.36 m^3/h
Exposure time of susceptible individuals (t)	10 h	This is based on the amount of time a person might spend inside a home overnight in close contact with an infectious TB patient
Absolute room ventilation (Q)	ACH value multiplied by the room volume	This is determined by calculating the ACH using Equation 1 or determined from the slope of CO_2 decay curves and then multiplying the value by the volume of the household groups
Infection rate	N_c	This is determined by dividing the number of new cases by the number of susceptible individuals

Lygizos et al. (2013) demonstrated that in household settings where windows and doors were closed, the TB transmission risk after ten hours of exposure to an infectious TB patient was 55.4%. When windows only were opened, the estimated TB transmission risk dropped to 14.1% while upon opening both windows and doors, there was a significant decrease in this risk to 9.6%. This significant decrease was achieved with a mean of 20 ACH (Lygizos et al., 2013). In Escombe et al.

(2007), opening both windows and doors provided median ventilation rates of 28 ACH and 33% infection risk.

In Escombe et al. (2007) study, the Wells-Riley airborne infection model predicted that in mechanically ventilated rooms 39% of susceptible individuals would become infected following 24 hours of exposure to untreated TB patients of infectiousness characterised in a well-documented outbreak. This infection rate compared with 33% in modern (17 ACH) and 11% in pre-1950 (40 ACH) naturally ventilated facilities with windows and doors open (Escombe et al., 2007). They observed that old buildings had higher ACH compared to the modern mechanically ventilated ones. This is because the pre-1950 buildings have large windows and high ceilings (Escombe et al., 2007).

For the most part, the requirement of a large population makes the Wells-Riley equation suitable for deterministic simulations to predict average infection risk (Noakes, 2008). In order to adapt the equation to understand risks for small numbers and to apply the model in stochastic simulations, Issarow et al. (2014) developed a mathematical model that predicts the risk of airborne infectious diseases in multiple environments. Their adaptation of the model suggests that the number of new cases (of TB) can be determined in terms of the prevalence in the given community, which is the product of probability of acquiring TB and the number of susceptible individuals (Issarow et al., 2014).

2.6 Summary of chapter

The literature reviewed in this chapter has identified that the possibility of transmission of drug-resistant TB into community and household settings because of unforeseen consequences of the policy framework for managing this type of TB, underscores the need to evaluate IPC measures to minimise this transmission in this setting. The literature highlighted that IPC interventions related to ventilation and airflow patterns, were an important traditional yet overlooked option for preventing exposure to aerosolized infectious agents such as TB. Mechanical ventilation was determined to be the best disinfection alternative but is costly for resource-limited settings, in terms of installation and maintenance while the practicable, cheapest and attractive option for resource-limited settings was natural ventilation. However, factors such as need for privacy, security, pest control, thermal comfort, design of buildings, human behaviour and attitude, cultural beliefs and outside weather condition contribute towards making natural ventilation an unreliable and inadequate option. Therefore, an alternative, which harnesses the natural forces while applying mechanical ventilation principles such as a wind-driven roof turbine, may just be what is needed in resource-limited settings. However, implementation and evaluation of such mechanisms, let alone in household settings, are still lacking. The chapter reviewed the minimum standards for ventilation in different settings, with particular reference to household settings. The challenges that are faced in setting such standards in the household or residential setting were also highlighted. The chapter evaluated the different techniques that are available for studying building air exchange rates and the implication this has on TB infection**.** In addition, mathematical modelling of risk using the Wells–Riley equation to estimate the effect of ventilation rate on infection risk for known airborne diseases was reviewed. The parameters used in the Wells–Riley model include ventilation rate, generation of droplet nuclei from the source (quanta/minute) and duration of exposure. The model premises that the probability of infection through infectious droplet nuclei is inversely correlated to the ventilation rate. This study seeks to determine the extent to which a wind-driven roof turbine accomplishes that.

The next chapter covers the research methodology used in this research.

CHAPTER 3

METHODOLOGY

3.1 Introduction

Due to an overburdened healthcare system in South Africa, incurable TB patients are released into communities. Furthermore, a confinement requirement for managing this type of TB deters patients from seeking healthcare and there have been reports of frequent patient escapes from confinement. This then poses a risk of ongoing community transmission of the disease. There is, therefore, a need to develop customised airborne infection control policies for the community into which drug-resistant TB patients are discharged or escape into. The central question in this research report asks:

- To what extent is the risk probability for TB transmission impacted upon when enhanced ventilation using wind-driven roof turbines is applied in domestic homes?

After reviewing the key concepts comprising this research in the previous chapters, the purpose of this chapter is to describe the actions that were taken to evaluate the use of household mechanical ventilation using wind-driven technology in resource-limited settings and to determine the risk of TB transmission.

The rationale for the application of specific procedures or techniques used to identify, select, process, and analyse information to answer these objectives is described. First, the study setting is described to establish the context in which the wind turbine technology was applied. This is followed by an explanation of the choice of research approach, then the research design, as well as the advantages and disadvantages of the approaches chosen. The chapter then goes on to discuss human participation, the sample size and the sampling strategy applied by the author. The monitoring protocol and the equipment used as well as the collection of subjective responses from the participants is discussed. Following this, the data analysis methods, which were used, are discussed. The chapter concludes with a brief discussion on the ethical considerations and limitations posed by the research methodology, as well as problems encountered during the research.

3.2 Setting – Sampling site description

The study was conducted in Diepsloot, which is a densely populated Region A township (Diepsloot.com, 2017) in the extreme north of Johannesburg Metropolitan Municipality in the Gauteng province of South Africa (Johannesburg Development Agency, 2013; Urban Landmark, n.d.). Diepsloot township, which has been deemed a developmental township (Johannesburg Development Agency, 2013; World Bank, 2018), comprises a mixture of informal and formal settlements that are demarcated into two wards: Ward 95 and Ward 113 (Diepsloot.com, 2017), which are further divided into 12 morphologies (Statistics South Africa, 2011). The census of 2011 reported a population size a third of what it is currently. Due to urban expansion and unplanned rapid land invasion, present estimates indicate that the township is now home to approximately 360 000 people, many of them (76%) living in backyard shacks (Figure 3.1) measuring 3m by 2m and assembled from scrap metal, wood, plastic and cardboard (Diepsloot.com, 2017; Urban Landmark, n.d.). Alongside this informal settlement are formal housing units such as Reconstruction and Development Programme (RDP) houses, self-built houses on serviced sites and a small number of bank-financed houses (Johannesburg Development Agency, 2013, Urban Landmark, n.d.).

Diepsloot was chosen as a resource-limited setting as the setting is typically characterised by a lack of funds to cover healthcare costs, on individual or societal basis. This leads to limited access to medication, equipment, supplies, devices or to less-developed infrastructure (electrical power, transportation, controlled environment/buildings), for instance (Figure 3.1).

Figure 3.1 Informal settlement alongside formal housing units in Diepsloot. **(Source:** Deutsche Welle, 2018**).**

Conducting the study in this climatic region, which presents a more wind-still climate that characterises Gauteng, provided a counter point to the study that was conducted by Cox et al. (2012) in Khayelitsha in the Western Cape Province which has a relatively windy climate.

3.3 Study approach

The study followed a quantitative, exploratory approach. The approach is quantitative as the study relies on measuring variables using a numerical system, analysing these measurements using some statistical models, and reporting relationships and associations among the studied variables (Lucas-Alfieri, 2015), for example, ventilation rate and risk for TB transmission. The approach is also exploratory in nature, as research is usually conducted to study a problem that has not been clearly defined yet, such as air exchange rates in household setting and the impact on third party infection risk from this setting. Explorative research, therefore, is effective in laying the groundwork that will lead to future studies.

3.4 Study design

This study's design is described as quasi-experimental that use control groups and pre-tests. The study aimed to demonstrate causality between an intervention (wind-driven roof turbine ventilation) and an outcome (stochastically simulated risk probability of infection) without using randomisation of the studied households (Harris et al., 2006). The design required an identification of a comparison household (control) group that was as similar as possible to the intervention household group in terms of baseline (pre-intervention) characteristics (Harris et al., 2006). Thus the control groups that were chosen are comparison groups. Harris et al. (2006) also observed that a design that involves pretesting measurements on the control and intervention groups aims to demonstrate the initial pre-intervention comparability of the groups. This is because where such comparability is shown, the smaller the likelihood there is of confounding variables differing between the two groups (Harris et al., 2006).

3.5 Baseline survey

A site visit of the area was done to determine the characteristics of the potential households such as the type of roof, and size of the rooms over which the turbine would be placed. For aesthetic purposes, the colour of the roof was also determined so that the turbine would be manufactured of the same colour.

An environmental assessment utilizing a walk-through questionnaire was then conducted to gather information on the determinants of air quality such as household characteristics, occupant number, indoor activities and outdoor activities that are likely to contribute to indoor air quality (Appendix A). This baseline survey assisted with the determination of the number of samples that were required and/or the number of sites to be visited in the township. Furthermore, this information was pertinent for establishing the eligibility criteria for the assignment of households to intervention and comparison groups which required a pairwise comparison methodology.

3.6 Household selection

Households were selected according to an adaptation of the procedure used by Ncayiyana (2015) in which geographic coordinates of the township were generated from an aerial map of the township. A total of 20 geographic coordinates were randomly selected within this extension and these coordinates were located using a geographic positioning system (GPS) device. The researcher then visited the extension and communicated with one of the gatekeepers of the community who then assisted with engagement and recruitment of the households for the study. The researcher purposively selected eight households that met the eligibility criteria which was generated from the results of the baseline survey.

The eligibility criteria included:

- The houses sampled had to be a formal housing units – an RDP. Therefore, all the sampled houses were all to be of the same construction design in terms of physical structure, floor size, volume of the house, roof type, presence of outbuildings and, the number and size of windows and doors.
- The houses had to be in the same extension, subjected to the same social and environmental conditions.

The respondents were invited to participate in the study after a comprehensive description of the study and its objectives were explained to them (Appendix B and Appendix C). Where the household approached refused to participate, it was replaced (Ncayiyana, 2016). A convenient date and time suitable for wind-turbine installation and subsequently data collection was set with an adult (≥18 years, owner of the house) in the household before data was collected.

A date and time were also set for a one-on-one interview (Appendix D) and walk through survey to determine factors that influence indoor air quality such as occupant number, human factors and activities such as window or door handling. Occupant behaviour is a key factor for influencing the indoor air quality and thermal comfort. The survey also presented an opportunity to identify the room through which the roof turbine was subsequently ducted and to set up appointments to come and conduct the air change measurements.

3.6.1 Assignment to intervention and control groups

Assignment to intervention or control groups used the pairwise comparison method for analysing multiple population means in pairs to determine whether they are significantly different from one another (Salkind, 2010). In this technique, the control group was selected such that it matches the treatment group using a comprehensive baseline survey (Appendix B) that evaluated the similarities in observed characteristics of the households identified in the Diepsloot township.

The criteria for pairwise comparison covered the eligibility criteria in addition to number of occupants, quality of the house structure and indoor activities. The groups were rank-ordered according to these criteria as established by the baseline survey as well as the intensity of preference for the determinants of air quality (Kułakowsk & Talaga, 2019). According to Bramley and Oates (2010), analysis of all the judgments creates a scale with each attribute represented by a number – its 'measure'. Thus for instance, for the variable, "number of occupants", a rank is created based on the numbers provided. This is done for all the other comparison variables. The differences between households are then compared using a paired t-test to establish if there is any statistical difference. The paired t-test was possible as ventilation measurements were collected twice from each house (turbine and control), one in the morning and one in the evening. This resulted in pairs of observations. Pairwise comparison, thus, ensures that the average characteristics of the intervention and control groups are similar, and this is deemed sufficient to obtain an unbiased estimate (Kułakowski et al., 2014; White, 2014).

3.7 Measurement period

The study was conducted over a 4-month period (18 July to 21 October 2019). Therefore, two South African seasons were covered in the study – winter and spring.

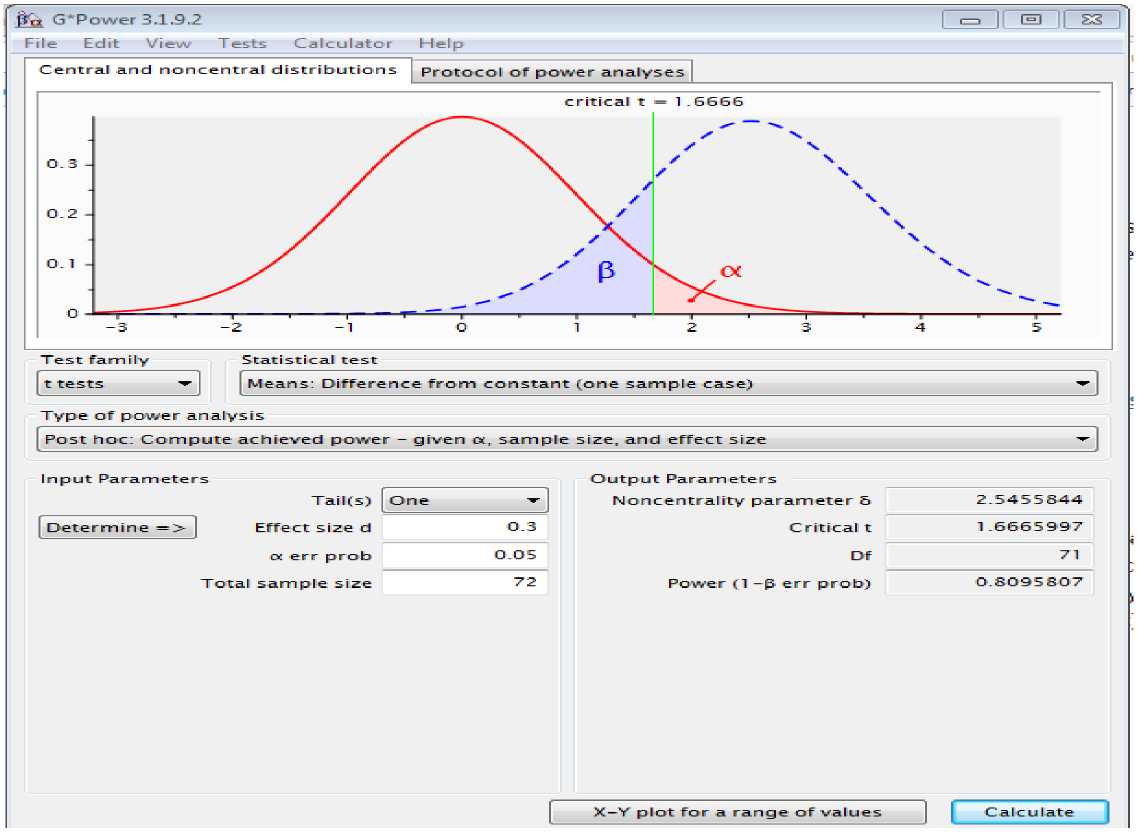
3.8 Pre-intervention air monitoring

Pre-intervention air monitoring was important to determine how similar the households are in terms of air exchange rates as these vary with activities that occur in each household. From the eight households, two matching households (one from the control group and the other from the intervention group) were selected and two measures per household were done using a CO_2 tracer gas technique. One measurement was conducted in the morning and the other in the evening. Thus, eight measures were collected in the pre-intervention stage. These measurements set a baseline for each household in the sample.

3.9 Sample size

In the pre-intervention stage, eight measures were collected. At the intervention stage, each household was visited four times, with a visit comprising a morning (duration of one hour) and evening (duration of one hour) measurement. This yielded a total of 32 measures from the intervention group and 32 measures from the control group. The total 64 measures in the intervention stage added to the 8 measures from the pre-intervention stage gave a sample size of 72 samples.

Due to time constraints inherent in the duration of the programme as well as financial constraints, the final survey comprised four households assigned to the intervention group and four households assigned to the control group. This resulted in a total of 36 pairwise observations. According to the power calculations, a relatively small difference (effect size 0.3) can be observed with a power of 0.8 (Figure 3.2). Effect size in sample size calculation is a way of quantifying the differences between two groups by emphasizing the size of the difference rather than the sample size. It is particularly valuable for quantifying the effectiveness of a particular intervention, relative to some comparison (Coe, 2002).



Test family: t tests

Statistical test: Means: Difference from constant (one sample case)

Type of power analysis: Post hoc: Compute achieved power – given α, sample size, and effect size

Input Parameters

Tail(s): One
Effect size d: 0.3
α err prob: 0.05
Total sample size: 72

Output Parameters

Noncentrality parameter δ: 2.5455844
Critical t: 1.6665997
Df: 71
Power (1−β err prob): 0.8095807

Figure 3.2 Power calculations.

3.10 Data collection

3.10.1 Objective measurements

These measurements included temperature, air velocity, and relative humidity and CO_2 concentration for both control and intervention households. For the intervention households, the data collection method followed that used by Cox et al. (2012) for their study in Khayelitsha where wind-driven roof turbines were installed by ducting them into rooms, either directly in cases where there was no roof space or via a duct from the roof to the level of the ceiling (Cox et al., 2012). For this study, the first option was applied. The turbines were directly installed in rooms in the four houses assigned to the intervention group the houses did not have a ceiling and thus the turbine were installed without any ducting. All roof turbines installed were constructed of aluminium, were spherical in shape, and made of 240mm diameter curved vane (as shown by turbine type b in Figure 1.1) and locally supplied by Turbovent Africa Pty Ltd.

There was no provision for air-intake in all cases with the freshest air for each house coming from infiltration. Each house was one 4.8m x 6.1m big room with this floor area comprising a corner bathroom that measured 1.9m x 1.9m. As all households were similar, there was no need to represent different building types, roof designs and room layouts.

3.10.1.1 House floor size and volume

A tape measure was used to measure the dimensions of the houses. The layout of the dwelling was drawn, in order to calculate the floor size and volume of the rooms used for the measurements.

3.10.1.2 Carbon dioxide concentration levels

After the households had been vacated by the occupants and windows and doors closed, a carbon-dioxide (CO_2) tracer gas technique, where a carbon dioxide gas, released slowly from a CO_2 gas cylinder, was injected in the household room (Cox et al., 2012) until it reached a level of 4500ppm. This technique is also called the step-down method and can be used when a space is vacated after occupancy (Batterman, 2017). After a period of allowing the carbon dioxide to mix with room air, the concentration decay of the injected carbon dioxide was recorded (Cui et al., 2015) over one hour, with measurements taken at five-minute intervals. Figure 3.3 and 3.4 shows the equipment used for CO_2 concentration levels. This injected CO_2 should have been mixed thoroughly with room air using an electric fan but during the measurement period, the area under study did not have electricity. Mixing was thus not achieved. The CO_2 was measured using an infra-red gas analyser, TSI's IAQ-Calc™ Indoor Air Quality Meter model 7525 (TSI Incorporated, 2020), one of the outstanding instruments for investigating and monitoring indoor air quality (IAQ). CO_2 concentration levels were recorded every five minutes over a total period of one hour. Short sampling intervals enable sufficient tracking of the concentration changes within the rooms (Kalliomaki et al., 2016). The equipment was calibrated before the start of the study's measuring period. The analyser (Figure 3.4) was placed in the centre of the room at head height for a seated person (which is about 50cm above the floor), away from doors and windows to avoid possible airstream disturbances.

Figure 3.3 Fan and CO_2 gas tank connected to a gas regulator. **Source:** Escombe et al., (2007).

The target concentration of CO_2 gas that was injected in the room was 4500ppm. The South African legal acts do not specify admissible concentrations of CO_2 in atmospheric air and in rooms intended for permanent residence. However, ASHRAE (2013) recommends CO_2 concentration between 1000ppm and 1500ppm for permanent occupancy of people. ASHRAE (2013) finds that CO_2 concentration greater than 5000 ppm within indoor environments can pose health risks (Sudhakaran & Shaurette, 2016). Therefore, gas injection was made into unoccupied rooms. As observed by ASTM (2014), the decay or step-down method is used when a space is vacated after occupancy or if there is a stepwise decrease in occupancy. In addition, measurements were made while windows and doors were closed. This is because opened windows and doors can lead to significant variation in concentration in the space, thereby violating the well-mixed assumption (Batterman, 2017).

In addition, an estimate was made of the relevance of the presence of wind turbine on the mean CO_2 concentration. This was determined using a mixed effects model

Figure 3.4 TSI's IAQ-Calc™ Indoor Air Quality Meter Model 7525 (TSI Incorporated, 2020).

The selection of CO_2 as a tracer gas was based on the fact that CO_2 has a relatively high permissible exposure limit, is inexpensive, is easy to obtain and measure (Laussmann & Helm, 2011).

3.10.1.3 Indoor air quality and comfort parameters

The TSI incorporated VelociCalc® Model 9545 Airflow Meter (Figure 3.5) was used to measure the time-varying factors that affect ventilation rates (VR) and air exchange rates (AER) in this study. This airflow meter simultaneously measures and logs several indoor air parameters such as air velocity, temperature, air flow and relative humidity, using a single, straight and telescopic probe with multiple sensors (TSI Incorporated, 2020). It was necessary to measure these parameters as ventilation rates and AERs can be affected by time-varying factors including internal heating and cooling loads, outdoor temperature and the indoor-outdoor temperature difference and wind speed and direction (Breen et al., 2014). The ventilation rates in turn influence air quality and comfort (Batterman, 2017; Rosbach et al., 2013; Sundell et al., 2011).

- *Wind speed:* The outside wind velocity was measured simultaneously with the room ventilation using a data-logging anemometer at the same level as the roof turbine. One-minute averages for a period of five minutes were averaged over each experimental session and results presented as mean wind speed. Wind speed is one of the driving forces for air exchange rate.

- *Roof turbine airflow:* Firstly, a smoke visualisation test using a hand-held smoke generator was conducted to visualise the direction of airflow in the installed turbines. Secondly, the air flowing directly through the roof turbine during the experiment was measured, with measurements being taken at five-minute intervals for sixty minutes and averaged over each experimental session. This resulted in 12 measurements per hour which were then averaged. Airflow was an important indicator for measurements that sought to determine the contribution of extraction by the roof turbine in total room ACH.

- *Temperature:* For ventilation purposes, temperature as a parameter is important for wind pressure drops which determine the direction of air flow. For example, when a mass of air is heated in some region, it floats up; therefore, a mass of cold air tries to cover the empty space that the floated air left. On the path to do this, the air hits the façades of the buildings, hence producing the airflow throughout them (Oropeza-Perez, 2019). This is referred to as the stack effect. Thus, internal room temperature and external air temperature were measured at the start and end of each experimental session to determine the temperature differences.

- *Relative humidity*: There is a high correlation between relative humidity and CO_2 concentration (Lazovic et al., 2015). In addition, indoor humidity is influenced by ventilation rate. Ventilation usually reduces indoor moisture levels (Batterman, 2017). Relative humidity was measured at the start and end of each experimental session.

Figure 3.5 VelociCalc® 9545 model, (TSI Incorporated, 2020).

- *Weather conditions:* In addition to measuring outdoor ventilation parameters (external temperature, wind velocity, wind direction and relative humidity), local weather stations' reported climate conditions on-site were recorded over the two seasons – winter and spring.

3.10.2 Subjective measurements

These measurements included the environmental survey and an interview conducted with the house owners.

3.10.2.1 Environmental survey

An environmental assessment utilising a walk-through checklist (Appendix A) was conducted in one of the nine extensions that have identical Reconstruction and Development Programme (RDP) houses (Extension 5, chosen using a simple random sampling technique) to gather information on the determinants of air quality such as household characteristics, indoor activities and outdoor activities that are likely to contribute to air quality.

3.10.2.2 Interview

An interviewer-administered structured interview schedule (Appendix D) was used to collect information on household factors such as the age of the dwelling, the total number of people in the household, total number of people per room in the household and whether they sleep with the windows open. Information was also gathered on indoor activities such as cooking and heating fuel that is used in the household, practices such as the burning of incense indoors, cleaning methods and bedtime/waking up times of the household as well as behavioural factors such as whether smoking is done indoors and opening of windows.

The purpose of the interview was to explain and better understand the household owner's experience of indoor air quality. The interview guide (Appendix D) included questions that covered occupant and building information.

