APPLICATION OF FOURTH INDUSTRIAL REVOLUTION TECHNOLOGIES TO VENTILATION DESIGN AND ENVIRONMENTAL MONITORING CRITERIA FOR PLATINUM MINING IN ZIMBABWE

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A thesis submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Doctor of Philosophy in Engineering.

Johannesburg, 2022

DECLARATION

I declare that this thesis is my own, unaided work. It is being submitted for the Degree of Doctor of Philosophy in Engineering at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

(Signature of candidate)

1st day of **August 2022**

at **Wits University**

ABSTRACT

Mine ventilation plays a pivotal role in underground mining operations. It is required to dilute and remove dust, gases, diesel contaminants and to remove heat thereby creating a thermally acceptable, conducive working environment. Most platinum mines on the Great Dyke of Zimbabwe are highly mechanised as they utilize trackless diesel equipment during the extraction process. The fourth industrial revolution was introduced to enhance productivity, safety, reduce costs, operational longevity and to monitor all processes in real time. The internet of things (IoT) together with other digital revolution techniques were then investigated and implemented in the mining industry for process optimisation and data analytics. The Great Dyke of Zimbabwe faces several challenges from fluctuating metal prices, safety concerns, productivity optimisation and a continuously transforming competitive landscape. Underground mining operations present a technically challenging and hazardous environment for workers, through inadequate ventilation, exposure to dust, heat and gas as well as threat of rock falls or mine collapse. Recent studies demonstrated that in highly mechanized platinum mines, primary ventilation systems account for 40-60% of the mines' energy consumption hence cognizance of this must be taken during mine design. The primary reason for this considerable expense is that most underground ventilation systems are designed for the peak demand regardless of the actual demand, which is commonly dictated by diesel equipment usage. The ever-increasing geological complexities, higher degree of mechanization and the espousal of more stringent health regulations have generally influenced more air demands in underground operations. Such increases in air quantity result in augmented energy consumption due to the cubic relationship of quantity and power. As a result, to mitigate prohibitive ventilation costs, underground mines must optimise their ventilation systems during their design and must explore cost cutting initiatives through digital transformation technologies. The adoption of electric vehicles, autonomous vehicles and ventilation on demand systems may be implemented in room and pillar platinum mines to reduce operating costs and to enhance safety and productivity.

Most platinum mines on the Great Dyke tend to operate their ventilation systems at peak level, despite the mine's air volume being well in excess of the "true" ventilation needs, due to a lack of appropriate ventilation controls. In this research, ventilation on demand system in a bord and pillar platinum mine was designed and installed to minimize the redundant use of air in underground operations. Fourth industrial revolution techniques were applied to environmental monitoring systems thereby optimizing airflow demands. The mine managed to reduce its annual power consumption by 23% through the implementation of manual control and time of day scheduling levels of the ventilation on demand concept. There was also a 6% productivity improvement mainly attributable to a significant reduction in the re-entry period. This thesis introduces a novel concept of ventilation optimisation through digital transformation in room and pillar platinum mines. A system was designed, installed and commissioned though there is currently an ongoing optimisation process to harness the full benefits of ventilation on demand (VOD).

In a large mechanised operation, if a mine can reduce airflow through eliminating redundant air supply, the resultant power consumption or cost will be reduced due to the cubic relationship of speed and power. The ventilation on demand concept had not been rolled out to any bord and pillar mining operation before 2016 due to the nature of mining operations. Efficient air distribution in bord and pillar platinum mines will be achieved through the integration of internet of things with empirical techniques extracted from real-time data. The ventilation system is adjusted in real time to meet the triggered ventilation demand based on the activities undertaken. This thesis describes various options to optimise and apply the concept to hard rock bord and pillar platinum mines operating on the Great Dyke of Zimbabwe. The increased power demand from ventilation systems necessitated the need to optimize the amount of air sent underground through the application of fourth industrial revolution techniques. The ventilation on demand systems coupled with advanced control processes modulate the airflow of main surface fans and auxiliary fans thereby optimizing mines ventilation systems.

KEY WORDS : mine ventilation, ventilation design, room and pillar mines, automation, ventilation optimisation, shaft, main fans

List of publications

The publications listed below have emanated from this research work so far:

1. Chikande T., Phillips, H. R. (2021) and Cawood. F. Ventilation optimisation through digital transformation, *Journal of the Southern African Institute of Mining and Metallurgy*

2. Chikande T., Phillips, H. R. (2021) and Cawood. F. Optimised ventilation design for mechanised bord and pillar platinum mines *Journal of the Southern African Institute of Mining and Metallurgy*.

The paper abstracts are included in Appendix A

DEDICATION

This thesis is dedicated to:

my wife Petronellah Nyirenda, my father Jeremiah Chikande and my mother Mynate Tau.

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List of Abbreviations

°C	Degrees Celsius
dB	Decibel
DB	Dry-bulb temperature
DPM	Diesel Particulate Matter
IARC	International Agency for Research on Cancer
Kg	Kilogram
kJ	Kilojoules
kPa	Kilopascal
ktpm	Kilo-ton per month (rock produced or blasted)
kW	Kilowatt
m/s	Metres per second
m^3/s	Cubic metres per second
mg/m^3	Milligram per cubic metre
MHSA (RSA)	Mine Health and Safety Act, 1996 (Act no. 29 of 1996)
MW	Megawatt
Ns^2/m^4	Friction factor for tunnels, pipes etc.
OEL	Occupational Exposure Limit
ppm	Parts per million
RBH	Raise bore hole
STEL	Short-term exposure limit
TMM	Trackless Mobile Machinery
VOD	Ventilation on demand
VRT	Virgin rock temperature
WB	Wet-bulb temperature

Definition of terms

Occupational exposure is when a person is exposed to potential health hazards at work.

Occupational Exposure Limit (OEL) means a time-weighted average concentration for an 8-hour workday and a 40-hour work week which nearly all workers may be repeatedly exposed to without adverse health effects.

Occupational Exposure - Ceiling limit (OEL-Ceiling) means an instantaneous value, which must never be exceeded during any part of the employee's exposure

CHAPTER 1: INTRODUCTION

1.0 Introduction

Good mining practices, together with sound ventilation design, will lead to improved productivity, less operating costs and improved safety. This research endeavours to improve the current ventilation design criteria and monitoring systems used in hard rock bord and pillar mines on the Zimbabwean Great Dyke. Such improvements are being driven by the need to improve safety and productivity, the increased investment to develop new mines, an appetite for reduced power costs and improved capital and operational efficiencies. Most underground mines have failed to reach the target milestone of zero harm in the sub-disciplines of mine ventilation and occupational hygiene. Applying traditional techniques in ventilation design and monitoring which rely primarily on human judgement are unlikely to improve the situation. Poor ventilation and environmental monitoring systems can inflict catastrophic effects on both personnel and equipment, hence measures should be taken to mitigate them.

This study makes use of data from platinum mines on the Great Dyke for back analysis in order to investigate ways to optimise mining key performance indicators. In this chapter, some brief background information required to comprehend the study is provided. Firstly, the location and the geology of the Great Dyke, where the research was conducted, is outlined. This chapter also gives a brief overview of mining operations. The case studies in this research cover extensive work on one mine on the Great Dyke but the research benefits can be extended to other mines which are in the same geological domain. In addition, this chapter addresses the problem statement, justification of the project, methodology, aims and objectives of the study. The contents of the thesis is also outlined in this chapter.

1.1 Background Information

Ventilation plays a critical role in providing adequate oxygen-in-air to support all work activities in any confined environment. It is also necessary to dilute and remove dust, gases, and particulates as well as to provide a thermally stable environment. Adequate air supply is required to maintain airborne pollutants and heat below the stipulated occupational exposure limits (OELs). Ventilation systems require a significant capital outlay as well as on-going and, in some jurisdictions, exorbitant operating costs due to power consumption. However, decisions surrounding the safety of employees and effective operation of the system are often based on partial and imprecise information. It is important to note that the standards set to protect the health and safety of workers are becoming more stringent. Occupational exposure limits for airborne pollutants and heat levels are being reduced, medical surveillance and compensation claims are being intensified and standards for escape and rescue are being tightened (Bonsu, et al., 2017). The regulatory bodies are setting out new milestones but they are not prescribing the roadmap to achieve the goals. In addition, there have been some significant changes in terms of mechanisation of mining operations which have all necessitated the need to review the current ventilation systems. It is against this backdrop that research needed for reviewing the current ventilation systems and application of fourth industrial revolution technologies to both ventilation design and monitoring has to be conducted. This is in order to ensure compliance with the emerging standards. The primary outputs of fourth industrial revolution technology should include the following:

- Effective communication through sensor and data integration systems
- Manage qualitative and quantitative data in one central database in real time
- Hazard identification, evaluation of risks and automatic reduction of airborne pollutants to acceptable levels
- Eliminating reliance on human interventions through leveraging business intelligence tools and automated systems
- Optimisation of mining key performance indicators

It is critical to determine the life of mine ventilation requirements at an early stage in order to provide adequate fresh air which yields acceptable underground environmental conditions under all future conditions. The focus of ventilation design in bord and pillar operations is to reduce the mine system resistance, where possible, with resultant main fan power saving together with the most efficient type of fan for the mining method. The overall airflow requirements for all platinum mines on the Great Dyke is based on airflow provision for diesel emission dilution, removal of blasting fumes and heat removal or provision of a ventilation rate based on a rule-of-thumb number per 1,000 tonnes mined per month, which-ever is the greatest. The current ventilation designs were based on a design rate of $0.10m^3/s$ per kW for diesel fuelled equipment using fuel with a Sulphur content of 500ppm. This research will analyse and improve the current ventilation design techniques applied to bord and pillar platinum mines.

1.2 Geological setting of the Great Dyke

Mines have different designs, influenced by ore body geometry and geological settings - and hence have different air requirements. Air borne pollutants associated with the geological structure of the ore body, coupled with the mining method employed greatly affect the design of primary ventilation systems. The Great Dyke is the second largest reserve of Platinum group elements (PGEs) globally following the South African Bushveld complex (Oberthür, et al., 2012). It is a linear layered intrusion that extends for about 550 kilometres with a maximum width of 11 kilometres (Prendergast, 1989). It is located in the Zimbabwean craton and it is dated to be 2.50 billion years old. Geologically, the Great Dyke is not considered to be a dyke, rather it is a lapolith (Prendergast, 1989). The generalised section of the Great Dyke is almost like a trumpet comprising of layers that are dipping towards the centre. The Great Dyke is longitudinally subdivided into a series of narrow contiguous stratified chambers and subchambers. There are four known geological complexes within the Great Dyke which contain the platinum group of minerals (PGMs) and the base metal deposit, namely: Wedza complex, Musengezi complex, Selukwe complex and the Hartley Geological complex. In all these complexes the one that contains the largest volume of PGM bearing strata is the Hartley Geological Complex, which contains about 80% of the known PGM resources in Zimbabwe (Oberthür, et al., 2012). Vertically, the Great Dyke is divided into a ultramafic sequence and a mafic sequence. Asymmetry in the layering pattern close to the walls is attributed to the physical shape of the chamber walls and the contrasting nature of the wall rocks, which are greenstones on the west, and granite on the east. Figure 1.1 shows the Great Dyke and various mines where this research was carried out. The map also shows mineral resources (PGE) contained by each complex of the Great Dyke.

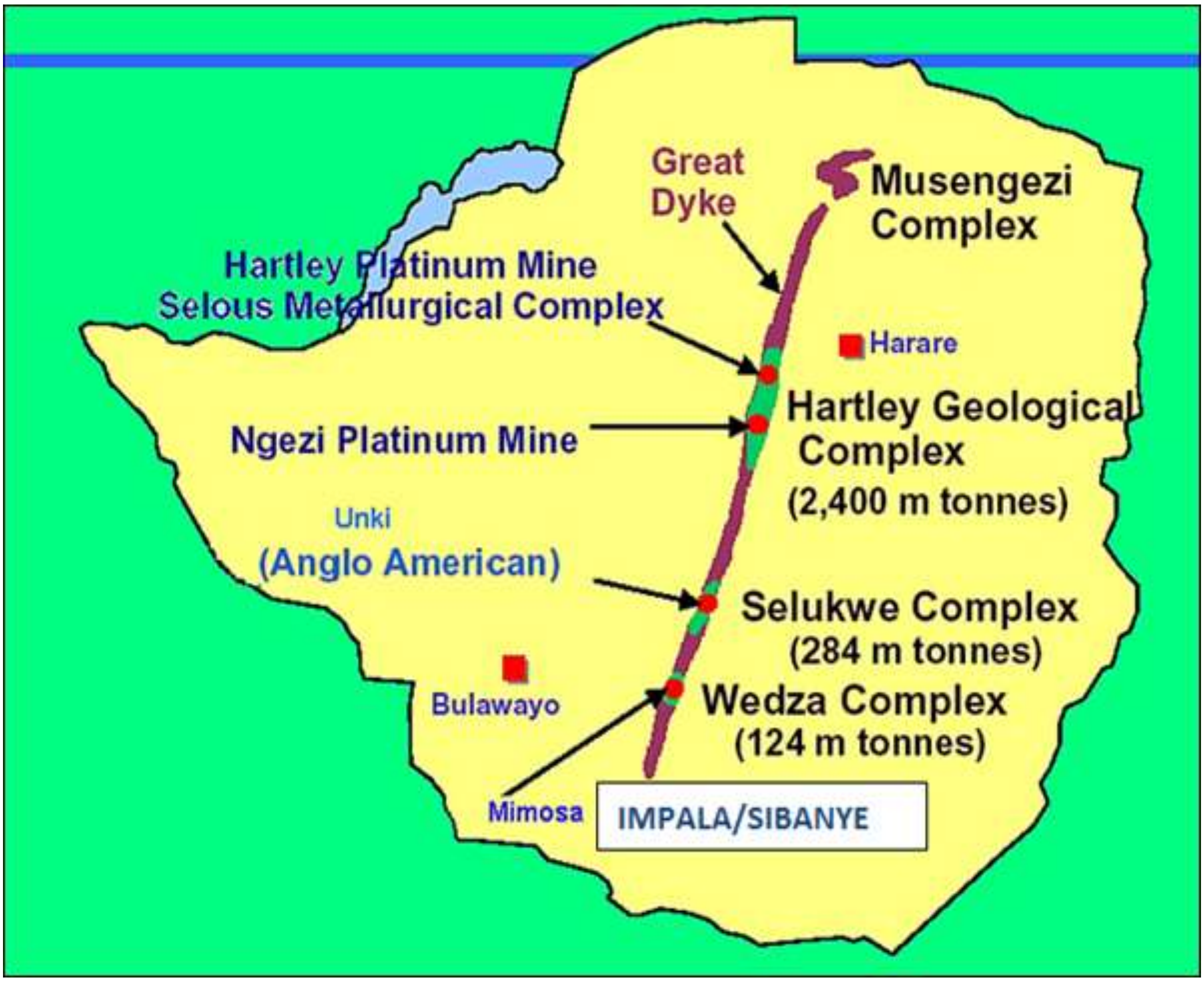

Figure 1.1: Great Dyke (Modified after Holding, 2010)

1.2.1 Local Geology

The ultramafic rocks (pyroxenite, harzburgite and dunite) crop out along the exposed margins of the central gabbronorite and peripheral to it with a narrow plagioclase websterite layer comprising the uppermost unit (Oberthür, et al., 2012). The underlying rocks include plagioclase pyroxenite, plagioclase olivine pyroxenite, plagioclase harzburgite, serpentinised dunite, and chromitite layers of the lower differentiated units. Figure 1.2 shows the transverse section presenting the synclinal structure of the layering and trumpet shape of the Dyke.

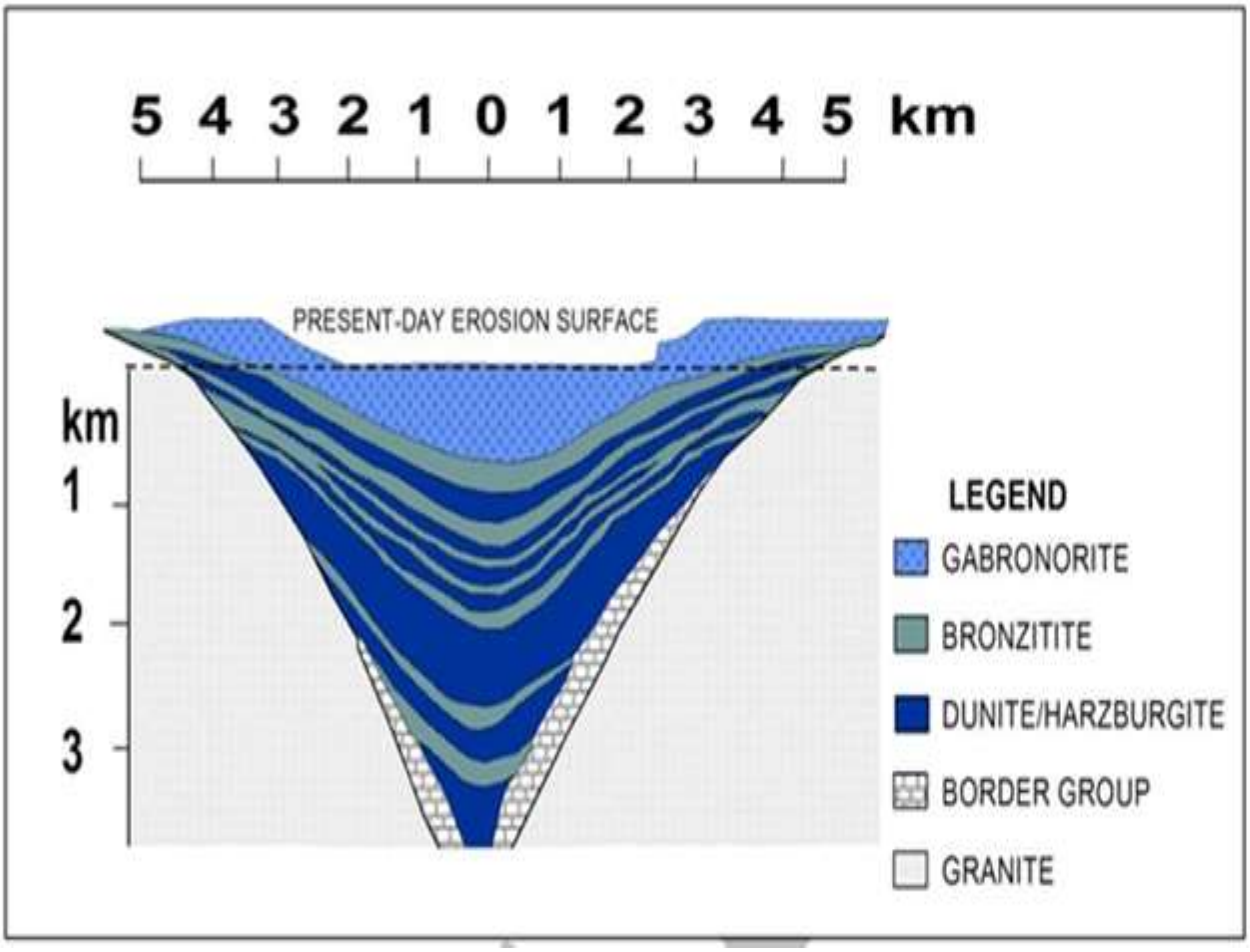

Figure 1.2: Transverse section showing the synclinal structure of the layering and trumpet shape of the Dyke (Modified after Wilson and Prendergast, 2001)

The target reef mined across the Great Dyke is called the main sulphide zone (MSZ). This reef is located in the pyroxenite layer, which is hosted in the ultramafic sequence. Figure 1.3 shows the lithology of the MSZ, which is between bronzite and websterite. The MSZ is a uniform layer which is about 2-3.5 metres thick dipping at around 10˚-14˚ from a surface outcrop towards the axis of the basin. The visible scattered sulphide at MSZ shows a typical and consistent vertical distribution of PGMs and base metal value.

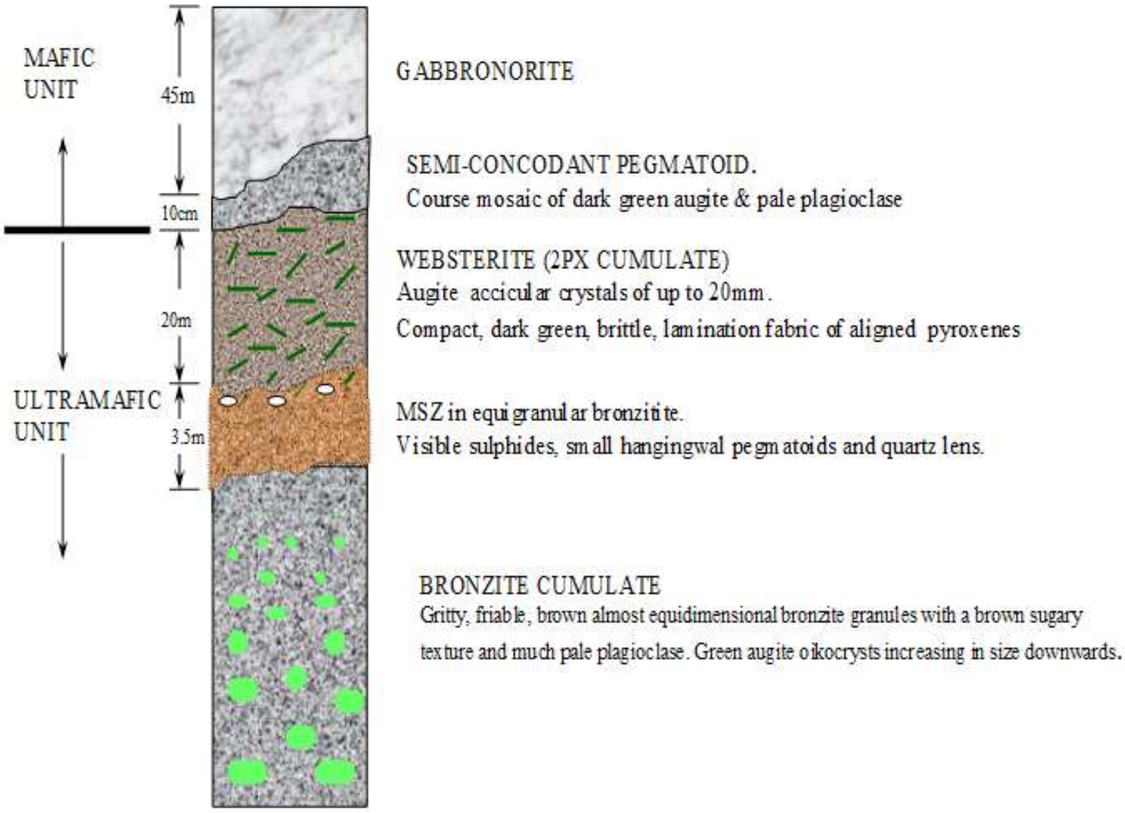

Figure 1.3: The Great Dyke stratigraphy – Schematic vertical section showing lithological features (Modified after Wilson and Prendergast, 2001)

The MSZ has a perfectly defined grade profile with a distinguishable reef horizon marker which aids grade control. Three main geological structures exist across the Great Dyke; East-West strike faults and aplite dykes, North-South striking shallow dipping joints and reef sub-parallel planes. Figure 1.4 shows the grade distribution of platinum, palladium, nickel and copper across the MSZ. From the grade distribution graph, the optimum recovery of platinum with minimum PGMs dilution can be achieved when mining within the prescribed boundaries.

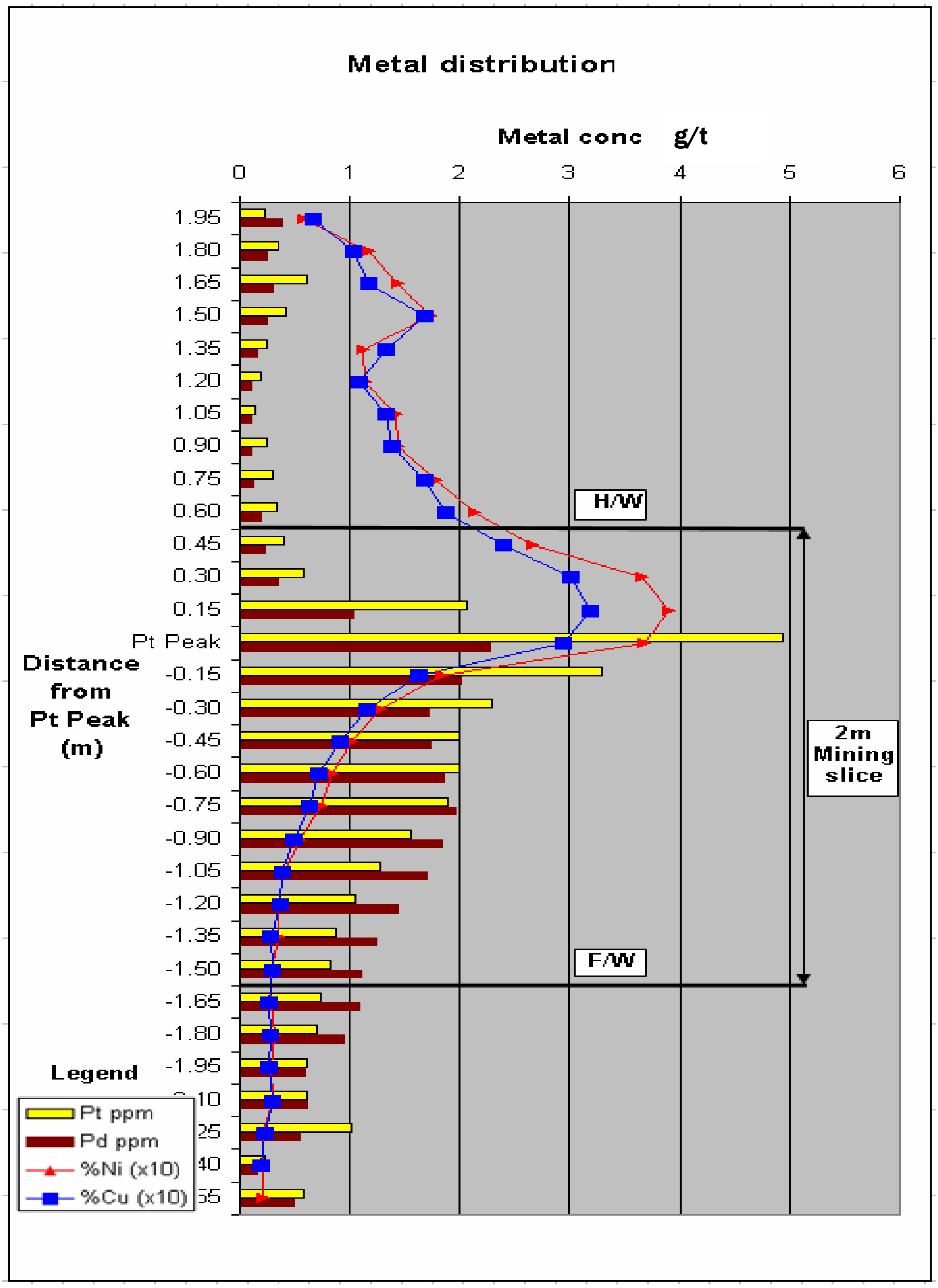

Figure 1.4: Platinum metal concentrations *(Oberthür, et al., 2012)*

1.2.2 Structural Geology

Faulting within the upper limits of the pyroxenite occur throughout all platinum mines of the Great Dyke. These faults have a steep dip and have relatively small throws hence are not necessarily detected during exploration. It can be anticipated that these faults and associated sympathetic joints have become prominent as mining progressed, resulting in poor ground zones around the fault zones. Advance horizontal borehole drilling should be used to predetermine the positions of these faults before mining approaches the area where they exist. Methane gas pockets can be found in geological structures hence the need for adequate ventilation bases on anticipated methane intersections (Mkhabela and Manzi, 2017). Footwall faults exist in some areas that occur within the footwall of the MSZ. This feature consists of highly altered, mylonitised and brecciated plagioclase pyroxenite. The high strain central portion consists of slickensided, anastomosing mylonite, breccia, and infill containing talc, sepiolite, serpentinite and magnesite (Chaumba, 2017). No potholes are expected to occur in the MSZ succession within the research area. Xenoliths are less common in the Eastern area of the Great Dyke and are known to exist on the western side of the dyke. The xenoliths intersected underground are very irregular and variable in size. Current mining has intersected granitic dykes which are associated with the step faults and poor ground zones emanating from fault sympathetic jointing (Chaumba, 2017). The granitic dykes generally strike from East to West. Strategies to manage intersection of gas pockets will be described in detail in the next Chapters.

1.3 Regional hydrology and surface ambient conditions

In most of Southern Africa, the rainfall occurs during the summer months from November to March, with the peak rainfall occurring from December to February (Chifurira, 2018). The occurrence of ground water in the plutonic igneous rocks of the Great Dyke is primarily a function of fracture-controlled permeability, degree of weathering, and rainfall recharge. The characteristics of a fractured aquifer depend on the number, length, depth, openness and distribution of the fractures (joints), and on connectivity to zones of recharge (Chifurira, 2018). The gabbronorite hosts a seasonal aquifer that coincides with the rainy months, and this ground water has been noted to occur very close to surface. Aquifers are essentially restricted to the weathered zones. Most platinum mines assume that the groundwater conditions are dry, however it is critical for the mines to use hydrological surveys in a bid to have an actual picture of groundwater conditions. The presence of groundwater affects the humidity and density of the air which will concomitantly reduce the performance of main surface fans thereby increasing costs (Biffi, et al., 2007). Chifurira (2018) noted that the average wet bulb and dry bulb temperatures on Great Dyke mines are 20^{o}C and 32^{o}C respectively. The geothermal gradient in rocks of the Main Sulphide Zone which immediately overlie the platinum reefs, is remarkably constant at 20.7 ± 1.3 K/km (Jones, 2018). The surface barometric pressure averages

88kPa at most operations. Due to the shallow depth of mining and the selected room and pillar mining method, no refrigeration requirements will be anticipated on most Great Dyke platinum mines during their life-of-mine.

1.4 Mining Operations Overview

All platinum mines on the Great Dyke are mechanised, with most operations carried out at depths which are less than 400m below the surface. The mining method used and the cyclic nature of drilling, blasting, lashing and supporting are all described in this section. Ventilation design needs to be sound in a bid to create thermally acceptable environmental conditions with airborne pollutants below OELs. Other platinum mines are considering automating (driverless) underground mobile machines which will have a positive impact on ventilation requirements and this will be described in detail in the next chapters.

1.4.1 Mining Method

The room and pillar mining method is currently utilized by all Zimbabwean platinum mines in layered orebodies to exploit resources. The mining operations are carried out from the main decline, advancing in the strike direction. The main decline divides the mine into two regions, the northern part and the southern region for all platinum mines. The size of the rooms mined varies with mining height, depth below surface and most important, ground quality for each mine. The target factor of safety for in stope pillars is 1.6. At one mine, 15m rooms are mined out in good grounds and 6m wide stopes are mined out in weaker ground conditions. The stope height is maintained at platinum peak to avoid PGMs dilution. Regional pillars which measures 10m long by 3m wide are left unmined and are separated by 6m ventilation holings. In the case of poor ground conditions, twin gullies ,which are 6m wide stopes, are mined leaving in-situ pillars of 3m by 3m. Drives are developed from the main decline to the working areas. Figure 1.5 shows the standard mining layout in good ground conditions for one of the mines. 15m rooms are mined out and regional pillars are left out for support. The 6m gulley leads the 9m panel by an advance of 3m.

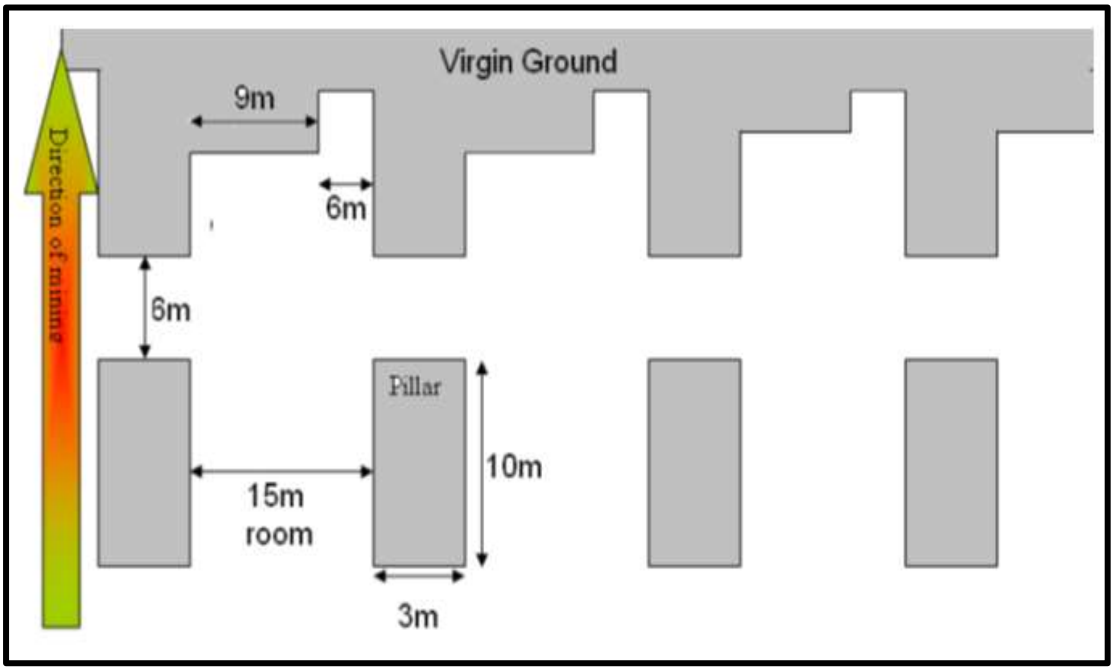

Figure 1.5: Mining layout in good ground conditions

Figure 1.6 shows the standard mining layout used in poor ground conditions at one of the portals. Twin rooms which are 6m wide are mined out and 3m by 3m in-situ pillars are left out between the twin gullies. Regional pillars of 10m by 3m are also left unmined outside the boundaries of the twin gullies. The mining layout shown in Figure 1.6 will be predominantly used in examples provided in this thesis since most of the research will be conducted in poor ground conditions.

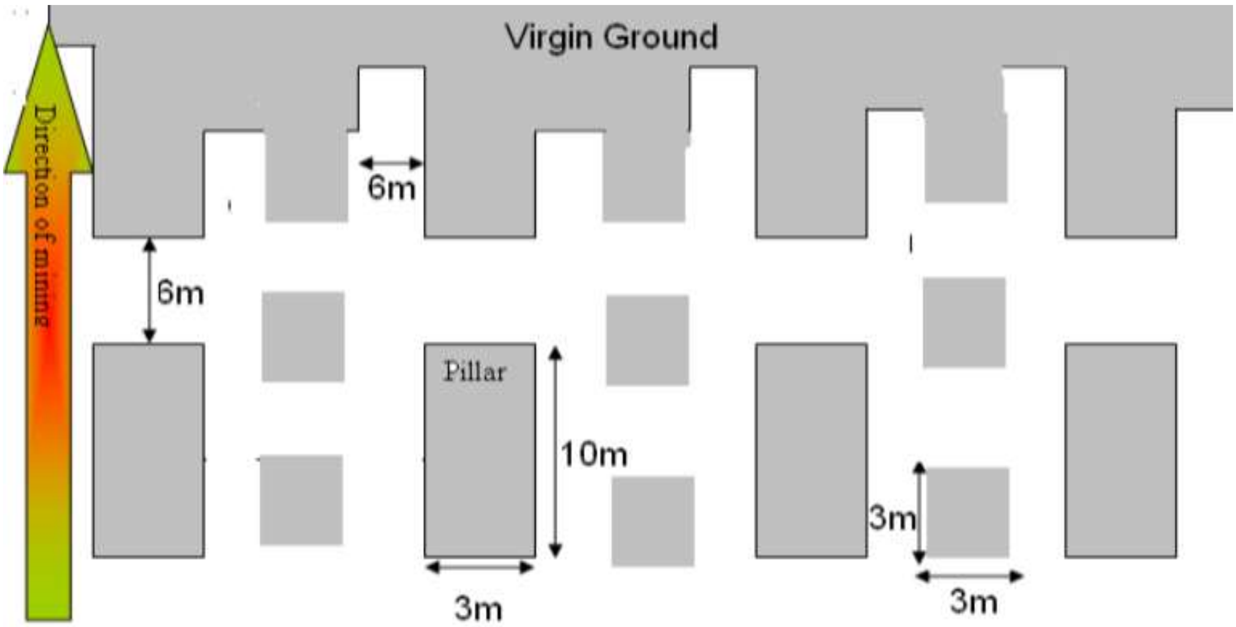

Figure 1.6: Mining layout in poor ground conditions

1.4.2 Drilling

All platinum mines, where the research was carried out, are mechanized. Drill rigs are used to drill holes with a diameter of 45mm. At one mine, 51 holes are drilled with three of these holes enlarged to 102mm to give a second free face. A 9m panel or a 6m gulley is first marked after being cleaned up by Load Haul Dump loaders (LHDs) and after all support installation has taken place.

1.4.3 Charging and Blasting

All platinum mines on the great Dyke make use of a centralised blasting system to reduce the risk of employee’s exposure to blasting fumes. Shock tubes with detonators are used in conjunction with nitroglycerine cartridges to form primers. Ammonium Nitrate Fuel Oil (ANFO) is then used to charge the drilled holes. ANFO is a high energy explosive and its effects on air quality and ventilation requirements will be described in the next sections (Maranda, 2011). For bord and pillar mines, the upper parts of the ore body are mined out first in a Christmas tree shape and this mining sequence plays a vital role in ensuring an adequate ventilation system (Biffi, et al., 2007).

1.5 Current Ventilation systems

All mechanised platinum mines use drilling and blasting techniques to break the rock and use mechanised equipment for crushing ore and for ore logistics. The mines are ventilated using an ascensional sequential system. The ventilation requirements are based on diesel dilution and heat load considerations. A greenfield case study will be presented with a footprint mining area of 6km along strike and 2km along the synform and the maximum mining depth will be approximately 300m below surface. The air quantity required to ventilate bord and pillar platinum mines on the Great Dyke depends on:

- The number of production sections operating at the same time
- Heat load due to equipment used, virgin rock temperature, rate of production and extent of airways
- Dilution and removal of airborne pollutants after blasting
- Air leakage through seals and increased strike distances
- Secondary ventilation requirements such as underground crushers, workshops, conveyor declines and refueling bays which can be ventilated direct to the main return airway.

The current ventilation systems are based on provision of maximum uniform air capacity throughout the day irrespective of diurnal and operational cycles. Fourth industrial revolution techniques in ventilating the mines in response to the levels of airborne pollutants and temperature control were considered in this research in order to optimise the mining key performance indicators of safety, production and costs. Mined out areas are controlled by means of seals to isolate fresh air from foul air as well as to redirect fresh air to the mine workings. Ventilation walls are being constructed from bricks and shotcrete. Brattices are also used to regulate air into production sections. Breaching of these ventilation controls will result in air leakages hence they must be well constructed on level ground and must be intact. This thesis will highlight strategies in monitoring air leakages in bord and pillar operations so as to prevent exposure of workers to airborne pollutants.

Most mechanised mines use a negative pressure ventilation system to provide adequate fresh air (Hardcastle, et al., 2005). This is largely driven by main surface fans, ventilation shafts and decline spines. Auxiliary ventilation is also used in development ends in the form of line brattices, jet fans and force exhaust systems. Underground infrastructure such as crushers and workshops are developed from the main declines spine. These require additional air and this must be factored in during ventilation design. Ventilation doors are used to minimise short circuiting of air. In bord and pillar operations, there are a significant number of interconnected airways and high leakage circuits hence less resistance to air flow. The mines must also have an emergency preparedness and response plan which includes the use of self-contained self-rescuers, refuge chambers and a second egress strategy. The current systems will be analysed and improved through the use of fourth industrial revolution technologies.

1.6 Airborne pollutants and occupational hygiene systems

Various airborne pollutants are generated in underground platinum mines by a variety of sources which include the explosives used, naturally occurring gases from geological structures, fuels, trackless machinery and engine exhaust. Airborne pollutants currently encountered include dust, gases and diesel particulate matter (DPM). Dust is formed across the whole mining chain, during many activities such as drilling, blasting, loading, hauling, crushing and tailings disposal. Various airborne pollutants affect the health and safety of workers hence robust ventilation systems must be put in place to combat their hazardous effects. Most Zimbabwean platinum mines have adopted the limits set by the Mine Health and Safety Council of South Africa as well as regulatory bodies in Zimbabwe. The occupational exposure limits for various airborne pollutants will be discussed in detail in Chapter 2.

Sampling of airborne pollutants is currently being done periodically through time weighted average (TWA) values (Belle, 2018). There is an opportunity to consider real time monitoring of airborne pollutants with smart sensors coupled with an artificial intelligence of auto adjustment of the whole ventilation system to reduce the pollutants to acceptable values. The system will also be linked to the medical surveillance and also the human resources database. This thesis will discuss smart sensors technologies required to monitor and manage occupational related hazards. The mines are currently utilising traditional sampling techniques to monitor air borne pollutants. The gases which are currently monitored include methane, carbon monoxide, nitrous fumes, carbon dioxide and hydrogen sulphide. Gases are produced by blasting operations, emanate naturally from a) rock strata, b) mobile equipment and c) from welding operations. Strategies to manage noxious gases and flammable gases will be described in detail in the next chapters. Other airborne pollutants being monitored include dust and diesel particulate matter. All mines are currently using diesel powered fleets, however the downside of this is the emission of DPM which was recently classified as a Class 1 carcinogen by the International Agency for Research on Cancer and the World Health Organisation (Ping & Guang, 2017). This thesis will also discusses strategies required to manage DPM in mechanised bord and pillar platinum mines. At present, medical surveillance is being undertaken across all operations through periodic collection, analysis and reporting of data in order to manage occupational health diseases.

1.7 Current ventilation surveying techniques

Most platinum mines are still using long-established systems for measuring air quality and quantity. These old methods include, a vane anemometer to measure air velocity, whirling hygrometer for wet and dry bulb temperatures and humidity. Other traditional instruments for measuring occupational hygiene data include lux meters for light intensity, sound level meters for noise and the Dragger type portable gas detectors. With these instruments, measurements are taken at different points in the mine at monthly intervals. This has seen workers being exposed to extreme conditions in the mine because no one will be aware of the mine conditions at any particular instant in time. At high temperatures, the human body loses little heat to the atmosphere and this affects worker health and productivity. The generation of meaningful results using this old system is not possible and hence the need to use sensors to collect data in real time before triggering an automatic modulation of airflow to manage environmental conditions.

1.8 Problem statement

Global underground mining history is littered with tragic disasters resulting from inadequate ventilation. Southern Africa's incidences of fires, explosions and gas-related events in mines are a subset of this experience (MacNeill, 2008). As a result of these disasters, this research seeks to strengthen regulations, improve risk management competency and drive cultural change towards zero harm, with demonstrable success in injury rates. Four Impala Platinum personnel lost their lives underground at Impala Rustenburg 14 Shaft on the 22nd of January 2016 following a conveyor belt fire incident (Nicolson, 2016). The fire broke out in the conveyor decline and four employees were affected by noxious fumes while they were escaping to safety (Implats, 2016). Such ventilation disasters prompted the need to analyse and improve the current ventilation and monitoring systems on platinum mines operating on the Great Dyke of Zimbabwe. The current ventilation survey interval is unreliable as the collected data lacks continuity, thus it has a limitation to have appropriate qualitative data analysis considering that an underground atmosphere is ever changing due to factors such as the existence of heavy machinery, blasting operations, failure and maintenance of controls, etc. The application of fourth industrial revolution technologies to environmental monitoring is sought to minimise such incidents.

Poor ventilation design and/or inadequate monitoring results in a concomitant decrease in production, higher injury frequency rates, as well as high operating costs. Underground operations' ventilation energy requirements constitute a significant portion of mine energy consumption and total energy costs. Main surface fans have high power motors and they run continuous throughout the year. Integration of empirical techniques with numerical modelling will assist in achieving optimum ventilation design. This research encompasses the design of a mechanised greenfield room and pillar mine which will require vast amounts of adequate fresh air.

This enormous air demand coupled with high operating costs, also necessitated this research so that platinum mines can reduce operating costs through the application of 4th industrial revolution technologies. This research will present how engineering design principles can improve the performance and efficiency of ventilation appliances, resulting in reduced power consumption and operating costs taking into consideration the future of energy supply. Evaluation of ventilation systems for platinum mining on the Great Dyke is vital to identify the "bottlenecks" in the current practice. As part of this application of fourth industrial revolution technologies on ventilation designs and remote monitoring is of paramount importance for improved safety, cost and productivity.

1.9 Relevance of the research

Recent disasters in mine ventilation reflect the gap between the current systems and the goal push to achieve zero harm. More robust controls need to be investigated and implemented to avoid recurrence of such accidents hence the need to conduct this research to continuously improve the systems thereby saving lives. The solution to such disasters is being sought through the application of 4^{th} industrial revolution technologies to ventilation systems so that underground risks can be analysed for action in real time. Moreover, ventilation specialists are constantly reminded of the high capital and operating costs of ventilation systems, but decisions affecting the safe and effective operation of these systems are based on incomplete and imprecise information. This also comes at a time when increasingly stringent standards regarding occupational health and safety are being set hence the need to investigate the application of 4^{th} industrial technologies to ventilation design and monitoring systems.

The research has to be conducted because of the following:

- Need to identify limitations of the current ventilation systems for platinum mining and to propose essential recommendations.
- To ensure a healthy environment (dilution of hazardous substances) underground so as to improve the health and safety of the workforce and avoid occurrence of emergencies through online real time monitoring.
- The need to improve productivity by ensuring that the targets set are achieved, as required, through provision of acceptable ambient working conditions.
- Minimize energy consumption costs through ventilation on demand.

1.10 Research questions

- How effective are current ventilation systems and strategies as a universal solution to manage underground environmental conditions?
- Can fourth industrial revolution techniques be applied to bord and pillar platinum mines to optimise ventilation systems?
- What is the impact of ventilation optimisation on productivity, health and cost of ownership?

1.11 Scope of research

The scope involved the design and installation of a demand based ventilation system through the application of fourth industrial revolution tools which can be used in bord and pillar mines to reduce power consumption, increase productivity, improve health and safety of underground workers.

1.12 Research aim and objectives

The main objective is to analyse and improve the current ventilation design and monitoring practices thereby optimising the three key performance indicators of platinum mining which are safety, productivity and costs.

The other objectives include understanding the:

- Fundamental ventilation design;
- 4th industrial revolution;
- Developments in energy and energy conservation; and
- Combining these three aspects into one system

This will be done through:

- Reviewing the current ventilation design and monitoring systems
- Evaluation of the benefits of ventilation on demand versus traditional ventilation management.
- Determine how real time risk management can be achieved in mines.
- Automation of mine ventilation monitoring systems.

1.13 Research methodology

The research started with an extensive literature review on optimised ventilation design, occupational hygiene, environmental monitoring strategies, numerical modelling techniques and mine ventilation economics. A detailed methodology is given in Chapter 3. In order to get a detailed understanding of the existing ventilation systems, the research was carried out in underground sections, with an emphasis on those with poor ventilation conditions. Underground observations, recordings and data collection were undertaken in platinum mines operating on the Great Dyke. Desktop studies were also used to gather ventilation data from other platinum mines and also for VOD benchmarking studies. Observations were made in each section and the following parameters were measured and noted:

- Ventilation surveys (velocity, areas, pressures, temperatures, wet kata etc.)

- Ventilation monitoring strategies.
- Current explosives used at the mines

The results of these observations were analysed using ventilation engineering principles thus both empirical studies and numerical modelling will be used for optimum analysis of results. In this research, a ventilation on demand system for bord and pillar platinum mines was designed and installed a to minimize the redundant use of air in underground operations.

1.14 Structure of Thesis

Chapter 1- Introduction

Chapter one outlines the background and introduction to the research problem. It describes the Great Dyke geology, mining methods used, current ventilation design and monitoring techniques, problem statement, justification of the research, aims and objectives of the research, methodology and structure of the thesis.

Chapter 2 - Literature review

Chapter two reviews the literature applicable to this research. The various aspects of ventilation design through empirical techniques and numerical modelling are discussed along with the occupational hygiene systems and fourth industrial revolution application to ventilation design and monitoring.

Chapter 3 - Methodology

Chapter three details a comprehensive methodology implemented for this research. It will also include development of a conceptual model and the use of the system to make a decision in real time.

Chapter 4 - Case study: Ventilation design for a Greenfield underground hard rock mine bord and pillar mine

This chapter gives an account of the case study used in air requirement considerations and the use of fourth industrial revolution technologies to validate assumption. Also included in this chapter are the financial analysis, sensitivity analysis and ventilation projects management.