3.11 Pilot study

According to In (2017), pilot studies are conducted to reflect all the procedures of the main study and to the feasibility of the study.

Pre-testing was done two weeks prior to the main study with three members from the community at a community centre in order to assess the inclusion and exclusion criteria of the study households, the feasibility of collecting the evening measurements, acceptance of the installation of the roof turbine by the community, the method of collecting data and its suitability (Benger et al., 2016) as well as safety and security related issues.

The methods were appropriately modified for the main study as indicated below:

- It was discovered that it was easier to gain access to the community via community gatekeepers, for example, the coordinator of one of the non-governmental organisations in the area.

- While the majority of the community members could converse in English, it was best to use the local language in the initial recruitment into the study. Having the physical turbine and a demonstration of how it works and images of what the final installation looked like helped in the recruitment. The participants verbalised this and chose roof turbines that matched their roof colours.
- The colour of the roof turbine had to be changed to match the roof colours of the individual households.
- There were questions added to the interview guide related to measures of comfort – one on thermal comfort, another on signs of moulds inside the house (to determine relative humidity) and another on ventilation and draft.
- The study's inclusion criteria were adjusted to include shacks as all households had a shack or more in the yard.
- The environmental survey added the checking of the opening status of windows/doors (closed, slightly open, half open or fully open) during the day and night.
- In addition to household occupants, pets, and flue-less heating or cooking appliances as sources of CO_2 sources in buildings were assessed.

3.12 Validity and reliability of data collection instruments

All objective data instruments were calibrated before the start of study measurements to ensure that the probes used gave useable results. The study methodology such as gaining access to the community, the language to use to seek approval to duct turbines on households and environmental survey parameters were pre-tested two weeks prior to the main study.

3.13 Data management

All manually collected data such as from environmental assessment and interviews were recorded on standard recording forms. Data was checked for completeness, cleaned, coded and recoded before data was entered in Microsoft Excel then exported to Stata version 15 (StataCorp, 2017) for analysis**.** The VelociCalc® 9545 model and IAQ-Calc™ Indoor Air Quality Meter model

7525 is equipped with a USB cable and LogDat2™ Downloading Software. Data from these devices was downloaded and transferred to Excel. The check codes for missing data or the not applicable responses was 999. Data was extracted from the data set and underwent cleaning to take care of extreme, illegal and inconsistent values. New variables were generated where there was a need and numerical variables were categorised for ease of analysis. For example, the variable "number of shacks in the yard", two response categories were generated: "more than 5" and "less than 5". To assure quality, the researcher appointed a field worker who performed double data entry.

3.14 Data analysis

All data analysis was done using Microsoft Excel 2016 and Stata version 15 (StataCorp, 2017). The cut-off of 0.05 was used to interpret the significance of the p-values of all analyses, therefore p values that were less than or equal to 0.05 ($p \leq 0.05$) were considered significant.

- For study *Objective 1:* To describe the physical and social characteristics of the participating households in Diepsloot, South Africa in 2019.

Results from the baseline survey established the evaluation criteria that were used to perform a pairwise comparison method that assigned households in the study site into intervention and control groups. This was done through quantifying and comparing the determinants of indoor air quality across the households. The groups were rank ordered according to these attributes (determinants of indoor air quality) creating a scale with each attribute represented by a number – its 'measure' (Bramley and Oates, 2010). An analysis of these household characteristics was computed as multiple means in pairs (pairwise t-test or a Wilcoxon-Mann-Whitney test) using the Stata software to determine whether they are significantly different from one another (Salkind, 2010). In addition, descriptive statistics such as mean, mode and median were used to summarise data from the environmental assessment (baseline survey) and participant interview. The results are presented in the form of frequency tables and by using graphics such as boxwhisker plots and bar charts. Furthermore, images depicting the floor size and external features of households, as well as the final installed roof turbine are also presented.

- For study *Objective 2:* To assess the impact of wind-driven roof turbines on room ventilation and air exchange rate in eight households (four intervention households, four control households) using a CO_2 tracer gas decay technique for measuring air changes per hour over a three-month period in Diepsloot, South Africa in 2019.

The attainment of this objective required the determination of the air exchange rate, measured in ACH, and the determination of the impact of the predictors of this rate such as wind speed, time of day, temperature and humidity. The CO_2 concentration was also averaged over the 60 minutes and presented as means and standard deviations.

To determine the air exchange rate – A natural logarithm ($\log_e$) of CO_2 decay concentrations was calculated and the values plotted on a graph, with the predictor variable being time (t) and the outcome variable being the log of CO_2 concentration levels. A least-squares fit on the graph gave a slope that determined the air exchange rate in air changes per hour (ACH). These were presented graphically in CO_2 decay curves. The house ventilation rate, measured in L/s, relative to the volume of each house was calculated using Equation 1:

Air-change rate (ACH) = [ventilation rate (L/s) × 3600 (s/hr)] × 0.001 (m^3/s)]/[room volume (m^3)]

Determining the impact of ventilation predictor variables - Data collected on the prevailing weather conditions (wind speed, wind direction, day length, humidity and temperature) and that of the ventilation parameters (wind speed, relative humidity, temperature) for the households was analysed using descriptive statistics such as means, standard deviations and range and presented in various tables and charts.

A comparison of the means of the ventilation measurements between intervention and control groups using the paired t-test was made. The mean airflow measurements through the turbines were also computed and comparison of the mean differences between groups were done using the t-test.

A multivariate regression analysis was run to explain the relationship between CO_2 concentration (dependent variable) and the predictor variables of time of day, season, presence of roof turbine, wind velocity, temperature and humidity differences. These predictor variables were selected a priori based on their potential contribution to the dependent variable. In this multiple regression analysis, CO_2 concentration decay was modelled as a function of these predictor variables using an equation that took the following format:

$$y = b_1 x_1 + b_2 x_2 + \dots + b_n x_n + c. \qquad \textit{Equation 4}$$

where,

- y is the predicted value of CO2 concentration decay
- x_1 through to x_n are the predictor variables of time of day, season, presence of roof turbine, wind velocity, temperature and humidity differences
- b_1 through to b_n are the estimated regression coefficients
- c is the value of CO_2 concentration decay when all the predictor variables are equal to zero

From the results of the multiple regression analysis, the top three predictor variables were inputted in a mixed effects regression modelling using repeated measures. This was performed to assess how significantly the wind-driven roof turbine impacted on CO_2

concentration decay while controlling for predictor variables such as time of day, season, temperature and humidity and wind velocity. In this mixed effects analysis model, CO_2 concentration decay was the single outcome measure of interest. For each CO_2 concentration decay measure there with 32 measures each for the control and the turbine households. Therefore, while each household represented a random effect, the CO_2 concentration decay values generated were not independent (https://errickson.net/stata2/mixed-models.html). Since each household was visited a number of times over a period of time (within subject factor), this 'repeated' nature of the measurements had to be considered.

- For study *Objective 3:* To estimate, using Wells-Riley mathematical model, the potential effect of wind-driven roof turbines to reduce the probability of TB transmission, assuming that all houses would have installed wind—driven turbines.

This was determined through the Wells-Riley equation (Equation 3) for determining risk probability for TB transmission.

$$N_C = S\left(1 - e^{-\frac{Iqpt}{Q}}\right)$$

Equation 3

Source: Noakes (2008)

The values that were used in this equation to achieve the risk probability, were:

- N_C (number of new infections) – the study wanted to determine this value, which stood for risk probability, expressed as a percentage (%).
- S (number of susceptible individuals) – this was taken as the median number of occupants in each household group (turbine and control households)
- I (number of infector individuals) = this was presumed to be 1

- p (pulmonary ventilation rate of a person in m^3/hour) – this study utilized the value of 0.6m^3/h in accordance with the findings of Lygizos et al. (2013) in their study in a household setting.
- q (quanta generation rate in 1/hour) – the study used the value of 13 as established by the studies of Wood et al.,(2011) and Furuya et al., (2009)
- t (exposure time in hours) – an average of 8 hours was used
- Q (absolute ventilation) – this was determined by multiplying the resulting ACH of the household groups with the volume of the household.

Once the risk probability for TB transmission was determined, the results were compared between pre-intervention and post intervention tests and, between turbine and control households, to determine the potential that enhanced ventilation has in reducing risk probability for TB infection.

3.15 Ethical considerations

Ethics approval for the protocol was obtained from the Human Research Ethics Committee of the Health Sciences Faculty of the University of the Witwatersrand (Appendix E). Written informed consent, after explaining the purpose of the study, was obtained from participants to use their households for the experiment (Appendix B and Appendix C). Emphasis on informed consent was placed on the voluntary nature of participation and confidentiality of data that was collected. Eligible participants who were not willing to participate were not coerced, while those willing to participate were made aware of the option to withdraw from the study at any time without suffering any consequences.

3.16 Summary of chapter

This chapter has outlined and justified the research methodology implemented in this research report and its validity. Because of the nature of the research, the author opted for the quantitative strategy, bound by an exploratory, quasi experimental design. The key research tools were airflow and velocity meters, supplemented by interviews and an environmental assessment with two groups of participants – intervention (turbine households) and control households. The participating households were carefully targeted and recruited through a purposive sampling technique. The selection criteria are described in detail. The physical measuring of the study parameters and the equipment used, as well as the protocol for collection of subjective responses from the participants and the environmental survey used were discussed. The chapter concluded with a description of the analytical approach, which was done using Stata software, for the results of the study. Finally, the ethical approval, which was obtained prior to the study was highlighted.

The major results and findings of this study are discussed in the following chapter.

CHAPTER 4

RESULTS

4.1 Introduction

The focus of this chapter is the analysis and presentation of the research findings of this study. Eight households (four turbines and four controls) were recruited in the study and each household was visited once a week for four weeks. For each of the visits, ventilation measurements were conducted in the morning between 08h00 to 12h00 and in the evening from 18h00 to 22h00. Given the quantitative strategy adopted in the design and methodology chapter, all data collected was treated quantitatively. After data collection, data cleaning was conducted and processed mainly using descriptive statistics and inferential statistics with Stata version 15. The findings are structured on the basis of the research objectives that frame this study.

4.2 Participating households

Eight (8) households were recruited to participate in the study. There were no refusals to participate in this study. The physical structure of the houses under study was similar. However, households differed in terms of the social characteristics. These social characteristics were rank ordered according to the key attributes collected from the environmental survey (Table 4.1). Table 4.1 profiles the attributes of case (turbine) and the matching control households that were compared. A pairwise comparison method using the pairwise t-test was conducted. The test showed that there was no significant difference between households recruited into control and intervention groups (t (8), = 2.36, p = 0.001) and that for each household in the intervention group there was a matching household in the control household.

Table 4.1 Key attributes of participating households used for pairwise comparison

	Pair 1		**Pair 2**		**Pair 3**		**Pair 4**	
Parameter	**T1**	**C1**	**T2**	**C2**	**T3**	**C3**	**T4**	**C4**
Number of occupants	5	6	4	3	5	5	4	7
Age of house/Year of construction	15	14	13	13	17	17	15	15
Indoor activities	Cooking; smoking	Cooking; smoking	Cooking	Cooking	Cooking	Cooking	Cooking	Cooking; smoking
Total hours sleeping	7	11	8	9	9	9	8	10
Actual number of shacks in the yard	6	7	4	3	6	5	4	4

Key: T represents turbine household and C represents a control household. The numbers indicate the paired T and C households.

4.2.1 Pre-intervention results

The pre-intervention investigation was done during mid-winter to determine the baseline performance of the households without any turbine and to determine if there was any significant difference in this performance. Two matched houses (one from the turbine households and the other from the control households) from the participating pool were used. Results revealed that there was no significant difference between the chosen households in terms of baseline CO_2 levels ($t = -0.96$, $p = 0.001$), mean CO_2 decay ($t = -0.68$, $p > 0.001$), mean temperature ($t = -1.48$, $p > 0.05$) but showed a marginal difference in mean humidity ($t = 1.95$, $p = 0.057$). There was a larger number of occupants in the turbine households (mean = 5) than in the control households (mean = 3.75) but this had no statistically significant implications on the levels of baseline CO_2 and baseline temperature, factors that determine indoor air quality.

4.3 Physical and social characteristics of the participating households

This covers the results from environmental survey and interview with household owners. The house used for both cases and controls was structurally similar (Figure 4.1). It has a pyramid top on a cube base.

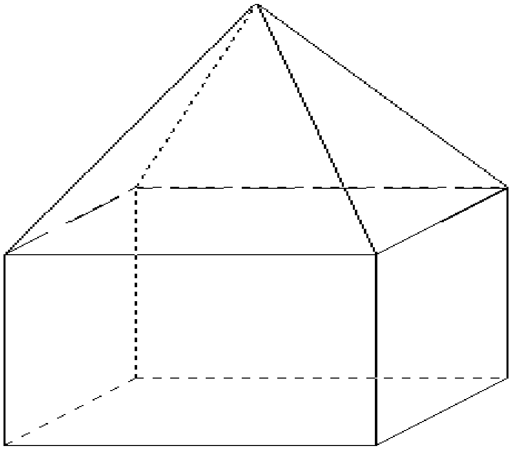


Figure 4.1 “Pyramid on a cube” shape of the studied house. **Source**: http://www.mathe-schumann.de/tokyo/Image99.gif

Figure 4.2 shows an example of the physical structure of the houses under study and their physical surroundings.

Figure 4.2 Images showing an example of the physical structure of the house under study.

4.3.1 Physical characteristics

The investigated house was a stand-alone RDP house which, covered an area of 29.28m^2, with a ceiling height from the floor of 2.36m. At its highest level, the ceiling height from the floor was 3m. The room volume is 70.86m^3. The RDP house was located in an urban, highly populated residential area. The mean age of the houses was 15.5 years (standard deviation [SD] = 2 years) and the median number of persons per home was 4 (range 3 - 7 people/home). The physical characteristics of the investigated houses are provided in Table 4.2.

Table 4.2 Physical house characteristics.

Characteristic	**N**	
Age (years)	8	15.5 (range 13 – 17)
Area size (m^2)	8	29.28
Volume (m^3)	8	70.86
Rooms	8	One, big room
Number of windows	8	3
Window dimensions (cm)	8	Window 1 (170 x 94) Window 2 (60 x 94) Window 3 (30 x 35)
Air vent availability	8	No
% windows and door left closed		100%
Persons per household	8	4 people/home (range: 3 – 7 people/home)
Number of doors	8	2

Number of shacks in the yard	8	
< 5		2 (25%)
≥ 5		6 (75%)

The house comprised one large room with a small corner bathroom that had an approximate area of 3.6m^2. Figure 4.3 shows the configuration of the house and Figure 4.4 depicts the floor plan of the house. This large room was then demarcated; using cloth material or pieces of furniture, into specific domestic areas such as bedroom, spare room and kitchen. The house had brick walls, had a cement floor type and used corrugated iron as its roofing material. Each house had no air vents but had three openable windows. The two large windows were on opposite walls of the house and the smallest window was located in the bathroom. The largest window, which measured 170 cm in length and 94 cm in height, was located on the wall with the door. This door, made of iron, measures 81 cm by 203cm and in all houses had a dent that made it fail to have a tight seal with the door frame when the door was closed. The other large window had these dimensions: 60 cm x 94 cm and was located on the wall with the bathroom window, which measured 30 cm in length and 35 cm in height.

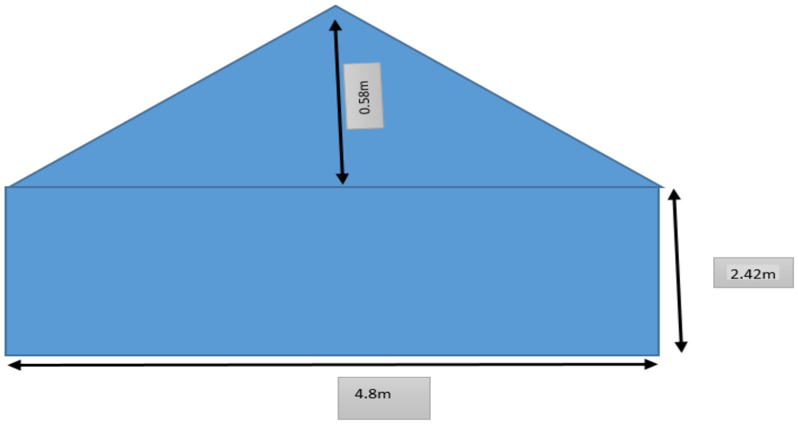


Figure 4.3 Configuration of the house.

There was one entrance into the house. The other room with a door (a wooden one) was the bathroom. One feature common to each house was the presence of shacks in each house's yard.

There was an average of 6 shacks in each yard (range 5 – 11 shacks/house) with 6 out of the 8 households (75%) having 5 or more shacks in their yards.

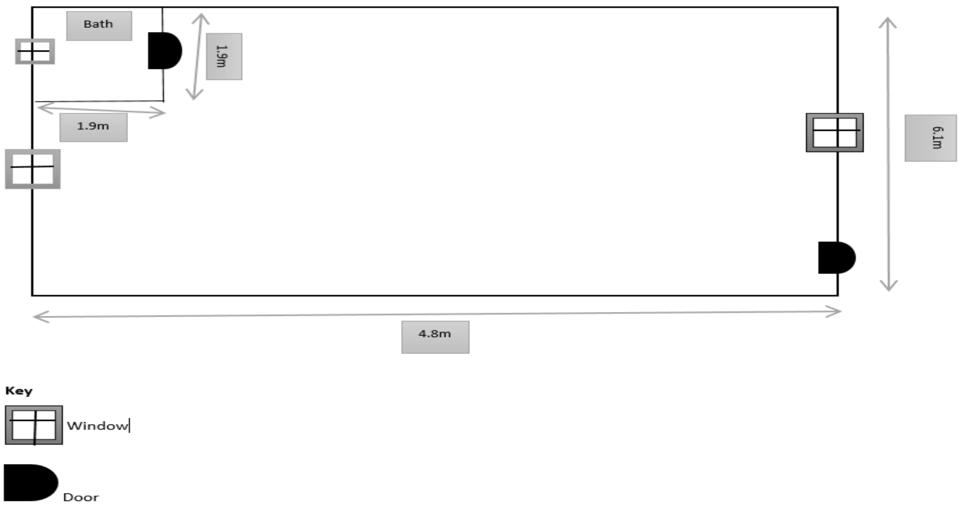


Figure 4.4 Representation of the floor plan of the house.

4.3.2 Social household characteristics

From the occupant's responses, the indoor air quality was perceived to be generally poor, with the majority indicating that it was cold in winter and stiflingly hot in summer. Some attributed this to the type of roofing used on the house while others indicated that it was because of the absence of air vents or spaces between where the roof meets the wall.

While the houses had openable windows, the occupants reported that these were never opened, especially at night. The main reasons provided for not opening windows were to exclude the horrible smells coming from the broken sewerage pipes (as depicted by the image in Figure 3.1 in Chapter 3), protection against draughts that happen especially towards night times and concerns about rats getting into the house as the study area has a rodent infestation. The average reported sleeping time was on 9 hours (SD = 2).

Concerning indoor CO_2 generating activities, all cooking happened indoors, utilising electricity. However, at the time of the study, the area had no electricity for a period of two months.

Therefore, the alternative cooking energy source for the households that was in use during the study period was paraffin. All of the occupants frequently burned incense (Zulu - *impepho*) indoors while one occupant from each of turbine (T1) and control (C1 and C2) household group stated that they smoked but only C1 smoked indoors.

In terms of the external CO_2 generating activities, all of the households were situated less than or equal to 0.8km from the main road and they were more than 5km from industry. All of the occupants were unemployed and thus they did not have working environments that were likely to bring infection to the house. However, infection could be brought from within the community itself. Each compound had at least 5 or more shacks and thus a yard could have as many as 35 people (range 6 - 35 people) living on it.

4.4 Final roof turbine installation

The households used in the study did not have ceilings and thus the turbines were installed without any ducting in the method as reported by Cox et al. (2012). The roof turbine was installed on the northerly side of each household, on an incline. The installed roof turbine had a diameter of 240mm, circular in shape with curved blades. Figure 4.5 to Figure 4.7 depict the final installed roof turbine.

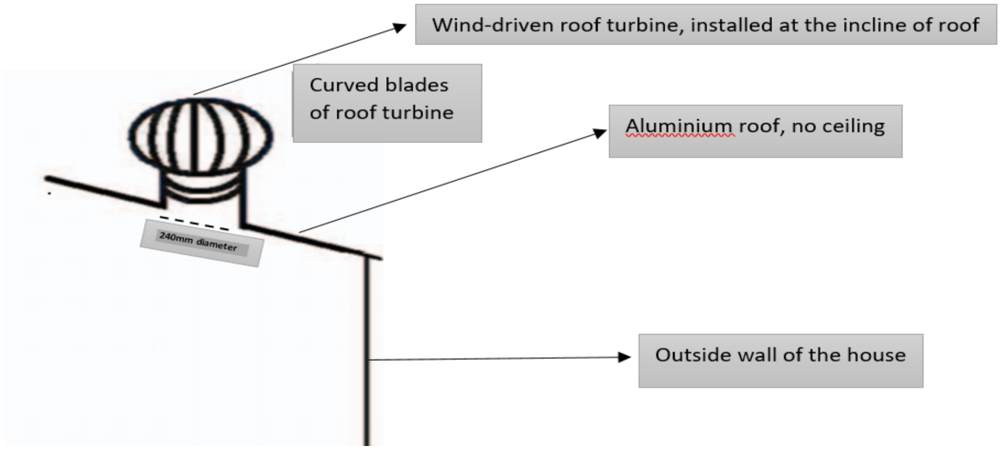


Figure 4.5 Installed wind-driven roof turbine. **Source**. Adapted from Cox et al. (2012).

A smoke visualisation test demonstrated air currents flowing from the room, in an upward motion, into the turbine for exhaustion outside.

Figure 4.6 The inside of the wind-driven roof turbine as viewed from inside the house.

4.5 Weather conditions prevailing at time of study

Indoor averages of temperature, relative humidity and CO_2 concentrations (Table 4.3) were monitored at each visit while outdoor parameters combined with on-site climatic conditions were recorded. The table below illustrates the prevailing weather conditions at the time of the study.

As can be seen in Table 4.3, it was generally cooler, drier and with slower wind speed in the winter month of July compared to the other months. As the seasons moved from winter to spring, there was a general increase in humidity, temperature and wind speed, although wind speed in October slows. While the wind direction was variable, it was predominantly northerly in all the seasons.

Table 4.3 On-site climatic conditions.

Weather condition	**WINTER**		**SPRING**	
	July	**August**	**September**	**October**
Day length (hours)	11	11	12	13
Sunrise to sunset times	6:30am to 5:40pm	6:20am to 5:24pm	5:50am to 6:09pm	5:15am to 6:23pm
Humidity (%)	45	48	56	65
Rain (days)	0	1	4	1
Average temperature (^{0}C)	20	21.5	22.8	23.8
Wind speed (m/s)	3.5	4.2	4.3	4.1
Wind direction	Northerly	Northerly	Northerly	Northerly and Westerly

Source. https://www.meteoblue.com/en/weather/week/diepsloot_south-africa_8764562.

4.6 Indoor air quality and comfort parameters

The indoor averages of indoor air quality (IAQ) and comfort parameters such as temperature, relative humidity and CO_2 concentrations were monitored with the climatic conditions. Table 4.4 summarises the results obtained from a preliminary analysis of these parameters.

Table 4.4 Indoor air quality and comfort parameters during the intervention period.

IAQ and comfort parameter		**Turbine** (n = 456)	**Control** (n = 456)	**t-value**	**Probability**
Average humidity at start of each visit (%)	M SD	22.5 (5.3)	29.9 (6.6)	-14.2	< 0.001
Average humidity at the end of each visit (%)	M SD	25.6 (10.1)	31.3 (7.4)	-7.4	< 0.001
Temperature difference (^{o}C) of	M	1.3	0.4	4.5	< 0.001

indoor and outdoor temperatures	SD	2.8	2.81		
Average CO_2 concentration	M	619	640	-5.91	< 0.001
	SD	117.3	144.4		
**Number of house occupants	M	24.4	28.7	-0.3	< 0.001
	SD	0.1	0.2		

Key: M = mean; SD = standard deviation **number excludes people living in shacks in the yard

Turbine houses performed better than control houses in all the IAQ parameters assessed during both times of the day (day and evening) at the end of the intervention period and as an average over this period. T-tests were used to analyse the differences of these predictors turbine and control households and the results show statistical significance ($p < 0.001$) in all parameters. Turbine households were noticeably cooler on average and had higher indoor-outdoor temperature and humidity differentials. The results also indicate that while the baseline CO_2 concentrations were comparable across turbine and control households, turbine households (M = 619, SD = 117.3) and control households (M = 640, SD = 144.4), with the intervention, turbine households reduced their CO2 concentrations more than the control ($t = -5.91$, $p = 0.001$). Overall, average CO_2 concentrations in both turbine and control households tended to be lower during the day and in winter and higher during evening times and in spring.

4.7 Roof turbine airflow

The mean air velocity flowing through the turbine was determined and Table 4.5 illustrates the results. The roof turbine had a diameter of 240 mm and the mean airflow flowing through it was 0.38 m/s (SD =0.15, range = 0.11 – 0.85) (Figure 4.7).

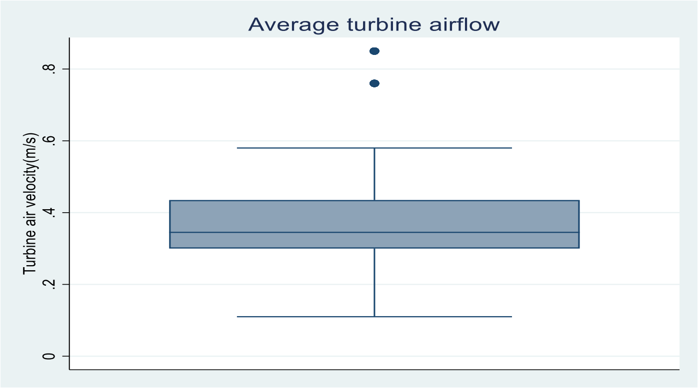


Figure 4.7 Mean airflow through the wind-driven roof turbine over the study period.

The average airflow within the turbine was high during the day (M = 0.46m/s, SD = 0.16, range 0.27 – 0.85) and in winter (M = 0.40m/s, SD = 0.18, range 0.11 – 0.85). The air flowing through the turbine during the evening and in spring tended to be 5% and 7% lower respectively. There was significant difference in the turbine airflow during the day compared to evening conditions (t= 11.9, p = 0.0000) and in the winter compared to spring times (t = -3.49, p = 0.0005). The results are displayed in Table 4.5 below.

Table 4.5 Mean air velocity flowing through the roof turbine.

Roof turbine airflow (m/s)	**N**	**M**	**SD**	**Min**	**Max**	**t-test**	**Probability**
During the day	448	0.46	0.16	0.27	0.85	11.9	<0.0001
In the evening	448	0.31	0.08	0.11	0.42		
In winter	448	0.40	0.18	0.11	0.85	- 3.49	0.0005
In spring	448	0.35	0.03	0.29	0.42		

4.8 Carbon dioxide concentration decay

The tracer gas measurements are illustrated in Figures 4.8 to 4.10. One ventilation condition was used: windows and exterior door fully shut. A characteristic exponential pattern was observed with the CO_2 concentration decay over a period of time. Figure 4.8 shows this typical concentration decay curve, demonstrating that as time increased there was a corresponding decrease in the concentration of CO_2. A multivariate regression analysis was run to predict CO_2 decay as influenced by time of day, presence of the wind-driven roof turbine, temperature and humidity difference, wind velocity and season (Equation 4). The top three variables which were shown to statistically significantly predict CO_2 concentration decay; $F(3, 892) = 8.60$, $R^2 = 0.03$, $p < 0.001$, were time of day, presence of the wind-driven roof turbine and season. Collectively, these three predictor variables accounted for 3% of the variance in CO_2 concentration decay. Of the three predictor variables, the presence of the wind-driven roof turbine was the strongest predictor as indicated by its regression weight ($t = 4.68$, $p = 0.000$) followed by season ($t = 3.97$, $p = 0.001$) and time of day ($t = -2.97$, $p = 0.003$). Wind velocity did not explain much with regards to the increased effectiveness of the turbine in this case, since all the households had the same wind exposure.

Overall, the 60 minutes decay of CO_2 concentration was greater in the turbine households (M = 1944 ppm, SD = 1353) compared to the control households (M = 1672 ppm, SD = 1237). Figure 4.10 and 4.11 illustrate the impact of time of day and season on CO_2 concentration decay in turbine and control households. The concentration decay tended to be higher in spring and during the day compared to the levels of decay in winter and during the evening.

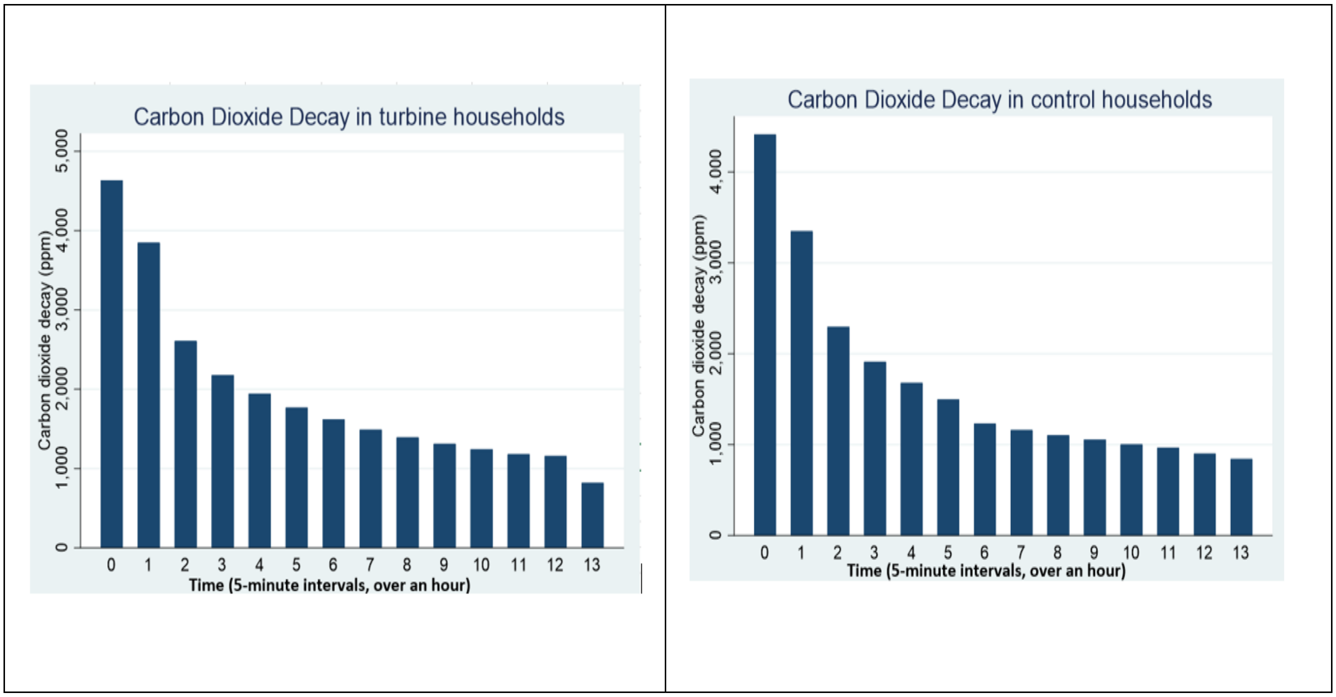


Figure 4.8 Bar graphs showing the exponential characterisic of the CO_2 concentration decay.

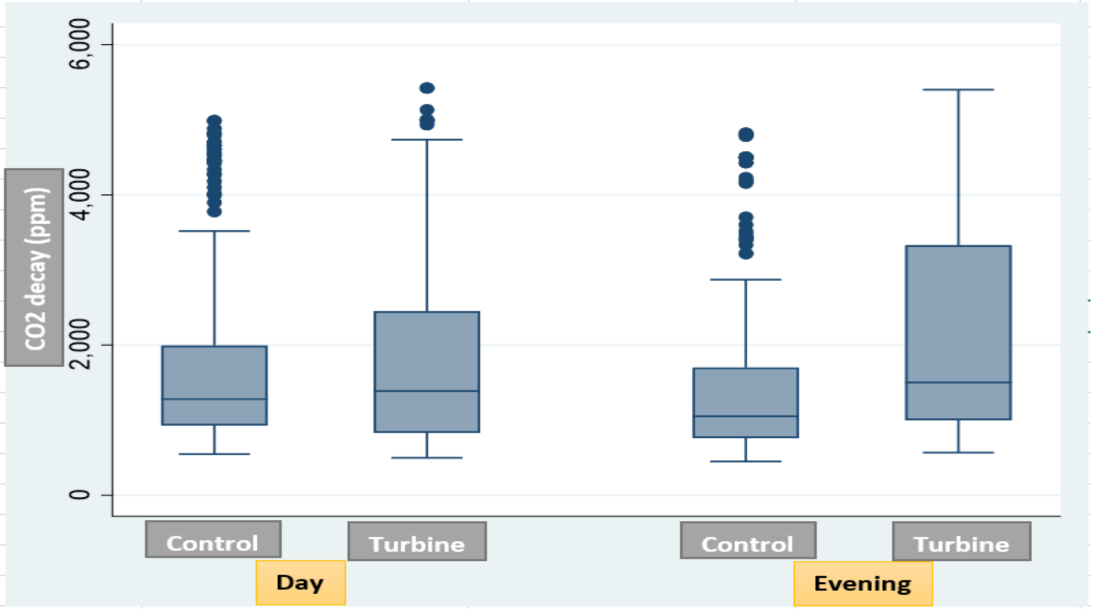


Figure 4.9 CO_2 decay in turbine versus control households according to time of day.

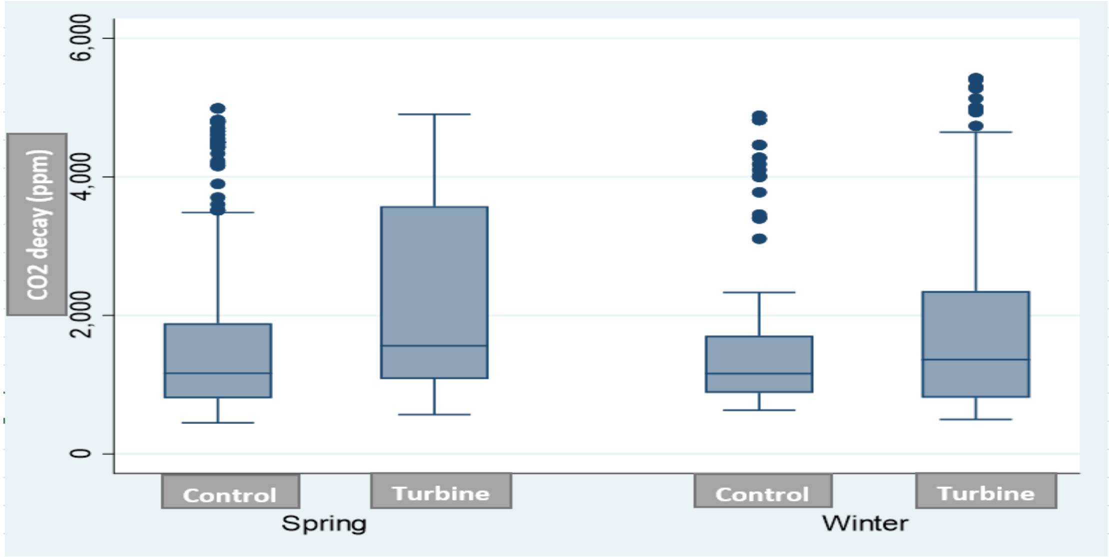


Figure 4.10 CO_2 decay in over 60 minutes turbine vs control households according to season.

To explore the extent to which the predictor variables of presence of roof turbine, time of day and season played a role in the decay of CO_2 concentration (and hence air exchange rate), a mixed effects regression modelling using repeated measures was run, while controlling for confounding factors such as mean outside velocity, indoor-outdoor temperature difference and humidity difference. Table 4.6 illustrates the output of this mixed effects regression model.

Table 4.6 Significance of predictor variables on CO_2 decay.

CO_2 concentration decay predictor variable	**Parameter estimate** (z)	**p-value (mixed effects regression)**	**Significance**
Presence of roof turbine	2.62	0.009	Significant
Time of day	-1.66	0.097	Not significant
Seasons	2.22	0.027	Significant

The presence of a roof turbine resulted in a strongly significant CO_2 concentration decay (M = 1944, SD =1353) than in the control household group (M = 1673, SD = 1237), z = 2.62, $p < 0.01$. CO_2 concentration was likely to decay by 460 ppm more in an hour in a turbine household than in a control one. Similarly, seasons had an impact, with CO_2 concentration decay likely to decay by 506 ppm more during spring (M = 1856, SD = 1349) than in winter (M = 1740, SD = 1239). While CO_2 concentration decay was higher during the day (M = 1824, SD = 1268) than in the evening (M = 1792, SD = 1338), regression results indicate a marginal (non-significant) difference, z = -1.66, p = 0.097.

4.9 Air exchange rates

To determine the air exchange rates in turbine and control households, natural logarithm transformed CO_2 concentration decay was plotted against time (60 minutes) on a graph (Figures 4.11 to 4.15). The air exchange rate (expressed in air changes per hour, ACH) was established from the least-squares fit slope line under the following predictor variables: time of day and season (Table 4.7).

Table 4.7 Mean air exchange rates in turbine versus control households as influenced by time of day and season.

	Mean air change rate per hour (ACH) **Ventilation condition:** Windows and exterior door fully shut			
Household	**Day, in winter**	**Evening, in winter**	**Day, in spring**	**Evening, in spring**
Turbine	1.14	1.22	1.30	1.62
Control	0.56	0.65	0.84	0.79

Turbine households had high air exchange rates under both conditions of time of day and season, with the highest mean air exchange rate seen during the evening in spring (1.62 ACH). The lowest mean air exchange rate was recorded in winter during the day in the control households (0.56 ACH). The highest air mean exchange rate for the control households was recorded during the day in spring (0.84 ACH). The differences are considered statistically significant as has already been established (Table 4.5).

Table 4.8 House ventilation rates.

	Ventilation rate (L/s) **Ventilation condition:** Windows and exterior door fully shut			
Household	**Day, in winter**	**Evening, in winter**	**Day, in spring**	**Evening, in spring**
Turbine	22.4	24	25.6	31.9
Control	11	12.8	16.5	15.5

Using Equations 1 and 2 (Chapter 2, page 29), the average volumetric flow rate was determined and the results are displayed in Table 4.8. The results show that the turbine households had, on average, the highest the ventilation rate, in L/s, in spring during the night and the lowest rates were observed in winter during the day time. For the control households the highest ventilation rate was observed during the day in spring time (16 L/s). Given the South African Residential Ventilation Building Code which recommends an average natural infiltration rate of 0.35 m^3/h.m^2 (SANS10400, 2011, South Africa), for the 29.28m^2 house used in this study, all households met this recommended rate. The average turbine household rates ranged from 0.75 m^3/h.m^2 to 1.08 m^3/h.m^2 which is more than double the recommended rate. Control household rates ranged from 0.37 m^3/h.m^2 to 0.53 m^3/h.m^2.

The house ventilation rates were further divided by the average and maximum number of occupants in the household to determine a flow rate for each occupant. Table 4.9 shows the results.

Table 4.9 Estimated ventilation rate (L/s per person) for average household occupancy.

	Per occupant ventilation rate (L/s per person) **Ventilation condition:** Windows and exterior door fully shut			
Household	**Day, in winter**	**Evening, in winter**	**Day, in spring**	**Evening, in spring**
Turbine	5.0	5.3	5.7	7.1
Control	2.1	2.5	3.1	3.4

On average, the estimated ventilation rate for turbine households was lowest in winter during the day at 5.0 L/s per person for the average occupancy (4.5 persons) and was 2.1 L/s per person for the average occupancy (5.2 persons) for the control households. For maximum occupancy in turbine households (5 persons), the highest per occupant ventilation rate was 6.4 L/s per person compared to 0.5 L/s per person for control households (7 persons).

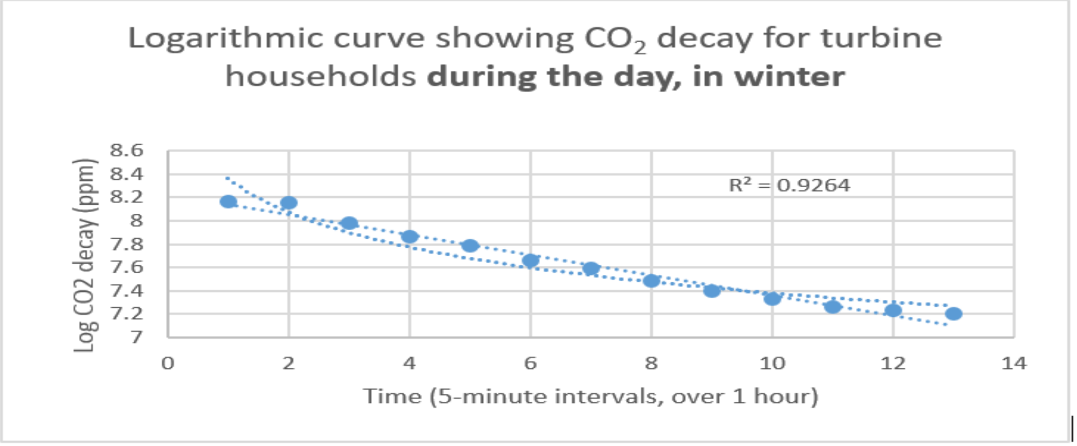


Figure 4.11 Logarithmic curve showing mean CO_2 decay in turbine households during the day in winter.

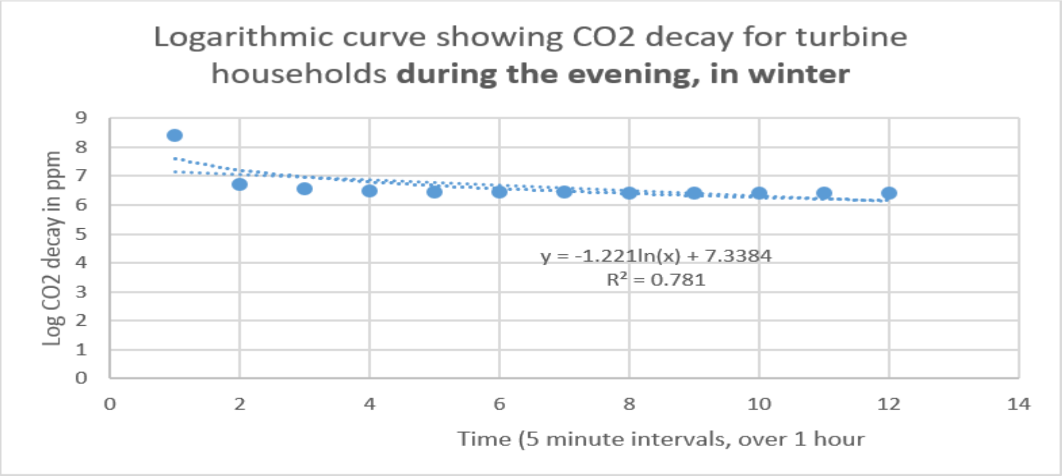


Figure 4.12 Logarithmic curve showing mean CO_2 decay in turbine households during the evening in winter

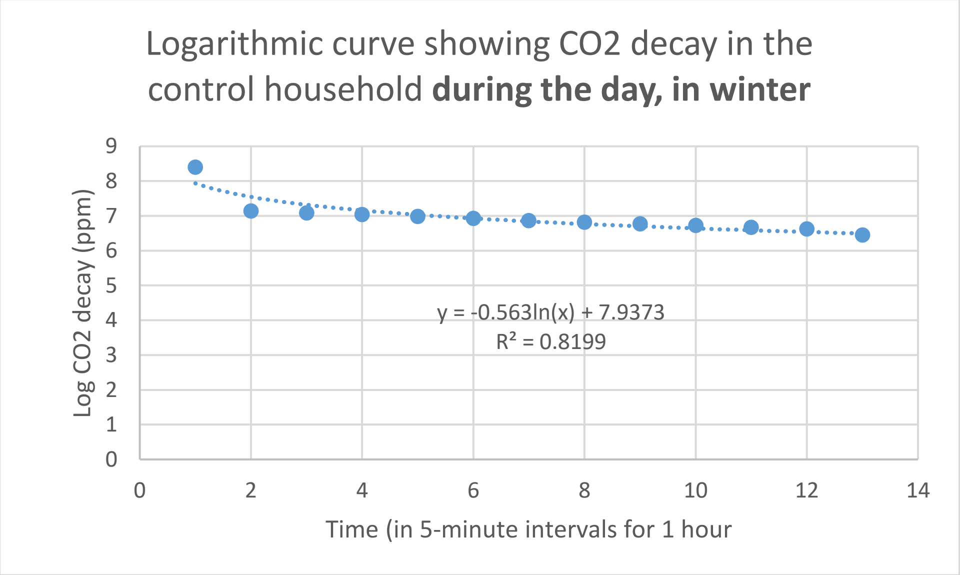


Figure 4.13 Logarithmic curve showing mean CO_2 decay in control households during the day in winter.

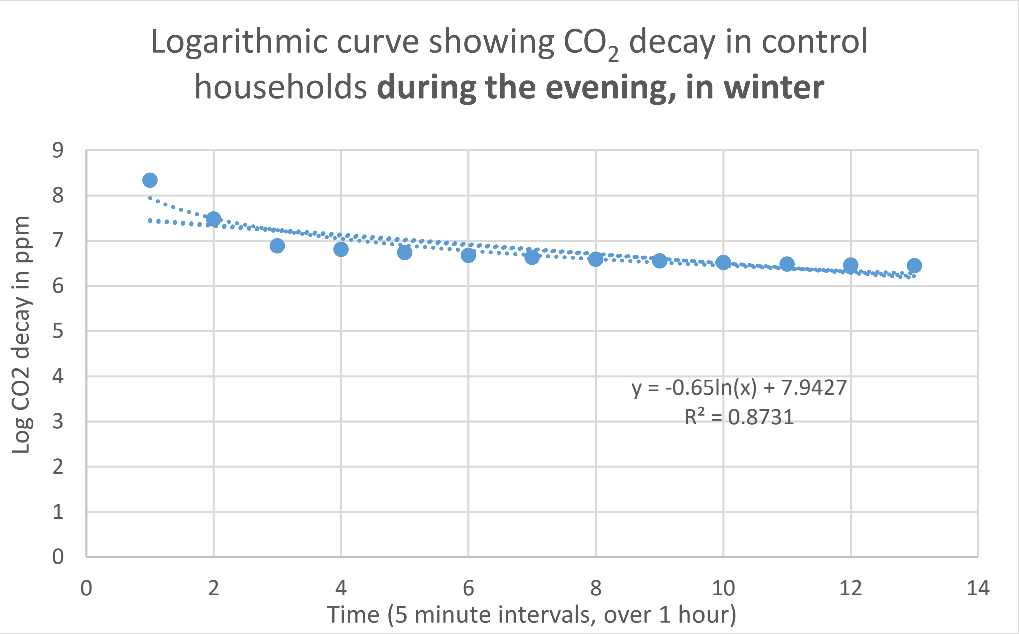


Figure 4.14 Logarithmic curve showing mean CO_2 decay in control households during the evening in winter.

4.10 Risk for TB infection

In the Wells-Riley model of airborne infection, absolute ventilation was used to determine potential disease transmission. Absolute ventilation was determined by multiplying the calculated ACH by the volume of the houses under study. Table 4.10 and 4.11 summarises the estimated infection risk for TB transmission in the turbine and control households.

Table 4.10 Infection risk for TB infection in turbine households.