Chapter 5 – Ventilation optimisation through digital transformation

This chapter reveals strategies in ventilation surveys, air borne pollutants management as well as sampling techniques. Also included in this chapter is the future of ventilation by incorporating various mining initiatives which include ventilation on demand, the use of electric fleets replacing diesel powered machines, the use of tunnel boring machines as opposed to drilling and blasting, etc. This chapter also describes the designed and installed system components and the results gathered from the system

Chapter 6 - Conclusion and Recommendations

This chapter gives the findings of the research, highlights the conclusions drawn, limitations of the study and the recommendations that emerge from this study.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Mine ventilation is a critical discipline, where advanced control strategies can bring major improvements in terms of cost, production and safety. Recent studies have shown that the ventilation system in highly mechanized platinum mines could be responsible for 40-60% of the mines' energy consumption (De Souza, 2018). Although the concept of ventilation in underground mines may seem relatively simple, getting the right quantity and quality of air to where and when it's needed in an expanding mining environment is an elaborate operation that requires an array of ventilation components. Typical ventilation systems consist of main surface fans, air regulators and doors that distribute air through the mine (Walters and Roman, 2014). There are also auxiliary systems that ventilate local production areas and workshops. Air requirements in an area depend on its location, the number of people there and the number and type of machines in use. The primary objective of any ventilation system is to ensure that adequate quantities of fresh air are provided in all sections of the mine thereby supporting all human activities. It is important to note that each mine has a unique extent, geometry and geological settings, and is affected by airborne pollutants related to the geological structure of the host rock, and to the mineral extraction strategy. As a result of such differentials, the corresponding patterns of airflow through airways of these underground operations are quite variable. Ventilation also plays a crucial role in diluting and removing gases, dusts and particulates that are encountered or produced in all underground workings (Grau, et al., 2004). This includes naturally occurring gases such as methane and pollutants resulting from blasting and the operation of diesel equipment. The air quantity required is dependent primarily on being below values in artificial environments as stipulated by Zimbabwean legislation or good practice. The provision of adequately effective ventilation regimes is intended to restrict gas concentrations to well below OELs. Ventilation is also necessary to remove heat emanating from various sources thereby creating acceptable environments (Grau, et al., 2004). Poor ventilation design can result in production losses, high costs of reconstruction, poor environmental conditions and tragic consequences to the health and safety of the workforce (Nixon T, et al., 1983). This thesis seeks to develop new ventilation control strategies for mechanised board and pillar platinum mines on the Great Dyke of Zimbabwe. The development and use of new mining technology have increased productivity, and these developments have also coincided with a general improvement of the work environments of the mining industry (Loow, 2022).

2.2 Fourth industrial revolution

Kumar, et al. (2019) described the internet of things as a network of objects rooted with sensors, software, communication backbone and computer capability that can collect and exchange data using connectivity for smart solutions. The fourth industrial revolution has been evolving for many years and has created an ever-increasing incentive for mining companies to embrace digital transformation in order to optimise mining key performance indicators. Internet of things, artificial intelligence and data analytics are all components of the fourth industrial revolution and have impacted on the way companies operate (Kumar, et al., 2019). Most mining companies are scoping to harness such emerging technologies and others have been proactively exploring fourth industrial revolution solutions over the last decade (Cawood, 2019). The ventilation sector seems to be moving slowly towards this automation trajectory. Substantial benefits and efficiencies are expected from the implementation of fourth industrial revolution techniques. Cawood (2021) pointed out that fourth industrial revolution technologies have predominantly lucrative features in the mining industry. A lot of work has been done in other mining activities such as the exploration field which has seen some development of sensing technologies to model geological deposits (Abrahamsson, et al., 2009).

Most mining companies particularly in the gold and platinum sectors have been struggling due to the longer term depressed commodity prices (despite more recent improvements) hence a paradigm shift from conventional or mechanisation to automation will be essential. Some fruitful gains from digital transformation include time-saving, lower energy costs, improved health and safety of employees and predictive maintenance which will subsequently improve machine availability (Jacobs, 2016). The application of fourth industrial revolution technologies to ventilation systems will mitigate the volatile and complex challenges that will inevitably be experienced in future mining. Without automation, the mines will fail to mine complex ore bodies and withstand depressed commodity prices, both of which will have a negative impact on the Zimbabwean economy thereby culminating in a failure to exploit the country’s resource in the long run. Odendaal (2019) highlighted that the mining industry is the heartbeat of the African economy hence the need to embrace digital transformation in all mining operations.

Odendaal (2019) pointed out that there is a gap that needs to be bridged in the mining sector on fourth industrial revolution technologies. Other sectors such as agriculture are already at the forefront of automation adoption to optimise leading indicators while there is a decline in performance indicators in the mining sector, despite being at the dawn of a technology revolution. It is imperative to adopt digital transformation throughout the whole mining value chain to improve processes aligned to value. Cawood (2019) highlighted that digital transformation in the mining industry should be anchored on automation, decision support and analytics. Matthews (2020) pointed out that a drive towards application of fourth industrial revolution techniques is mainly attributable to a changing global demand, market volatility and increased costs. Ventilation being a critical aspect of any underground mining operation should therefore not be spared because it accounts for a greater proportion of power costs and has a bearing on the health and safety of employees. With mining operations becoming more difficult and new technologies being introduced to exploit resources, it is critical to have sound and efficient ventilation systems that can sustain the required productivities within desired cost margins (Bliss, 2018). Digital transformation in mine ventilation will provide a great insight into safety, process and performance. There is still little clarity on how fourth industrial revolution technology will unfold and its overall bearing on ventilation systems (Acuna and Allen, 2017). An optimised ventilation system was developed and installed for trial purposes at one of the Zimbabwean platinum mines and will therefore be used as a base case for illustrating the benefits of ventilation on demand systems.

The Fourth Industrial Revolution will bring about data-driven planning, control, and decision-making tools (Hermanus, 2017). The mining industry needs to timeously adopt digital innovations to improve safety, operational efficiency, profit margins and to remain competitive in an evolving world. Cawood (2019) pointed out that more research is required to address the following mining challenges:

- To get communication backbone networks that work from a complex, hostile underground environment to control rooms and back to underground workings in real time;
- To locate where employees and equipment are in the mine and their proximity to risk – in real time;
- To have the computing power to combine sensors systems and software for advanced analytics to identify and address risks in real time; and
- Drifting from alarms on key risks to decisions in real time

The current ventilation systems lack visibility to online remotely accessible real time accurate information. This hinders the ability to monitor and track resource performance and optimise equipment uptime. More complete, timely, and insightful information and leading indicators enables leadership and frontline teams to intervene more proactively through the use of smart sensors. The primary outputs of fourth industrial revolution technologies to ventilation are:

- Centralised management of quantitative and qualitative exposure assessment data to clearly identify hazards and evaluate risks remotely.
- Provision of online real time processing and analysis tools
- Leverage business intelligence tools such as smart sensors through communication backbones such as Wi-Fi.
- Ensure statistical validity and quality assurance of ventilation surveys and monitoring data.

2.2.1 Mining technologies

The introduction of intelligent systems to underground mining can provide a significant improvement in the performance of a mine when compared to conventional mining techniques (Baiden, 2001). There is a thrust in the mining fraternity for continuous advancement in technology to optimise all mining key performance indicators of costs, safety and productivity. Several initiatives are being considered hence the need for ventilation departments to embrace technology as well as to prepare for such mining changes which will subsequently affect the ventilation design and mining practices in the future.

Cawood (2019) highlighted that digitalisation, sustainability and automation will have a huge impact on the future of the mining industry. The core of a social licence to mine is through sustainable operations with reduced health and safety risks. Several mines have transitioned from conventional techniques to mechanisation and now the vision is to embrace digital transformation through the application of fourth industrial revolution technologies (Cosbey, 2019). Some companies have started to replace diesel equipment with battery electric vehicles. The future of ventilation will be based on phasing out of traditional sampling techniques and replacing them with smart sensors. In addition, as mining reserves become depleted, mining becomes more onerous hence the need to apply fourth industrial revolution to mining applications thereby creating a safe working environment. All these changes must dovetail with ventilation systems to reduce ventilation related accidents. This thesis thus discusses the future of ventilation.

Cawood (2019) described the internet of things (IoT) as a network of objects rooted with sensors, software, communication backbone and computer capability that can collect and exchange data using connectivity for smart solutions. The fourth industrial revolution has been evolving for many years and has created an ever-increasing demand for mining companies to embrace digital transformation in order to optimise mining key performance indicators. Internet of things, artificial intelligence and data analytics are all components of fourth industrial revolution and have impacted on the way companies operate (Cawood, 2019). The ventilation sector seems to be moving slowly towards the automation trajectory hence the need for this research. Substantial benefits and efficiencies are expected from the implementation of 4IR techniques. Odendaal (2019) pointed out that fourth industrial revolution technologies have predominantly lucrative features in the mining industry.

Some fruitful gains from digital transformation include time-saving, lower energy costs, improved health and safety of employees and predictive maintenance which will subsequently improve machine availability (Khawaja, 2022). The application of fourth industrial revolution technologies to ventilation systems will mitigate the volatile and complex challenges that will inevitably be experienced in future mining. Mining companies can be exempted from re-entry periods through automation since conducive environments suitable for 24hour operations can be achieved.

It is imperative to adopt digital transformation throughout the whole mining value chain to improve processes aligned to value. Tapia (2020) highlighted that digital transformation in the mining industry should be anchored on automation, decision support and analytics. With mining operations becoming difficult and new technologies being introduced to exploit resources, it is critical to have sound and efficient ventilation systems that can sustain required productivities within desired cost margins (Bliss, 2018). Digital transformation in mine ventilation will provide great insight into safety, process and performance.

2.2.2 Case studies of mines that have embarked on digital transformation

The expectations for fourth industrial revolution technologies are very high particularly due to a current dip in productivity at many mines , depressed metal prices and the ongoing review of health and safety regulations. Automation strategies have been put forward as a momentous stride so that mining companies can improve productivity within the space of a few years after adoption. Creamer (2018) noted that autonomous dump trucks introduced at an opencast coal mine in South Africa yielded a 100% increase in productivity in 2018. In addition, Syama gold mine in Mali also embraced machine learning with its fully autonomous fleet comprising of trucks, loaders and drills (Odendaal, 2019). Anglo American developed a robotic rock cutting mechanism in underground operations. The developed system is continuous and enhanced, through machine leaning, with a potential 20-30% increase in productivity at steady state operation (Odendaal, 2019).

There has been a significant thrust in mining operations to embrace automation, however, there is a stagnant situation or little traction in optimizing ventilation systems. The expectation from the mining industry is to improve productivity and reduce operating costs by up to 30% (Odendaal, 2019). Underground mines are also set to benefit from fourth industrial revolution techniques to mine with better health and safety procedures in place. Odendaal (2019) noted that the environmental load of mechanical equipment used in mechanised mines poses a huge safety and operational risk hence fourth industrial revolution techniques will assist in terms of predictive maintenance and real time monitoring of underground conditions. It is imperative to design systems that can monitor and forecast environmental conditions using machine-learning based predictive technology. Several conferences and seminars have been hosted to delve deeper into the issue of fourth industrial revolution techniques in mining. Odendaal (2019) asserts that the mining industry is responsible for driving fourth industrial revolution technique to reduce costs, extract higher grades, improve health and safety of employees and optimise underground mines. There is still little clarity on how fourth industrial revolution technology will unfold and its overall bearing on ventilation systems. This research describes the ventilation optimisation process through digital transformation. A ventilation on demand system was designed and successfully installed in the research area. The developed system will enhance the health of employees, improve productivity and reduces operating costs.

2.3 Ventilation strategies

The orebody in the research area is narrow and tabular with a width (thickness) ranging from 2m to 3.5m. The mining operation involves mechanised drilling and blasting which entails that most workers operating in active production and development faces will be exposed to numerous hazards which include dust, gases, diesel particulate matter (DPM) and heat. To minimise the risk of gassing incidents, all blasting operations and a safe re-entry period need to be synchronised and observed rigorously (Wu, et al., 1991). Most mines in this research are using centralised blasting systems to limit the possibility of worker exposures to blasting fumes. The bord and pillar mining method is currently utilised by all mining operations to extract platinum reserves in the research area and the principal mining direction is on strike from the central decline positions towards the extremities of the orebody. It is important to note that mining follows an upside down Christmas tree shape by depleting the upper portions of the orebody first before mining bottom sections on dip as shown in Figure 2.1.

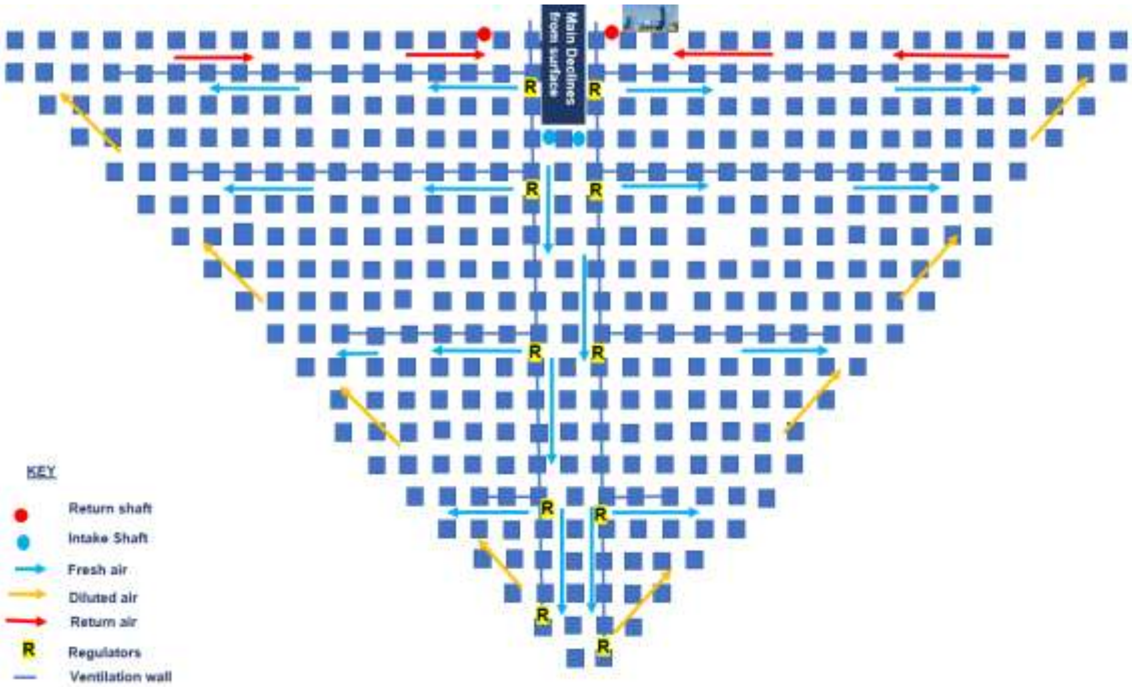

Figure 2.1: Schematic plan for board and pillar mining operations

Phillips and Rawlins (2005) pointed out that the ventilation infrastructure and associated air quantities for mechanised underground operations are based on the following parameters:

- Number of active panels in the mine
- Heat loads arising from rock temperature and operation of underground equipment such as Load – Haul – Dump machines (LHDs) and dump trucks
- Rate of production
- Utilised diesel engines
- Post blast re-entry periods based on adequately attainable gas dilution requirements
- Air leakage particularly through seals and mined out areas
- Dust and fumes extraction systems feeding directly to the exhaust airway system
- Ancillary ventilation requirements and strategies related to ventilating hazardous areas such as conveyor haulages and underground workshops

The primary ventilation strategy for a bord and pillar mining method consists of an ascensional sequential system whereby fresh air is delivered to all sections. Bord and pillar operations employ extensive blasting to fracture the rock and require mechanised equipment to transport, crush and hoist large tonnage of ore (Biffi, et al., 2007). The daily cost of operating a ventilating system is directly proportional to the frictional resistance of the network, which in turn depends on the geometry and dimensions of airways, the quality of excavations and the manner in which airways are connected. Typically, air utilisation for bord and pillar operations ranges between 40% and 70% hence the need to have a sound monitoring system to identify and correct any leakages in the system (Du Plessis & Biffi, 2014). Air utilisation (% usefully utilised) decreases as mining progresses due to increased pressure differentials and more mined out excavations which need to be sealed.

Wallace, et al. (2015) noted that there are basically two types of mine ventilation; that is natural ventilation and artificial ventilation. Natural ventilation involves the supply of air to the underground workings due to pressure differences (caused by the density of cool air descending and the density of hot air returning to surface) without the use of ventilation fans. Artificial ventilation encompasses the use of mechanical infrastructure such as main surface fans to create a pressure difference. All mines in the research area primarily rely on artificial ventilation with most primary fans situated on surface. Adequate ventilation is maintained through a negative pressure system whereby main surface fans draw foul air from the underground workings thereby creating a negative pressure. Fresh air will then flow into the mine through downcast shafts and access declines. It is critical to ensure that a sound ventilation system is maintained to sustain the life of mine production. This thesis will provide an optimum ventilation design for hard rock bord and pillar mines as well as an automated environmental monitoring and control system. It is always imperative to ensure that underground employees are not exposed to occupational hazards presented by airborne pollutants. Requisite controls must be put in place in order to maintain conducive underground conditions.

2.4 Mine health and safety statistics

The South African Department of Mineral Resources (DMRE) (2019) highlighted that the number of mining fatalities has significantly improved from historical tragedies which claimed many more lives. However, despite a lot of effort and technologies being incorporated in the mining sector, the industry continues to record a number of fatalities on a yearly basis which impedes the objective of achieving zero harm. All mining companies have an obligation to protect the health and safety of all their employees for sustainability of their operations. DMRE (2019) noted that poor health and safety records in mining operation pose a potential reputational risk, decreased productivities and additional costs to any organisation. Dhillon

(2010) noted that over 55% of global mining fatalities are attributable to flammable gas explosions and added that about 20% of the accidents are attributable to fires. Most ventilation fatalities are a consequent of accumulation of gases, poor environmental monitoring strategies, late evacuation of affected employees and inadequate ventilation (Dhillon, 2010). Mining accidents have a negative effect on the businesses as they result in productivity reduction, increase in litigation costs and may cause reputational damage to the mining house. In the event of explosions and fires, more capital costs will be incurred to replace the damaged infrastructure. It is against this backdrop there is a need to apply fourth industrial revolution techniques to monitor environmental conditions thereby mitigating the risk posed by underground fires and/or explosions. The DMRE (2019) recommended all mining companies utilise strategies that identify, assess and manage underground risks. Bonsu et al. (2017) pointed out that revenue worth billions is being lost in South African mines due to the frequency of accidents.

Harris (2020) pointed out that a reporting culture is imperative for root cause analysis of accidents in high risk industries. Underground mining is considered to be a high risk due to the nature of the operating environment. Most accidents occur after employees have identified the risk, however there is a need to eliminate human reliance during risk identification and control hence the need to embrace forth industrial revolution technologies. Mining accidents in Russia are said, amongst other things, to be have been caused by inadequate ventilation and accumulation of gases (Harris, 2020). The Zimbabwean mining industry, has been reacting slowly in the journey of embracing technology. Most of the mines in Zimbabwe are currently using traditional technologies to monitor airborne pollutants. A sound environmental monitoring system coupled to ventilation on demand can detect and act to reduce pollutants without human reliance. Real time environmental monitoring of air quality, noise, dust and gas has the potential to make a significant difference in the mining industry. This approach is expected to reduce the number of occupational health diseases and eliminate ventilation related fatalities.

2.4.1 Recent Southern African major ventilation incidents

Fires that develop in underground operations present significant hazards to employees. A number of underground fires have occurred in the Southern Africa industry in recent years and these have led to multiple fatalities and significant infrastructural damage. Underground fires are mainly caused by accumulation of gases and can also occur in conveyor belt structures (Du

Plessis & Biffi, 2014). Most notable underground fire incidents include the Northam conveyor fire (which happened in September 2004) where nine employees lost their lives, the Impala 14 Shaft fire (which occurred in January 2016) where four employees died and lastly and most recently the Palabora conveyor fire (which happened in July 2018) and which resulted in the death of six employees (DMRE, 2019). It is important to note that these aforementioned three major incidents happened in the last two decades. Key learnings from the abovementioned incidents include the need to improve on monitoring and management of environmental conditions. Other learnings include the need to automate ventilation systems from the design stage. In order to avoid recurrence of such fire or gassing related incidents, a sound monitoring strategy is required in the form of automation to all environmental monitoring systems. This thesis applies forth industrial techniques in ventilation systems to mitigate ventilation related incidents.

2.4.2 Russia coal mine explosions

The global mining industry is littered with tragic incidents such as methane explosions and or gassing incidents. Recently, the Russian coal mining industry recorded a series of methane explosions which claimed several lives. In February 2020, 36 lives were claimed at a coal mine in the northern town of Vorkuta in Russia (Shtokal, 2016). Despite having a low risk of methane explosions in platinum mines, several platinum mines have recorded methane gas intersections resulting from exposed gas pockets. In 2010, about 91 people were again killed due to methane explosion in Raspadskaya mine which is in Russia (Kurlenya, 2017). It is sensible to apply fourth industrial revolution techniques which monitor flammable gases, unventilated areas as well as conveyor belt operations to mitigate risks posed by flammable gases. The Russian authorities pointed out that all methane explosions recorded in the last two decades were attributable to a sudden release of methane which was ignited by mechanical means (Shtokal, 2016). The Great Dyke is infested with geological disturbances such as faults, dykes and shear zones and these can be potential sources of flammable gasses such as methane. It is important to note that as mining progresses in the research area, there has been an increase in geotechnically challenging ground conditions which actually requires diligent gas monitoring strategies to mitigate the risk posed by methane gas. Shtokal (2016) noted that one of the most common findings highlighted by the Russian investigation teams following the recent explosions is the over reliance of men to record gas readings. Underground employees can tamper with ventilation monitoring instruments in order to meet their set productivity targets.

It was also noted that the methane build up at Vorkuta in Russia was further exacerbated by an earlier collapse of a ventilation roadway which resulted in ventilation inadequacies in that particular area (Shtokal, 2016). Through fourth industrial revolution technologies, it is to be hoped that any resistances or leakages in the system will be flagged and corrected without delay. It is important to continuously monitor atmospheric conditions such as dust, noise, DPM, humidity, gases and airflow in all mining operations. The long-term stability of all mining operations is dependent on the health and safety of workers.

2.4.3 Hwange explosion disaster

In Zimbabwe, the Hwange coal mine disaster took place on 6 June 1972 when a series of underground explosions occurred at the Wankie No.2 colliery (Edgecombe, 1990). With 427 fatalities, it remains the deadliest mine accident to date in the country's history. Historical records established that the accident was caused by an underground methane/dust explosion and despite several attempts by the mine rescue team to rescue mine workers, the severity of the disaster was such that the mine shaft had to be sealed off (Edgecombe, 1990). This disaster was a wake-up call to all Zimbabwean mining operations to put in place proactive measures to negate the effects of poor ventilation and underground fires. Several lessons were learnt from these disasters and ever since, there have been significant strides in managing ventilation risks.

Casey (2020) pointed out that the mining industry continues to be the mainstay of the Zimbabwean economy, with mineral exports accounting to 60% of Zimbabwe's export earnings as of October 2018. In addition, Casey (2020) further stated that the mining sector contributes around 16% of national gross domestic product (GDP). The Zimbabwean government has also planned to quadruple the mining sector's total value contribution to US$12 billion by 2023 as it sets out to explore abundant natural resources on the Great Dyke (Casey, 2020). The Great Dyke is the second largest reserve of Platinum group elements (PGEs) globally following the South African Bushveld complex (Oberthür, et al., 2012). Because of the criticality of the mining industry to the Zimbabwean economy, proactive measures must be in place to ensure smooth continuity of operations through sustainable measures thereby managing and controlling the health and safety of all employees. It is a mandate of every employer to ensure that all health and safety risks are managed in a logical way thereby improving shareholder returns through optimised productivity, costs and safety. The application of fourth industrial revolution technology to ventilation systems is expected to show a sustainable downward trend to the number of occupational diseases, injuries and fatalities.

2.4.4 Occupational fatalities

Figure 2.2 shows fatalities trend recorded in the last two decades in the South African mining industry. From the graph, it can be noted that there is a downward trend in the number of mining fatalities as a result of improved strategies implemented in the mining industry. The DMRE (2019) highlighted that the major causes of mining fatalities are falls of ground, inadequate ventilation, transportation and mining practices. South African statistics was used due to data availability and such information is relevant to platinum operations in Zimbabwe as they are operating within the same domain.