Turbine household	**Mean ACH for the households**	**Volume of house**	**Absolute ventilation (Q)**	**Risk of infection (%)**
Day, in winter	1.14	$70.86m^3$	80.78	53
Evening, in winter	1.22		86.45	51
Day, in spring	1.30		92.12	49
Evening, in spring	1.62		114.74	42

Table 4.11 Infection risk for TB infection in control households.

Control household	Mean ACH for the households	Volume of house	Absolute ventilation (Q)	Risk of infection (%)
Day, in winter	0.56	70.86m^3	39.68	79
Evening, in winter	0.65		46.06	74
Day, in spring	0.84		59.52	65
Evening, in spring	0.79		55.98	67

The above tables show that the Wells-Riley airborne infection model predicts that in households where a roof turbine was installed, approximately 42 - 53% of the susceptible individuals i.e. individuals belonging to the households (taken as the median number of 4 occupants in the households), would become infected following an 8-hour exposure to an infected person. This risk was at or above 65% in the control households, being higher particularly in the winter season.

Table 4.12 Comparison of the ratio of risk between turbine and control households

Conditions	**Risk of infection (%)**		**Extent of reduction in risk of infection (%)**
	Control	**Turbine**	
Day, in winter	79	53	33
Evening, in winter	74	51	31
Day, in spring	65	49	25
Evening, in spring	67	42	37

Table 4.12 compares the extent of the reduction of the risk of infection between turbine and control households under the four conditions (time of day and season). For instance, a daytime exposure of 8 hours in winter, the turbine reduces the risk of infection from 79% to 53%, which

is a decline in risk by about 33%. This risk reduction values are extraordinarily high given the immunity to TB in many South Africans from past exposure. Thus this infection probability should be seen as an index rather than an actual probability.

The association between infection risk and absolute ventilation is illustrated in Figure 4.15. In Figure 4.15, the big dots represent the variation of infection risk against absolute ventilation. The small dotted line is the coefficient of determination (represented by R^2), which expresses the percentage of the infection risk variation against absolute ventilation explained by the Wells-Riley model. The shape of the curve shows there is an inverse relationship between infection risk and absolute ventilation. As absolute ventilation increases, the infection risk decreases. Infection risk initially decreases at a faster rate as absolute ventilation increases. At higher absolute ventilation, the infection risk is shown to be decreasing more slowly.

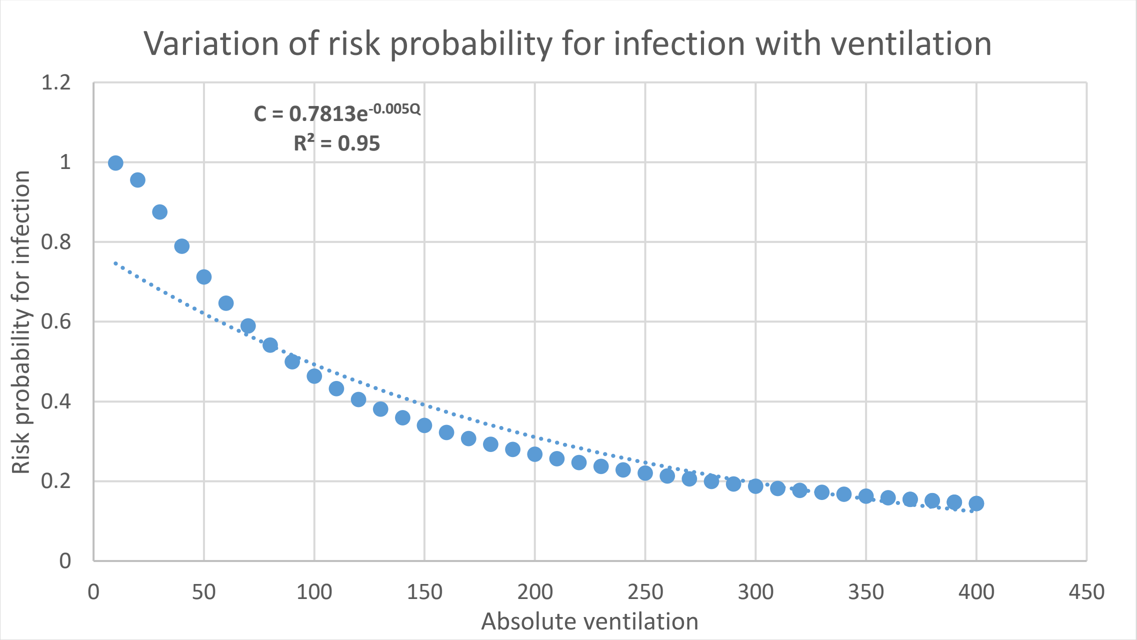


Figure 4.15 Variation of risk rates for infection with ventilation.

CHAPTER 5

DISCUSSION

5.1 Introduction

This study set out with the aim of determining the potential that enhanced ventilation using wind-driven roof turbines has on the risk probability for TB transmission in Diepsloot, which is a resource-limited community in the Gauteng province within South Africa.

In this chapter, a discussion of the results reported in the previous chapter is provided. The chapter begins by discussing the physical and social characteristics of the participating households in this resource-limited community as well as the weather conditions prevailing at the time of the study. These characteristics are to show if there were any confounding variables associated with the wind-driven turbine ventilation performance. Following that, a discussion is provided on the indoor air quality and comfort parameters, which were found to be significantly influenced by the presence (or absence) of the wind-driven roof turbine ventilator. The results of the carbon dioxide concentration decay are discussed after including the most influential predictor variables in a multivariate regression analysis. In addition, because of the repeated measures nature of this study, a discussion is provided afterwards on the impact of the significance of these predictor variables on carbon dioxide decay. Accordingly, a discussion is provided afterwards on the implications of the impact of the presence of the turbine ventilator on the air exchange rates and ventilation rates per person. Based on these exchanges rates, a discussion of the TB infection risk estimated using the Wells-Riley model is discussed. The chapter concludes with the limitations of the study.

Conclusions drawn from the findings of the study together with suggestions for future work are presented in the following chapter.

5.2 The physical and social characteristics of the participating households in Diepsloot, South Africa

Results from the study found a cluster of physical and social characteristics of the study setting inclusive of unemployment, pollution, overpopulation, poor quality of housing and infrastructure. These characteristics symbolise many urban South African townships, which consist of informal settlements comprising a mix of a series of high density shacks and government-subsidised brick houses (Himlich, Engel & Mathoho, 2014), such as the RDP house studied. According to the Johannesburg Poverty and Livelihoods Study conducted in 2006 among the eight poorest urban informal settlements including Diepsloot in the City of Johannesburg, it was found that Diepsloot had the highest TB burden per household (Ncayiyana, 2016). This is not surprising as the setting covers a small area, the size of 12km^2 (Johannesburg Development Agency, 2013) and with a total population of 360 000, this translates to 30 000 people per km^2 making it very densely populated. When these clusters of characteristics are combined with a high heterogeneity in health system capacities, they impact on disease transmission gradients and the effectiveness of public health strategies for disease prevention and control. Harnessing low-cost infection control strategies becomes important.

The houses under study had a 'pyramid on cube' shape, had a mean age of 15.5 years, a floor area of 29.28m^2, a volume of 70.86m^3, a ceiling height from the floor of 2.36m and had corrugated roofing material (Table 4.2). This cluster of characteristics is also described, though not as consistent complete set, in previous research on ventilation and TB transmission (Makaka et al., 2018; Chamie et al., 2013; Lygizos et al., 2013; Mushayabasa, 2013; Cox et al., 2012; Yoshimo et al., 2006). Lygizos et al. (2013), for instance, further describes the window to room ratio, roof and wall thickness and cross-ventilation while Makaka et al. (2018) also specifies the direction the windows faced and links them to the position of the sun and thus reception of solar radiation. These building characteristics have implications on air exchange rates and ventilation rates (WHO, 2009; Escombe et al., 2007; Bouhmra, Elkilani & Abdul-Raheem, 1998) and indoor air quality conditions which are discussed later in this report. In addition, it is expected that in a residential building specific activities such as smoking, cooking and showering occur would contribute to various emissions. Consequently, Persily and Levin (2011) observe the need for these characteristics (in addition to measurement method, instrumentation and their calibrations, timing, number of measurements and meteorological conditions) to be specified in studies on ventilation rates to enable comparisons of results that will eventually inform consideration of technologies for infection control. Van Buggenhout et al. (2009) found in their study that almost 50% of the time, these characteristics are not described consistently.

According to the National Building Regulations and Building Standards Act No. 103 of 1977, as amended, (herein referred to as the Building Regulations Act), the floor of any permanent category building may be smaller than $27m^2$ and temporary buildings can be as small as $15m^2$, but any permanent building that is used as a dwelling house must not be less than $30m^2$. The house under study meets the permanent category building requirements.

In terms of the Act, roof material determines the minimum gradient or incline of the roof. According to the Building Regulations Act, a minimum gradient of $10 – 15^o$ is expected of roof material made of corrugated sheets. As the roof inclination was not determined in this study, based on the roof material used, the study assumed the minimum slope as provided by the Building Regulations Act. However, the wind-driven turbine was installed at the highest possible point on the roof (Figure 4.5). The inclination angle of a roof can influence the airflow and efficiency associated with a wind-driven turbine ventilator (Tien & Ahmed, 2011). In their study to determine the effect of roof inclination on the airflow associated with wind-driven roof turbine ventilators, they found that the total force acting on the ventilator and its rotational speed tended to decrease with an increase in the inclination angle of the roof (Tien & Ahmed, 2011). While this may be true, if the effect is small the impact on risk may not be consequential. Nevertheless, this points to the importance of determining the structural characteristics of buildings in resource-constrained environments. It is not just about harnessing the natural ventilation with innovative and economical technologies but also about where it will be done to ensure effectiveness.

With regards to ceiling height from the floor, higher roofs would generally require larger diameter roof turbines while lower roofs require smaller turbines. Escombe et al. (2007) points out building construction and age as a factor that influences ventilation rates. They reiterate that facilities built more than 50 years ago are largely characterized by large windows and high ceilings. This translates to greater ventilation. In this study, the mean age of the households was 15.5 years.

5.3 Impact of wind-driven roof turbines on temperature, moisture levels, CO_2 concentration, room ventilation and air exchange rate

The results presented in the previous chapter revealed statistically significant associations between the presence of the roof turbine and improved air quality and comfort parameters of CO_2 concentration, temperature and humidity levels (Table 4.4). The present findings seem to be consistent with those observed in previous research (Makaka et al., 2018; Chamie et al., 2013; Lygizos et al., 2013; Mushayabasa, 2013; Cox et al., 2012; Yoshimo et al., 2006). Ventilation is intended to remove or dilute pollutants and to control the thermal environment and humidity in buildings (Seppanen & Kurnitski, 2009). On average, turbine households recorded better thermal, moisture and carbon dioxide levels compared to the control households during both seasons (winter and spring) and time of day (day and evening). An explanation of these results is advanced by Khan et al. (2008) who state that the rotation of the roof turbine creates an updraft in the turbine which in turn extracts warm, stale and moist air from the interior of the house, thereby dropping the temperature in the building and allowing the supply of fresh air via infiltration (vents, windows and doors when they are open). A study by West (2008) supports this premise. In this study, one ventilation condition was used: windows and doors fully shut. The decrease in temperature and moisture levels can thus be attributed to the performance of the turbine ventilator. The roof turbine ventilator used in this study had a diameter of 240mm. According to energycut.com (2020) and West (2008), a wind-driven roof turbine constructed of aluminium material and with a diameter between 240 – 300mm has an extraction rate of between 924- 1000m^3 per hour given wind speeds of 5 m/s. Thus, it is to be expected that a roof turbine with a bigger diameter would have a higher extraction rate and even better IAQ and comfort levels. A reported advantage by the manufacturers of the wind-driven roof turbine over open doors and windows is the absence of draught (roofwhirly4Africa, 2020). However, from public health and occupational hygiene perspectives, the benefits of the turbine are not just about avoidance of draught but are linked to the fact that the effectiveness of the turbine is not primarily dependent on human behaviour. The Cox et al. (2010) study support this. The study not only showed that the turbine was better than open windows but that the turbine and open windows did even better. This points to the turbine's efficiency as a ventilation strategy.

A finding of note is that of the indoor-outdoor temperature differences (Table 4.4), more so during the winter season and in the evening. During winter, wind speeds and outdoor temperatures were lower (Table 4.3). This has implications on the performance of the wind-driven roof turbine, which predominantly relies on the presence of wind for its effectiveness. In this study, however, because every household had presumably the same wind exposure, the increased effectiveness of the turbine with wind was not evident. Natural ventilation systems like the wind-driven roof turbine rely on pressure difference to extract air from a building. This pressure difference is a result of wind and buoyancy effect created by temperature and moisture differences (between inside and outside of a building). The good IAQ and comfort levels in the turbine households during winter and evening are explained by this buoyancy effect as during these conditions there was low wind speeds and the sun is low in the sky (Makaka et al., 2018). The buoyancy effect posits that in the absence of wind or presence of a low breeze, the wind-roof turbine still rotates on its vertical axis. This rotation is caused by warmer air indoors which has been created by solar radiation that heats the thermal mass which later at night radiate thermal radiation that heats the indoor environment (Makaka et al., 2018). This in turn creates thermal currents which rotate the turbine, drawing warm air out of the building. This is referred as the stack effect and is what makes the wind-driven ventilator earn the term 'passive ventilation' (Makaka et al., 2018; Khan et al., 2008).

The prevailing weather conditions at the time of the study were specified. Detailing the prevailing climatic conditions such as season, wind direction and speed, is important, as the WHO (2009) reiterates, when results of implementation of natural ventilation as an infection prevention control measure are reported. This is because these factors affect ventilation needs and efficiency. As a general rule, the extraction rates provided for different diameters of wind-driven roof turbines assume winds speeds of 5 m/s. Therefore considering the prevailing climatic conditions enables to determine the effectiveness of the technology itself.

In this study, carbon dioxide was used and its decay was used to determine the rate (measured in ACH) at which the wind-driven roof turbine cleared in from the house. This was done with all the windows and exterior door fully shut and with the occupants outside. While the multivariate regression analysis revealed other factors, such as season and time of day, that influenced decay, the presence of the wind-driven roof turbine was the strongest predictor (and also the most modifiable) factor of its decay (Table 4.6). This finding mirrors other studies that attribute the rate of decay to the wind-driven roof turbine (Brouwer et al., 2015; Lygizos et al., 2013; Cox et al., 2012). Although this CO_2 concentration decay may seem obvious, it is important to note that most previous studies conducted have been done in the healthcare and settings other than households (Taylor et al., 2016; Brouwer et al., 2015; Ogbonnaya et al., 2014; Buregyeya et al., 2013; Cox et al.,2012).

The recommended typical level of indoor CO_2 concentration that creates indoor air quality conditions to maintain a comfortable environment for most occupants is pegged at 1 000 parts per million (ppm) (WHO, 2009). In this study, approximately 4 500 ppm was injected into the house and after an hour of monitoring of the decay, each house ended with a concentration that was between 600 and 700 ppm (in turbine households) and between 750 to 900 ppm in control households , levels that meet the recommended minimum levels. For this indoor level to be maintained, there has to be outdoor concentration of CO_2 that varies from 350-400ppm because this is where the amount of fresh air being supplied to the household is coming from. The amount of CO_2 indoor determines the air quality and its concentration indicate the ventilation rate within a space (Makaka et al., 2018). It should be noted that poor positioning of the CO_2 concentration sensor can cause tracer gas decay ventilation rate errors of up to 55% (Van Buggenhoutet al., 2009). The ASHRAE (2013) recommends a ventilation rate of approximately 7.1 L/s per person for achievement of this maintenance of comfortable indoor conditions. Results from this study show that these comfortable indoor conditions were only met by the turbine households in spring during the night (Table 4.8). The most likely time when the indoor air is mostly contaminated is at night when all the designed ventilation components would be closed and all the occupants being indoor (Makaka et al., 2018), thus this result from the study is satisfying.

The South African Residential Ventilation Building Code recommends an average natural infiltration rate of 0.35 $m^3/h.m^2$ (SANS 10400, South Africa). This is equivalent to 6.9 L/s per person. Compared to international standards which recommend minimum ventilation rate of 10 L/s per person (in the UK) and 7.1 L/s per person (in the USA) means that on average and contrary to expectations, the majority of the households failed to meet these standards per average number of occupants, with the exception of the turbine households during the evening in spring which achieved a ventilation rate of 7.1 L/s per person. These turbine households also had the highest air exchange rate of 1.62 ACH. Without the wind-driven roof turbine, the average per occupant ventilation rate was below 3.5 L/s (Table 4.9). Seppanen, Fisk and Mendell (1999) demonstrated that ventilation rates below 10 L/s per person are associated with significantly higher prevalence of one or more health outcomes or with worse perceived air quality.

Both turbine and control household met the recommended infiltration rate of 0.35 $m^3/h.m^2$ per area size of the house ($29.28m^2$). The houses under study are classified under formal houses and thus it is expected that its construction meets the standards specified by the National Building Regulations. Undoubtedly, this finding highlights the impact of other factors on the infiltration rate, which for this study included the houses' airtightness, prevailing climatic conditions and presence of the wind-driven roof turbine in determining the ventilation rate. This is in agreement with the findings of Yoshimo et al. (2006), ASHRAE (2001) and an earlier study by Brundett and Poulney (1985). In Yoshimo et al. (2006) study, the conclusion was that ventilation requirements could be met in most cases with about 1.26 m^3/hour per square metre of floor area of a $100m^2$ house. This translates to 0.5 ACH for a $100m^2$ house. The WHO (2009) differentiates between the ventilation rate and the air change per hour (ACH) in terms of the purpose of each rate and pollutant concentration. The ventilation rate is specified for the control of exposure to pollutants while the ACH is primarily used where there is a need to reduce the concentration of the pollutant (WHO, 2009).

Air exchange rate (measured in ACH) is a combination of infiltration and ventilation. The house under study did not have air vents, nor was there a space between roof and wall junctions. However, infiltration could be achieved through cracks and penetrations in the building such as doors, windows and electrical sockets. The driving forces of air exchange rate are stack effect and wind. A major limitation of naturally ventilated techniques is the unpredictability of the driving forces (ASHRAE, 2001).

A high value of air exchange rate of 1.62 in the evening, in spring was achieved by the turbine households (Table 4.7). While this result was in most part in agreement with values advanced by earlier household ventilation studies (Yamamoto et al., 2010; Eskola et al., 2007), it is in contrast with the findings by Liuliu et al. (2012) who found that the air exchange rate was higher in winter and lowest in spring and Pandian, Ott and Behar (1993) who established that multi-level residences had higher exchange rates than single-level residences. It should be noted, however, that these studies were conducted with houses in the developed countries which tended to have air conditioners or mechanical ventilation of some sort. In the current study, comparing it with a similar setting study by Lygizos et al. (2013), shows that in their study, average rates of 3 ACH were achieved in the same ventilation situation of windows and doors tightly shut.

An explanation of this difference is the volume of the two types of houses under Lygizos et al. (2013) study which was higher (91.3 m^3 and 36.6 m^3) and structural features such as shape (box and round) and roofing material (thatch and metal sheeting). Another study which used a wind-driven roof turbine (Cox et al., 2012) and thus forming a comparison platform with the present study reported air exchange rates ranging between 6.3 and 8.1 ACH with windows, doors and grates shut. This study, was however, conducted in a healthcare facility, with rooms that had smaller volumes (21.7 to 33 m^3/h) and using bigger diameter wind-driven roof turbines (300 – 500 mm). Assuming wind speeds of 5 m/s, a 300 – 500 mm diameter wind-driven has an extraction rate between 1 155 m^3/h to 3 770 m^3/h (Turbovent, 2020).

Air quality studies have shown variation in air exchange rates based on geographical differences in weather conditions, building characteristics and occupant behavior. Occupant behaviour did not have any influence in the current study as the ventilation condition simulated was that of doors and windows fully shut with no occupants inside during the measurement period. Previous studies have shown that opening of doors and windows in addition to the presence of the wind-driven roof turbine could increase air exchange rates even above WHO-recommended ones (engineringtoolbox.com, 2019; Lygizos et al., 2013; Cox et al., 2012; Escombe et al., 2007). There are no real ways in which human behaviour could reduce the effectiveness of the turbines unless an occupant decided to block it up, which would have been extremely rare. The turbine is a technology that does not rely on someone opening a window or door to maintain ventilation. Building characteristics look at the tightness of the building envelope, the surrounding terrain and any local wind sheltering. While the households had informal dwellings (shacks) in their yards, these were not high enough to act as wind sheltering which would interfere with the wind-induced rotation of the wind-driven roof turbine.

5.4 Estimating the potential effect of wind-driven roof turbines to reduce the probability of TB transmission

It should be highlighted on the outset that the Wells-Riley model in this study was used as a tool to evaluate the impact of the turbine intervention on a hypothetical risk index which is not actually real. The risk for infection shown by the model in this study is not an actual infection risk. The infection probabilities should be seen as an index rather than an actual probability.

The Wells-Riley airborne infection model predicted a strong association between absolute ventilation and risk for TB transmission (R2 = 0.95). Since, in turbine households, the absolute ventilation is approximately twice that of the control households, control households would have approximately a twofold infection risk i.e. 67 – 79% of susceptible individuals would become infected following an 8-hour exposure to an infected person versus a risk of 42 – 53% in the turbine household. These results seem to be consistent with earlier studies (Lygizos et al., 2013; Escombe et al., 2007). The presence of the wind-driven turbine, in addition to open windows and doors generated air exchange rates that reduced TB infection risk to 9.6% (Lygizos et al., 2013) and 33% (Escombe et al., 2007). Jensen et al. (2005) showed the airborne contaminant removal efficiency of 99% with an exchange rate of 20 ACH (Table 2.1). Wan et al. (2009) demonstrated a decrease in infection risk through airborne transmission by 41% when ventilate rate was nearly doubled.

Room ventilation dilutes the room air and thus exposes people in the room to fewer potentially infectious particles including TB (Memarzadeh, 2013; Bolashikov, Melikov, & Georgiev, (2011; Knibbs et al., 2011).

While there is evidence to support this advantage of ventilation on reducing TB infection risk (Memarzadeh, 2013), the maximum ventilation rate at which there is no further reduction of risk is, however, not clear.

There are some studies that also do not support the positive relationship between high ventilation rate and reduced infection risk (Sze-To et al., 2014) Their study postulates that higher ventilation rates have higher dispersion than dilution of infectious particles. This dispersion then leads to more susceptible people being exposed even when they are located far away from the source of infection.

When it comes to the Wells-Riley model in predicting infection risk, Noakes & Sleigh (2009) point out its limitation in acknowledging the role that chance effects play in determining infection risk. For instance, infection risk is influenced by the number of inhaled doses of the infectious particles (Fennelly, & Jones-López, 2015). These doses are influenced by proximity of contact to the source case, individuals sharing a bed with people with TB, the intensity of the exposure as well as host variables such as smoking and environmental factors such as air pollution (Lin, Ezzati & Murray, 2007).

The model further assumes that in a short period of time there is only one new infection which is likely. As such, they also point out that in order to gain an understanding of risks for small populations, such as the ones for the present study, the model has to be used in a stochastic simulation. Aside from these pitfalls of the model, it is ideal to use in a deterministic way particularly when examining the impact of interventions on progression of an infection and where there is a large population (Noakes & Sleigh, 2009). In the present study, the population was small and the CO_2 concentration decay depended on individual characteristics such as house physical and social structures, location and prevailing climatic conditions, therefore, the stochastic model applies. The outcome of the study would not be predicted with 100% certainty in another setting with similar characteristics as the demographic and environmental factors will always bring in some randomness to the results (Noakes and Sleigh, 2008).

5.5 Acceptability of the intervention

A gap in the literature is the likely adoption of new technologies such a wind-driven roof turbine. This study established the efficacy of the intervention as a first step in reducing risk for TB infection. However before the intervention can be considered for roll-out, it becomes imperative to determine the likely acceptability of the intervention by the people in the community. As shown by Abney (2011) study, people's perceptions of the TB infection will indicate whether the proposed technologies would fit into their world views or not.