Figure 2.2: Occupational fatalities in the South African mining industry *(DMRE, 2019)*

The South African mining industry recorded the lowest ever number of fatalities in 2019 due a collective effort to improve safety. The South African mining industry has continuously recommitted to the shared aspiration of zero harm, which aims to ensure that mineworkers return home from work unharmed every day (Liedtke, 2019). However, zero harm has not been achieved yet particularly in underground operations hence the necessity to monitor and manage ventilation risks through the application of fourth industrial revolution technologies to environmental monitoring and ventilation design. The health and safety of employees remains a key priority for sustainability of mining operations (Liedtke, 2019). The DMRE categorised fatalities recorded in 2019 for each mining sector as shown in Figure 2.3. "Other sector" in Figure 2.3 encompasses diamonds, chrome, copper, zinc, sand, lime, granite, manganese, nickel and bricks.

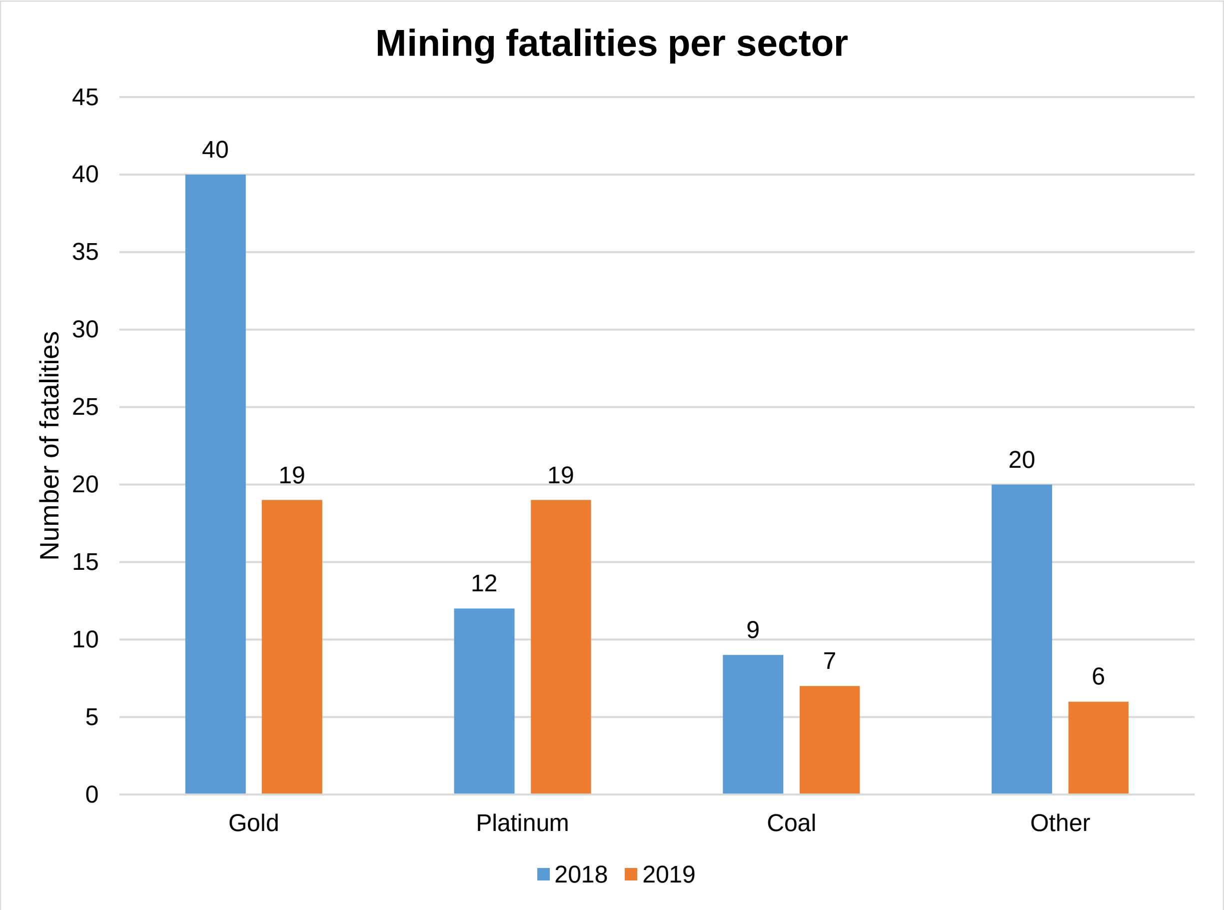

Figure 2.3 : 2018/2019 Mining fatalities per sector *(DMRE, 2019)*

Figure 2.3 shows that there was a significant safety improvement in most sectors except for a regression in safety performance for the platinum sector. This thesis outlines continuous improvement initiatives mainly related to ventilation design and underground environmental monitoring in bord and pillar platinum mines.

2.4.5 Occupational diseases and related deaths

Problems associated with potential lung disease as a result of exposure to respirable dust remain one of the major risks in South African mines (Biffi, et al., 2007). The Leon Commission of enquiry into the health and safety of mineworkers felt justified in concluding that there was no evidence to indicate a decline in prevalence of any occupational disease for the South African mining industry (DMRE, 2019). New ventilation strategies are therefore required to deal with serious occupational health problems particularly in ventilation design, environmental monitoring systems and medical surveillance. The DMRE (2019) highlighted that deaths recorded in the mining industry are mainly attributable to occupational diseases. In 2018, the platinum sector recorded three deaths, the gold sector recorded forty two deaths and lastly, the coal sector recorded two medical deaths and all of these were attributable to occupational diseases (DMRE, 2019).

The number of occupational diseases reduced from 4 483 in 2017 to 3 458 in 2018 (DMRE, 2019). In addition, the DMRE (2019) stated that silicosis from dust cases reduced by 29%, pulmonary tuberculosis statistics decreased by 24% and noise-induced hearing loss (NIHL) cases decreased by 22% compared to the previous year. This reduction in occupational diseases reflects a great commitment from mining companies to combat health risks. However, despite such improvements and initiatives being implemented, the mining industry has not achieved the main goal of zero harm as it continues to record new cases annually. Such statistics also apply to platinum mines in Zimbabwe as they operate under similar circumstances. In addition, most of the ventilation key performance indicators are following South African standards. This research plays a crucial role in improving underground conditions through monitoring and management of health and safety risks in Zimbabwean platinum industry.

Du Plessis and Belle (2014) pointed out that eliminating pneumoconiosis is a priority of the International Labour Organisation (ILO) and World Health Organisation (WHO). Figure 2.4 shows the number of pneumoconiosis cases recorded in Zimbabwe over the past two decades. Other industries shown in Figure 2.4 include construction, foundry grinding, power generation, asbestos, shoe and chemical manufacturing.

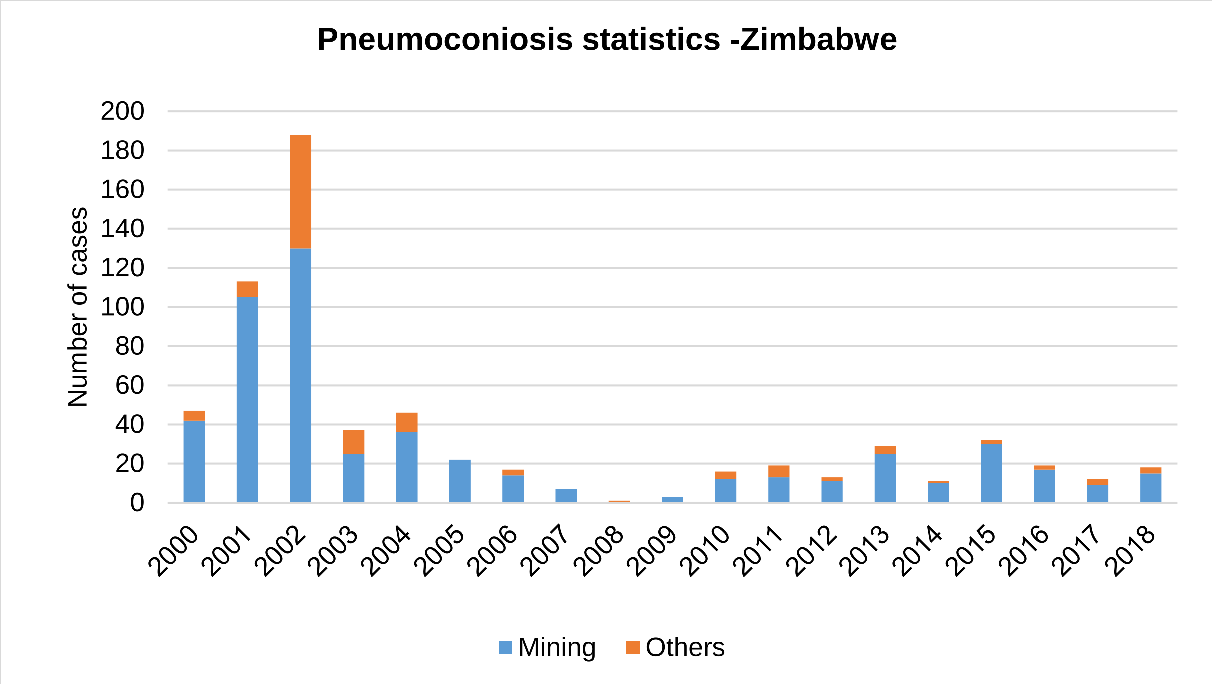

Figure 2.4: Pneumoconiosis statistics in Zimbabwe *(NSSA, 2019)*

From the above statistics, it can be noted that majority of pneumoconiosis cases were recorded in the mining industry. This is in agreement with public literature which acknowledges that the highest prevalence of occupational lung diseases lie in the Witwatersrand gold sector which is mainly influenced by the nature of the rock. Table 2.1 shows types of pneumoconiosis and their proportions in South African deaths between 2006 and 2015.

Table 2.1: Types of pneumoconiosis and their proportions in South African deaths between 2006 and 2015 *(Wilson, et al., 2019)*

Pneumoconiosis type	Number of deaths (%)	Median age (yrs)
Coal worker's	9 (2)	62
Asbestos and mineral fibres	152 (34)	74
Dust with silica	63 (14)	61
Inorganic dust	0	
Unspecified	182 (40)	68
With TB	44 (10)	57
Total	450	64

The most common reported pneumoconiosis was Unspecified although this group appears to contain some misclassified deaths. Those with pneumoconiosis and TB appeared to die at a younger age while those with asbestos and mineral fibres exposure died at a later stage as seen in Table 2.1. All mines in the research area conduct annual chest x-rays on all employees for pneumoconiosis screening. A gap between worker exposure and medical surveillance was identified since the frequency of medical screening is currently independent of actual exposure. With the application of fourth industrial revolution technologies, the medical database will be directly linked with actual exposure concentrations.

2.5 Ventilation design

In order to maintain adequate ventilation throughout the life of a mine, careful advance planning is critical. Wallace, et al. (2015) highlighted that advance ventilation planning considers two principal factors which are:

- The total volume flow rate of air required by the mine and its economic distribution,
- The pressure required by the mine fan(s).

A well-designed ventilation system should be effective, flexible, and economical. The research will integrate empirical techniques with numerical modelling for optimum ventilation design.

2.5.1. Empirical methods of determining ventilation requirements

The simplest approach for preliminary selection of primary ventilation quantities is based on the statistics of the air to tonnage ratio from past projects and existing mines. For example, for the large South African (RSA) gold mines, statistics indicate primary ventilation ratios ranging from low values of 3 kg/s of air per kiloton of broken rock per month to high values of 8 kg/s per kt/month, while for the large RSA platinum mines this ratio ranges from low values of 2 kg/s per kt/month to high values of 5 kg/s per kt/month (Bluhm & Smit, 2014). Figure 2.5 shows several factors that contribute to ventilation hazards and the corresponding control measures.

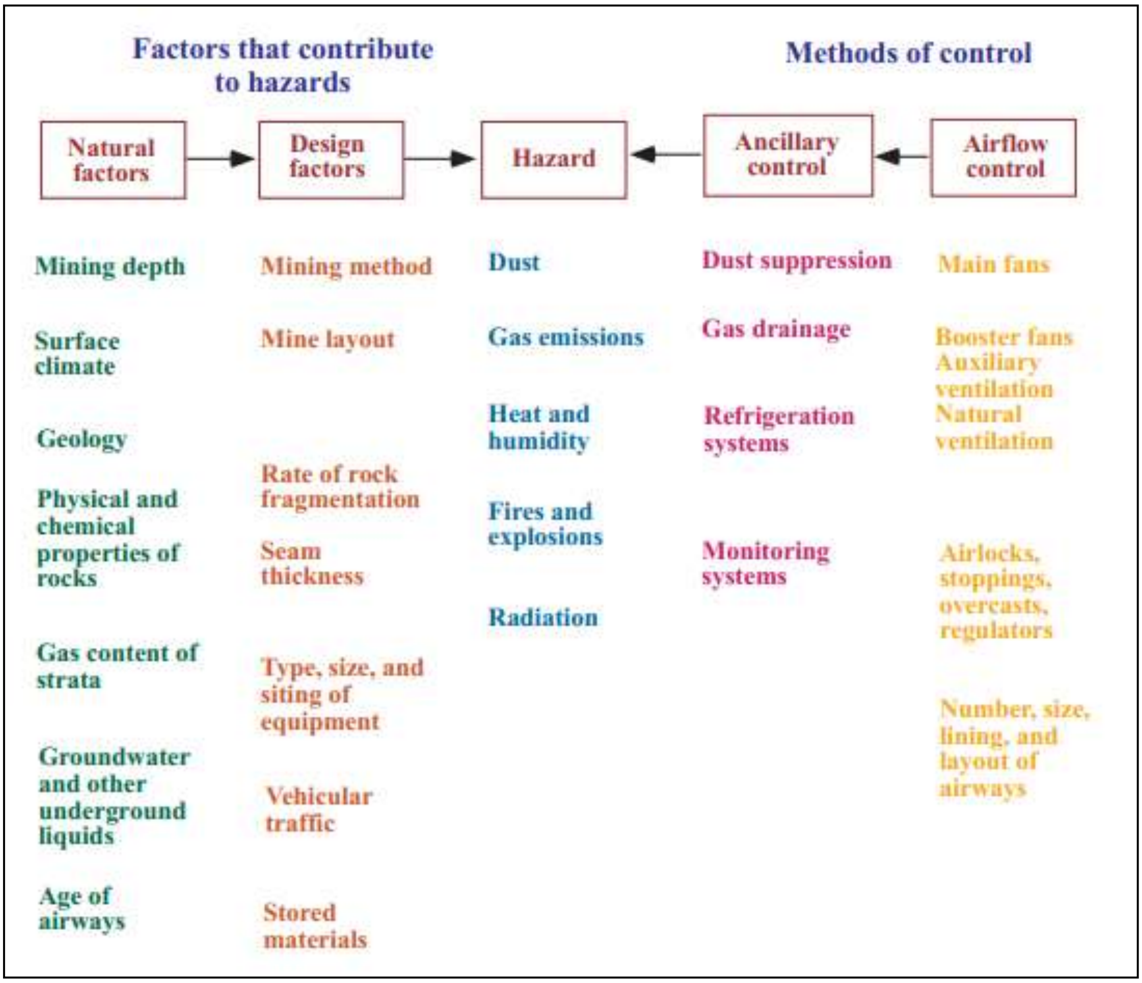

Figure 2.5: Ventilation design factors (McPherson, 1993)

The overall ventilation quantity requirements are generally dictated by the need to remove heat and blasting fumes or for the dilution of diesel emissions (Biffi, et al., 2007). It is important to note that in relatively low virgin rock temperature operations such as the research area, heat from diesel engines can be the critical issue in determining overall ventilation quantities. For diesel mechanised operations, another global approach considers diesel emission dilution criteria only. The research was conducted in shallow underground mechanised mines. The rule of thumb for estimating overall primary ventilation requirements for the dilution of diesel fumes is taken as 0.10 kg/s to 0.15 kg/s per kW (diesel rated) on a mine-wide basis (Bluhm & Smit, 2014). The initial step in designing a life of mine ventilation system in platinum mines is determining the total air quantity necessary for effective dilution of Diesel Particulate Matter (DPM) and other contaminants. Despite the existence of numerous noxious airborne contaminants, the principal hazard to health is DPM and thus ventilation design in platinum mines is geared to the need to dilute it (Bluhm & Smit, 2014). Du Plessis and Biffi (2014) pointed out that this factor includes service ventilation requirements and allowance for ventilation leakage [at final point of operation, specific dilution needs will be lower (typically 0.06 m^3/s per kW) depending on engine specifications and state of maintenance].

Minimum ventilation quantities can also be determined by reference to the relevant regulations which state required face velocities and quantities based on face areas. For example, RSA regulations for metal mines refer to the following minimum criteria i.e. 0.3 m/s average air velocity along stope faces, 0.15 m^3/s per m^2 of development face area (timed-blast), 0.50 m^3/s per m^2 of development face area (non-timed blast). The planner can apply these factors, carry out an overall audit and hence evaluate the primary (and secondary) flow requirements. However, planners must be aware that these are minimum values only and planning on this minimum basis for hot, hard rock mines will often lead to serious shortfalls. In highly mechanized metal mines the air volume requirements are usually based upon diesel exhaust dilution criteria such as 0.063 m^3/s per kW of rated engine power (Gangal and Grenier, 2002). In hot, hard-rock mines, heat dilution will generally require quantities in excess of these minimum amounts. Most Zimbabwean platinum mines use South African standards on ventilation design criteria where Zimbabwean regulations are silent.

In addition, the primary ventilation must provide air for service ventilation such as crushers, tips, workshops and pump stations. Provision for leakage throughout the mine must also be made. Air leakage depends on mine layouts but typically provision is made for losses of primary downcast ventilation in the shaft system and in the intake airways of about 30%.

2.5.2. Numerical modelling

Mining theory and techniques for designing and planning ventilation systems have evolved and modern approaches take full advantage of the availability of computer software. Ventilation simulation software packages are now an indispensable part of ventilation planning and design (Lilic, 1997). These enable the incorporation of both empirical and numerical modelling techniques in mine ventilation.

Numerical modelling is one method to estimate the flow rates in various entries. A numerical model of various ventilation scenarios shows that the number of main entries determines the effectiveness of the ventilation system (Marx & Butterworth, 2014). Numerical modelling can easily simulate several scenarios and assists in decision making. Ventsim software was used for optimum ventilation design during this research. Simulation software packages in mine ventilation are developed to assist ventilation engineers and practitioners during the planning and design stages and as well as during the lifetime of the mine. Their capabilities include development of simulation models of the current network and scenario modelling with different fans or controls in place. They also allow simultaneous modelling incorporating airflow, thermodynamic behaviour and gases or dust emissions (Kocsis and Hardcastle, 2004).

2.6 Ventilation sampling techniques and monitoring strategies

Ventilation surveys generally fall within one of the following types, that is point surveys for analytical decision making, routine surveys to establish compliance and continuous measurement within a monitoring system (Hardcastle, et al., 2014). The efficiency, economics and effectiveness of a ventilation system can only be analysed with confidence when the ventilation surveys are accurate and reliably done. Air velocity, quantity and pressure measurements are used to assess fan performance efficiencies and heating loads. Hardcastle (2014) pointed out that it is of utmost importance to ensure that analytical measurements are pre-planned and accurately performed. Du Plessis and Biffi (2014) highlighted that all survey measurements should be accurate to within ±5%. Most Zimbabwean platinum mines adopted this best practice, however, the actual surveys are outside the required range hence the need to apply forth industrial techniques to improve on accuracy.

The most common method to determine volumetric flow is the measurement of air velocity and cross-sectional area. Vane anemometers are widely used in the research area to determine air velocity. Various instruments are used to measure pressure or pressure difference in the mine system and such instruments are grouped into manometers and barometers (Hardcastle and Kocsis, 2004). One important aspect of ventilation is the effective and efficient distribution of air in any underground mine. Pressure surveys are conducted to measure pressure losses in an airway. Watrant (2008) pointed out that pressure surveys are conducted to prepare specifications for a new fan, investigate abnormalities in the ventilation flow, audit the ventilation system, determine the ability to cope with future production plans and to enable ventilation network analysis.

Ventilation surveys are done to acquire data that quantify distributions of airflow, pressure and air quality throughout the main flow paths of a ventilation system. Current instruments used in the research area for conducting ventilation surveys are explained in this section. Such instruments measure air velocities, air quantities, humidity levels, dust, noise levels, gas readings, pressure readings, resistance and air leakages. All mines in the research area are currently using traditional techniques when carrying out ventilation surveys. These surveys are conducted on a monthly basis and results obtained represents monthly atmospheric conditions. It is important to note that results obtained from monthly surveys are spot measurements hence they do not incorporate exceptional exposure readings which can be recorded during the course of the shift or month. This research focuses on application of fourth industrial revolution technologies to continuously monitor environmental conditions throughout the shift so that accurate and reliable readings can be obtained which can reliably inform decision makers. These techniques will have a positive impact for the mining industry in eliminating occupational related diseases. The current monthly survey results for the health of trackless mobile equipment do not currently fully analyse the state and condition of underground machines in real time, however, they can only flag the machine status at the point of survey which is normally after 30 days. This poses potential health risks to the workforce if a defective machine is continuously used throughout the month particularly if it produces airborne pollutants such as gases and diesel particulate matter in the underground workings without being noticed. The use of smart sensors to monitor trackless mobile equipment and underground workings will be discussed later in this thesis.

Traditional instruments currently used in the research area include whirling hygrometers, lux meters, noise level meters and vane anemometers. A typical whirling hygrometer shown in Figure 2.6 is currently used to measure wet and dry bulb temperatures of the atmospheric air. This instrument can also be used to determine the atmospheric humidity.

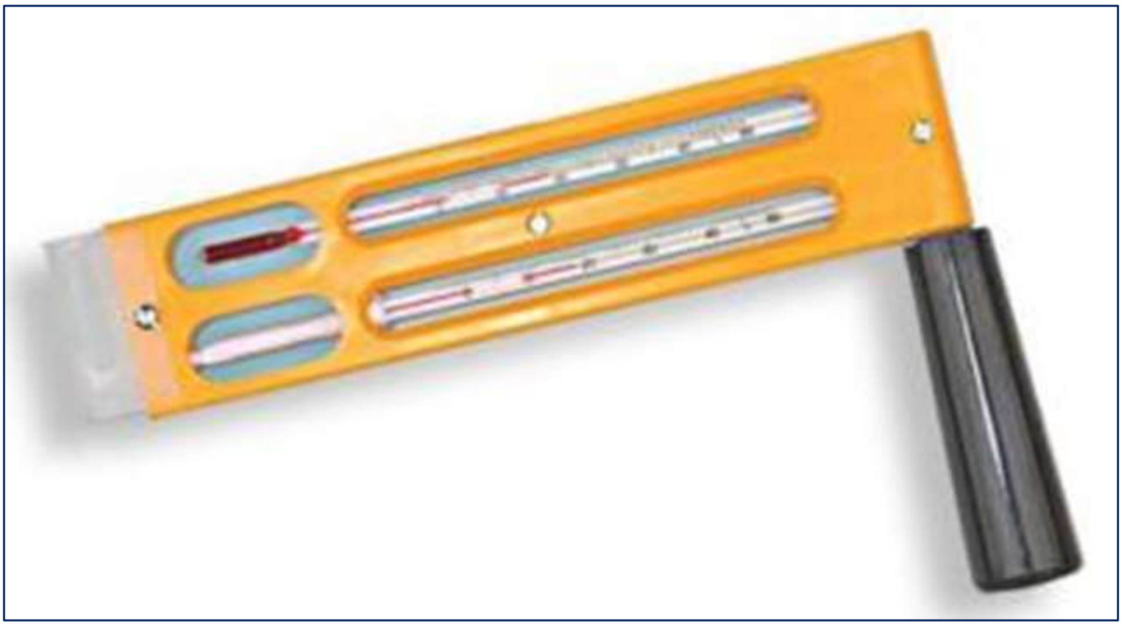

Figure 2.6: Whirling Hygrometer (Zeal Whirling Hygrometers Co, 2019)

Vane anemometers shown in Figure 2.7 are currently used to determine air velocities which in turn will be used in air quantities calculations. The total air quantity (m^3/s) is given by the product of cross-sectional area (m) by the measured air velocity (m/s) (Hardcastle, et al., 2014).

Figure 2.7: Vane anemometer (Sensing Precision, 2014)

Illumination also plays an important role when performing any underground mining operation. Inadequate lighting reduces visibility which may cause accidents in the mine. Luminance is measured in lux and lux meters are currently used to measure the amount of light in any environment.

Sound level meters are currently used to measure the amount of noise in all operations. Noise is measured in decibels and average time weighted noise levels must be kept below 85 decibels (Howes, et al., 2014). Figure 2.8 shows a typical sound level meter which is currently used to deduce noise levels in the research area.

Figure 2.8 : Sound level meter *(AMS Haden, 2020)*

Exposure to gases remains one of the major challenges in most underground mechanized platinum mines. Various activities generate both flammable and noxious gasses such as carbon monoxide, carbon dioxide, nitrous fumes, methane, ammonia and hydrogen sulphide. Portable handheld gas monitors (GDI's) are currently used in all mining operations in the research area to measure gas concentrations. Figure 2.9 shows a typical handheld gas monitor which is currently used by most mines.

Figure 2.9: Drager gas detector (Drager, 2020)

It is important to note that traditional techniques do not account for fluctuations in the system as they give time weighted average (TWA) values. Pollutants enter ventilation airstreams from various sources and the aim of any ventilation system is to dilute and remove pollutants to safe levels below the OELs. The most common types of pollutants encountered in mechanised bord and pillar operations include gases, dust, heat, humidity and particulates (McPherson, 1993). The primary method of controlling atmospheric conditions in any underground operation is by means of controlling airflow.

2.7 Gases

Gases are common forms of airborne pollutants in all underground operations (McPherson, 1993). These gases are normally classified based on their effects and properties. Sources of gases include blasting operations, trackless mobile machinery, natural sources such as sills, dykes and fissures, oxidation of timber, stagnant water, refrigerants and unscheduled occurrences such as fires. Gases have different properties hence they have different psychological effects on human beings. Some gases have mild effects while toxic gases have a potential to cause fatalities. Since its inception, the mining industry has been recording gassing and explosion incidents, however, there is a notable downward trend in the number of such accidents. There has been a significant improvement in terms of gassing incidents due to improvement in technology. However, despite implementation of several initiatives, the mining industry continues to record gassings. Most common gases found in the research area include carbon monoxide, carbon dioxide, nitrous fumes, hydrogen sulphide and oxygen. Compared to coal mines, platinum mines have recorded a small number of flammable gas intersection such as methane or hydrogen in underground operations. Despite having less methane intersections, all mines must continuously monitor the accumulation of such gases particularly when mining across geotechnically challenging ground conditions such as dykes and faults. Geotechnical structures present a risk of accumulating gas pockets hence sound mitigatory measures must be put in place to curb the risk of underground fires and explosions (Wallace, et al., 2015). The current control measures implemented by most mines in the research area include adequate ventilation, diligent monitoring and observing re-entry protocols.

The amount of gases produced by explosives varies depending on the conditions of use, hardness of the rock, water content of the drill holes and other factors (Du Plessis and Beukes, 2014). Apart from drilling and blasting activities, diesel engines also emit noxious gases such as carbon monoxide, carbon dioxide, nitrous fumes through internal combustion of fuel. In addition, stagnant water in underground operations also act as a source of hydrogen sulphide which can be liberated into underground workings when stirred or disturbed (McPherson, 1993). Apart from face and support drilling activities, diamond drilling also poses a risk of intersecting gas fissures such as methane pockets particularly in areas where faults and aplite dykes are prevalent. Abandoned and worked out areas are often regarded as oxygen deficient hence sound control measures must be put in place to ensure that oxygen levels are continually monitored. Typical gases found in mechanised hard rock platinum mines are shown in Table 2.2

Table 2.2: Underground gases in mechanised mines *(Stanton, et al., 2014)*

Gas	**OEL**	**STEL**	**Characteristics**	**Sources**
Carbon monoxide	30ppm	100ppm	Poisonous	Fires, explosions, blasting operations, exhaust gases from diesel operated vehicles
Carbon dioxide	5,000ppm	30,000ppm	Asphyxiant, headaches	Slow oxidation matter, breathing, fires, explosions, diesel vehicles and poorly ventilated areas
Hydrogen	1.4%	-	Non-toxic, explosive range 4-75%	Battery stations and can be associated with methane
Hydrogen sulphide	10ppm	15ppm	Poisonous	Stagnant water, water fissures, faults and dykes
Methane	1.25%	1.4%	Non-toxic, explosive range 5-15%	Water fissures, dykes, faults and coal strata
Oxides of nitrogen	NO – 25ppm NO_2 – 3ppm	NO – 35ppm NO_2 -5ppm	Poisonous	Blasting, exhaust gases from diesel operated vehicles
Oxygen	>19%	-	Necessary to sustain life	Constituents of air

A baseline risk assessment conducted in the research area necessitated the need to apply fourth industrial revolution techniques to eliminate any potential gassing and explosion incidents.

2.7.1. Implications of gases

Many gassing incidents have been recorded in the history of mining. Atmospheric pollutants affects several tissues when absorbed into the bloodstream. Local effects of gases occur at the site of contact with the tissue and usually develop in three stages i.e. irritation, oedema and inflammation (Du Plessis and Beukes, 2014). Asphyxiant gases prevent the blood from transporting oxygen from the lungs or prevent normal oxygenation of tissues, even though the blood is well oxygenated. Some gases have a cumulative effect while others have a delayed effect which causes blisters in the lungs and consequently result in pulmonary oedema. A good ventilation system ensures that all gases are within OELs. Flammable gases such as methane may result in explosions with subsequent catastrophic effects such as loss of lives, decreased productivities and increased capital costs due to increased financial burden required to resuscitate the damaged infrastructure.

2.7.2. Methods of monitoring gases

Testing for gases is often done primarily to check compliance of atmospheric conditions to regulations governing the health and safety of underground workers. It is thus critical to monitor concentrations of airborne contaminants so that conducive underground conditions are maintained. The frequency and accuracy of any gas monitoring system must be sound to eliminate any potential gassing or explosion incidents. Fourth industrial revolution developments become the answer for integrated data collection, analytics and automatic response to exceptional gas readings. Most mines in the research area are currently using handheld gas monitors to detect and monitor underground gases throughout the shift. This traditional approach has a lot of limitations in terms of proactive measures to be undertaken to reduce gas concentrations.

2.8 Diesel particulate matter

It is a recognised fact that diesel powered mining equipment has allowed the mining industry to achieve tremendous improvements in productivity over the past years. This is mainly because the diesel engine is an economical source of power and also diesel powered machines are rugged, mobile and versatile (Gangal and Grenier, 2002). The International Agency for Research on Cancer (IARC) in 2012 declared diesel exhaust to be a class 1 human carcinogen

(IARC, 2012). The main sources of DPM in mining are underground vehicles such as LHDs and dump trucks in bord and pillar operations. Failure to manage DPM will result in an increased number of cancer cases. Most mines in the research area are not monitoring DPM since the Zimbabwean legislation is silent on DPM measurements. The legal limit for Australian mines is 0.16 mg/m^3 of Total carbon at point of operation in the general body of air (IARC, 2012). A DPM 4000 gravimetric sampler was initially used in the research area to conduct a baseline assessment for DPM exposures. A comprehensive analysis of DPM monitoring and management system will be described later in this thesis. In addition, an optimum ventilation design for a greenfield platinum mine in the research area will also be described in Chapter 4. For point of operation, the diesel dilution factor must be greater than 0.06m^3/s/kW to reduce the risk of exposing people to diesel fumes (Phillips and Rawlins, 2005). This thesis thus bridges the gap between emission, exposure and control measures thereby reducing exposure risks to DPM as stipulated by the WHO. Exposure to DPM emissions depends on fuel selection, engine selection, engine maintenance and ventilation design.

2.8.1. Fuel Selection

Diesel fuel with a sulphur content of 50ppm has a lower DPM emission as compared to Diesel 500ppm (Bluhm & Smit, 2014). More air will be required to dilute and disperse DPM particles when diesel 500ppm is being used. This has a huge impact in terms of capital costs and safety. All mines in the research area are currently using diesel with a sulphur content of 50ppm in underground operations. A detailed comparative study on the implications of fuel selection on DPM exposures will be described later in this thesis.

2.8.2. Engine Selection

There are various engine types in the market globally from Tier 1 engines to Tier 5 engines (Zheng, 2015). These engines types emit different levels of DPM. Most mines in the research area use Tier 2 and Tier 3 engines which are currently operating on diesel 50ppm fuel. Results of DPM emissions for both Tier 2 and Tier 3 engines are presented in Chapter 4 including the corresponding design rates.

2.8.3. Ventilation

Ventilation is the primary method for controlling DPM emissions. DPM reduction is proportional to airflow, for example, doubling the airflow will result in a 50% reduction in

DPM (Nundlall, 2014). It is imperative to effectively design the mine ventilation so that sufficient air is supplied to areas where diesel machinery will be operating. The design diesel dilution factor for South African mines ranges from 0.06 to 0.12 m^3/s/kW depending on engine selection and fuel used (Du Plessis & Biffi, 2014). This standard was adopted as best practice by platinum mines operating on the Great dyke of Zimbabwe. Most mines use a thumb suck figure of 0.1m^3/s/kW which can be an overdesign or an under design depending on various circumstances as described in Chapter 4. Overdesigning the ventilation system results in unnecessary air quantities and hence has a negative impact on capital costs due to excessive design of ventilation infrastructure such as raise bore shafts and main surface fans. This will also result in increased operating costs mainly driven by increased power consumption. A quantitative approach on ventilation design will also be described in Chapter 4.

2.8.4. Implications of uncontrolled DPM exposures

The primary objective for measuring DPM is to protect worker health by ensuring that exposures are complying with regulations (Zheng, 2015). Available evidence confirms that there are health hazards associated with exposure to diesel exhaust. These hazards include acute symptoms of exposure, chronic cancer respirator effects and lung cancer (Nundlall, 2014). Examples of acute exposure effects of DPM include irritation of eyes, throat, light-headedness and respiratory symptoms such as coughing and phlegm (Nundlall, 2014). Occupationally related cancers are characterized by a long latency period between first exposure and clinical presentation and up 50 years in some cases thus presentation can be in retirement (IARC, 2012). Nundlall (2014) pointed out that underground employees in mechanised mines tend to have much higher DPM exposure levels than in all other industries , due to the restricted nature of the ventilation flow.

2.9 Dust

Ore extracted from the mines is crushed and pulverised at various stages along the mining value chain. During this process, significant quantities of dust are generated and it is therefore imperative that the amount of respirable dust that is emitted into the atmosphere is minimised or eliminated altogether. As such, various companies have set up systems that ensure that the operations sustainably control dust levels starting from underground face drilling to the processing plant. To complement the control processes modern dust measurement and monitoring techniques should be used to evaluate the risk to employees in all work areas (Brouwer & Rees, 2020). Furthermore, a comprehensive wellness programme and regular screening for dust exposure by the medical team must be in place to ensure that the health of employees is monitored (Brouwer & Rees, 2020).

2.9.1. Sources of dust

Dust is generated through activities such as blasting, channel sample cutting, face and support drilling which due to water suppression generate low to moderate quantities of dust into the underground environment. Primary blasting accounts for the bulk of dust which requires a four hour re-entry period to allow the dust and gasses to be safely dissipated from operating faces using mechanical ventilation systems. The process of loading the blasted rock into dump trucks and crushing it underground or on surface also releases latent dust which is however suppressed by watering the broken rock during each of the activities. Critical locations such as the crushers should be equipped with modern dust extraction systems that keep dust emissions well within the prescribed limits. This thesis describes fourth industrial revolution techniques to combat dust across the mining value chain.

2.9.2. Nature and chemistry of dust in the research area

Dust can be described as finely divided solid matter which is generated by rapid impact on rock during activities such as drilling, blasting, crushing and handling or transporting (Belle, 2018). The fine mineral particles suspended in the atmosphere during mining and processing activities are classified as dust and are measured in milligrams per cubic metre of air (mg/m^3). Studies by Occupational Health and Safety (OHAS) specialists in South Africa and Australia have demonstrated that in the mining industry, harmful dust is a respirable dust fraction which contains high levels of crystalline silica (silicon dioxide), asbestos and coal which cause long term conditions such as silicosis, asbestosis and coal worker pneumoconiosis (CWP) respectively (Du Plessis & Belle, 2014). Belle (2018) noted that respirable dust particles (median aerodynamic diameter of 7µm on the Johannesburg Curve) are small enough to penetrate deep into the lungs. While inhalable dust can refer to particles as large as 100 microns in diameter, the upper limit for particles that may be inhaled into the lungs is about 10 microns. Therefore, inhalable dust is typically calculated by measuring particulate matter less than 10µm (PM_{10}) levels (Du Plessis & Belle, 2014).

The chemical composition of the disseminated particles in the air depends on the mineralogy of the source rock which is from the ultramafic rocks of the Great Dyke plus some silicate intrusive such as dykes and quartz veins that are occasionally encountered underground. The host rock for the main sulphide zone ore body in the research area is bronzitite which is a variety of the pyroxenites which fall under the family of ultramafic rocks (Oberthür, et al., 2012). The chemical composition of this bronzitite variety is $(Mg,Fe)SiO_3$. The composition and mineral assemblage of the research area host rock is clearly illustrated in microscope thin sections which are cut from drill core showing the cumulate structure of all the minerals that make up the rock shown in the micro-photographs in Figure 2.10. Plagioclase feldspar ($CaAl_2Si_2O_8$) and sulphides are the main interstitial minerals with no free quartz/crystalline silicates identified in the rock.

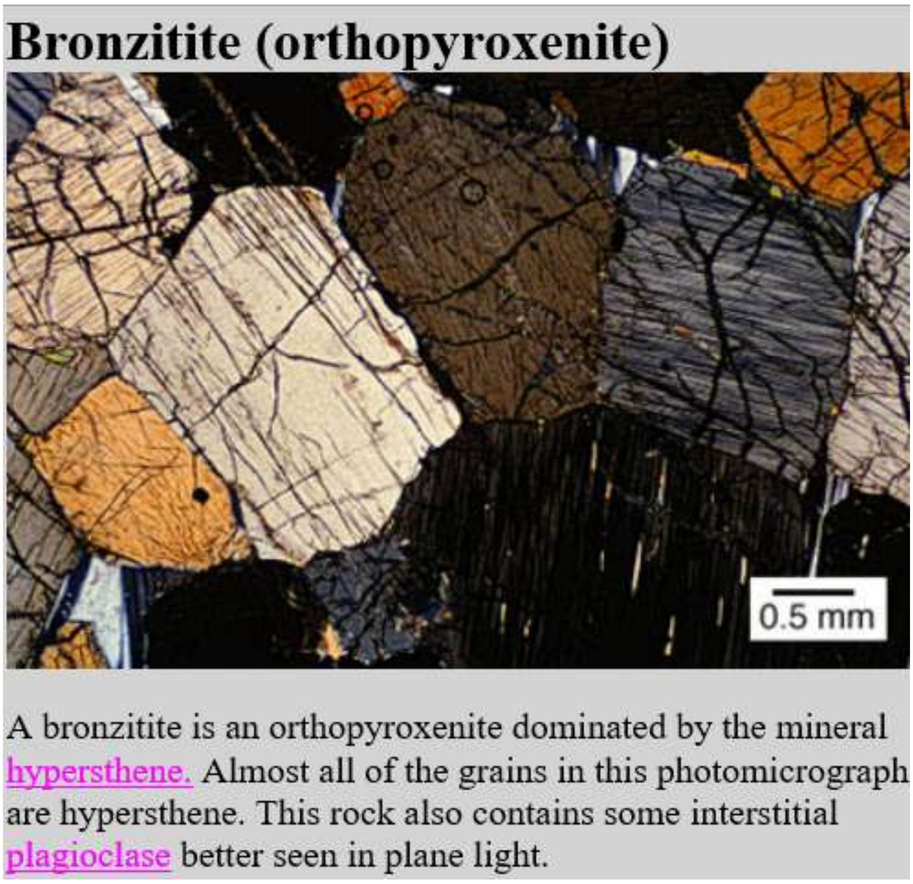

Figure 2.10: Microscope photograph of a typical bronzitite (Stillwater Complex) showing orthopyroxene *(Jenkins & Mungall, 2018)*

No primary mineralisation of silicates has been reported in the main sulphide zone and hence the rock type does not fall within the defined or known sources of harmful dust. As a result, alpha quartz therefore occurs in very small quantities in the research area, from silica bearing intrusive dykes in the ore. Table 2.3 shows the alpha quartz analysis which was done at one mine in the research area to confirm the silica content of rock measured. An on-filter X-ray diffraction (XRD) method was used by National Air pollution services to analyse the silica content. No silica content was detected in all samples sent for analysis hence a minimum detectable value of 0.004mg/m^3.

Table 2.3: Alpha quartz analysis results

Area sampled	**Activity**	**Filter no.**	**Corrected mass (mg)**	**AQ Results (mg/m^3)**
North Decline	Hauling	1	0.28	< 0.004
Stoping panels	Lashing	2	0.64	< 0.004
Crusher station	Crushing	3	0.71	< 0.004
Stop Order section	Face drilling	4	0.63	< 0.004

An average silica content less than 0.004mg/m^3 was obtained from various test locations which is well below the silica OEL of 0.1mg/m^3 hence the host rock for platinum mines in the research area may not pose a health risk to underground employees.

2.9.3. Implications of uncontrolled dust and residual values

There is a need to clearly understand sources of dust within the research area so as to remove employees from unsafe areas and to allay the dust at source before it is released into the environment. To aid in this process, occupational hygiene surveys that include dust monitoring are conducted regularly for both underground and on surface working areas in order to assess any risk to employee health and wellbeing so that appropriate controls are assigned. Excessive dust generation affects worker health and impacts negatively on employee productivity and other performance indicators impacted by visibility. Ensuring adequate precautions against harmful dust is a requirement of the Mining Health and Safety Act in South Africa (Du Plessis & Belle, 2014). Belle (2018) noted that failure to comply with regulations will result in stringent penalties, compensation claims, litigation costs, decreased productivity and reputational damage to the organisation. The residual dust levels are monitored regularly at all operations based on homogenous exposure groups (HEG). Typical dust concentrations recorded in the research area are shown in Table 2.4.

Table 2.4: Underground abatement methods and residual exposure *(Du Plessis & Belle, 2014)*

Activity	Control method	Detected TWA (mg/m^3)	Platinum OEL (mg/m^3)	Respirable dust OEL (mg/m^3)
Lashing	• Ventilation • Watering down	1.7	3.0	5.0
Hauling	• Ventilation • Water bowsers • Stillage molasses	1.35	3.0	5.0
Face and support drilling	• Wet drilling	1.51	3.0	5.0
Crushing	• Primary ventilation • Dust extraction fans and scrubbers	1.90	3.0	5.0
Shotcreting	• Pre-dampening and washing down of rock surfaces	1.40	3.0	5.0

Note: TWA -Time weighted average concentration (8 hours)

The highest exposure levels are recorded during lashing and crushing due to the nature of the work being carried out and the proximity of the worker to the loose rock being handled. Due to the application of water and efficiency of the underground ventilation systems the mines operate well within the respective OEL.

2.9.4. Dust control methods in mining

Dust abatement is done at point of generation to minimise the risk of dust exposure to employees. Exposure of personnel to dust generated by blasting is mitigated at all mines through removal of men from the area prior to blasting and clearing the area of dust and fumes before employees return after a prescribed four-hour re-entry period. In addition, water blasts are used in development ends to dilute dust and noxious gases present in the air. Blasted rock is watered down prior to any lashing operations to suppress dust. This watering down process is repeated during the lashing process for continuous dust suppression. All mines use wet drilling during face and support drilling. Water bowsers are also used to suppress dust in underground travelling ways. In raise boring operations, dust is controlled by means of a muck pile built to mask the bottom of the raise, in which case care is exercised to ensure that it does not build up too far and consolidate in the raise. At the underground crushing stations, exhaust or de-dusting systems are in place and the operator is isolated in an enclosed booth supplied with fresh, dust free air from the intake airway.

Personnel exposed to concentrations of dust for only short periods in cases where remnant dust exists use personal protective equipment such as dust masks and respirators (Du Plessis & Belle, 2014). In addition, personnel working in areas where there is a risk of occasional dust level spikes exceeding occupational exposure limits such as in the underground mining environment are issued with respirators. Such operations include crushing plants, assay laboratories, transfer points and the tipping dome. It is noted that while the time weighted average exposure is below the OEL, the cyclical nature of mining production tasks means that certain activity phases during the shift produce high dust concentration levels for a short time interval, during which added protection is required. Figure 2.11 shows a typical dust monitoring dashboard extracted from the Trolex system installed in the research area. Such graphs can only be obtained through real time dust monitoring system. This thesis will describe various fourth industrial revolution techniques that were applied to underground operations to mitigate the risk of dust exposure.

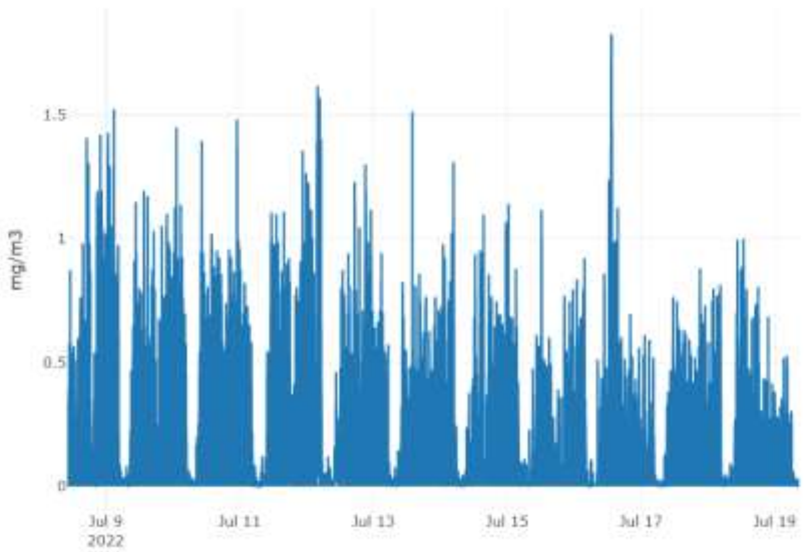

Figure 2.11: Real-time respirable dust concentration in the research area (extracted from research - Trolex system)

As such, all mines should ensure that there is a fool proof dust management system which can be sustainably employed at each of the operations along the value chain in order to reduce risk levels.

2.10 Heat

In most underground mines, heat remains a major challenge and provision of acceptable working conditions requires considerable expenditure on ventilation systems (Hemp & Rawlins, 2014). Heat is transferred to the airflow from a variety of sources. There are basically two types of heat classes which are natural sources and artificial sources. Natural heat sources include heat transfer from strata and oxidation of rock strata. Rawlins and Phillips (2005) pointed out that virgin rock temperature increases with depth due to the heat from beneath the earth surface. It is important to note that thermal conductivities of rocks affect the virgin rock temperature and therefore directly affect the ventilation systems. If the virgin rock temperature is greater than the ventilating air temperature, heat will be transferred from the rock to the air thereby increasing the environment temperature (Phillips and Rawlins, 2005). The research area is shallow with a maximum operating depth of 600m. The effect of virgin rock temperature was considered during the design stage. Oxidation of minerals which include pyrite constitutes an exothermic reaction which releases a significant amount of heat (Chaumba, 2017). Several mines in Australia have experienced this challenge however this exothermic reaction has not been experienced in Zimbabwean platinum mines. Autocompression is not necessarily a source of heat but leads to a conversion of potential energy into enthalpy (Rawlins and Phillips, 2005). This issue affects any fluid, thus air and water flowing into a mine, particularly in deep mines, are both affected. The increase in temperature is sometimes referred to as the adiabatic lapse rate (Biffi, et al., 2007). If there is no interchange in heat or moisture content of the air in the shaft, the compression occurs adiabatically, with the temperature rise following the adiabatic law (Hemp & Rawlins, 2014). The enthalpy increase associated with autocompression serves to reduce the amount of heat that the fluid is able to remove. The increase in enthalpy due to autocompression is typically 9.79 kJ/kg for every 1 000 m (Hemp & Rawlins, 2014). Artificial sources of heat arise from day to day activities which take place in the mine.