Based on the researcher's practical experience during data collection, overall, there was high acceptability of the intervention in the community. Households committed a lot in the study such as vacating their homes during the day and night, and four weeks apart and allowing for the turbine to be installed on their roofs. In addition, the participants having to ask for the turbine to be of the same colour as their roofs points to some degree of acceptance of the technology.

Furthermore, when other members in the community saw the turbines being installed, they came to enquire about the turbine and also wanted to have the turbine installed as well. Due to researcher's financial constraints, the maximum sample size she could use had been reached. When community members heard about what the turbine does and particularly the cost of the turbine, others then went on to engage with the manufacturer and sourced their own.

5.6 Limitations of the study

The findings of this research report are subject to at least three limitations. One limitation of this study is that the number of turbine and control households was small. Acquiring the households was constrained by the time limitation (and financial requirements) within which the study had to be completed. Also, this time constraint inherent in the study lead to shorter term follow-up assessments after intervention implementation. This time limitation means that the study findings need to be interpreted cautiously. These results may not be attributed to all resource-limited household settings and all geographical locations. It would have been more useful and generalizable if this study was conducted in a variety of household settings than was covered in the present study.

The study worked under the assumptions of equal host susceptibility, uniform sizes of droplets, uniform ventilation, homogeneous mixing of air, and minimal elimination of infective particles other than by removal by ventilation. At the time of the study, the study area did not have electricity. As a result, homogenous mixing of air aided by a fan when CO_2 gas had been injected in the house was not achieved. As such, the study did not consider the random effects in a small population and environmental factors that may affect risk estimation.

5.6 Summary of chapter

This chapter highlighted and discussed the key findings of this study. According to the intervention study, turbine households performed significantly better in all parameters assessed: indoor air quality and comfort, ventilation and air exchange rates and infection risk. While natural ventilation on its own has been shown to meet ventilation requirements, it has limitations as it depends type of dwelling and air tightness of this dwelling, the number and behaviour of the occupants. If natural ventilation is harnessed by ventilation technologies such as wind-driven roof turbines, it has been shown to improve indoor air quality and comfort and air exchange rates that generate adequate replacement air that can dilute airborne infectious particles.

The next chapter presents conclusions drawn from the findings of the study. Furthermore, suggestions for future work are made and presented in the following chapter.

CHAPTER 6

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

The aim of this chapter is to present the conclusions drawn from the results of the analysis of the study findings and then make recommendations for further research.

6.2 Summary

The objectives of the study can be restated as follows:

- To describe the physical and social characteristics of the participating households in Diepsloot, South Africa.
- To assess the impact of wind-driven roof turbines on indoor temperature, indoor moisture levels, CO_2 concentration, room ventilation and air exchange rate in eight households (four intervention households, four control households) using a CO_2 tracer gas decay technique for measuring air changes per hour over a three-month period in Diepsloot, South Africa in 2019.
- To estimate, using the Wells-Riley mathematical model, the potential effect of wind-driven roof turbines to reduce the probability of TB transmission.

To fulfil the above objectives of the study, a quantitative strategy bound by an exploratory quasi experimental design was planned. A low-cost and low-maintenance intervention, in the form of wind-driven roof turbines, that harnessed natural ventilation, was decided upon. This intervention, supplemented by interviews with household owners and environmental assessment, required the purposive allocation to and comparison of intervention and control households. Extensive literature was consulted to provide a background on ventilation as an infection prevention and control strategy for resource-limited community settings with an exploration of the technology behind the wind-driven roof turbine, ventilation rates considered appropriate for indoor air quality and comfort, techniques for studying building air exchange and mathematical modelling of risk for infection with a specific focus on the Wells-Riley model.

Pursuing the objectives of the study, the research design had the following major features: interview with the household owners and an environmental survey to determine the characteristics of households that facilitated recruitment into the study, pairwise comparison of households allocated to the intervention and control groups using results from interviews with the household owners and environmental assessment, installation of the wind-driven roof turbine, repeated measures of the rate of clearance (assessed as ACH) of an injected amount of carbon dioxide and the determination of TB risk infection using a Wells-Riley model.

6.2.1 Major findings and contribution to knowledge

- *Objective 1:* To describe the physical and social characteristics of the participating households in Diepsloot, South Africa.

In accordance with the first objective of the study, the most significant physical and social household variables which emerged from the analyses and which have implications for air exchange rate were those connected with building structural characteristics (floor area, shape, volume, number, window area and location of windows and doors and, roof material), number of occupants and weather conditions. The physical and social characteristics of the households were consistent with those typically found in settlements within resource-constrained communities. A cluster of crises such as unemployment, low income, pollution, high numbers of inhabitants (overpopulation) and the poor quality of infrastructure and housing explain why there is a steeper disease transmission gradient in the first place. These characteristics place the resource-limited communities at a vulnerability that motivates the consideration for economical yet effective public health strategies for disease prevention and control. For disease prevention and control strategies, such as those that harness natural ventilation, consideration should be made that ensure effectiveness with regards to reducing exposure and concentration of infectious particles in such spaces as Diepsloot whose typology of social and physical characteristics place it at a vulnerability.

- *Objective 2*: To assess the impact of wind-driven roof turbines on indoor temperature, indoor moisture levels, CO_2 concentration, room ventilation and air exchange rate in eight households (four intervention households, four control households) using a CO_2 tracer gas decay technique for measuring air changes per hour over a three-month period in Diepsloot, South Africa in 2019.

The current temperature, humidity and carbon dioxide levels in Diepsloot households rely solely on natural ventilation, more specifically infiltration. Due to a rampant rat infestation, security reasons, draughts and the stench of widespread land pollution in the community, the occupants reported that they do not open windows and doors. They further reported that the indoor thermal conditions were not too ideal. The poor thermal conditions were further compounded by the number of occupants in the household and the activities that occur within such as cooking. People are more likely to report thermal sensations and judge the adequacy of the indoor air quality using this parameter. Thus, considerations should be made which target thermal comfort as an outcome of IPC interventions. The results of the study confirm that harnessing natural ventilation with a low-cost innovation such as the wind-driven roof turbine generated ventilation or air exchange rates that improved the indoor air quality and thermal comfort.

The results show that the ventilation requirements of the household could be met by the infiltration rate, however, physical and social characteristics of the households, and the setting itself (in terms of the climatic conditions), impeded this achievement. However, these ventilation requirements are subject to two driving forces: stack effect and wind induction. These two driving forces are unpredictable. This is another limitation of relying on natural ventilation alone to meet ventilation requirements of a household. Thus any airborne infection prevention and control that will utilise ventilation as a control measure will require to ensure the harnessing of these two driving forces.

In determining the adequacy of a space to meet its ventilation requirements, it is important to report the air exchange rate, assessed in air changes per hour (ACH) and the ventilation rate (VR), assessed in L/s per occupant or L/s per m^2. The ACH is concerned with replacement air in a space and reduction of a contaminant while the VR is should be specified for control of exposure to airborne contaminants. The VR is a function of building use and occupancy to provide adequate indoor air quality for spaces. Therefore, the ACH and the VR express different interpretation of ventilation. Nevertheless, any air quality studies, as this current one, should document and acknowledge the extent to which weather conditions, building characteristics and occupant behaviour as well as the presence of outbuildings have on the variation of established air exchange rates. The challenge of house to house variability, however, was not experienced in this study. The study design included pretesting measurements whose assumption was that if the turbine and control household characteristics were similar at pre-intervention stage, there was little chance for confounding variables when differences, e.g. impact of the intervention, between the groups were determined.

- *Objective 3*: To estimate, using the Wells-Riley mathematical model, the potential effect of wind-driven roof turbines to reduce the probability of TB transmission.

Kato-Maeda et al. (2019) showed that while there was a higher frequency of transmission of TB in non-household settings, there was a higher incidence of new infections among household contacts compared to non-household contacts. In relation to the third objective, the results also confirm that the probability of disease transmission is reduced by almost half in households that had a wind-driven roof turbine compared to the control ones. This risk had to be determined using the absolute ventilation which was an air-change rate (ACH) relative to the volume of the space studied. The higher the ACH, the higher the absolute ventilation and thus a reduction in the risk of infection.

6.3 Recommendations

In the light of the findings of this research and in view of the study's limitations, the researcher wishes to make some recommendations, which, if taken into consideration, might bring some positive changes to the current approach:

- Canvasing and using heterogeneous household characteristics in order to have diverse information when comparing results of the effectiveness of the intervention.
- Use of a probability sampling method in order to collect results that are representative of the entire population in a resource-limited setting.
- Conduct the study with a variety of household settings in the resource-limited setting in order to determine the challenges of house to house variability on air exchange rates.
- Where time permits, use a modified Wells-Riley model by Issarow et al. (2015) that predicts the risk of airborne infectious diseases in multiple environments.
- A probabilistic approach where the distribution of the parameters in the Wells-Riley are taken aboard may overcome the assumptions under which the present study worked.

6.4 Indications for further research

The study has highlighted a number of researchable aspects that could be pursued further by those involved in air quality studies. These studies have to be more broadly based in order to aid generalization. For instance:

- The results from the study showed the health system capacities underpinned by physical and social characteristics of resource-limited community settings that impact on ventilation as a measure to control aerosol infection. When studies on air quality are conducted, it is important to highlight the health system capacities that focus on health equality, health equity and hygiene precautions in order to have standards that cover all situations or circumstances.

- This research, which has implications stretching far beyond resource-limited community settings in the Gauteng Province, can serve as a point of departure for residential ventilation and other settings such as schools, prisons, taverns and fast-food restaurants.
- Due to the unpredictability of the two driving forces of the air exchange rate (stack effect and wind-induction) studies can be explored where another natural source such as solar power can be incorporated with a wind-driven roof turbine to boost its efficiency and reliability.
- A prospective study with guinea pigs the impact of the wind-driven roof turbine can be conducted so that infection rates can be determined with real pathogens and not a surrogate such as carbon dioxide.
- Taking this study towards programmatic implementation will require some social science research into acceptability. It is important to understand the attitudes and beliefs of community members as there is no point in rolling out an intervention (no matter how effective it is) if the people's attitudinal, social and behavioural factors have not been taken into account.
- A study on the cost-benefit analysis of the low-cost and low-maintenance aerosol infection prevention and control measures should be conducted to stablish a business case that would provide justification for undertaking these innovations.

6.5 Concluding remarks

Given the strongly significant associations established by the study, it seems reasonable to conclude that the overall results provide evidence of the relevance and importance of the provision of ventilation systems as an extra measure of protection in household settings. Previous studies have also affirmed this finding. Strategies that deal with this ventilation as an infection prevention and control in resource-limited settings should be easy to implement, of low-cost and low maintenance. Furthermore, if these results are valid, it is also reasonable to conclude that ventilation systems for resource-limited settings that harness the natural forces of nature (wind, water and solar) may just provide the promising alternative reducing concentration and exposure to infectious aerosols.

Finally, this study provided a counter point to Cox et al. (2012) study which also determined the efficacy of wind-driven roof turbines to achieve recommended ventilation rates. While Cox et al. (2012) study utilised a healthcare setting, a bigger diameter wind-driven roof turbine, simulated more than one ventilation conditions and was conducted in a setting with higher wind speeds, the current research findings are in agreement. It is therefore, encouraging to compare the results and contributes towards vouching for home confinement for people with resistant forms of TB who either escape from the forced confinement or are released early into the community before they have finished treatment.

REFERENCES

Abney, K. (2011). Who said a little “dirt” didn’t hurt: Exploring tuberculosis (TB)-related stigma in Khayelitsha (Unpublished master’s dissertation). Department of Social Anthropology, University of Cape Town, South Africa.

Addo, K.K., van den Hof, S., Mensah, G.I., et al. (2010). A tuberculin skin test survey among Ghanaian school children, *BMC Public Health*, 10: 35.

Afonso, C. (2015). Tracer gas technique for measurement of air infiltration and natural ventilation: case studies and new devices for measurement of mechanical air ventilation in ducts, *International Journal of Low-Carbon Technologies*, 10 (3): 188 – 204.

Aliabadi, A., Rogak, S.N., Bartlett, K.H. and Green, S.I. (2011). Preventing Airborne Disease Transmission: Review of Methods for Ventilation Design in Health Care Facilities, *Advances in Preventive Medicine*, 21 pages, (doi: https://doi.org/10.4061/2011/124064).

American Institute of Architects. (2001). Guidelines for design and construction of hospitals and health care facilities. Washington, The American Institute of Architects Academy of Architecture for Health, [Online] Available at: https://www.brikbase.org/content/guidelines-design-and-construction-hospitals-and-healthcare-facilities Accessed: 20 March 2020.

ASHRAE (2001) Ventilation and infiltration, 26.1– 26.32. In: R Parsons. (ed.) 2001 ASHRAE Fundamentals Handbook, SI edition, Atlanta, Georgia: The American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE. (2013). ANSI/ASHRAE Standard 62.1-2013, Ventilation for Acceptable Indoor Air Quality, Atlanta, Georgia: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Assimakopoulos, D.N., Chrisomallidou, N., Klitsikas, D., Mangold, P., Michael, M., Santamouris, A. & Tsangrassoulis, A. (2001). Energy and Climate in the Urban Built Environment, [Online] Available at: https://doi.org/doi:10.4324/9781315073774 Accessed: 23 March 2020.

Atkinson J. (2009). Natural ventilation for infection control in health-care settings. Geneva: WHO [Online] Available at: http://www.who.int/water_sanitation_health/publications/natural_ventilation.pdf Accessed: 26 March 2020.

Atkinson, J., Chartier, Y., Pessoa-Silva, C. L., Jensen, P., Li, Y., & Setim, W.-H. (2009). Natural ventilation for infection control in health-care settings. Geneva: WHO Publication/Guidelines.

Auld, S.C., Sarita Shah, N., Mathema, B., Brown, T.S., Ismail, N., Omar, S.V., Nelson, J.N., Allana, S., Campbell, A., Mlisana, K., Moodley, P. & Gandhi, N.R. (2018). Extensively drug-resistant tuberculosis in South Africa: genomic evidence supporting transmission in communities, *European Respiratory Journal*, 52 (4): 1800246; **doi:** 10.1183/13993003.00246-2018

Azimi, P. and Stephens, B. (2013). HVAC filtration for controlling infectious airborne disease transmission in indoor environments: Predicting risk reductions and operational costs, *Building and Environment*, 70: 150-160.

Bady, M., Kato, S., Takahashi, T. & Huang, H. (2011). Experimental investigations of the indoor natural ventilation for different building configurations and incidences, *Building and Environment,* 46: 65–74 [Online] Available at: https://doi.org/10.1016/j.buildenv.2010.07.001 Accessed: 14 September 2019.

Barlow, J.F. & Coceal, O. (2009). A Review of Urban Roughness Sublayer Turbulence, Met Office Research and Development, [Online] Available at: http://centaur.reading.ac.uk/38572/ Accessed: 18 March 2020.

Basu, S., Andrews, J.R., Poolman, E.M., Gandhi, N.R., Shah. N.S., Moll, A., et al. (2007). Prevention of nosocomial transmission of extensively drug-resistant tuberculosis in rural South African district hospitals: an epidemiological modelling study, *Lancet,* 70: 1500 – 1507.

Batterman, S. (2017). Review and Extension of CO2-Based methods to determine ventilation rates with application to school classrooms, *International Journal of Environmental Research and Public Health*, 14 (2): 145.

Beggs, C. (2002). The use of engineering measures to control airborne pathogens in hospital buildings, [Online] Available at: (http://wwwefmleedsacuk/CIVE/MTB/CBB-Nov8pdf). Accessed: 12 March 2017.

Benger, J., Coates, D., Davies, S., Greenwood, R., Nolan, J., Rhys, M., et al. (2016). Randomised comparison of the effectiveness of the laryngeal mask airway supreme, i-gel and current practice in the initial airway management of out of hospital cardiac arrest: a feasibility study, *British Journal of Anaesthesiology*, 116: 262-268.

Bjarne, W., Olesen, A.S., Michal, K., Causone, F. and De Carli, M. (2016). Experimental Study of Air Distribution and Ventilation Effectiveness in a Room with a Combination of Different Mechanical Ventilation and Heating/Cooling Systems, *International Journal of Ventilation*, 9 (4): 371-383, (doi: 10.1080/14733315.2011.11683895).

Bock, N.N., Jensen, P.A., Miller, B. & Nardell, E. (2007). Tuberculosis infection control in resource-limited settings in the era of expanding HIV care and treatment, *Journal of Infectious Diseases*; 196 (suppl 1): S108–13.

Bolashikov, Z.D. and Melikov, A.K. (2009). Methods for air cleaning and protection of building occupants from airborne pathogens, *Building and Environment*, 44: 1378-1385, (doi: 10.1016/j.buildenv.2008.09.001).

Bolashikov, Z.D., Melikov, A.K. & Georgiev, E. (2011). Exposure to exhaled air from a sick occupant in a two-bed hospital room with mixing ventilation: Effect of distance from sick occupant and air change rate. Proceedings of the Indoor Air, Texas, USA, 2011, paper#877, [Online] Available at: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7169243/ Accessed at: 23 March 2019.

Bouhamra, W.S., Elkilani, A.S. and Abdul-Raheem, M.Y. (1998). Predicted and measured air exchange rates, *ASHRAE Journal,* August 1998: 42-45 [Online] Available at: http://www.aivc.org/sites/default/files/airbase_11620.pdf Accessed: 15 May 2018.

Bramley, T. and Oates, T. (2010). Rank ordering and paired comparisons – the way Cambridge Assessment is using them in operational and experimental work. [Online] Available at: http://www.cambridgeassessment.org.uk/Images/125350-summary-of-rank-ordering-and-paired-comparisons-research.pdf Accessed: 18 May 2018.

Breen, M. S., Breen, M., Williams, R. W., and Schultz, B. D. (2010). Predicting Residential Air Exchange Rates from Questionnaires and Meteorology: Model Evaluation in Central North

Carolina. *Environmental Science & Technology*, *44*(24), 9349–9356. (doi: http://doi.org/10.1021/es101800k).

Brouwer, M., Coelho, E., das Dores Mosse, C. & van Leth, F. (2015). Implementation of tuberculosis infection prevention and control in Mozambican health care facilities, *International Journal of Tuberculosis and Lung Disease*; 19: 44 – 49.

Brouwer, M., Katamba, A., Katabira, E. T., & van Leth, F. (2017). An easy tool to assess ventilation in health facilities as part of air-borne transmission prevention: a cross-sectional survey from Uganda, *BMC Infectious Diseases*, 17: 325. (doi: http://doi.org/10.1186/s12879-017-2425-6).

Buonanno, G., Stabile, L. Morawska, L. (2020). Estimation of airborne viral emission: Quanta emission rate of SARS-CoV-2 for infection risk assessment, *Environment International*, 141: 105794.

Buregyeya, E., Nuwaha, F., Verver, S., et al. (2013). Implementation of tuberculosis infection control in health facilities in Mukono and Wakiso districts, Uganda, *BMC Infect Dis*, 13: 360.

Cain ,K.P., Nelson, L.J. & Cegielski, J.P. (2010). Global policies and practices for managing persons exposed to multidrug-resistant tuberculosis. *International Journal of Tuberculosis and Lung Dis*ease, 14 (3): 269–74.

Centers for Disease Control and Prevention. (1994). Guidelines for preventing the transmission of Mycobacterium tuberculosis in health-care facilities, *MMWR Recomm Rep*, 43 (RR-13): 1–132.

Centres for Disease Control and Prevention. (2006). Emergence of Mycobacterium tuberculosis with extensive resistance to second-line drugs – world-wide, 2000-2004, *MMWR Morb Mortal Wkly Rep*, 55: 301-305.

Chamie, G., Wandera, B., Luetkemeyer, A., Bogere, J., Mugerwa, R.D., Havlir, D.V. and Charlebois, E.D. (2013). Household ventilation and transmission in Kampala, Uganda, *Int J Tuberc Lung Dis*, 17(6):764-70, (doi: 10.5588/ijtld.12.0681).

Chao, C.Y., Wan, M.P. & Law, A.K. (2004). Ventilation performance measurement using constant concentration dosing strategy, *Building and Environment,* 39: 1277–1288, [Online] Available at: https://doi.org/10.1016/j.buildenv.2004.03.012 Accessed: 14 September 2020.

Chao, C.Y.H. & Tung, T.C. (2001). An empirical model for outdoor contaminant transmission into residential buildings and experimental verification, *Atmos. Environ*., 35: 1585– 1596.

Chao, J., Mu, X., Xue, Y., Li, F., Li, W., Lin, C. –H., Pei, J. & Chen, Q. (2014). A modified tracer-gas-concentration decay method for ventilation rate measurements in large, long and narrow spaces, *Indoor and Built Environment*, 23: 1012 – 1020.

Charlsworth, P.S. (1988). Air exchange rate and airtightness measurement techniques- An applications guide, [Online] Available at: https://www.aivc.org/sites/default/files/members_area/medias/pdf/Guides/GUAG%20MEASUREMENT%20TECHNIQUES.pdf Accessed: 27 March 2019.

Coker, I., Nardell, E.A., Fourie, B., Brickner, P.W., Parsons, S., Bhagwandin, N. and Onyebujoh, P. (2001). Guidelines for the utilisation of ultraviolet germicidal irradiation (UVGI) technology in controlling the transmission of tuberculosis in health care facilities in South Africa. Pretoria (South Africa): South African Centre for Essential Community Services and National Tuberculosis Research Programme, Medical Research Council; 2001. pp. 1– 40.

Cox HS, McDermid C, Azevedo V, Muller O, Coetzee D, Simpson J, et al. (2010) Epidemic Levels of Drug Resistant Tuberculosis (MDR and XDR-TB) in a High HIV Prevalence Setting in Khayelitsha, South Africa, *PLoS ONE*, 5(11): e13901, (doi:10.1371/journal.pone.0013901).

Cox, H., Escombe, R., McDermid, C., Mtshemla, Y., Spelman, T., Azevedo, V., Barnard, M., Coetzee, G., van Custem, G., Goemaere, E. and London, L. (2012) Wind-Driven Roof Turbines: A Novel Way to Improve Ventilation for TB Infection Control in Health Facilities, *PLoS ONE*, 7(1): e29589, (doi:10.1371/journal.pone.0029589).

Cox, H., Ramma, L., Wilkinson, L., Azevedo, V. and Sinanovic, E. (2015), Cost per patient of treatment for rifampicin-resistant tuberculosis in a community-based programme in Khayelitsha, South Africa, *Trop Med Int Health*, 20: 1337–1345, (doi:10.1111/tmi.12544).

Cox, H., Hughes, J., Daniels, J., Azevedo, V., McDermid, C., Poolman, M., Boulle, A. Goemarer, G. and van Custem, G. (2014). Community-based treatment of drug-resistant tuberculosis in Khayelitsha, South Africa, *Int J Tuberc Lung Dis*, 18: 441–448.

Cox, H.S., McDermid, C., Azevedo, V., Muller, O., Coetzee, D., Simpson, J., Barnard, M., Coetzee, G., van Cutsem, G. & Goemaere, E. (2010). Epidemic levels of drug resistant tuberculosis (MDR and XDR-TB) in a high HIV prevalence setting in Khayelitsha, South Africa, *PLoS One*, (11): e13901.

Cui, S., Cohen, M., Stabat, P. and Marchio, D. (2015). CO_2 tracer gas concentration decay method for measuring air change rate, *Building and Environment,* 84: 162 – 169.

Cui, X., Mohan, B., Islam, M.R., Chou, S.K. and Chua, K.J. (2017). Energy saving potential of an air treatment system for improved building indoor air quality in Singapore, *Energy Procedia*, 143: 283 – 288, (doi: https://doi/10.1016/j.egypro.2017.12.685).

Dale, J.D. & Ackerman, M.Y. (1999). Evaluation of the performance of attic turbine ventilators, *ASHRAE Transactions,* 99 (1): 14–22.

Department of Health. (2013). Policy guidelines: Management of drug-resistant TB. Updated-January 2013. Department of Health: South Africa.

Deutsche Welle, (2018). A glimpse inside Johannesburg's Diepsloot slum, [Online] Available from: http://www.dw.com/en/a-glimpse-inside-johannesburgs-diepsloot-slum/a-17720678 Accessed: 20 May 2018.