2.10.1 Sources and implications of uncontrolled heat

Underground machinery that is used in platinum mines can be powered by electricity, diesel or compressed air. Electrically driven machinery converts the electrical energy into either heat energy or useful work (Hardcastle, et al., 2005). Electrical machinery such as electric motors, pumps and fans converts electricity into heat and mechanical energy. The increase of heat dissipated from electric machinery differs in specific design mainly because of utilised motor power and the application required. In Zimbabwean platinum mines, increased mechanization, equipment utilization and increasing power demands have resulted in such underground equipment being considered as major sources of heat. Diesel equipment also generates significant amount of heat because a greater portion of primary energy consumed by the engine is released as heat (Rawlins and Phillips, 2005). Platinum mines in the research area are all mechanised and they use LHDs and dump trucks which generate significant amount of heat particularly when travelling over significant gradients. It is important to note that diesel vehicles will produce about three times more heat than a mechanically similar electrical powered machine (Bluhm & Smit, 2014). The range of heat production depends upon the equipment power rating and the work load performed. Underground employees function by internally combusting foodstuffs which result in emission of heat. Typical heat generated values by people are 90 to 115W when at rest, 200W when doing light work, 330W when doing moderate work and 470W when doing hard work (Bluhm & Smit, 2014). This amount of work may seem insignificant, however for a mine with more employees such as 1 500 underground people, this may result in a substantial source of heat. Explosives also generate large amounts of heat and that heat must be cooled. All platinum mines on the Great Dyke are using drilling and blasting techniques to break the rock. Baiden (2001) pointed out that with the use of electronic detonators and computer controlled blasting, as much as 40-50% of the heat produced by production and development blasts could be rapidly removed along with the blasting fumes. Different explosive properties will be described in detail later in this thesis and their subsequent effect on ventilation requirements will also be highlighted.

Workers exposure to heat has a negative impact on productivity, safety, health and costs. The wet bulb heat rejection temperatures for human beings is 27.5°C (Du Plessis & Biffi, 2014). Work output will not be affected by temperatures below this rejected temperature. As the temperature increases, the body tries to compensate by sweating more which can result in cramps, skin disorders, heat stroke or heat exhaustion (Schneider, 2016). In addition, people subjected to high heat levels tend to make more mistakes which can lead to accidents and low morale as a result of depression.

2.10.2 Current abatements methods

Good ventilation design creates a conducive working environment. It is critical for primary ventilation systems to cool off most heat generated in the system. For this reason, air entering the section must have adequate cooling capacity to reduce the heat load in the system. In addition, real time monitoring of thermal conditions is imperative to ensure that the productivity and safety indicators are optimised. Currently, most mines in the research area are using whirling hygrometers to monitor temperature. These readings are often taken on a monthly basis hence the need to apply fourth industrial revolution techniques to monitor and manage thermal conditions in real time. Underground mines must monitor, temperature readings, airflow readings, humidity, wet kata readings and heat stress levels.

2.11 Fire protection and emergency preparedness

There is always a fire risk in all mechanised underground operations due to utilisation of diesel equipment and generation of toxic gases. As a result, there is need to continuously monitor gas levels in underground operations to eliminate catastrophic methane explosions. Many fatal explosions have been recorded in the mining industry, mainly attributable to accumulation of gases hence the need to apply fourth industrial revolution technologies to manage fire risks. Environmental monitoring and adequate ventilation systems are critical components for ensuring compliance to mining regulations. Underground mines must be equipped with systems that meet the Mine Health and Safety Act in South Africa (MHSA) standards to combat fire. Du Plessis and Biffi (2014) pointed out that air velocity significantly affects fire detection and suppression proficiencies. Most Zimbabwean platinum mines use fire resistant and antistatic (FRAS) conveyor belts which conforms with SANS971:2013. Underground conveyor belts in mechanised operations can produce smoke and toxic gases when they burn and this can cause fatal gassing incidences as highlighted earlier in this chapter. A number of options are available to ensure that environmental conditions are safe thereby minimising the risk of fire. Proposed options to manage the fire risk will be described in detail in Chapter 5.

2.12 Ventilation on demand

Ventilation on Demand (VOD) is the ability to direct air in an underground mine to the area that requires it, at the quantity needed for the local activities and ambient conditions at the time (Acuña, et al., 2014). According to Tran-Valade and Allen (2013), there are five control strategies that are considered for VOD:

- ✓ User control, also referred commonly as manual control (level 1)
- ✓ Time of Day scheduling (level 2)
- ✓ Event based (level 3)
- ✓ Tagging (level 4)
- ✓ Environmental (level 5)

The five identified strategies can be used singularly or in combination. VOD techniques were considered in the research area and the results are given in Chapter 5. Ventilation is an absolute necessity for underground mining and is becoming increasingly expensive (Wang et al, 2014). Prevailing trends within the global mining industry, including greater depth, are generally demanding a greater quantity of air not only for ventilation but also for cooling purposes, which has the consequence of higher power consumption at the main fans. The drive to minimise greenhouse emissions increases the importance of managing power consumption in the mining industry (Hardcastle and Kocsis, 2001).

2.13 Diesel versus electric fleets

Diesel machinery provides high levels of equipment mobility and productivity but also provides high heat loads and potential harmful gases and particulate emissions. The critical diesel emissions are diesel particulate matter (DPM), respirable carbon particles, (RCP), nitrous fumes as well as carbon monoxide. Varaschin and De Souza (2017) pointed out that diesel engines produce emissions over a wide range of concentrations depending on:

- Engine type

- Work Cycle
- Fuel type
- Operator habits
- Maintenance level
- Exhaust treatment system

A cost benefit analysis was conducted on the introduction of battery powered (electric) fleets against the current diesel equipment. The benefits of electric fleets include sustainability in terms of safety, production and cost, significant lower emissions generated (Varaschin and De Souza, 2017). When electric fleets are introduced there are challenges in establishing engineering criteria since the ventilation requirements are not the same as with diesel equipment and there are no empirical data for new equipment in terms of power load, productivity, maintenance and safety requirements. All these considerations will be described in this thesis.

Electric vehicles are preferably used in the mining industry to reduce carbon footprint as well as to improve site safety (Varaschim and De Souza, 2017). Since these vehicles have zero local emissions, the quality of air in underground operations will be far better as opposed to diesel engines which generate particulates and harmful gases such as nitrogen oxide. Over exposure to nitrous fumes result in difficulties in breathing, inflammation of lungs and asthma (Du Plessis & Beukes, 2014). Acute exposure to nitrogen oxide causes headaches, irritation of eyes nose and throat. This can subsequently reduce the effectiveness of underground workers. Underground working environments are regarded as confined spaces hence the need to reduce the amount of airborne pollutants (Stanton, et al., 2014).

Electric vehicles offer a reliable solution which improves underground air quality. It is generally known that for mine workers to be more productive, they must be healthy and the underground conditions must be conducive. In addition to minimum airborne pollutants, electric vehicles can travel faster than diesel engines due to increased torque and better handling (Varaschim and De Souza, 2017). Electric engines also emit less heat than diesel fleets and have a minimal risk of the engine overheating. Furthermore, there is low noise generation which improves the health of underground workers (Varaschim and De Souza, 2017). Electric vehicles were also observed to give less vibrations when compared to diesel machines. Over exposure to vibrations will result in occupational diseases such as Reynolds syndrome, arthritis and can cause stresses for structures and compromise their integrity (Tekin, 2022). Blekhman (2012) pointed out that vibrations are a contributing factor to wear and tear. Since there is minimum vibration in electrical vehicles, the maintenance of electrical vehicles will be reduced. This thesis will discuss the impact of electric vehicles on ventilation design and monitoring since the future of mining is aligned towards the use of electric vehicles.

2.14 Effect of explosives on ventilation

Various types of explosives were looked at and their benefits and disadvantages were evaluated for ventilation design purposes. Different explosives have different proportions of shock energy and gas energy (Bohanek, et al., 2013). Ammonium nitrate-fuel oil (ANFO) is an explosive widely used in the mining industry. Its advantages include simple manufacture, it is cheaper than the alternatives and a safety feature is its lack of sensitivity to mechanical impacts during mechanical loading of drill holes (Mather, 1997). ANFO also has some disadvantages which include lack of water resistance and low detonation parameters which reduce their range of use to dry blasting holes in geotechnically challenging ground conditions (Maranda, 2011). Since ANFO has some serious after-effects on ventilation, it was necessary to investigate the use of other bulk explosives that include emulsion and watergel. The merits of bulk emulsion explosive over ANFO and packaged products include, easy transportation, handling, string charging, low gas emissions, water resistant, full coupling, increased velocity of detonation, detonator sensitivity and improved work environment (Maranda, 2011).

The energy released by a blast is liberated in the form of heat hence blasting can also be considered a significant source of heat. Part of the heat generated by development and production blasts is stored within the blasting fumes, which can cause a peak heat load into the ventilating air. The remaining heat is stored within the fragmented ore (Develo, et al., 2016). The amount of heat stored within the fragmented ore can depend upon the extraction method and in particular upon the quality of ore fragmentation. With the use of electronic detonators and computer controlled blasting, as much as 40-50% of the heat produced by production and development blasts could be rapidly removed along with the blasting fumes (Maranda, 2011).

2.15 Ventilation and the future of energy

Hardcastle et al. (2005) pointed out that mining operations are becoming increasingly mechanized, therefore health and environment standards for underground workers are becoming more stringent. To varying degrees, these observed trends coupled with increasing energy costs continue to challenge the economic sustainability of underground mines, including the economic provision of ventilation in large underground metal mines. There are a number of challenges across the African continent for the reliable supply of electricity as evidenced by power outages (Emetere, et al., 2021). For this reason it is very important to manage the power consumption in the mining industry. In underground platinum mines, ventilation operating costs account for up to 40% of the total energy costs (De Souza, 2018). The future landscape of the energy industry is set to be transformed by technological innovations that drive it towards a more convenient, efficient and ecological infrastructure. Energy systems of the future will be vastly different to those we know and use today and the scale of change over the next couple of decades will be considerable (De Souza, 2018).

The IoT is an emerging technology which is already receiving a significant amount of press coverage and attention. This type of technology is starting to be utilised to deliver a greener approach to energy use. The Internet of Energy (IoE) transforms energy production, supply, and consumption to fulfil high energy demands via intelligent automation of industrial energy producers and consumers (Shahzad, et al., 2020). The ‘internet of energy’ will make use of connected digital systems to control how energy is used and stored. Modern appliances are being designed with a level of interconnectivity (Shahzad, et al., 2020). This means each item can be programmed to use or not use energy when selected. Furthermore, the internet of energy will allow users to coordinate supply and demand autonomously among themselves and is also equipped with smart forecasting systems (De Souza, 2018).

The DMRE (2019) emphasised the need to reduce mine power consumption as well as to come up with a contingent plan to cater for power supply interruptions. This research focuses on reducing power consumption through optimised ventilation designs and power management strategies such as ventilation on demand in bord and pillar operations.

2.16 Chapter summary

The thesis contains extensive discussions on available publications, personal visitations and references that deal with ventilation design through empirical techniques and numerical modelling. The section also covers occupational hygiene systems and fourth industrial revolution techniques applicable to ventilation design and monitoring. Limitations of the current system were highlighted and the gap will be addressed by this research. The next chapter discusses the methodology used to attain the set objectives.

CHAPTER 3: METHODOLOGY

3.1 Introduction

The research started with an extensive literature review on the fourth industrial revolution, optimised ventilation design, occupational hygiene, environmental monitoring strategies, numerical modelling techniques and mine ventilation economics. Figure 3.1 shows a typical flow chart which was implemented during the course of the research.

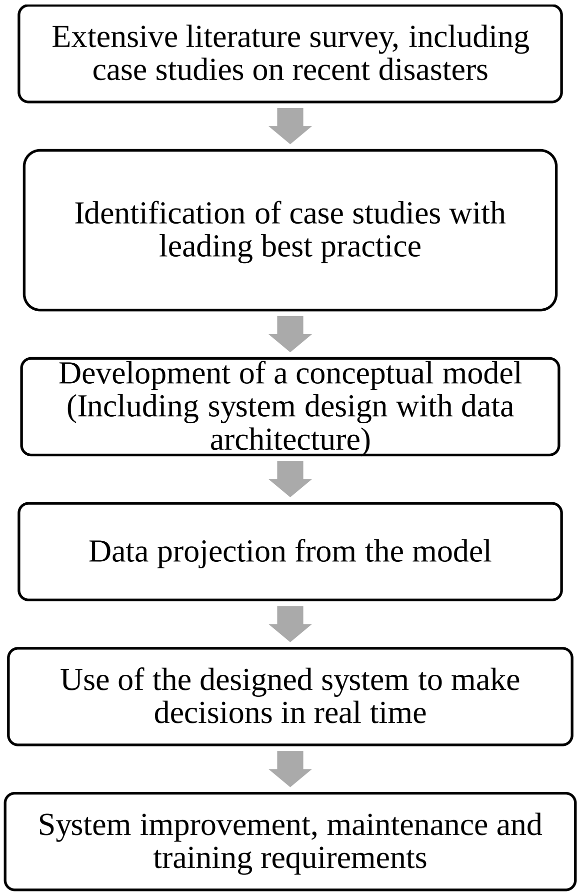

Figure 3.1: Methodology flowchart

In order to get a comprehensive understanding of existing ventilation systems, the research was carried out in various mining sections on the Great Dyke, with an emphasis on those without optimised ventilation systems and also for greenfield projects. Underground observations, recordings and data collection were made in some platinum mines operating in the research area. Desktop studies were undertaken to gather ventilation data from other platinum mines as well as for benchmarking VOD systems. The research was partitioned into two portions, that is optimisation of ventilation design and secondly the application of fourth industrial revolution systems to underground environmental monitoring systems. The current conventional techniques used for ventilation design and monitoring were initially reviewed and analysed before applying fourth industrial revolution techniques to optimise ventilation designs and environmental monitoring systems. Observations were made at different mining properties and the following parameters were measured and analysed:

- Ventilation surveys (air velocity, quantity, pressures, temperatures, wet kata etc.)
- Ventilation monitoring strategies.
- Fan power consumption
- Current explosives used at the mines
- Airborne pollutants
- Medical surveillance systems
- Mining operating costs particularly power costs

The gathered data was analysed using ventilation engineering principles, that is the application of both empirical techniques and numerical modelling thereby optimising ventilation systems. Figure 3.2 shows a typical ventilation optimisation chart that was followed during empirical ventilation design with a few modifications.

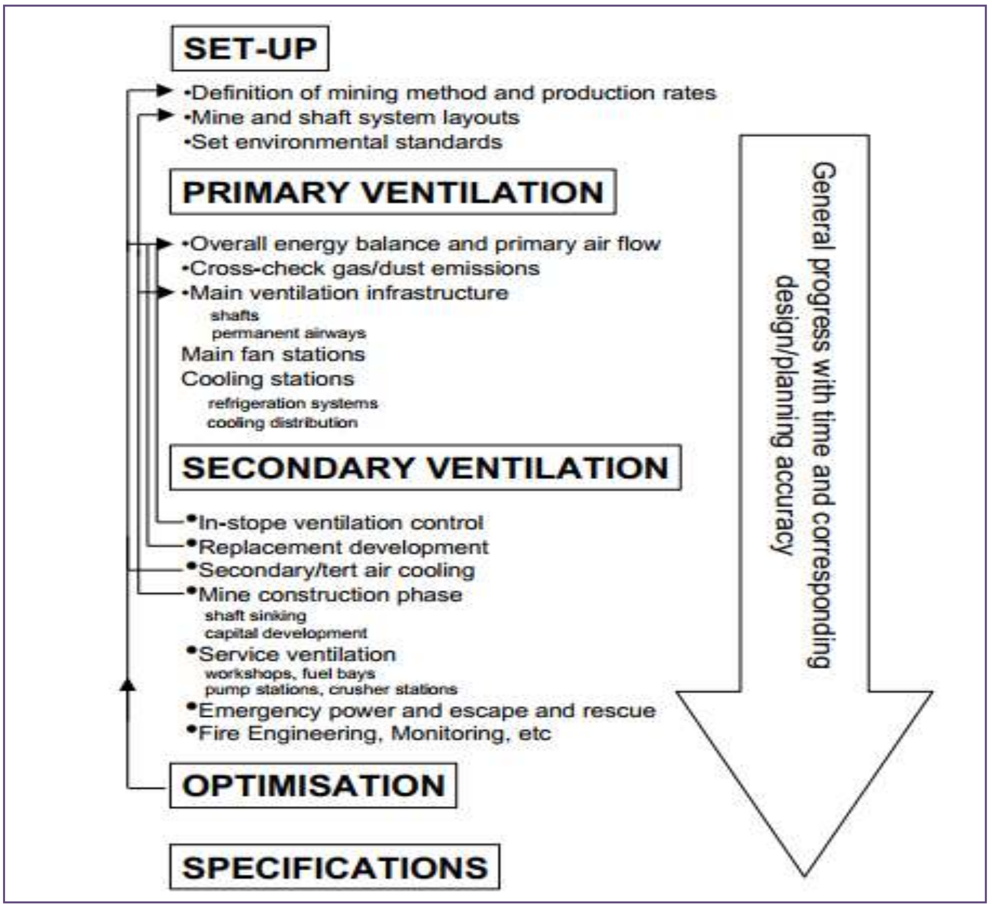

Figure 3.2: Ventilation optimisation (Watrant, 2008)

The research focused on room and pillar mines operating on the Great Dyke of Zimbabwe with the main emphasis on application of digital transformation to ventilation and environmental monitoring systems. A greenfield project was used as a base case for optimizing ventilation designs. The various techniques used during the research to optimize ventilation designs will be described in detail in Chapter 4. The Zimbabwean mining legislation and regulations were used to govern occupational exposure limits (OELs) and where such standards are silent, best practice standards were adopted. The research considered primary and secondary ventilation systems for both greenfield and brownfields projects. The overall air requirements and energy balance were optimized using the various techniques described in Chapter 4. Air borne pollutants associated with mechanized equipment were also investigated and measures to mitigate the risks posed by such were put in place throughout the whole value chain. In addition, corrective controls such as emergency preparedness systems were also analysed and optimised. Digital revolution techniques such as remote monitoring tools encompassing smart sensors and internet of things were also considered during the research. A full financial evaluation for the designed and proposed systems was done to determine the viability of the project. The practicality of the recommended systems was also tested through identification of case studies with leading best practice as well as engagements with various stakeholders. There was also wide consultation with various experts in the field of ventilation to validate the findings and proposed recommendations. Lastly, but not least, a model was developed in order to bridge the gap between any theoretical hypothesis and the practical components of the digital revolution systems.

3.2 Ventilation optimisation

Zimbabwe has a severe energy crisis because its major sources of electricity are struggling to keep up with demand (Ndlovu, 2021). Ventilation on demand systems reduces power costs and improves the health of underground employees. The concept has been discussed within the last decade at various platforms worldwide. However, there has been minimum or no traction on implementation and rolling out of such systems in African mines. Minimum effort has been applied in researching such systems particularly in room and pillar operations. The Great Dyke of Zimbabwe being the second largest platinum reserve following the Bushveld complex was used to optimise mining key performance indicators which are safety, productivity and costs. All platinum mines operating in the Great Dyke use the room and pillar mining method to exploit the resources. Numerous levels of underground ventilation controls have already been installed in some more developed countries with an attempt to harness the benefits of optimised ventilation systems. However, currently, the full advantages of the VOD concept have not been realised mainly due to the lack of automated ventilation controls and the `associated software required to deliver adjustable air quantities to underground workings. Another factor is the lack of fourth industrial revolution techniques to be used for predicting the potential economic and environmental benefits of demand-based ventilation system. This current research developed a demand-based ventilation system through the application of fourth industrial revolution tools which can be rolled out to room and pillar platinum mines to reduce power consumption and improve the health and safety of underground employees. The designed demand-based schedule will then become the fundamental basis of underground ventilation systems.

3.3 Underground Surveys

Underground surveys were carried out to assess the current environmental conditions and to identify mines that would significantly benefit if their ventilation systems were to be optimised. Such surveys were carried out in brownfield projects and the key learnings and findings were then cascaded to greenfield operations. Various parameters which affect primary and secondary ventilation systems were analysed. Such parameters include the type of trackless mobile machinery (TMM) used, airway types, production rates, ventilation controls and secondary infrastructure such as conveyor belt excavations and underground workshops. For each underground mining operation involved, the main and auxiliary ventilation requirements were analyzed and evaluated. The configuration of the mining footprint, heat load, auxiliary ventilation setup, the applicability and practicality of the ventilation on demand concept were analyzed and discussions were held with the relevant authorities during underground visits.

3.4 Air utilisation and VOD

The research focused on reviewing and improving the efficiency of underground ventilation systems through the application of fourth industrial revolution techniques in ventilation design and environmental monitoring. Air utilisation was initially used as a measure of the effectiveness of underground ventilation systems. Chalmers (2008), defined air utilisation as the sum of air quantities reaching development and production faces as well as underground service facilities divided by the total volume delivered by main surface fans. Typical air utilisation in platinum bord and pillar operations ranges from 50 to 70% depending on the effectiveness of the ventilation controls used (Bluhm & Smit, 2014). During the current research a system was designed that can monitor and improve air utilisation through the application of fourth industrial revolution techniques. Air utilisation cannot be used as an independent parameter to determine the effectiveness of a ventilation system because the mine can have a high air utilisation but at the same time it can be highly inefficient due to frictional and shock pressure losses. The author empirically designed a system that can measure the efficiency of a ventilation system by integrating the total quantities delivered by main surface fans with the actual air demand in real time through automation. The system was further optimised through the application of fourth industrial revolution techniques to integrate ventilation redundancy with ventilation on demand systems. This thesis describes how smart sensors and other digital revolution tools will be strategically positioned in future ventilation systems so that artificial intelligence and machine learning can be incorporated into the system. This was done to optimise ventilation systems through a reduction in energy consumption as well as an improvement of the health and safety of employees since the system will be operating below all applicable OELs. Case studies were also identified and used as part of the methodology.

Case Study 1: Review of ventilation design and environmental monitoring

The main objective of this study was to review and improve current ventilation systems at one of the platinum mine operating on the Great Dyke through an analysis of ventilation redundancy and air utilisation. The author reviewed the current systems used for life of mine ventilation design. This was done through an analysis of the current production profiles and the quantity and type of trackless equipment currently used. Actual air utilisation factors used were measured and analysed through measurements of air quantities reaching the working areas against total deliverables from main surface fans. This was done in conjunction with environmental monitoring of occupational hazards such as temperature, gas, DPM and dust. The other area of focus was to identify "inactive" time intervals during the shift and peak load periods so that modulation of airflow based on demand can be implemented. The output was then used together with ventilation simulation to determine potential power savings through the introduction of ventilation on demand and other fourth industrial revolution techniques. The other focus area was the general underground conditions during various activities since the mine is using specialized teams to exploit its resources. As a result, each section requires a different air quantity with the lashing and hauling activities requiring most of the air. Determination of potential operating cost savings for ventilation on demand systems was done through ventilation simulation and empirical techniques. The system was benchmarked against other operations with leading best practices which were located in Canada and Mexico.

Underground activities were monitored using temperature and humidity sensors for a duration of six months. This was done in real time to analyse the trends. The aforementioned temperature and humidity trends had the ability to highlight the activity cycle time, the peak active periods, non-active periods and environmental conditions generated by the mining equipment. In addition to temperature and humidity measurements, gas and dust monitoring was also undertaken in the research area. Current explosives used in the research area were also analysed since they have a direct bearing on ventilation systems. A trial was conducted using ammonium nitrate fuel oil (ANFO) and emulsion explosives and such a comparative study will be provided in detail in the next sections of this chapter.

Case Study 2: Analysis of fan power consumption

In a mechanised operation, the ventilation system may supply excessive air quantity over and above what is required. This is mainly attributable to a constant supply of air despite lack of activities in some mining sections. Air supplied can also be greater than the required volumes in active working areas due to less demands when machine engines are not operating. As part of this study the whole value chain in the mining division was reviewed to pinpoint areas that can be harnessed for power saving initiatives. In addition, notice was also taken of the actual times when a machine is operating throughout the shift. The actual ventilation conditions were also compared with long term life-of-mine plans. It was found that in bord and pillar operations, the mine supplies excessive air to compensate for leakages due to poor ventilation controls. A ventilation system was designed to incorporate fourth industrial revolution tools to monitor system resistance, air leakages and power consumption. The engine conditions were also monitored because of their effect on underground conditions. It was also noticed that some of the machines in use had already exceeded the expected machine life but there were still in use. These machines were emitting excessive airborne pollutants and the mine compensated by pumping in more air which resulted in high power consumption. This research also involved the design of a system to continuously monitor the engine condition and a system to be used for predictive maintenance. This will be described in detail in Chapter 5.

3.5 Automated ventilation systems

This research introduced a novel ventilation design and monitoring system that enables the determination of actual air quantity requirement through process ventilation simulations. These were performed using Ventsim to integrate actual heat load, production profiles, main surface fans and digital revolution tools. To determine the activity-based air volume requirements, an underground ventilation model was developed for the greenfield project. The ventilation output data generated by discrete-event process simulations was automatically converted into air volume requirements based upon the mining activity schedules, environmental conditions and fan operating duties. The system was also designed to automatically adjust itself to suit the current underground conditions and demand. In order to accurately determine the economic benefits, environmental benefits and practical considerations, this new ventilation architecture involving fourth industrial revolution tools was applied to the life of mine airflow demands for both conventional and demand-based ventilation systems for the greenfield project, which is planned to operate in the same geological domain. The benefits of the designed systems will be extended to other operations since they use the same philosophy.

Based upon the analysis of the gathered data from operating mines as well as the simulations undertaken, energy consumption was determined for the conventional systems as well as through ventilation on demand. A full financial evaluation for the automated system will be described in Chapter 5. In addition, environmental considerations for optimised ventilation systems are also outlined in Chapter 5.

3.6 Engine selection for diesel equipment and impact on ventilation

There has been a significant movement in the development of engine types from Tier 1 to Tier 5 engines (IARC, 2012). Platinum mines operating in Zimbabwe are currently using Tier 2 and Tier 3 engines. The current trackless mobile machinery (TMM) replacement philosophy considers the use of cleaner engines (Tier 3 and above) as an interim measure to manage DPM contaminants. Various engine types were considered during ventilation design as they affect the rate of diesel emissions. The development of autonomous machines and the use of battery electric vehicles was also analysed and incorporated into the research. Design diesel dilution factors were optimised based on engine types and the rate of emissions. Air flow sensors and diesel particulate monitors were used during this research.

3.7 Ventilation design and environmental monitoring for a greenfield project

The research involved the optimised ventilation design of a greenfield bord and pillar mine using several techniques. The design started with empirical designs followed by numerical modelling. That integration was done to optimize ventilation systems so that any system gaps will be eliminated thereby managing any potential ventilation risk. Figure 3.3 shows the shafts arrangement during mining operations which will be required to sustain the desired production. The details regarding the full design will be discussed in Chapter4. In addition, fourth industrial revolution techniques applied to ventilation design and environmental monitoring will be discussed in Chapters 4 and 5.

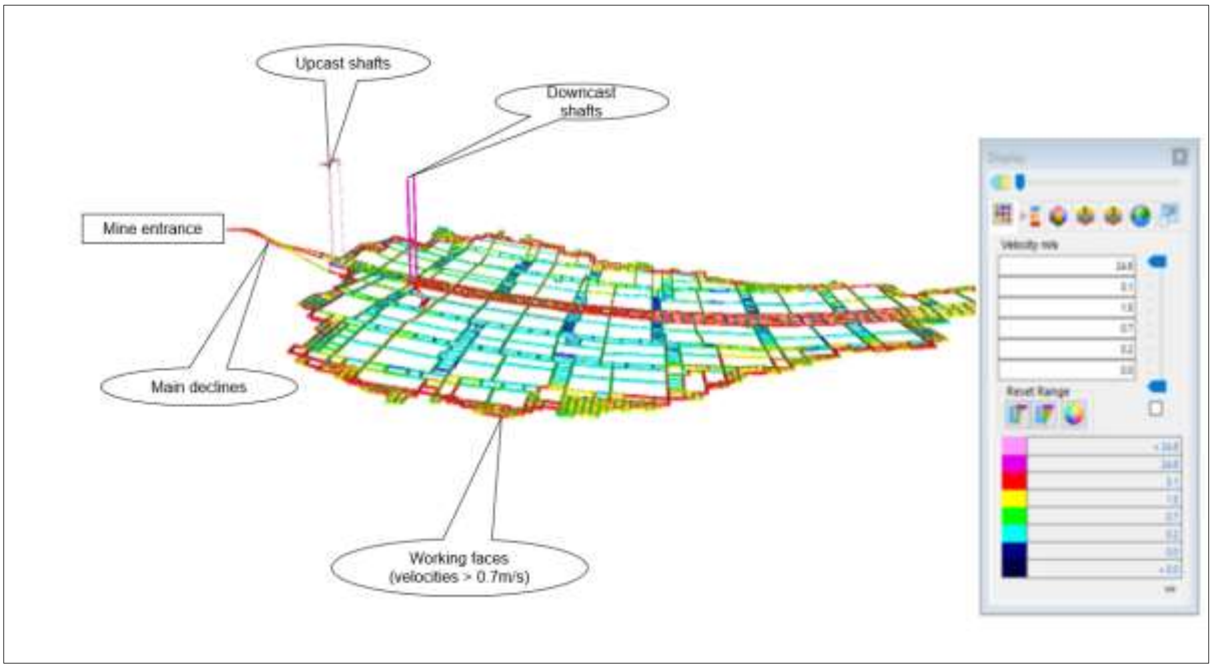

Figure 3.3: Ventilation layout designed during this research

3.7.1 Air velocity determination and measurement

The efficiency and economics of any ventilation system can only be determined when air velocities and quantities are accurately and reliably measured and monitored. The author looked at how velocities vary as mining progresses. The research area comprises of mechanised operations with more diesel engine power hence network simulation was done using Ventsim software. The simulation incorporated the airway resistance determined from survey measurements and frictional pressure losses. Air velocity, quantity and density were used to determine fan efficiencies. This research involved using air velocity during the design phase and operational stage to ensure compliance with legislation and air demands. The author also reviewed the current instruments used and the frequency of measuring air velocities at various platinum mines on the Great Dyke. Figure 3.4 shows simulated velocities during life of mine for the designed greenfield project.

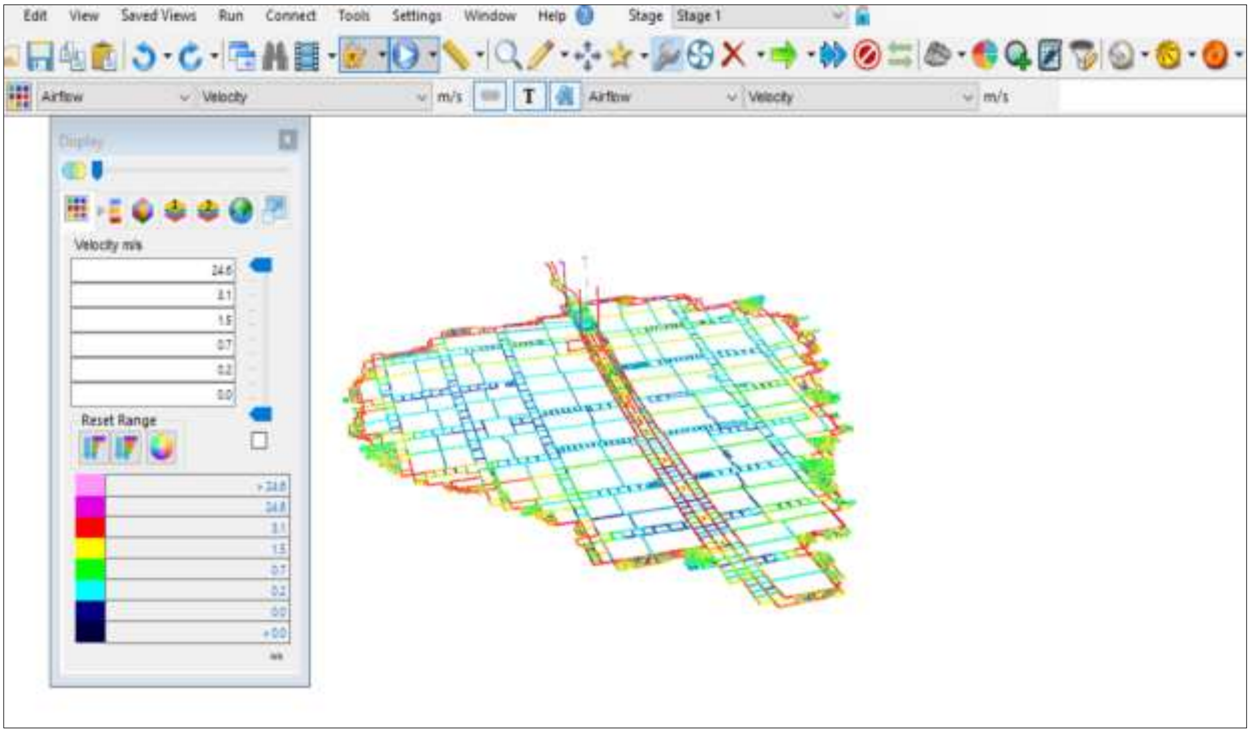

Figure 3.4: Air velocities in a mine

The mines are currently using conventional tools such as vane anemometers to determine air velocities and this exercise is normally done on a monthly basis. In this research a system was proposed that makes use of fourth industrial revolution tools such as smart sensors, connectivity and machine learning when monitoring air velocity. This was necessary to flag any anomalous air behaviour in the system and for the system to automatically adjust itself to yield conducive underground conditions. Real time monitoring of air velocities is vital for safe and productive operations. Planned velocities were integrated during the design stage with actual air velocities so that any deviations will be addressed automatically. Dynamic monitors were used to mimic smart airflow sensors during simulation and this will be described in Chapter 5. The system was designed to modulate air velocities based on the actual demand. Air quantity was also used as a direct measure of ventilation efficiency since it is a function of air velocity and cross-sectional area. In this research, the ventilation system was optimised through integration of empirical techniques with numerical modelling. The overall air quantity was determined using various techniques such as the diesel dilution techniques, air tonnage ratio and the Canada Centre for Mineral and Energy Technology (CANMET) approach. Air quantity was accurately determined and optimised for safe operating conditions thereby eliminating potential gassing incidents and for power costs management. The direct bearing of air quantity on safety, productivity and costs necessitated to apply fourth industrial techniques during design and operational phases to ensure that conducive working environments are created. Figure 3.5 shows the projected air quantity distribution at full production for the greenfield project as mining progresses. This design will then be integrated with the actual quantities using smart sensors and software so that any deviations can be addressed accordingly. The average air quantity in the last through roads is 15m^3/s. this quantity is adequate to dilute DPM. It can be noted that the red colour represents quantities above 50 m^3/s. Such quantities are predominantly in the main return airways.

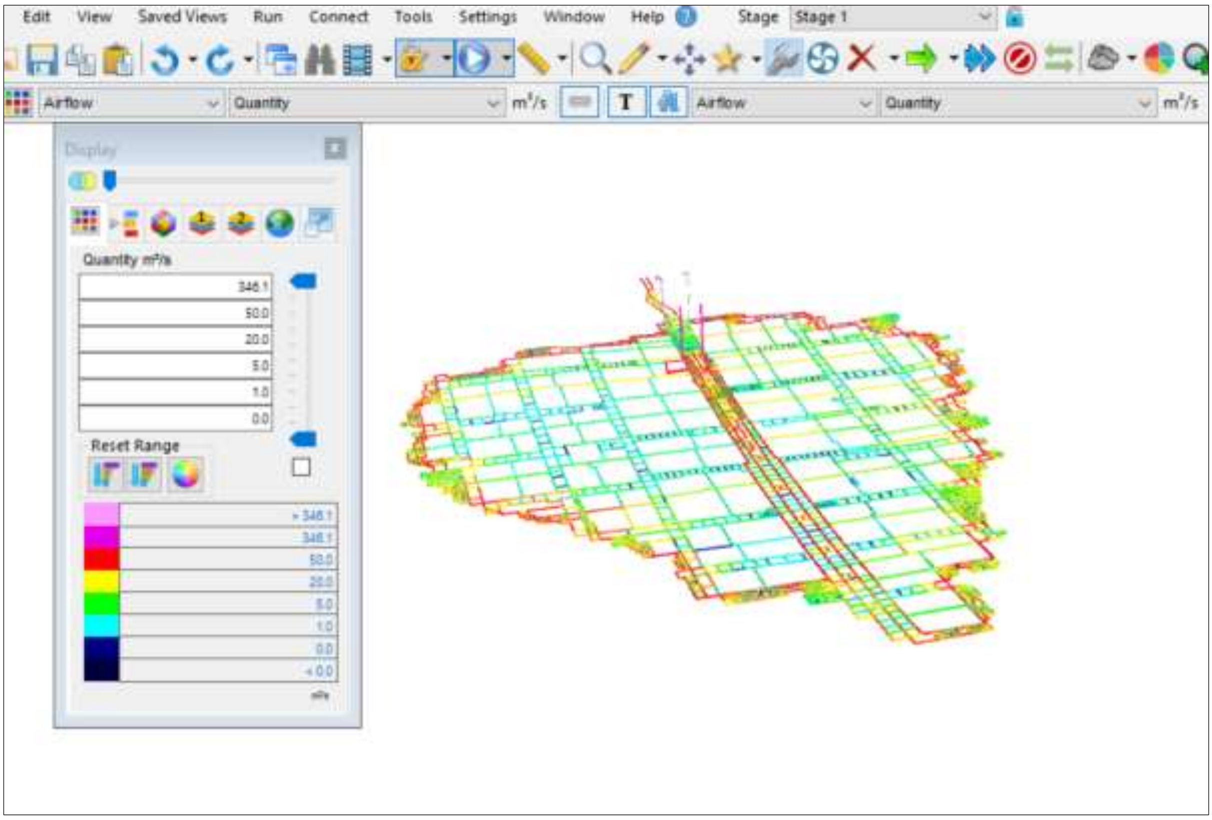

Figure 3.5: Variation of air quantity during life of mine

It is important to note that the ventilation on demand system designed during this research was primarily based on air quantity and pressure loss. The safety and cost benefits at any underground operation can only be achieved if the air quantity is adequate. The life of mine ventilation plan for the greenfield mine considered VOD systems. Several smart sensors to monitor environmental conditions will be positioned inside fan drifts, working areas, intake and return airways. The desired air quantity trends will be superimposed on actual measurements picked by smart sensors which will allow remedial action to be put in place automatically in real time. Air quantity will also be linked to smart sensors monitoring airborne pollutants so that if readings are above OELs, then the system will automatically adjust itself to normalise the readings.

3.7.2 Fire simulation and management

Most platinum mines operating on the Great Dyke are equipped with underground conveyor belts and use large mobile machinery. Following several fire incidents involving conveyor belts and mobile machinery fires described in Chapter 1, a series of evaluations associated with specific theoretical scenarios in the research area, particularly for the greenfield project were conducted. Any underground fire poses a serious threat that can result in loss of life and revenue. The management of underground fires starts with mine design and ventilation systems hence fire simulations were done. These evaluations included the development of ventilation models utilizing the computerized VentSim and VentFire modelling tools to evaluate the hypothetical fire scenario as it may potentially develop. These tools were used since they are already available in the research area. Alternative solutions such as VUMA can also be used to achieve similar results. This modelling exercise provides significant data on the fire-related products and thermal conditions which can be expected to be generated by such fires and the potential risks to the health and safety of underground employees. Such modelling was done to quantify the heat load, optimise ventilation design and to develop appropriate fourth industrial revolution tools that can monitor the fire risk. Again, dynamic monitors were used in the model during the design phase and will be replaced with smart sensors during implementation stage.

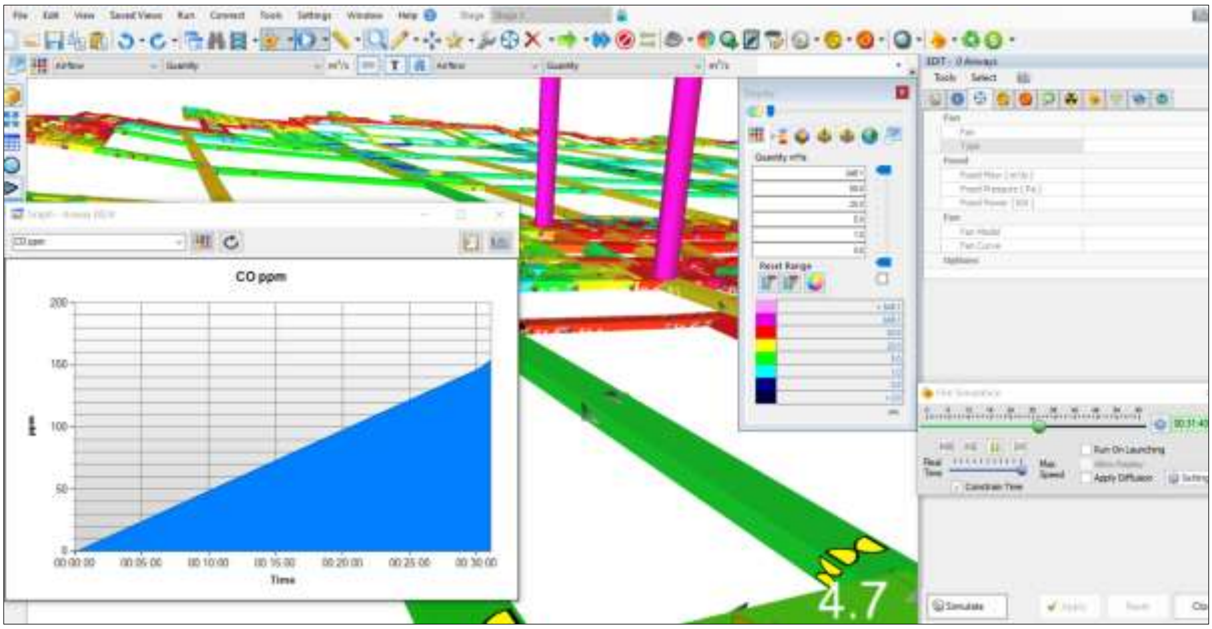

Figure 3.6: Fire modelling for conveyor excavations

3.7.3 Visibility

Visibility was also simulated in the event of an underground fire as part of emergency preparedness. This was done by generating smoke through burning of several fire loads such as trackless mobile machinery and conveyor belts. Figure 3.7 shows a typical simulation graph on visibility after a conveyor belt segment burnt.

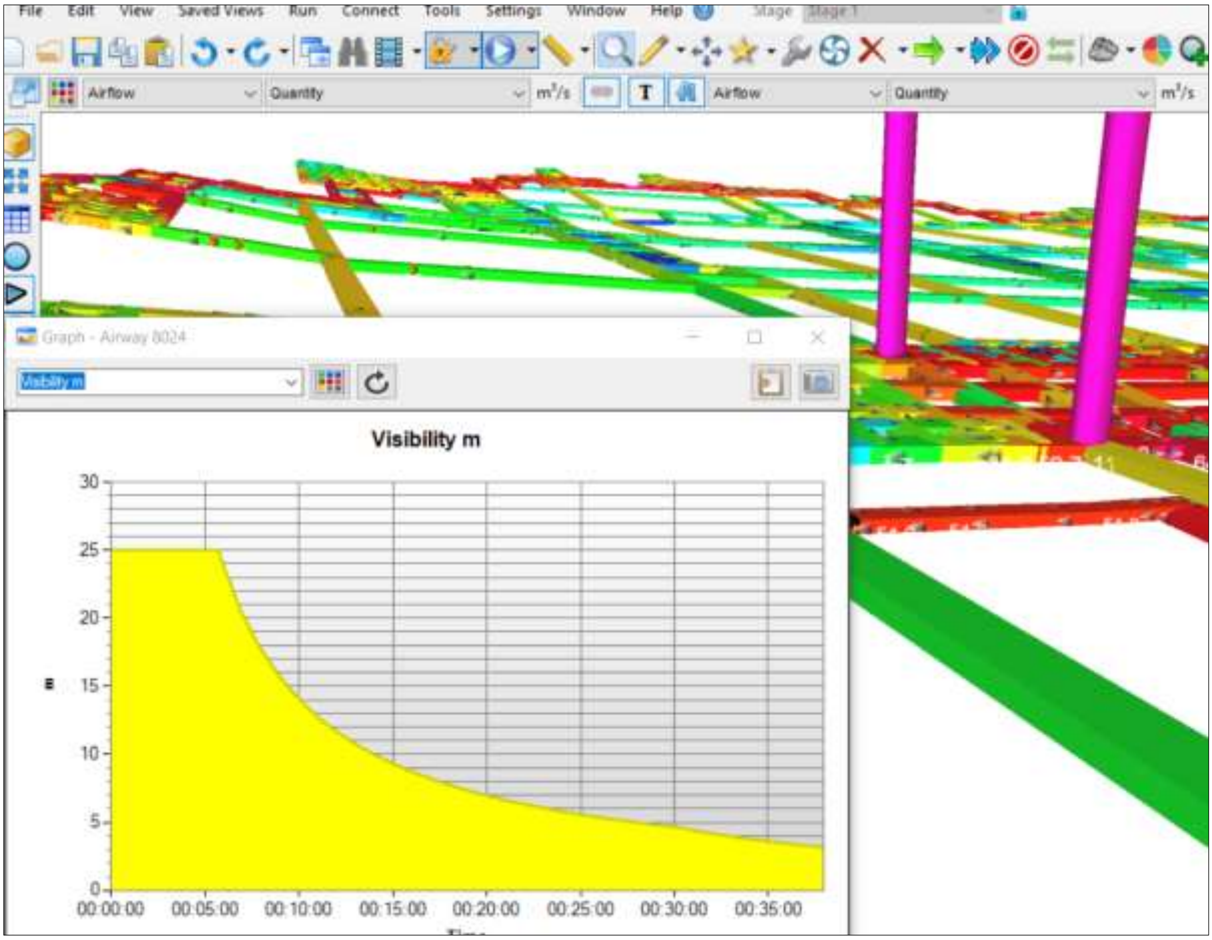

Figure 3.7: Underground Visibility

This will assist designers and management to monitor visibility and provide data on how to reduce the effects of fires on the underground personnel through application of fourth industrial revolution techniques and to evacuate men from affected areas. The simulation assisted with the design of ventilation systems and implementation of fire containment devices, smart sensors and the required connectivity. Dynamic monitors were used to resemble smart sensors and display visibility trends in response to change in atmospheric conditions particularly in the event of an underground fire. Emergency preparedness equipment such as refuge chambers were proposed with the latest technologies or specifications that incorporate fourth industrial revolution techniques to warn employees and manage risks. Main routes from working faces to refuge chambers were also equipped with modern techniques that will lead employees to safe areas, as opposed to conventional techniques. Such fourth industrial revolution techniques were considered to mitigate potential fire risks which have historically resulted in fatal gassing incidents.

3.7.4 Temperature monitoring

Temperature being one of the key ventilation indicators was also considered during design and monitoring phases. The current legislation on the heat rejection temperature was applied both during design and monitoring. For the design of the greenfield project, a heat rejection temperature of 27.5°C was used as a cut off. Figure 3.8 shows a typical heat map for dry bulb temperatures at full production.

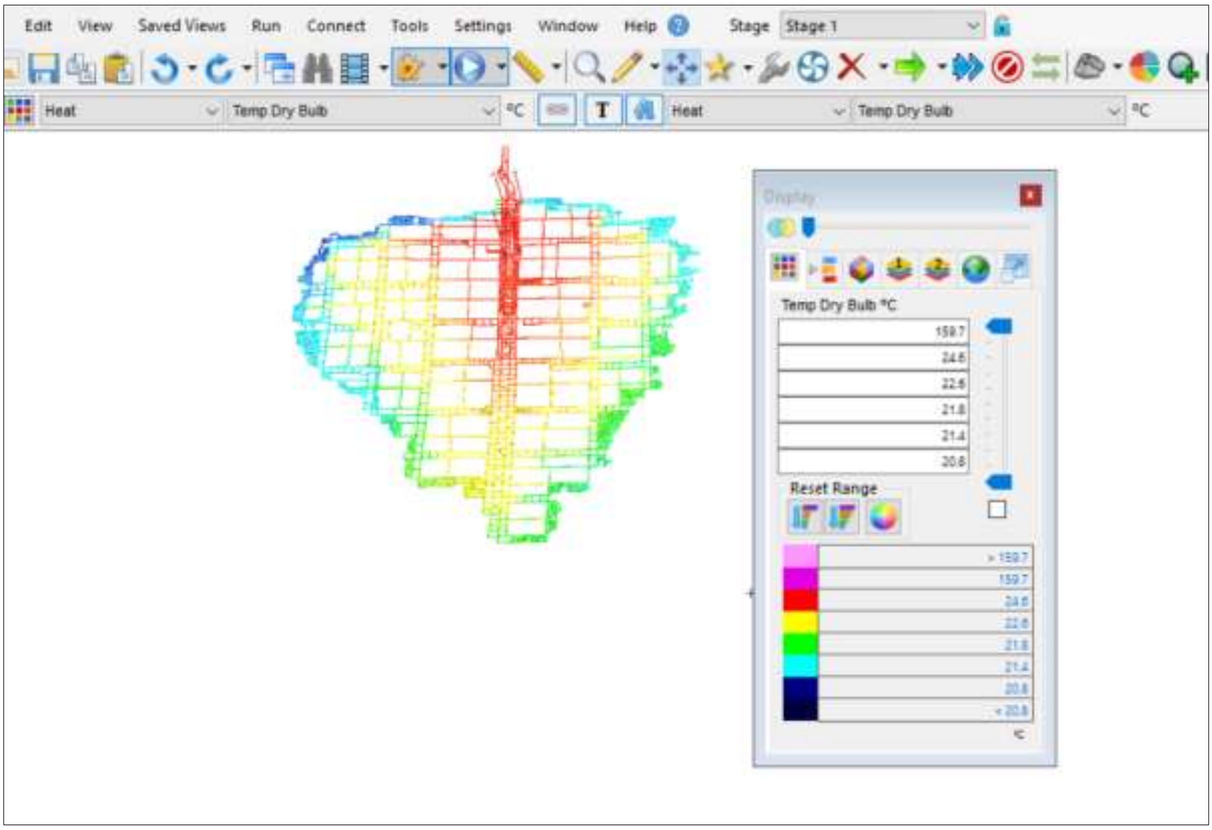

Figure 3.8: Dry bulb temperature simulation

A measurement of temperatures will assist in mitigating health related risks such as heat stroke and heat exhaustion. There is always a gap between design and implementation regarding temperature variations. During this research a system will be designed that will integrate designed conditions with actual environmental conditions so that remedial action can be undertaken in real time. Smart temperature sensors were considered during this research and their output will be integrated with the designed parameters. Figure 3.9 shows the expected temperature distribution at peak load during mining. No refrigeration will be required in the research area because of shallow depths as shown in the model.