Dharmadhikari, A., Mphahlele, M., Venter, K., et al. (2010). Upper room ultraviolet germicidal irradiation (UVGI) air disinfection on an MDR-TB ward in sub-Saharan Africa—effects of humidity. *Am J Respir Crit Care Med*; 181 (meeting abstracts): A5383. [Online] Available at: http://www.atsjournals.org/doi/abs/10.1164/ajrccm-conference.2010.181.1_MeetingAbstracts.A5383. Accessed 29 October 2015.

Dheda, K., Limberis, J.D., Pietersen, E., Phelan, J., Esmail, A., Lesosky, M., Fennelly, K.P., Te Riele, J., Mastrapa, B., Streicher, E.M., Dolby, T., Abdallah, A.M., Ben-Rached, F., Simpson, J., Smith, L., Gumbo, T., van Helden, P., Sirgel, F.A., McNerney, R., Theron, G., Pain, A., Clark, T.G., Warren, R.M. (2017). Outcomes, infectiousness and transmission dynamics of patients with extensively drug-resistant tuberculosis and home discharged patients with programmatically incurable tuberculosis: a prospective cohort study, *Lancet Resp Med*, 269 – 281, [Online], Available at: http://dx.doi.org/10.1016/s2213-2600(16)30433-7 Accessed: 9 March 2017).

Diepsloot.com. (2017). Diepsloot. [Online] Available from: http://www.diepsloot.com/ Accessed: 18 May 2018.

Dols, W. S. & Persily, A. K. (1992). A Study of Ventilation Measurement in an Office Building, NISTIR 92-4905, USA: National Institute of Standards and Technology.

Doocy, S.C., Todd, C.S., Llainez, Y.B., Ahmadzai, A. & Burnham, G.M. (2008). Population-based tuberculin skin testing and prevalence of tuberculosis infection in Afghanistan, *World Health Popul,* 10: 44–53.

Engineering Toolbox. (2019). Air changes rates in typical rooms and buildings, [Online] Available at: https://www.engineeringtoolbox.com/air-change-rate-room-d_867.html, Accessed: 25 April 2020.

Ershova, J.V., Podewils, L.J., Bronner, L.E., Stockwell, H.G., Dlamini, S.S. and Mametja, L.D. (2014). Evaluation of adherence to national treatment guidelines among tuberculosis patients in three provinces of South Africa, *S Afr Med J*, 104 (5): 362-368, (doi:10.7196/SAMJ.7655).

Escombe, A.R., Moore, D.A.J., Gilman R.H., et al. (2009) Upper-room ultraviolet light and negative air ionization to prevent tuberculosis transmission, *PLoS Med*, 6: e1000043.

Escombe, A.R., Oeser, C., Gilman, R., Navincopa, M., Ticona, E., Pan, W., Martnez, C., Chacaltana, J., Rodriguez, R., Moore, D.A.J., et al. (2007). Natural ventilation for the prevention of airborne contagion, *PLoS Med*, 4 (2): e68-e68. (doi: 10.1371/journal.pmed.0040068).

Eskola, L., Kurnitski, J.,Jokisalo, J., Jokiranta, J., Palonen, J. & Vinha, J. (2007). Room Airflow Rates in Finnish Houses, Proceedings of Clima 2007 WellBeing Indoors, [Online] Available at: http://www.inive.org/members_area/medias/pdf/Inive%5Cclima2007%5CA06%5CA06B1511.pdf, Accessed: 20 April 2020.

Etheridge, D. (2012). Natural Ventilation of Buildings Theory Measurement and Design, *International Journal of Ventilation*, 10:4, 405 – 406, (doi: 10.1080/14733315.2012.11683965).

Falzon, D., Gandhi, N., Migliori, G.B. et al. (2013). Resistance to flouroquinolones and second line injectable drugs: Impact on multi-drug resistant TB outcomes, *Eur Resp J*, 42: 156-168.

Falzon, D., Mirzayev, F., Wares, F., Baena, I.G., Zignol, M., Linh, N., Weyer, K., Jaramillo, E., Floyd, K. & Raviglione, M. (2015). Multidrug-resistant tuberculosis around the world: what progress has been made? *Eur Respir J*., 45 (1): 150–160.

Farley, J.E., Ram, M., Pan, W., Waldman, S., Cassell, G.H., Chaisson, R.E., Weyer, K., Lancaster, J. & Van der Walt, M. (2011). Outcomes of multi-drug resistant tuberculosis (MDR-TB) among a cohort of South African patients with high HIV prevalence, *PLoS One*, 6(7): e20436.

Farley, J.E., Tudor, C., Mphahlele, M., Franz, K., Perrin, N.A., Dorman, S. & Van der Walt, M. (2012). A national infection control evaluation of drug-resistant tuberculosis hospitals in South Africa, *Int J Tuberc Lung Dis*., 16(1): 82–89.

Fennelly, K.P. & Jones-López, E.C. (2015). Quantity and quality of inhaled dose predicts immunopathology in tuberculosis. *Front Immunology*, 6:1–13.

Fennelly, K.P. & Nardell, E.A. 2015. The Relative Efficacy of Respirators and Room Ventilation in Preventing Occupational Tuberculosis. *Infect Control and Hospital Epidemiol*, 19(10): 754-759, (doi: https://doi.org/10.2307/30141420).

Fisk, W. (2013). Health benefits of particle filtration, *Indoor Air,* 23(2): 357 – 368.

Fisk, W.J. (2000). Review of health and productivity gains from better IEQ. In: Proceedings of Healthy Buildings (vol. 4, pp. 23 –34), Espoo, Finland.

Fokazi, S. (2014). Infectious XDR-TB patients being sent home. IOL News, Western Cape; 7 April 2014. [Online] Available at: http://www.iol.co.za/news/south-africa/western-cape/infectious-xdr-tb-patients-being-sent-home-1672257 Accessed: 7 March 2017.

Friedland, G., Moll, A., Shenoi. S.V., et al. (2012). Extensively and multidrug resistant tuberculosis (XDR/MDR TB) in Tugela Ferry, South Africa: five years later; 43rd Union World Conference on Lung Health: 2012; Kuala Lumpur, Malaysia.

Furuya H, Nagamine M, Watanabe T (2009) Use of a mathematical model to estimate tuberculosis transmission risk in an Internet café, *Environ Health Prev Med,* 14: 96–102.

Geshwiler, M., Howard, E. and Helms, C. (Eds). (2003). HVAC design manual for hospitals and clinics. Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Gandhi, N.R., Moll, A., Sturm, A.W., et al. (2006). Extensively drug-resistant tuberculosis as a cause of death in patients co-infected with tuberculosis and HIV in a rural area of South Africa, *Lancet*; 368: 1575-1580.

Goemaere, E., Ford, N., Berman, D., McDermid, C. & Cohen, R. (2007). XDR-TB in South Africa: Detention is not the priority. *PLoS Med*, 4(4): e162. (doi:10.1371/ journal.pmed.0040162).

Gopi, P.G., Subramani, R., Nataraj, T. & Narayanan, P.R. (2006). Impact of BCG vaccination on tuberculin surveys to estimate the annual risk of tuberculosis infection in south India, *Indian J Med Res*, 124: 71–76.

Gough, H. (2017). Effects of Meteorological Conditions on Building Natural Ventilation in Idealised Urban Settings, PhD thesis, University of Reading, Department of Meteorology.

Gupta, J.K., Lin, C.H. and Chen, Q.Y. (2010. Characterising exhaled airflow from breathing and talking. *Indoor Air*, 20: 31-39.

Halios, C.H., Helmis, C.G., Deligianni, K., Vratolis, S. & Eleftheriadis, K. (2014). Determining the ventilation and aerosol deposition rates from routine indoor-air measurements, *Environ. Monit. Assess.,* 186: 151–163 [Online] Available at: https://doi.org/10.1007/s10661-013- Accessed: 11 April 2020.

Hang, J., Li, Y., Ching, W.H., Wei, J., Jin, R., Liu, L. & Xie, X. (2015). Potential airborne transmission between two isolation cubicles through a shared anteroom, *Building and Environment*, 89: 264-278, (doi: 10.1016/j.buildenv.2015.03.004).

Hardy, M. (2015). Consideration of Displacement Ventilation vs Mixed Flow Ventilation for Building Owners and Designers, Ambthair Services Ltd, [Online] Availabe from: http://www.ambthair.com/displacement_vs_mixed_flow_ventilation.html Accessed: 28 March 2017.

Hargreaves, J.R., Boccia, D., Evans, C.A., Adato, M., Petticrew, M. and Porter, J.D.H. (2011). The Social Determinants of Tuberculosis: From Evidence to Action, *Am J Public Health*, 101 (4): 654–662, (doi: 10.2105/AJPH.2010.199505).

Harris, A.D., McGregor, J.C. & Finkelstein, J. (2006). The use and interpretation of Quasi-Experimental studies in medical Informatics, *Journal of the American Medical Informatics Association,* 13 (1): 16 – 23.

Hayati, A. (2017). Natural Ventilation and Air Infiltration in Large Single Zone Buildings. Measurements and Modelling with reference to Historical Churches, PhD Dissertation, Faculty of Engineering and Sustainable Development, University of Galve, [Online] Available at: http://hig.diva-portal.org/smash/get/diva2:1117979/FULLTEXT01.pdf Accessed: 28 March 2020.

Heale, R. & Twycross, A. (2015). Validity and reliability in quantitative research, *Evidence-Based Nursing,* 18: 66-67.

Health Systems Trust. (2017). Tuberculosis, [Online] Available at: https://www.hst.org.za/publications/District%20Health%20Barometers/9%20(Section%20A)%20Tuberculosis.pdf Accessed: 29 June 2019.

Himlich, R., Engel, H. and Mathoho, M. (2014). Case Study: Kliptown and Diepsloot. PLANACT, [Online] Available at: http://www.planact.org.za/wp-content/uploads/2014/08/6.-Case-Study-Kliptown-and-Diepsloot.pdf Accessed: 18 May 2018.

Hoa, N.B., Cobelens, F.G., Sy, D.N., Nhung, N.V., Borgdorff, M.W. & Tiemersma, E.W. (2013). First national tuberculin survey in Viet Nam: characteristics and association with tuberculosis prevalence, *Int J Tuberc Lung Dis*, 17: 738–744.

Houben, R.M.G.J., Dowdy, D.W., Vassal, A., Cohen, T., Nicol, M.P., Granich, R.M., Shea, J.E., Eckhoff, P., Dye, C., Kimerling, M.E. and White, R.G. (2014). How can mathematical models advance tuberculosis control in high HIV prevalence settings? *Int J Tuberc Lung Dis*, 18(5):509–514, (doi: http://dx.doi.org/10.5588/ijtld.13.0773).

Hughes, J. & Osman, M. (2014). Diagnosis and management of drug-resistant tuberculosis in South African adults, *S Afr Med J.*, 104 (12): 894.

Hori, M., Soma, M. & Mizoguchi, T. (2005). Measurement of ventilation rate by concentration decay method with law-environmental-loading tracer gas, Proceedings of the 10th International Conference on Indoor Air Quality and Climate - 4-9 September 2005, Beijing, China.

Iizuka, A., Okuizumi, Y. & Yanagisawa, Y. (2010). Estimation of uncertainty in tracer gas measurements of air exchange rates*, International Journal of Environmental Research and Public Health,* 7 (12): 4238 – 4249.

In, J. (2017). Introduction of a pilot study, *Korean Journal of Anesthesiology*, 70 (6): 601- 605.

Ismail, M. and Rahman, A.M.A. (2012). Rooftop Turbine Ventilator: A review and Update, *Journal of Sustainable Development,* 5(5): 121-131.

ISO. (2004). ISO-16000-1: 2004 Part 1: General Aspects of Sampling Strategy, *Indoor Air,* 16000: 1.

ISO. (2007). ISO-16000-8, Part 8: Determination of Local Mean Ages of Air in Buildings for Characterizing Ventilation Conditions ISO 16000-8:2007, *Indoor Air,* 16000: 1.

ISO. (2012). ISO 12569:2012: Thermal Performance of Buildings and Materials—Determination of Specific Airflow Rate in Buildings—Tracer Gas Dilution Method. Geneva, Switzerland: International Organization for Standardization.

Issarow, C.M., Mulder, N. and Wood R. (2014). Modelling the risk of airborne infectious disease using exhaled air, *Journal of Theoretical Biology*, 372: 100 -106.

IUSSNS Task team. (2014). IUSS HEALTH FACILITY GUIDES: Primary Healthcare Facilities [Online] Available at: https://www.iussonline.co.za/docman/document/clinical-services/76-phc-gazetted/file Accessed: 17 September 2020.

Ivanov, M. & Markov, D. (2014). Analyses for CO2 time variation records in naturally ventilated occupied spaces, *Mathematical Modelling in Civil Engineering*, 10 (2) (doi:10.2478/mmce-2014-0008).

Jafari, M.J., Hajgholami, M.R., Salehpour, S., Amiri, Z. and Tabarsi, P. (2014). The influences of ventilation on biological concentration of air in a tuberculosis patient room, *Occupational Medicine*, 6 (2): 1– 12.

Jaksuwan, R., Patumanond, J., Tharavichikul, P., Chuchottaworn, C., Pokeaw, P. & Settakorn, J. (2018). The prediction factors of pre-XDR and XDR-TH among MDR-TB patients in Northern Thailand, *Journal of Tuberculosis Research*, 6: 36 – 48.

Jensen, P.A., Lambert, L.A., Iademarco, M.F. and Ridzon, R. (2005). CDC Guidelines for preventing the transmission of Mycobacterium tuberculosis in health-care settings, *MMWR Recomm Rep,* 54 (RR-17): 1–141.

Jiamjarasrangsi, W., Bualert, S., Chongthaleong, A., Chaindamporn, A., Udomsantisuk, N. & Euasamarnjit, W. (2009). Inadequate ventilation for nosocomial tuberculosis prevention in public hospitals in Central Thailand, *International Journal of Tuberculosis and Lung Disease*, 13 (4): 454 – 459.

Ji Yeon Lee, M.D. (2016). Tuberculosis Infection Control in Health-Care Facilities: Environmental Control and Personal Protection, *Tuberc Respir Dis,* 79(4): 234–240.
(doi: 10.4046/trd.2016.79.4.234).

Johannesburg Development Agency. (2013). Diepsloot Ready for Development. Johannesburg: JDA, 2013:1-8.

Joshi, R., Reingold, A.L., Menzies, D. & Pai, M. (2006). Tuberculosis among health-care workers in low- and middle-income countries: a systematic review, *PLOS Medicine*, 3(12): e494.

Kato-Maeda, M., Choi, J.C., Jarlsberg, L.G., Grinsdale, J.A., Higashi, J., Kawamura, M., Osmond, D.H. & Hopewell, P.C. (2019). Magnitude of *Mycobacterium tuberculosis* transmission among household and non-household contacts of TB patients, *Int J Tuberc Lung Dis*, 23 (4): 433 -440.

Kalliomaki, P., Saarinen, P., Tang, J.W. and Koskela, H. (2016). Airflow patterns through single hinged and sliding doors in hospital isolation rooms – Effect of ventilation, flow differential and passage, *Building and Environment*, 107: 154-168.

Keshavjee, S., Gelmanova, I.Y., Farmer, P.E., et al. (2008). Treatment of extensively drug-resistant tuberculosis in Tomsk, Russia: a retrospective cohort study, *Lancet*, 372: 1403–09.

Khan, N., Su, Y. & Riffat, S.B. (2008). A review on wind-driven ventilation techniques, *Energy and Buildings*; 40: 1586 – 1604.

Knibbs, L.D., Morawska, L., Bell, S.C. and Grzybowski, P. (2011). Room ventilation and the risk of airborne infection transmission in three health care settings within a large teaching hospital, *American Journal of Infection Control*, 39 (10): 866-872.

Kompala, T., Shenoi, S.V. & Friedland, G. (2013). Transmission of tuberculosis in resource-limited settings, *Curr HIV/AIDS Rep*., 10: 264–272. (doi: 10.1007/s11904-013-0164-x).

Kritzinger, F.E., den Boon, S., Verver, S., et al. (2009). No decrease in annual risk of tuberculosis infection in endemic area in Cape Town, South Africa, *Trop Med Int Health*, 14: 136–142.

Kułakowski, K. & Talaga, D. (2019). Inconsistency indices for incomplete pairwise comparisons matrices, [Online] Available at: https://arxiv.org/pdf/1903.11873v3.pdf Accessed: 22 September 2020.

Kułakowski, K., Szybowskib, J. and Tadeusiewiczc, R. (2014). Tender with success - the pairwise comparisons approach, *Procedia Computer Science*, 35: 1122 – 1131.

Kuyinu, Y.A., Mohammed, A.S. & Adeyeye, O.O. (2016). Tuberculosis infection control measures in health care facilities offering TB services in Ikeja local government area, Lagos, South West, Nigeria, *BMC Infect Dis*, 16: 126, [Online] Available at: https://doi.org/10.1186/s12879-016-1453-y, Accessed: 20 April 2020.

Laussmann, D. and Helm, D. In Mazzeo, N. (eds). (2011). Air change measurements using tracer gases, **Chemistry, Emission control, Radioactive pollution and Indoor air quality**, [Online] Available from: http://www.intechopen.com/books/chemistry-emission-control-radioactive-pollution-and-indoor-air-quality, Accessed: 20 May 2018.

Lazovic, I., Stevanovic, Z., Jovašević-Stojanović, M., Zivkovic, M. & Banjac, M. (2015). Impact of CO_2 concentration on indoor air quality and correlation with relative humidity and indoor air temperature in school buildings, Serbia. *Thermal Science*, 20: 173-173.

Levermore, G.J., Robertson, A.P., Rideout, N.M. & Shea, A.D. (2010). Measurements of the performance of a wind-driven ventilation terminal, *Struct. Build*., 163: 129–136 [Online] Available at: https://doi.org/10.1680/stbu.2010.163.2.129 Accessed: 20 April 2019.

Li, H. & Li, X. & Qi, M. (2014). Field testing of natural ventilation in college student dormitories (Beijing, China), *Build. Environ.,* 78: 36–43 [Online] Available at: https://doi.org/10.1016/j. buildenv.2014.04.009 Accessed: 20 April 2019.

Li, Y., Leung, G.M., Tang, J.W., Yang, X., Chao, C.Y.H., Lin, J.Z., Lu, J.W., et al. (2007). Role of ventilation in airborne transmission of infectious agents in the built environment – a multidisciplinary systemic review, *Indoor Air*, 17: 2-18, (doi: 10.1111/j.1600-0668.2006.00445.x).

Liao, C. M., Chen, S. C. and Chang, C. F. (2008). Modelling respiratory infection control measure effects. *Epidemiology and Infection*, 136: 299–308. [Online] Available at: http://doi.org/doi:10.1017/S0950268807008631 Accessed: 13 March 2017.

Liao, C.-M., Lin, Y.-J. and Cheng, Y.-H. (2013). Modelling the impact of control measures on tuberculosis infection in senior care facilities. *Building and Environment*, 59: 66–75. [Online] Available at: http://doi.org/10.1016/j.buildenv.2012.08.008 Accessed: 20 February 2018.

Lin, H.H., Ezzati, M. & Murray, M. (2007). Tobacco smoke, indoor air pollution and tuberculosis: a systematic review and meta-analysis. *PLoS Med*; 4 (1):e20. doi: 10.1371/journal.pmed.0040020.

Liuliu, D., Batterman, S. Godwin, C., Chin, J-Y., Parker, E., Breen, M., Brakefield, W., Robins, T. & Lewis, T. (2012). Air change rates and intrzonal flows in residences and the need for multi-zone models for exposure and health analyses, *International Journal of Environmental Research and Public Health,* 9: 4639- 4661.

London, L. (2008). Confinement in the management of drug-resistant TB: the unsavoury prospect of balancing individual human rights and the public good. *South African Journal of Bioethics and Law*, *1*(1), 11+. [Online] Available at: https://go.gale.com/ps/anonymous?id=GALE%7CA256932573&sid=googleScholar&v=2.1&it=r&linkaccess=abs&issn=19997639&p=HRCA&sw=w Accessed: 13 March 2019.

Loveday, M., Wallengren, K., Brust, J., et al. (2015). Community-based care vs. centralised hospitalisation for MDR-TB patients, KwaZulu-Natal, South Africa, *Int J Tuberc Lung Dis*, 19 (2): 163–171.

Lucas-Alfieri, D. (2015). Marketing the 21st century library: the time is now. Waltham, MA: Chandos.

Luksamijarulkul, P., Supapvanit, C., Loosereewanich, P. and Aiumlaor, P. (2004). Risk assessment towards tuberculosis among hospital personnel: administrative control, risk exposure, use of protective barriers and microbial air quality, *Southeast Asian J Trop Med Public Health*, 35 (4): 1005– 1011.

Lygizos, M., Shenoi, S.V., Brooks, R.P., Bhushan, A., Brust, J.C.M., Zelterman, D., Deng, Y., Northrup, V., Moll,.A.P. & Friedland, G.H. (2013). Natural ventilation reduces high TB transmission risk in traditional homes in rural KwaZulu-Natal, South Africa, *BMC Infect Dis,* 13: 300 [Online] Available at: https://doi.org/10.1186/1471-2334-13-300 Accessed: 28 May 2018.

Maharajan, S. (eds). (2014). Economics of South African Townships. Special focus on Diepsloot. World Bank Study, Wahsington, DC: World Bank Group.

Mahyuddin, N. & Awbi, H. (2012). A review of CO2 measurement procedures in ventilation research, *Int. J. Vent*., 10: 353–370 [Online] Available at: https://doi.org/10.1080/14733315. 2012.11683961 Accessed: 21 September 2019.

Makaka, G., Xuza, V., Meyer, E. & Mukumba, P. (2018). On Impact of the Ventilation Components on the Ventilation Rate in a Passive Solar Energy Efficient House, *Biomedical Journal of Scientific and Technical Research*, 8 (2): 6337 – 6343.

Malangu, N. and Mngomezulu, M. (2015). Evaluation of TB infection control measures implemented at primary health care clinics in KwaZulu-Natal province of South Africa, *BMC Infect Dis*, 15: 117, (doi: 10.1186/s12879-015-0773-7).

Medecins Sans Frontieres (2011) Khayelitsha 2001–2011, Activity report: 10 years of HIV/TB care at primary health care level. [Online] Available at: http://www.msf.org/sites/msf.org/files/khayelitsha_2001-2011.pdf Accessed 11 March 2017.

Medecins Sans Frontieres. (2018). Five deadly barriers to effective TB care [Online] Available at: https://reliefweb.int/report/south-africa/five-deadly-barriers-effective-tb-care Accessed: 20 April 2020.

Menzies, D., Fanning, A., Yuan, L. and Fitzgerald, M. (2000). Hospital ventilation and risk for tuberculosis in Canadian health care workers, *Ann Intern Med*, 133: 779-789.

Menzies, D., Joshi, R. & Pai, M. (2007). Risk of tuberculosis infection and disease associated with work in healthcare settings, *Int J Tuberc Lung Dis*., 11 (6): 593-605.

Memarzadeh, F. (2013). Literature Review: Room Ventilation and Airborne Disease Transmission [Online] Available at: https://www.semanticscholar.org/paper/Literature-Review-%3A-Room-Ventilation-and-Airborne-Memarzadeh/7055a3d47891dc943990a0bc9e6cae3184055aea Accessed: 18 August 2020.

Meteoblue. (2019). Weather – Diepsloot, Gauteng, South Africa, 25.93°S 28.01°E, 1410m asl, [Online] Available at: https://www.meteoblue.com/en/weather/week/diepsloot_south-africa_8764562, Accessed: 13 July 2019.

Moll, T. (2007). TB on the back burner, losing curable status. *Int J Tuberc Lung Dis*, 11: 355.

Mudarri, D.H. (2010). Building codes and Indoor air quality, Arlington: US Environmental Protection Agency, [Online] Available from: https://www.epa.gov/sites/production/files/2014-08/documents/building_codes_and_iaq.pdf Accessed: 20 May 2018.

Munim, A., Rajab, Y., Barker, A., Daniel, M. & Williams, B. (2008). Risk of *Mycobacterium tuberculosis i*nfection in Somalia: national tuberculin survey 2006, *East Mediterr Health J*, 14: 518–530.

Mushayabasa, S. (2013). Application of Wells-Riley equations on a Mathematical Model for Assessing the Transmission of tuberculosis in Prison Settings. *Int. J. Model. Simul. Sci. Comput., 4*, 1350010, [Online] Available at: https://www.semanticscholar.org/paper/Application-of-wells-Riley-equations-on-a-Model-for-Mushayabasa/07260a1d9ce9f20af68d9833a3f5e3072ed17497 Accessed: 18 April 2020.

Myatt, T.A., Johnston, S.L., Zuo, Z., Wand, M., Kebadze, T., Rudnick, S. and Milton, D.K. (2004). Detection of airborne rhinovirus and its relation to outdoor air supply in office environments, *Am J Respir Crit Care Med,* 169: 1187-1190.

Nabinger, S.J., Persily, A.K. & Dols, W.S. (1994). Study of Ventilation and Carbon Dioxide in an Office Building. *ASHRAE Transactions*, 100 (2): 1264-1274.

Naidoo, S., Seevnarain, K. & Nordstrom, D.L. (2012). Tuberculosis infection control in primary health clinics in eThekwini, KwaZulu-Natal, South Africa, *Int J Tuberc Lung Dis*, 16: 1600 – 1604.

Nardell, E. & Dharmadhikari, A. (2010). Turning off the spigot: reducing drug-resistant tuberculosis transmission in resource-limited settings, *Int J Tuberc Lung Dis*., 14: 1233–43.

Nardell, E., Vincent, R. & Sliney, D.H. (2013). Upper-room ultraviolet germicidal irradiation (UVGI) for air disinfection: a symposium in print, *Photochem Photobiol*, 89:764 – 769.

Nardell, E.A. (2016). Indoor environmental control of tuberculosis and other airborne infections. *Indoor Air*, 26: 79-87.

Nardell, E.A., Keegan, J., Cheney, S.A. and Etkind, S.C. (1991). Airborne infection: theoretical limits of protection achievable by building ventilation. *Am Rev Respir Dis*, 144: 302-306.

Nathanson, E., Nunn, P., Uplekar, M., Floyd, K., Jaramillo, E., Lönnroth, K., Weil, D. & Raviglione, M. (2010). MDR tuberculosis—critical steps for prevention and control, *N Engl J Med*., 363 (11): 1050–1058.

National Department of Health, South Africa. (2009). National Tuberculosis Management Guidelines 2009. Pretoria: NDoH, 2009. [Online] Available at: http://familymedicine.ukzn.ac.za/Libraries/Guidelines_Protocols/TB_Guidelines_2009.sflb.ashx Accessed: 20 March 2018.

National Department of Health, South Africa. (2014). National Tuberculosis Management Guidelines 2014. Pretoria: NDoH, [Online] Available at:

www.doh.gov.za/docs/hivAids/NationalTBManagementGuidelines.pdf Accessed: 20 March 2018).

National Department of Health, South Africa. (1999). The Management of Multidrug Resistant Tuberculosis. Pretoria: South African National Department of Health.

National Department of Health, South Africa. (2013). Management of drug-resistant tuberculosis: Policy Guidelines. Pretoria: South African National Department of Health.

National Department of Health, South Africa. (2016). South Africa and South African National AIDS Council - South African HIV and TB Investment Case – Summary Report Phase 1 [Online] Available at:http://sanac.org.za/wp-content/uploads/2016/03/1603-Summary-Report-LowRes-18-Mar.pdf Accessed: 2 May 2020.

National Department of Health, South Africa. (2019). MDR - a policy framework on decentralised and de-institutionalised management for South Africa. Pretoria: South African National Department of Health.

National Institute for Communicable Diseases, South Africa. (2016). South African Tuberculosis Drug Resistance Survey 2012–14, South Africa: National Health Laboratory Service.

Nazaroff, W.W. (2016). Indoor bioaerosol dynamics, *Indoor Air*, 26: 61-78.

Ncayiyana, J.R. (2015). Latent tuberculosis infection prevalence, spatial clustering and risk factors in a South African urban informal settlement, PhD dissertation, unpublished, University of North Carolina.

Ndjeka N. (2013). Drug-resistant tuberculosis in South Africa. Pretoria: South African National Department of Health.

Noakes, C.J. and Sleigh, P.A. (2008) Applying the Wells-Riley equation to the risk of airborne infection in hospital environments: The importance of stochastic and proximity effects. In: Indoor Air 2008 : The 11th International Conference on Indoor Air Quality and Cl. Indoor Air 2008, 17-22nd August 2008, Copenhagen, Denmark. , Copenhagen.

O'Donnell, M.R., Daftary, A., Wolf, A., Aldous, C., Horsburgh. C.R. & Padayatchi, N. (2014). Prospective Study of Antiretroviral and Antimycobacterial Medication Adherence in Patients with Extensively Drug Resistant Tuberculosis (XDR-TB) and HIV/AIDS, JAIDS, (In Press).

O'Donnell, M.R., Padayatchi, N., Master, I., Osburn, G., Horsburgh, C.R. (2009). Improved early results for patients with extensively drug-resistant tuberculosis and HIV in South Africa, *Int J Tuberc Lung Dis*, 13: 855–61.

Ogbonnaya, L.U., Chukwu, J.N., Uwakwe, K.A., et al. (2011). The status of tuberculosis infection control measures in health care facilities rendering joint TB/HIV services in "German Leprosy and Tuberculosis Relief Association" supported states in Nigeria, *Niger J Clin Pract*, 14: 270 – 275.

Oropeza – Pereza, I. (2019). Fundamentals of Natural Ventilation Design within Dwellings [Online] Available at: DOI: http://dx.doi.org/10.5772/intechopen.85141 Accessed: 22 March 2020.

Padayatchi, N. & Friedland, G. (2008). Decentralised management of drug-resistant tuberculosis (MDR- and XDR-TB) in South Africa: an alternative model of care, *Int J Tuberc Lung Dis*., 12 (8): 978–980.

Padayatchi, N., Naressa Naidu, N. & Loveday, M. (2014). Drug Resistant Tuberculosis Control in South Africa – Scientific Advances and Health System Strengthening are Complementary, *Expert Opin Pharmacother,* 15(15): 2113–2116. (doi:10.1517/14656566.2014.953053).

Pandian, M.D., Ott, W.R. & Behar, J.V. (1993). Residential air exchange rates for use in indoor air exposure modeling studies, *J. Expo. Anal. Environ. Epidemiol*., 3, 407– 416.

Persily, A.K. (1997). Evaluating building IAQ and ventilation with indoor Carbon Dioxide. *ASHRAE Transactions,* 103 (2): 193-204.

Persily, A. & Levin, H. (2011). Ventilation measurements in IAQ studies: problems and opportunities, Proceedings of Indoor Air 2011, 12th International Conference on
Indoor Air Quality and Climate, 2011.

Persily, A.K. and Emmerich, S.J. (2009). Effects of air infiltration and ventilation. [Online] Available at: https://ws680.nist.gov/publication/get_pdf.cfm?pub_id=861039 Accessed: 18 May 2018.

Perumal, R. and Desai, H. (2014). The role of process analysis and expert consultation in implementing an electronic medical record solution for multidrug-resistant tuberculosis, SA *Journal of Information Management*, 16(1): a617,
(doi: https://doi.org/10.4102/sajim.v16i1.617).

Pietersen, E., Ignatius, E., Streicher, E.M., Mastrapa, B. et al. (2014). Long-term outcomes of patients with extensively drug-resistant tuberculosis in South Africa: a cohort study, *Lancet*, 383 (9924): 1230 – 1239. (doi: http://dx.doi.org/10.1016/S0140-6736(13)62675-6).

Pinna, G.D., Maestri, R., La Rovere, M.T., Gobbi, E., Fanfulla, F. (2006). Effect of paced breathing on ventilatory and cardiovascular variability parameters during short-term investigations of autonomic function, *Am J Physiol Heart Circ Physiol*, 290 (1): 424-433.

Pooran A, Pieterson E, Davids M, Theron G, Dheda K. What is the cost of diagnosis and management of drug resistant tuberculosis in South Africa? *PloS One*, 8(1): e54587.

Porfirio, R. (2004). The uses of rotary turbine ventilator for controlling the air temperature and ventilation in greenhouse. [Online] Available at: http://www.teses.usp.br/teses/ Accessed: 18 April 2020.

Reichman, R., Shirazia, E., Colliverb, D.G. and Pennell, K.G. (2017). US Residential Building Air Exchange Rates: New Perspectives to Improve Decision Making at Vapor Intrusion Sites, *Environ Sci Process Impacts,* 19(2): 87–100, (doi:10.1039/c6em00504g).

Remion, G., Moujalled, B. & Mankibi, M. (2018). Review of tracer gas-based methods for the characterization of natural ventilation performance: comparative analysis of their accuracy, [Online] Available at: https://www.sciencedirect.com/science/article/pii/S0360132319303907 Accessed: 20 March 2020.

Richardson, E.T., Morrow, C.D., Kalil, D.B., Bekker, L-G. & Wood, R. (2014). Shared Air: A Renewed Focus on Ventilation for the Prevention of Tuberculosis Transmission, *PLoS ONE*, 9(5): e96334. [Online] Available at: https://doi.org/10.1371/journal.pone.0096334 Accessed: 20 March 2020.

Riley, E.C., Murphy G. and Riley R.L. (1978). Airborne spread of measles in a suburban elementary school. *American Journal of Epidemiology*, 107, 421 – 432.

Roofwhirlys4Africa.(2020). About wind turbine ventilation. [Online] Available at: https://roofwhirlys4africa.co.za/about-wind-turbine-ventilation/ Accessed: 15 March 2020.

Rosebach, J.T.M., Vonk, M., Duijim, F., van Ginkel, J.T., Gehring., U.& Brunekreef, B. (2014). A ventilation intervention study in classrooms to improve indoor air quality: The FRESH study, *Environ. Health*, 12: 110.

Rudnick, S.N. & Milton, D.K. (2003). Risk of indoor airborne infection transmission estimated from carbon dioxide concentration, *Indoor Air*; 13 (3): 237-45. (doi: 10.1034/j.1600-0668.2003.00189.x).

Salehi, A., Torres, I. and Ramos, A. (2016). An analytical approach to the ventilation effectiveness of Mediterranean buildings, *Energy Procedia*, 96: 613 – 619, (doi: 10.1016/j.egypro.2016.09.109).

Salkind, N. J. (2010). Pairwise comparisons. *Encyclopedia of research design*. Thousand Oaks, CA: SAGE Publications Ltd, (doi: 10.4135/9781412961288).

SANS 10400, South Africa. (2011). National Building Regulations: Ventilation [Online] Available at: https://www.sans10400.co.za/regulations-2/ventilation/ Accessed: 28 July 2020.

Schnippel, K., Firnhaber, C., Conradie, F., Ndjeka, N. & Sinanovic, E. (2018). Incremental Cost Effectiveness of Bedaquiline for the Treatment of Rifampicin-Resistant Tuberculosis in South Africa: Model-Based Analysis. *Appl Health Econ Health Policy* **16,** 43–54, (doi: https://doi.org/10.1007/s40258-017-0352-8).

Schnippel, K., Long, L., Meyer-Rath, G., Sanne, I., Rosen, S. & Stevens, W. (2013). Impact and cost of algorithms for the diagnosis of adults with pulmonary tuberculosis in South Africa, *S Afr Med J.*, 103 (7): 436.

Schnippel, K., Rosen, S., Shearer, K., et al. (2013). Costs of inpatient treatment for multi-drug-resistant tuberculosis in South Africa, *Trop Med Int Health*, 18 (1): 109–116.

Shah, N. S., Auld, S. C., Brust, J. C., Mathema, B., Ismail, N., Moodley, P., Mlisana, K., Allana, S., Campbell, A., Mthiyane, T., Morris, N., Mpangase, P., van der Meulen, H., Omar, S. V., Brown, T. S., Narechania, A., Shaskina, E., Kapwata, T., Kreiswirth, B., & Gandhi, N. R. (2017). Transmission of Extensively Drug-Resistant Tuberculosis in South Africa. *The New England Journal of Medicine*, 376(3), 243 – 253. https://doi.org/10.1056/NEJMoa1604544

Shenoi, S., Escombe, A. & Friedland, G. (2010). Transmission of Drug-Susceptible and Drug-Resistant Tuberculosis and the Critical Importance of Airborne Infection Control in the Era of HIV Infection and Highly Active Antiretroviral Therapy Rollouts; *Clinical infectious diseases*, 50 (Suppl 3): 231 – 237 (doi - 10.1086/651496).

Sherman, M.H. (1990).Tracer-gas techniques for measuring ventilation in a single zone, *Build. Environ.*, 25: 365–374 [Online] Available at: https://doi.org/10.1016/0360-1323(90) 90010-O. Accessed: 28 March 2019.

Shezi, B., Jafta, N., Sartorius, B. and Naidoo, R.N. (2017). Developing a predictive model for fine particulate matter concentrations in low socio-economic households in Durban, South Africa, *Indoor Air*, 1 – 10.

Shin, HS., Lee, JK., Ahn, YC. *et al.* (2005). Measurement of indoor air quality for ventilation with the existence of occupants in schools. *J Mech Sci Technol,* **19,** 1001–1005 (https://doi.org/10.1007/BF02919183)

Shinohara, N., Kataoka, T. & Gamo, M. (2010). Modified perfluorocarbon tracer method for measuring effective multi-zone air exchange rates, International Journal of Environmental Research and Public Health, 7 (9): 3348 – 3358.

Shiraz, E. and Pennell, K.G. (2017). Three-dimensional vapor intrusion modeling approach that combines wind and stack effects on indoor, atmospheric, and subsurface domains, *Environ. Sci.: Processes Impacts,* 19: 1594-1607, (doi: 10.1039/C7EM00423K).

Smith, I. (2003). *Mycobacterium tuberculosis* Pathogenesis and Molecular Determinants of Virulence, *Clinical Microbiology Reviews*, 16 (3): 463 – 496.

Solar Whiz. (2015). Roof ventilation: residential and commercial [Online] Available at: https://www.solarwhiz.com.au/ Accessed: 26 March 2020.

Sonnenberg, P., Glynn, J.R., Fielding, K., Murray, J., Godfrey-Faussett, P. and Shearer, S. (2005). How soon after infection with HIV does the risk of tuberculosis start to increase? A retrospective cohort study in South African Gold mines. *Journal of Infectious Diseases*, 191: 150-158.

South African National Department of Health and the World Health Organization (2016). Towards Universal Health Coverage: Report of the evaluation of South Africa drug resistant TB programme and its implementation of the policy framework on decentralised and deinstitutionalised management of multidrug resistant TB. Geneva: WHO.

StataCorp. (2017). *Stata Statistical Software: Release 15*. College Station, TX: StataCorp LLC.

Statistics South Africa (StatsSA). (2011). Statistics from 2011 Census and 2011 Community Residential Survey. Pretoria: Presidency of the Republic of South Africa.

Statistics South Africa. (2011). Census 2011 Fact sheet. Pretoria: Statistics South Africa.

Strategic Development Information and GIS Department (SDI&GIS) CoCT. (2013). City of Cape Town – 2011 Census Suburb Khayelitsha. City of Cape Town: Cape Town.

Sudhakaran, S. & Shaurette, M. (2016). Tempereature, Relative Humidity and Carbon Dioxide Modulation in a Near-Zero Energy Efficient Retrofit House, International High Performance Buildings Conference, Paper 236, School Of Mechanical Engineering, Purdue University [Online] Available at: https://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=1235&context=ihpbc Accessed: 20 March 2018.

Sundell, J., Levin, H., Nazaroff, W.W., Cain, W.S., Fisk, W.J., Grimsrud, C.T., Gyntelberg, F., Li, Y., Persily, A.K., Pickering, A.C., Samet, J.M., Spengler, J.D., Taylor, S.T. & Weschler, C.J. (2011). Ventilation rates and health: multidisciplinary review of the scientific literature, *Indoor Air*, 21: 191–204 [Online] Available at: https://doi.org/10.1111/j.1600-0668.2010.00703.x Accessed: 23 March 2019.

Sze-To, G.N., Yang, Y., Kwan, J.K.C., Tu, S.C.T. & Chao, C.Y.H. (2014), Effects of surface material, ventilation and human behaviour on indirect contact transmission risk of respiratory infection, *Risk Analysis*, 34 (5): 818 – 830.

Tang, J.W., Koskela, H., Kalliomaski, P. and Saarinen, P. (2016). Airflow patterns through single hinged and sliding doors in hospital isolation rooms – Effect of ventilation, flow differential and passage, *International Journal of Ventilation,* 14(2): 111-126, (doi: 10.1080/14733315.2015.11684074).

Taylor, J.G., Yates, T.A. & Altamirano, H. (2016). Measuring ventilation and modelling M.tuberculosis transmission in indoor congregate settings, rural KwaZulu-Natal, *International Journal of Tuberculosis and Lung Disease*, 20 (9): 1155 – 1161.

Tien, S.T. & Ahmed, N.A. (2011). Effect of inclined roof on the airflow associated with a wind-driven turbine ventilator, *Energy and Buildings*, 43 (3): 358 – 365.

The Lung Institute, South Africa. (2018). Centre for TB Research Innovation (CTBRI). University of Cape Town, [Online] Available at: http://lunginstitute.co.za/ctbri/ Accessed: 28 May 2018.

TBfacts.org. (2019). TB in South Africa - Burden, strategic plan, key populations, [Online] Available at: https://tbfacts.org/tb-south-africa/ Accessed: 28 May 2018.

Tuberculosis Coalition for Technical Assistance (TBCTA) 2010. Implementing the WHO policy on TB infection control in health-care facilities, congregate settings and households. A framework to plan, implement and scale-up TB infection control activities at country, facility and community level. [Online] Available at: http://www.stoptb.org/wg/tb_hiv/assets/documents/TBICImplementationFramework1288971813.pdf. Accessed: 19 September 2019

Turbovent. (2019) Whirlybird Turbine Ventilator, [Online] Available at: https://www.turbovent.co.za/product/whirlybird-turbine-ventilator/ Accessed: 20 March 2018.

Urban Landmark. (n.d.). Diepsloot. Ready for Development. [Online] Available at: http://www.urbanlandmark.org.za/downloads/diepsloot_brochure.pdf Accessed: 23 May 2018.

Van Buggenhout, Van Brecht, A., Eren Özcan, S., Vranken, E., Van Malcot, W. & Berckmans, D. (2009). Influence of sampling positions on accuracy of tracer gas measurements in ventilated spaces, *Biosyst. Eng*. 104: 216–223 [Online] Available at: https://doi.org/10.1016/j.biosystemseng.2009.04.018. Accessed: 15 March 2019.

Van Rie, A., Kunneke, M. & Gie, R.P. (1999). Childhood tuberculosis in an urban population in South Africa: Burden and risk factor. [Online] Available at: https://www.researchgate.net/publication/13089267 Accessed: 21 September 2019.

Verkuji, S. and Middelkoop, K. (2016). Protecting our front-liners: Occupational tuberculosis prevention through infection control strategies. Tuberculosis Infection Control for Health *Workers*, 62 (Suppl 3): S231-S237.

Vijayan, V. K., Paramesh, H., Salvi, S. S., and Dalal, A. A. K. (2015). Enhancing indoor air quality – The air filter advantage. *Lung India : Official Organ of Indian Chest Society,* 32(5): 473–479. (doi: http://doi.org/10.4103/0970-2113.164174)

Waitt, C.J. and Squire, S.B. (2011). A systematic review of risk factors for death in adults during and after tuberculosis treatment. *Int J Tuberc Lung Dis,* 15(7):871-885, (doi:10.5588/ijtld.10.0352).

Wallace, L., Emmerich, S. & Howard-Reed, C. (2002). Continuous measurements of air change rates in an occupied house for 1 year: The effect of temperature, wind, fans, and windows. J Expo Sci Environ Epidemiol 12, 296–306, [Online] Available at: https://doi.org/10.1038/sj.jea.7500229 Accessed: 27 March 2019.

Wallengren, K., Scano, F., Nunn, P., et al. (2011). Drug-Resistant tuberculosis, KwaZulu-Natal, South Africa, 2001–2007. *Emerg Infect Dis*., 17 (10): 1913 – 1916.

Wan, M.P. and Chao, C.Y.H. (2005). Effect of changing the air distribution system on the dispersion of droplet phase aerosols in an enclosure, 10th International Conference on Indoor Air Quality and Climate, Beijing, China, 4-9 September 2005, pp. 2696-2700.

Wargocki, P., Sundell, J., Bischof, W., Brundrett, G., Fanger, P.O., Gyntelberg, F., Hanssen, S.O., Harrison, P., Pickering, A., Seppänen, O. and, Wouters, P. (2002). Ventilation and health in non-industrial indoor environments: report from a European multidisciplinary scientific consensus meeting (EUROVEN), *Indoor Air*, 12(2):113-28, (doi: https://www.ncbi.nlm.nih.gov/pubmed/12216467).

Warren, P.R. & Parkins, L.M. (1985). Single-sided ventilation through open windows, Conf. Proc. Thermal Performance of the Exterior Envelopes of Buildings, ASHRAE, Florida, 1985p. 20.

Wells, W.F. (1955). Airborne Contagion and Air Hygiene: An Ecological Study of Droplet Infections. Boston: Harvard University Press.

West, S.T.K. (2008). Design and development of natural ventilation products and associated improvement of indoor environmental quality in world sustainability Conference – Sustainable Buildings 08, September 2008, CIB International Conference, Melbourne, Australia.

Weyer, K., Lancaster, J., Brand, J., van der Walt, M. & Levin, J. (2004). Survey Of Tuberculosis Drug Resistance In South Africa 2001 – 2002. Pretoria: Medical Research Council.

White, H. and Sabarwal, S. (2014). Quasi-experimental design and methods. Methodological Briefs Impact Evaluation No. 8. Italy: UNICEF Office of Research.

Whyte, W., Ward, S., Whyte, W.M. and Eaton T (2014). Decay of airborne contamination and ventilation effectiveness of cleanrooms, *International Journal of Ventilation*, 13(3): 211-219.

Wilson, A.L., Colome, S.D., Tian, Y., Becker, E.W., Baker, P.E., Behrens, D.W., Billick, I.H. & Garrison, C.A. (1996). California residential air exchange rates and residence volumes, *J. Expo. Anal. Environ. Epidemiol*., 6: 311– 326.

Wood, R., Johnstone-Robertson, S., Uys, P., Hargrove, J., Middelkoop, K., et al. (2010) Tuberculosis transmission to young children in a South African community: modeling household and community infection risks, *Clin Infect Dis* 51: 401–408

Wood, R., Lawn, S.D., Johnstone-Robertson, S. & Bekker, L.G. (2011). Tuberculosis control has failed in South Africa—time to reappraise strategy, *S Afr Med J*; 101: 111–114.

World Health Organisation [WHO]. (2008). Anti-tuberculosis drug resistance in the world, Fourth global report: the WHO/IUATLD Global Project on Anti-Tuberculosis Drug Resistance Surveillance. Geneva: WHO.

World Health Organisation [WHO]. (2009). WHO policy on TB infection control in health-care facilities, congregate settings and households, [Online], Available at: https://whqlibdoc.who.int/publications/2009/9789241598323_eng.pdf. Accessed: 29 September 2019.

World Health Organisation [WHO]. (2010). Multidrug and extensively drug-resistant TB - 2010 global report on surveillance and response, Geneva: WHO.[Online] Available at: https://www.who.int/tb/publications/tb-mxdr-report/en/ Accessed: 20 April 2020.

World Health Organisation [WHO]. (2012). Global Tuberculosis report-2012. Geneva: WHO. wwwwhoint/tb/publications/global_report/en/2012 Accessed: 20 April 2020.

World Health Organisation [WHO]. (2013). Global tuberculosis report. Geneva, Switzerland: World Health Organization [Online] Available at: http:// wwwwhoint/tb/publications/global_report/en/2013 Accessed: 20 April 2020.

World Health Organisation [WHO]. (2015). Global Tuberculosis Report 2015. Geneva: WHO, [Online] Available at: www.who.int/tb/publications/global_report/en Accessed: 2 March 2018.

World Health Organisation [WHO]. (2016). Global Tuberculosis Report. Geneva: WHO; wwwwhoint/tb/publications/global_report/en/2016 Accessed: 20 April 2020.

Xie, X., Li, Y., Chwang, A.T.Y., Ho, P.L. and Seto, W.H. (2007). How far droplets can move in indoor environments – revisiting the wells evaporation falling curve, *Indoor Air*, 17: 211-225.

Yamamoto, N., Shendell, D.G., Winer, A.M. & Zhang, J. (2010). Residential air exchange rates in three major US metropolitan areas: Results from the Relationship Among Indoor, Outdoor, and Personal Air Study 1999–2001, *Indoor Air*, 20, 85–90.

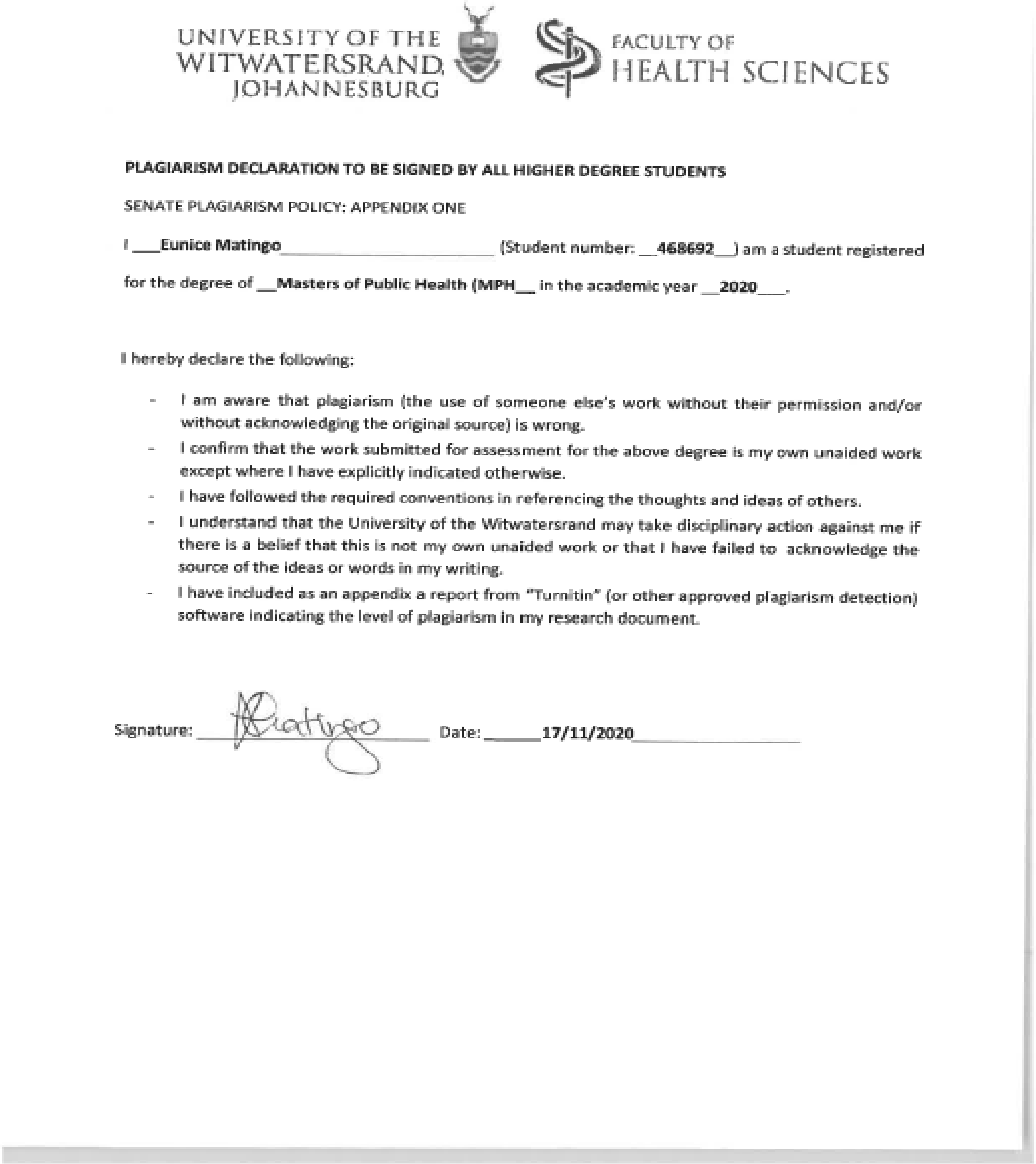
Yates, T.A., Khan, P.Y., Knight, G.M., Taylor, J.G., McHugh, T.D., Lipman, M., White, R.G., Cohen, T., Cobelens, F.G., Wood, R., Moore, D.A.J. & Abubakar, I. (2016). The transmission of Mycobacterium tuberculosis in high burden settings, *Lancet Infect Dis*, 16: 227 – 238.

Yoshino, H., Murakami, S., Akabayashi, S., Kurabuchi, T., Kato, S., Tanabe, S., Ikeda, K., Osawa, H., Sawachi,. T., Hukushima, A. & Adachi. M. (2006). Survey on minimum ventilation rate of residential buildings in fifteen countries, [Online] Available at: https://www.aivc.org/sites/default/files/members_area/medias/pdf/Conf/2004/2004028_Yoshino.pdf Accessed: 20 July 2020.

You, Y., Niu, C., Zhou, J., Liu, Y., Bai, Z., Zhang, J., He, F. & Zhang, N. (2012). Measurement of air exchange rates in different indoor environments using continuous CO_2 sensors, *Journal of Environmental Sciences*, 24 (4): 657 – 664.

Zhang, W., Wang, L., Ji, Z., Ma, L. & Hui, Y. (2015). Test on ventilation rates of dormitories and offices in university by the CO2 tracer gas method, Procedia Eng 121: 662–666 [Online] Available at: https://doi.org/10.1016/j.proeng.2015.08.1061. Accessed: 10 February 2019.

PLAGIARISM DECLARATION



UNIVERSITY OF THE
WITWATERSRAND,
JOHANNESBURG

FACULTY OF
HEALTH SCIENCES

PLAGIARISM DECLARATION TO BE SIGNED BY ALL HIGHER DEGREE STUDENTS

SENATE PLAGIARISM POLICY: APPENDIX ONE

I ___**Eunice Matingo**________________________ (Student number: __**468692**__) am a student registered for the degree of __**Masters of Public Health (MPH**__ in the academic year __**2020**___.

I hereby declare the following:

- I am aware that plagiarism (the use of someone else's work without their permission and/or without acknowledging the original source) is wrong.
- I confirm that the work submitted for assessment for the above degree is my own unaided work except where I have explicitly indicated otherwise.
- I have followed the required conventions in referencing the thoughts and ideas of others.
- I understand that the University of the Witwatersrand may take disciplinary action against me if there is a belief that this is not my own unaided work or that I have failed to acknowledge the source of the ideas or words in my writing.
- I have included as an appendix a report from "Turnitin" (or other approved plagiarism detection) software indicating the level of plagiarism in my research document.

Signature: ____________________ Date: ______**17/11/2020**__________________

APPENDIX A – BASELINE ENVIRONMENTAL SURVEY

Household factors	**Building characteristics**	**Indoor activities**	**Outdoor exposure sources**	**Behavioural**
Household size – total number of individuals staying in the household Presence and number of shacks on the yard	- Size in m^2 - Presence of visible mould and dampness	Cooking and heating fuel used -wood -kerosene -LPG	Mobile sources -close to roads, airports etc.	Smoking indoors
Age of the house	Number of rooms	The use of incense	Stationary sources -industrial area -landfill site -filling station -panel beating -welding etc.	Hygiene practices
Crowding – number of adults per bedroom in the household	Presence of windows	Bedtime and waking up time	Pollution generating activities	

Sleep with windows open	Presence of opening windows		Distance of household from major roads and industries	
Type of dwelling -stand-alone RDP -stand-alone house, non RDP -shack (in backyard or not in backyard)	Availability of air vents	Cleaning methods -sweeping -dusting		
General health of household occupants	Gaps between the wall and roof			
Working environments of household occupants	Roof type -roof tiles -corrugated iron -wood -tarpaulin -asbestos			
Hygiene awareness of the	Floor type -cement			

household occupants	-carpet -tiles -mat/rug -ground			
	Material of main walls -bricks/cement -corrugated iron -plastic or cardboard -wood -mud			
	Cooking site -inside -outdoors -both			

Source. Adapted from Shezi et al. (2017).

APPENDIX B – PARTICIPANT INFORMATION SHEET AND CONSENT FORM

(INTERVENTION GROUP)

Dear Sir/Madam

My name is Eunice Matingo and I am a Masters student in Public Health at Wits University in Johannesburg. As part of my studies I have to undertake a research project, and I am investigating the potential for enhanced ventilation using wind-driven roof turbines in reducing the risk for tuberculosis transmission in households in Diepsloot, South Africa. The aim of this research project is to find out if wind-driven roof turbines are systems that can reduce the transmission of tuberculosis in the community if the community were to all have the turbines installed for them. This may help us to establish a baseline for an acceptable air exchange rates within a household set-up which will inform the design of other types of ventilation systems that maybe applicable for such set-ups.

As part of this project I would like to invite you to take part in this study which will involve the following procedures:

1. Sit down with you for about 5 minutes to have an interview to gather information about your household structure such as the number of rooms in the household, the common room in the household, number of persons per room, number of windows and doors, percentage of time windows and doors are left open per day.
2. Conduct a walk-through survey to identify the room over which the roof turbine will be installed and to measure the size of this room. I would like your permission to take photographs of this room. These photos will only be used in the research report to demonstrate the physical characteristics of the room used for the study.
3. With your permission, I would also like to have the wind-driven roof turbine installed on your roof.
4. I will then pump a traceable gas into this chosen room and then measure the time it takes the roof turbine to clear this room of that gas. This will be done on four separate days and the researcher will spend a maximum of 1 hour per session on these days.

The only direct benefit to you for your participation on this study is having to keep the installed wind-driven roof turbine. There are no disadvantages or penalties for not participating. You may withdraw at any time or not answer any question if you do not want to. The interview will be completely confidential and anonymous as I will not be asking for your name or any identifying information, and the information you give to me will be held securely and not disclosed to anyone else. I will be using a pseudonym (false name) to represent your participation, in my final research report. If you experience any distress or discomfort, we will stop the interview or resume another time.

If you have any questions afterwards about this research, feel free to contact me on the details listed below. This study will be written up as a research report which will be available online through the university library website. If you wish to receive a summary of this report, I will be happy to send it to you upon request (optional). If you have any queries, concerns or complaints regarding the ethical procedures of this study, you are welcome to contact the University Human Research Ethics Committee (non-medical), telephone + 27(0)11 717 1408, email hrec-medical.researchoffice@wits.ac.za/ Shaun.Schoeman@wits.ac.za

Yours sincerely,

Eunice Matingo

Researcher name: Eunice Matingo **email**: eunice.mutava@yahoo.com **phone number**:084-887-7688
Supervisor name: Prof. Derk Brouwer **email**: derk.brouwer@wits.ac.za **phone number**: 011-717-2387
Co-supervisor name: Dr. Tanusha Singh **email**: tanusha.singh@nioh.nhls.ac.za **phone number**: 011-712-6400

CONSENT

Title of study: Determining the potential for enhanced ventilation using wind-driven roof turbines in reducing risk probability for tuberculosis transmission in households in Diepsloot, South Africa, 2018.

Name of researcher: Eunice Matingo

I ………………………………………. agree to participate in this research project. The research has been explained to me and I understand what my participation will involve.

I agree for a wind-driven turbine to be installed on my household ☐YES ☐NO

I agree that my participation will remain anonymous ☐YES ☐NO

I agree that the researcher may take photos of my household ☐YES ☐NO

I agree that the information I provide may be used anonymously by other researchers following this study ☐YES ☐NO

…………………………………… (signature)

…………………………………… (name of participant)

…………………………………… (date)

APPENDIX C – PARTICIPANT INFORMATION SHEET AND CONSENT FORM (CONTROL GROUP)

Dear Sir/Madam

My name is Eunice Matingo and I am a Masters student in Public Health at Wits University in Johannesburg. As part of my studies I have to undertake a research project, and I am investigating the potential for enhanced ventilation using wind-driven roof turbines in reducing the risk for tuberculosis transmission in households in Diepsloot, South Africa. The aim of this research project is to find out if wind-driven roof turbines are systems that can reduce the transmission of tuberculosis in the community if the community were to all have the turbines installed for them. This may help us to establish a baseline for an acceptable air exchange rates within a household set-up which will inform the design of other types of ventilation systems that maybe applicable for such set-ups.

As part of this project I would like to invite you to take part in this study which will involve the following procedures:

1. Sit down with you for about 5 minutes to have an interview to gather information about your household structure such as the number of rooms in the household, the common room in the household, number of persons per room, number of windows and doors, percentage of time windows and doors are left open per day.
2. Conduct a walk-through survey to identify the room over which the roof turbine will be installed and to measure the size of this room. I would like your permission to take photographs of this room. These photos will only be used in the research report to demonstrate the physical characteristics of the room used for the study.
3. With your permission, I would also like to measure the air exchange rate of this room. I will pump a traceable gas into this chosen room and then measure the time it takes to clear this room of that gas. This will be done on four separate days and the researcher will spend a maximum of 1 hour per session on these days.

There is no direct benefit to you for your participation on this study. There are no disadvantages or penalties for not participating. You may withdraw at any time or not answer any question if you do not want to. The interview will be completely confidential and anonymous as I will not be asking for your name or any identifying information, and the information you give to me will be held securely and not disclosed to anyone else. I will be using a pseudonym (false name) to represent your participation, in my final research report. If you experience any distress or discomfort, we will stop the interview or resume another time.

If you have any questions afterwards about this research, feel free to contact me on the details listed below. This study will be written up as a research report which will be available online through the university library website. If you wish to receive a summary of this report, I will be happy to send it to you upon request (optional). If you have any queries, concerns or complaints regarding the ethical procedures of this study, you are welcome to contact the University Human Research Ethics Committee (non-medical), telephone + 27(0)11 717 1408, email hrec-medical.researchoffice@wits.ac.za/ Shaun.Schoeman@wits.ac.za

Yours sincerely,
Eunice Matingo

Researcher name: Eunice Matingo **email**: eunice.mutava@yahoo.com **phone number**:084-887-7688
Supervisor name: Prof. Derk Brouwer **email**: derk.brouwer@wits.ac.za **phone number**: 011-717-2387
Co-supervisor name: Dr. Tanusha Singh **email**: tanusha.singh@nioh.nhls.ac.za **phone number**: 011-712-6400

CONSENT

Title of study: Determining the potential for enhanced ventilation using wind-driven roof turbines in reducing risk probability for tuberculosis transmission in households in Diepsloot, South Africa, 2018.

Name of researcher: Eunice Matingo

I ……………………………………. agree to participate in this research project. The research has been explained to me and I understand what my participation will involve.

I agree that my participation will remain anonymous ☐YES ☐NO

I agree that the researcher may take photos of my household ☐YES ☐NO

I agree that the information I provide may be used anonymously by other researchers following this study ☐YES ☐NO

…………………………………… (signature)

…………………………………… (name of participant)

…………………………………… (date)

APPENDIX D - INTERVIEW SCHEDULE

Thank you for taking time to sit down and talk to me. This interview should take between 5 to 10 minutes to complete. I am going to ask you some questions regarding the household and the indoor activities that occur in the household.

HOUSEHOLD FACTORS

1. How many people are staying in the household? …………………………………………………………………

2. How old is this house? When was it built? ……………………………………………………………………………

3. Do people in this household sleep with the windows open? ☐**Yes** ☐**No**

4. Is there a household occupant (s) who is more or less likely to bring infection home unawares from their work? ☐**Yes** ☐**No**

4b. If yes, where do they work?...

5. How would you rate the general health of the occupants of this household?

☐**Very poor**

☐**Poor**

☐**Fair**

☐**Good**

☐**Very good**

6. What is the age range of the occupants of this household? ………………………………………………….

7. What would you say was the quality of hygiene awareness and practices (for example, cough etiquette, washing hands etc.) of the occupants of this household?

☐**Unsatisfactory**

☐**Needs development**

☐**Somewhat effective**

☐**Capable and effective**

☐**Very effective**

8. How many shacks do you have in the yard?...........................What is the total number of people living in the shacks on the yard? ……………………………..

INDOOR ACTIVITIES

1. What type of cooking and heating fuel is used in the household?

☐**Wood** ☐ **Kerosene** ☐**LPG** ☐**Electricity**

☐**Other (please specify)** ……………………………………………………………………………………………………

2. Do you burn incense indoors? ☐**Yes** ☐**No**

3. What is the usual bedtime and waking up time of the household?

Bedtime…………………………………. **Waking up time**……………………………………………………

4. What method do you use to clean the house?

☐**Sweeping** ☐**Dusting** **If dusting,** is it ☐**wet dusting or** ☐**dry dusting)**

☐**Vacuuming** ☐**Other (please specify)**…………………………………………………………….

BEHAVIOURAL FACTORS

1. Do you have people that smoke in the household? ☐**Yes** ☐**No**

If Yes,

Where do they usually smoke? ☐ **Indoors** ☐**Outdoors**

2. How often do you open windows in the house?

3. What is the opening status of the windows in this house during the day and at night?

☐**Closed**

☐**Slightly open**

☐**Half-open**

☐**Fully open**

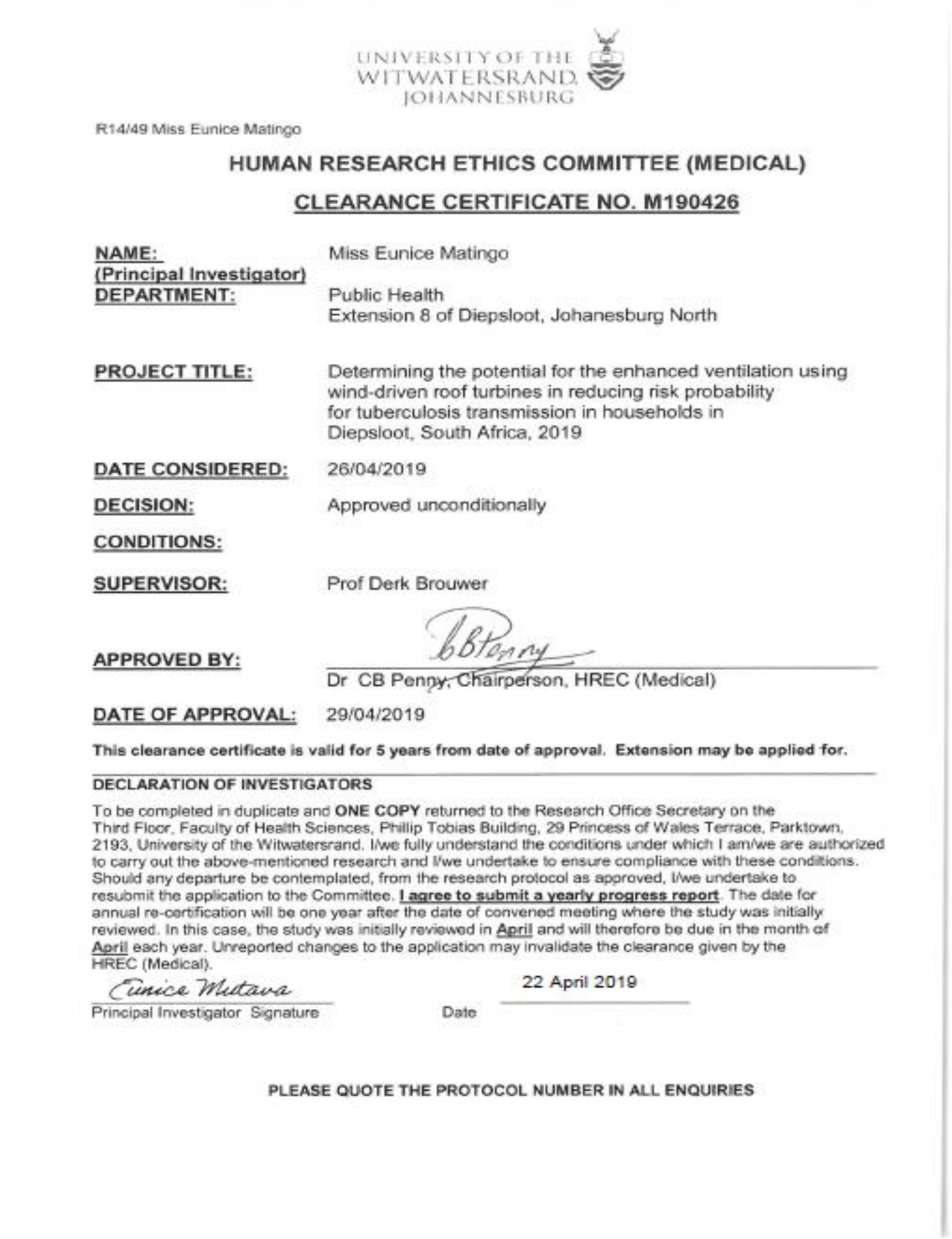
Provide a reason for your answer……………………………………………………………………………………………

Overall, how do you judge the quality of air in your house?

Overall, how do you judge the temperature (hot or cold) of the house?

THANK YOU FOR YOUR PARTICIPATION

APPENDIX E - INSTITUTIONAL ETHICS LETTER



UNIVERSITY OF THE
WITWATERSRAND,
JOHANNESBURG

R14/49 Miss Eunice Matingo

HUMAN RESEARCH ETHICS COMMITTEE (MEDICAL)

CLEARANCE CERTIFICATE NO. M190426

NAME: **(Principal Investigator)**	Miss Eunice Matingo
DEPARTMENT:	Public Health Extension 8 of Diepsloot, Johanesburg North
PROJECT TITLE:	Determining the potential for the enhanced ventilation using wind-driven roof turbines in reducing risk probability for tuberculosis transmission in households in Diepsloot, South Africa, 2019
DATE CONSIDERED:	26/04/2019
DECISION:	Approved unconditionally
CONDITIONS:	
SUPERVISOR:	Prof Derk Brouwer
APPROVED BY:	Dr CB Penny, Chairperson, HREC (Medical)
DATE OF APPROVAL:	29/04/2019

This clearance certificate is valid for 5 years from date of approval. Extension may be applied for.

DECLARATION OF INVESTIGATORS

To be completed in duplicate and **ONE COPY** returned to the Research Office Secretary on the Third Floor, Faculty of Health Sciences, Phillip Tobias Building, 29 Princess of Wales Terrace, Parktown, 2193, University of the Witwatersrand. I/we fully understand the conditions under which I am/we are authorized to carry out the above-mentioned research and I/we undertake to ensure compliance with these conditions. Should any departure be contemplated, from the research protocol as approved, I/we undertake to resubmit the application to the Committee. **I agree to submit a yearly progress report**. The date for annual re-certification will be one year after the date of convened meeting where the study was initially reviewed. In this case, the study was initially reviewed in **April** and will therefore be due in the month of **April** each year. Unreported changes to the application may invalidate the clearance given by the HREC (Medical).

Eunice Mutava
Principal Investigator Signature

22 April 2019
Date

PLEASE QUOTE THE PROTOCOL NUMBER IN ALL ENQUIRIES

COMH7175 Research Report E Matingo

ORIGINALITY REPORT

12%	7%	9%	11%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	Submitted to University of Witwatersrand Student Paper	6%
2	Submitted to Intercollege Student Paper	1%
3	www.plosone.org Internet Source	1%
4	Submitted to Mancosa Student Paper	1%
5	edoc.rki.de Internet Source	1%
6	www.who.int Internet Source	1%
7	academic.oup.com Internet Source	1%
8	centaur.reading.ac.uk Internet Source	1%
9	health-policy-systems.biomedcentral.com Internet Source	1%

✓

2020 -11- 17