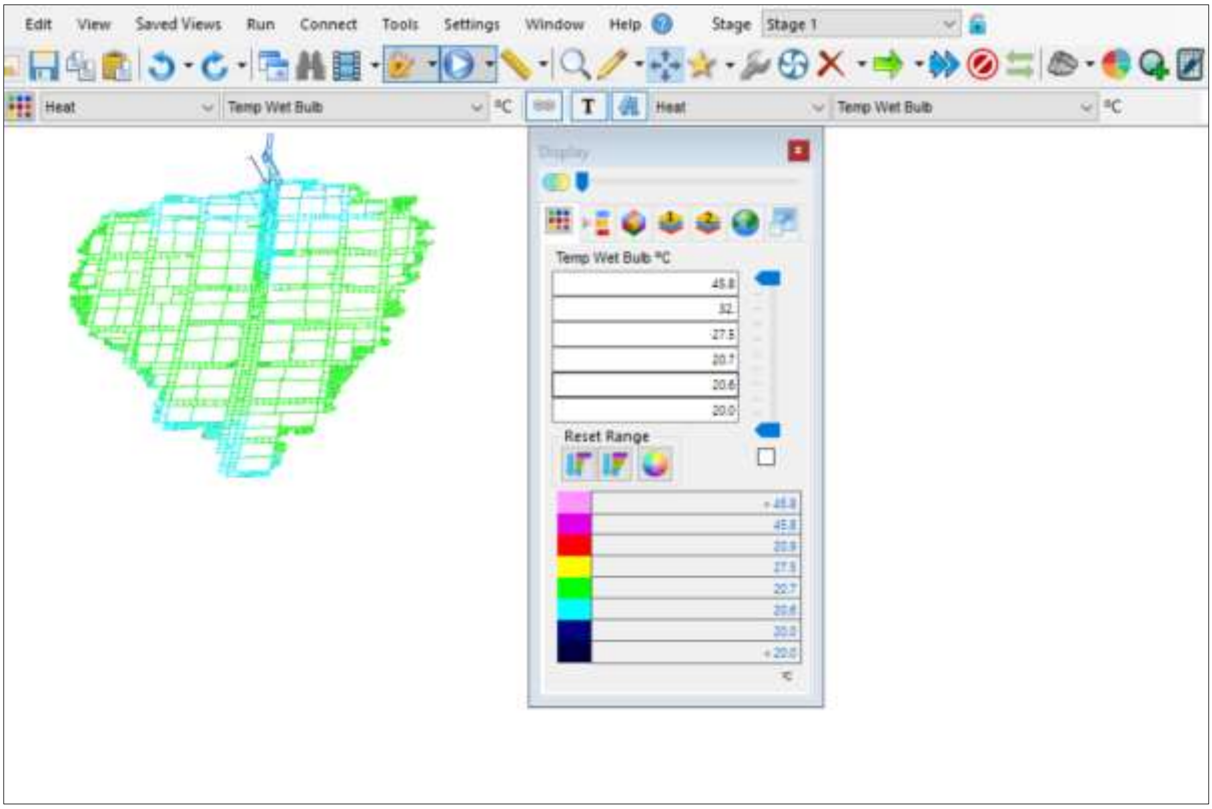

Figure 3.9: Wet bulb temperature variation

The heat stress index will be populated in real time data through remote monitoring. A thermal system was designed to automatically respond to incremental temperature increases without human reliance. The designed system will bridge the gap between environmental monitoring and medical surveillance. The system will therefore improve the health and safety of employees as well as yield optimum productivity due to conducive working environments.

3.7.5 Dust management

Excessive dust generation will affect workers' health and impact negatively on employee productivity and other performance indicators. Ensuring adequate precautions against harmful dust is a requirement of the Zimbabwean Mining Management and Safety Regulations (S.I. 109 of 1990) and adherence to this clause is necessary to protect the company's licence to operate. Failure to comply can result in compensation claims, litigation costs, decreased productivity and reputational damage to the organisation. Minimising dust exposure to all workers is a priority of both the International Labour Organisation and the World Health Organisation. Respirable dust was also considered during the design phase as well as its monitoring due to its harmful effects. Most mines ignore the anticipated dust levels during ventilation design and only focus on the residual dust levels during operations. Dust levels for the greenfield mine were projected based on simulation results and historical experience during the design phase so that the risk of pneumoconiosis can be eliminated. Figure 3.10 shows typical dust simulation conducted near the crushing plant of a greenfield project. Potential high dust areas were identified and various control measures were put in place to ensure that residual dust levels are within OELs. The whole essence of such simulations was to incorporate fourth industrial revolution techniques during the ventilation design and implementation stages as part of dust management strategies.

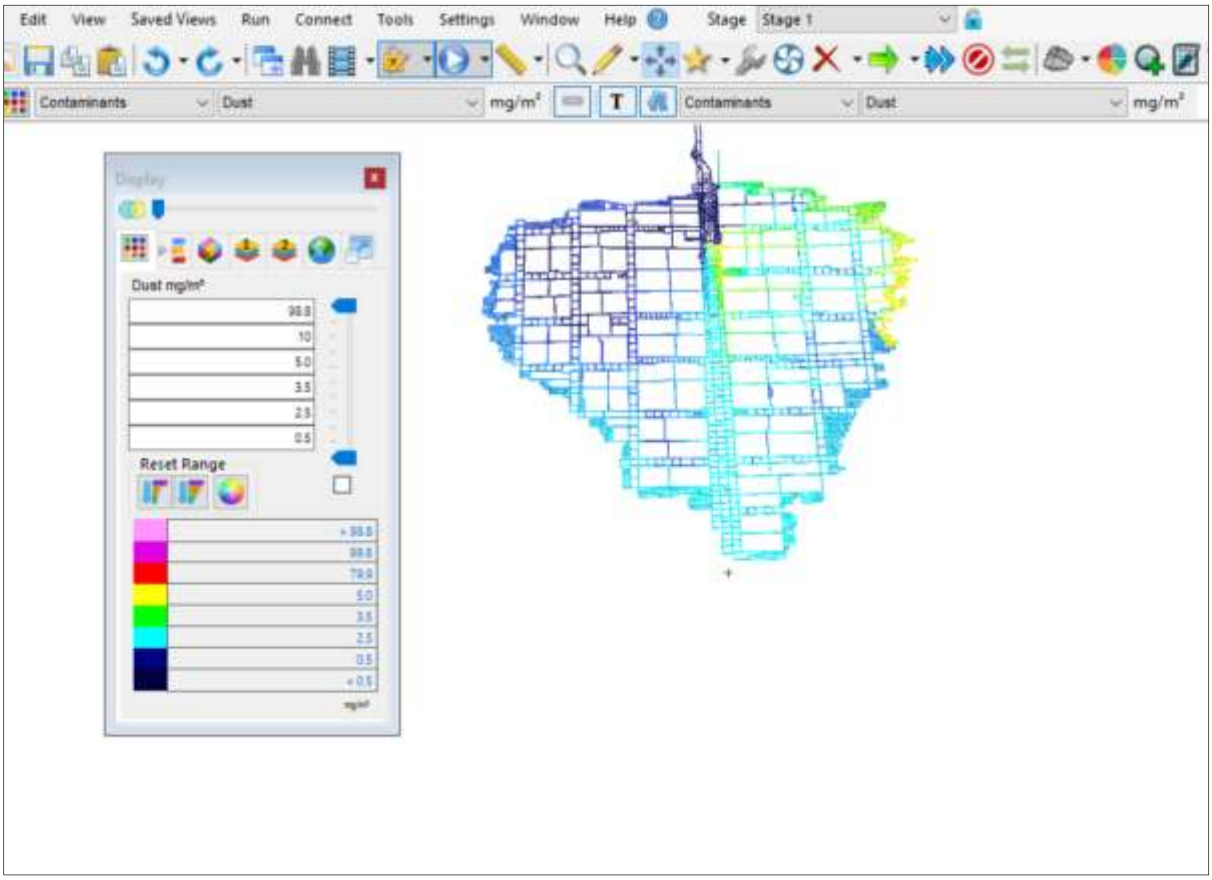

Figure 3.10: Dust simulation

Trolex dust monitoring systems were used in high risk areas so that the system will detect dust in real time and automatically adjust the ventilation requirements to combat any dust levels above OELs. Fixed dust monitoring (Trolex) results were compared against readings from handheld dust monitoring (AMS Haden). Such telepathic systems will be discussed in detail in Chapter 5. The designed system comprises of smart dust sensors, communication backbone and other digital revolution components.

3.8 Explosives

Since explosives are currently used for blasting operations in the research area, various explosives properties were looked at so that ventilation systems could be optimized. The ventilation system was further optimised through reviewing current explosives used and also considered other possible explosives on the market. An underground simulation on blasting was done using different explosives so that air contaminants generated during blasting can be managed accordingly. Figure 3.11 shows how blasting using ammonium nitrate fuel oil affects the overall ventilation circuit.

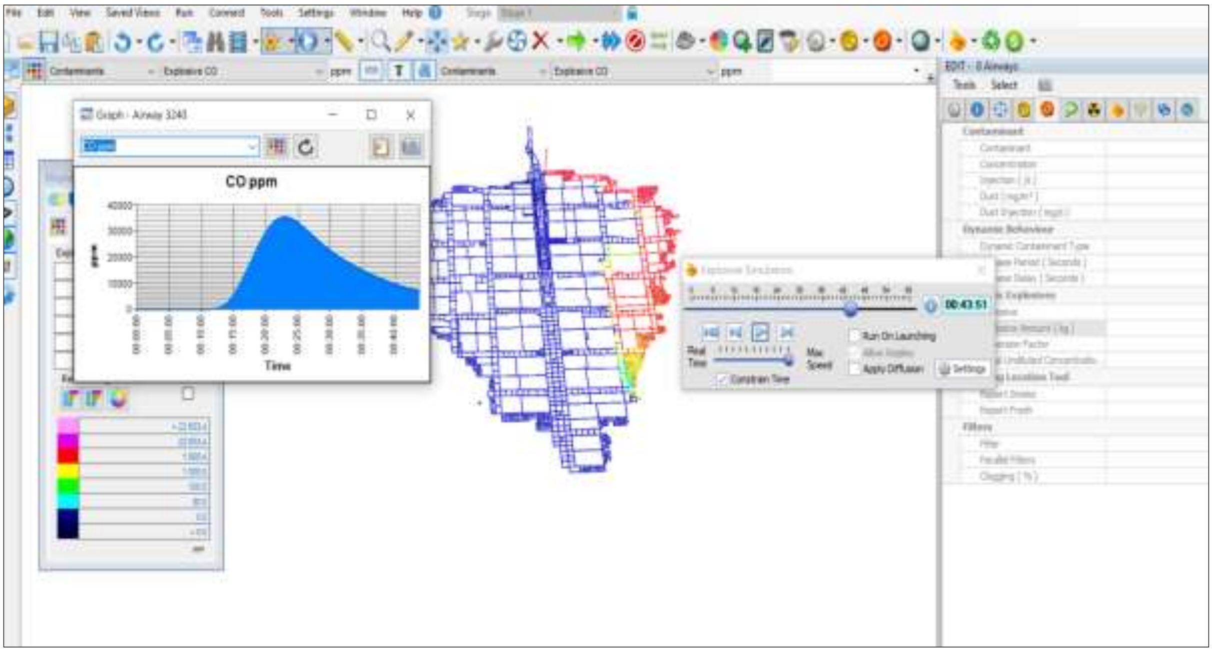

Figure 3.11: Variation of gasses when blasting using ANFO

The impact of blasting using ANFO was assessed on the overall ventilation system and these results were compared with other explosives such as emulsion. Figure 3.12 shows how blasting using emulsion affects the whole ventilation system. All this was done to determine an effective ventilation system that is safe and cost effective. Digital revolution techniques were therefore considered during blast design and monitoring since they also affect underground conditions. A cost benefit analysis on explosive types was also done and recommendations were subsequently proposed.

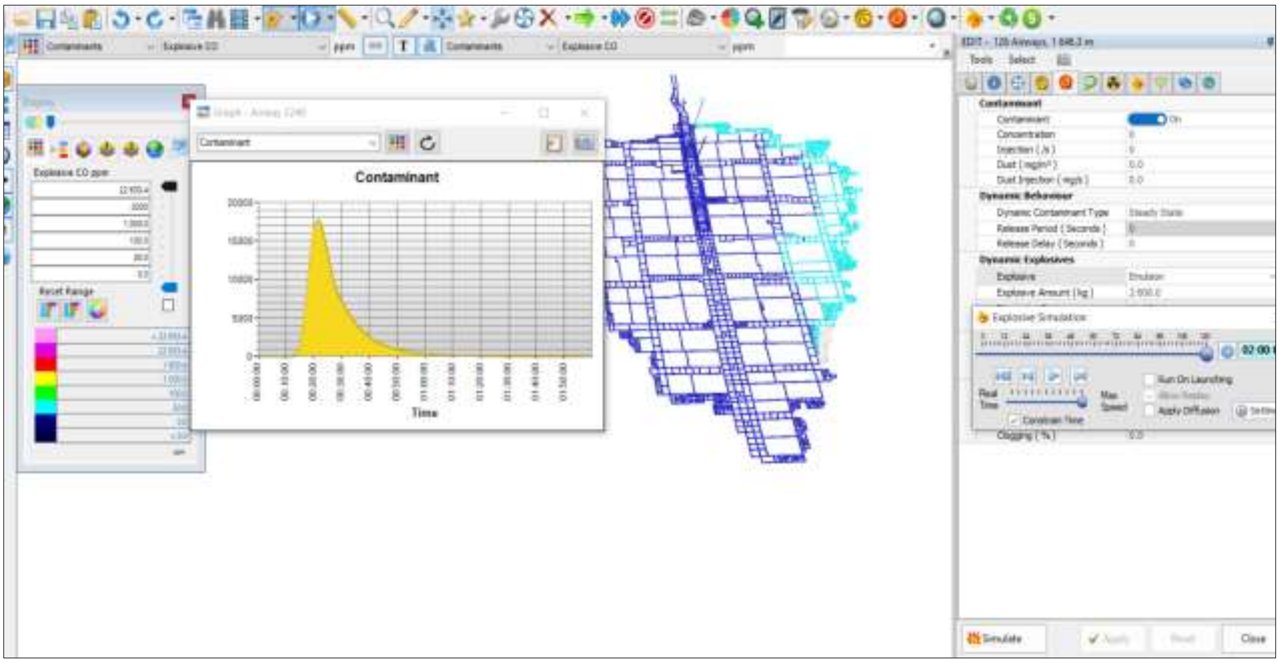

Figure 3.12: Gas levels when blasting using emulsion

A dynamic simulation was conducted as part of the environmental monitoring strategy and dynamic monitors were used to represent underground smart sensors. Figure 3.13 shows typical dynamic simulation results that can be expected when blasting operations take place.

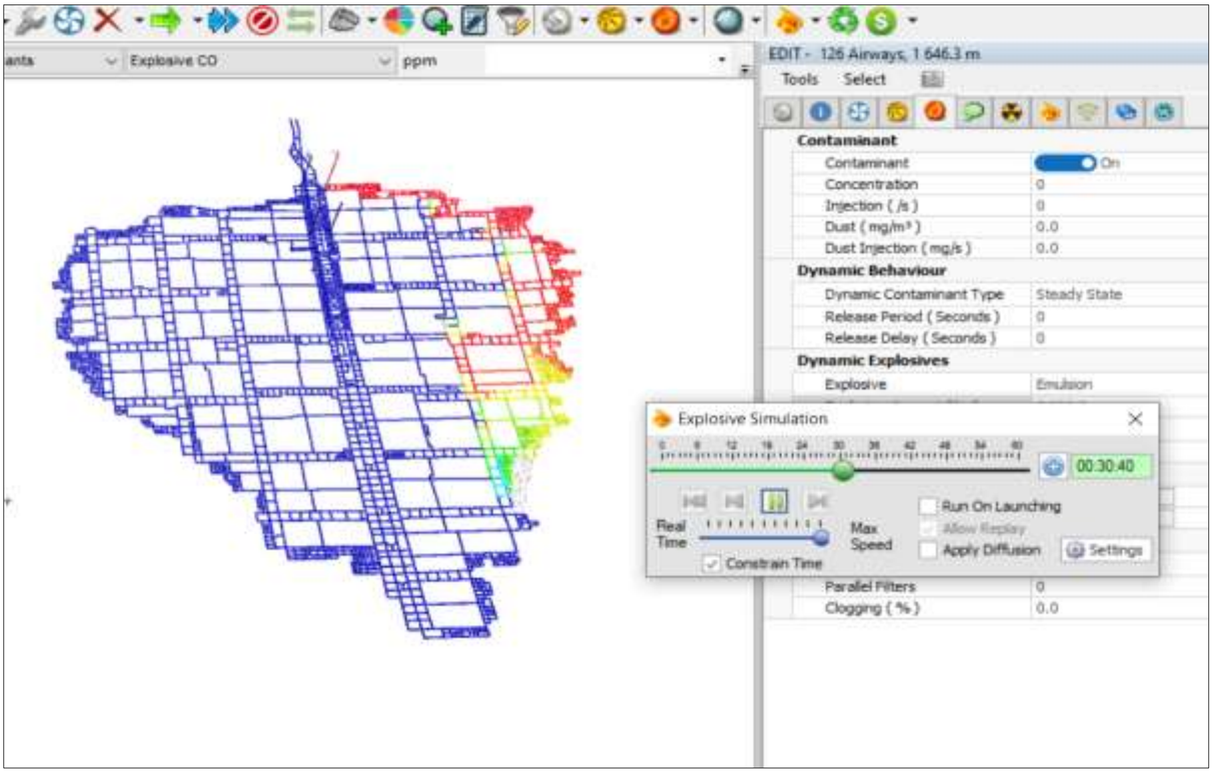

Figure 3.13: Dynamic simulation

3.9 Escape and rescue

Emergency escape routes play a pivotal role in underground mines particularly in the event of an incident such as an explosion or fire since employees need to be warned and evacuated to a safe place. Various preventative controls were discussed previously and emergency systems will be used as corrective controls. The current emergency systems such as escape routes, self-rescuers, refuge bays and chambers were also reviewed. The current techniques used on platinum mines on the Great Dyke are based on conventional means hence a system was designed to incorporate fourth industrial revolution techniques in the event of an accident or incident to save lives. Figure 3.14 shows a typical heatmap for refuge chambers referenced to maximum face distances in a greenfield project. The simulation results apply to ventilation design, however, fourth industrial revolution techniques will be needed to ensure that mines comply without relying on human measurements.

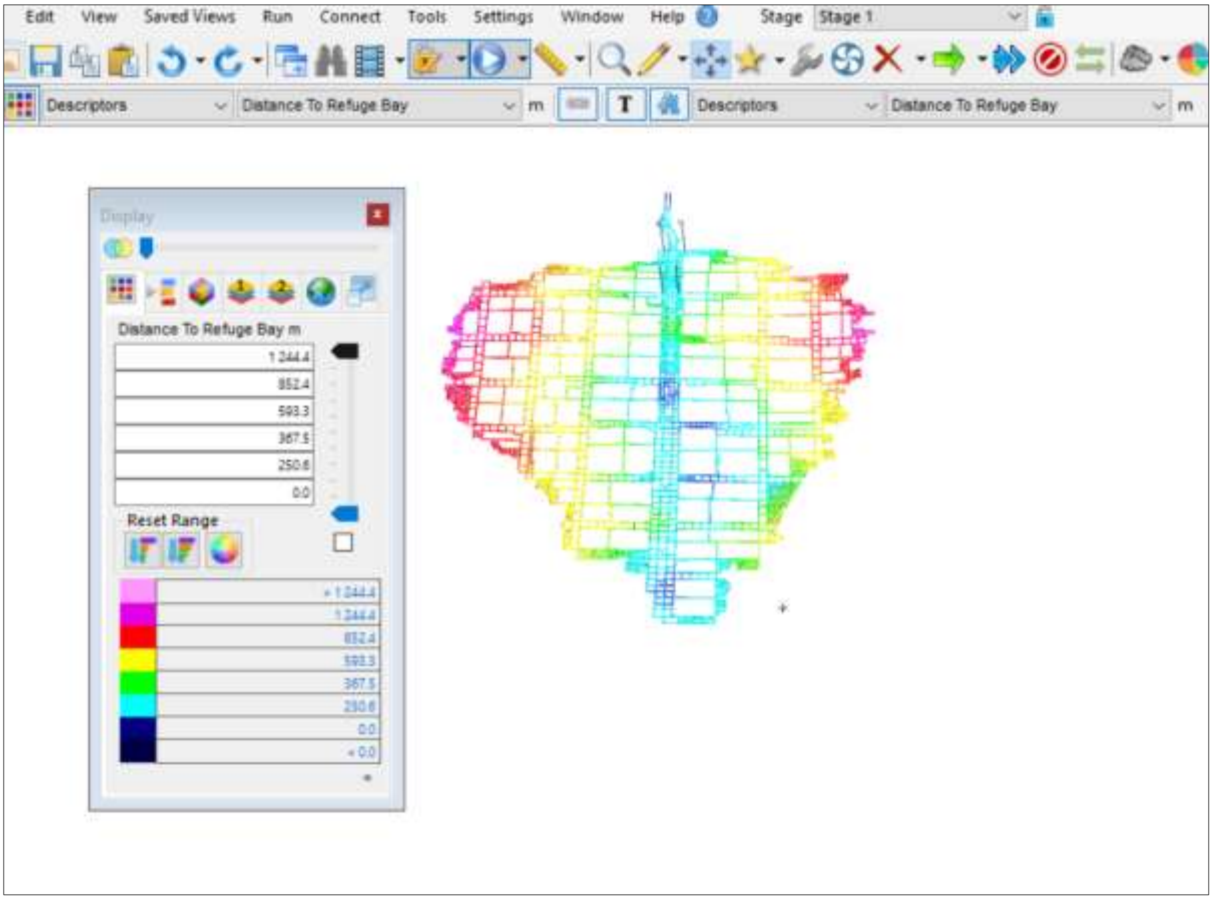

Figure 3.14: Simulation of refuge chamber distances from the face

Smart sensors were integrated with designed systems so that any anomalous behaviour can be flagged and addressed. A system was therefore designed that will warn and direct individual employees to nearest refuge chambers. The designed system involves sensors that will give the shortest route to take to a nearby refuge chamber and the maximum number of people that can be accommodated. That system coupled with the tagging and tracking components will help mining companies to account for all individuals in the mine at any given time. If a certain individual is trapped elsewhere, the commissioned smart sensors will be used to locate the individual and warn him through various means as discussed in Chapter 5. Figure 3.15 shows typical escape routes options that will be displayed on the battery cap lap for the employee to reach the nearby safest refuge chamber. This will be archived through visual communication. Smart sensors will also be installed along the escape routes so that employees will be guided even in cases of zero visibility. Simulation results were verified using actual measurements during mock drills on emergency preparedness.

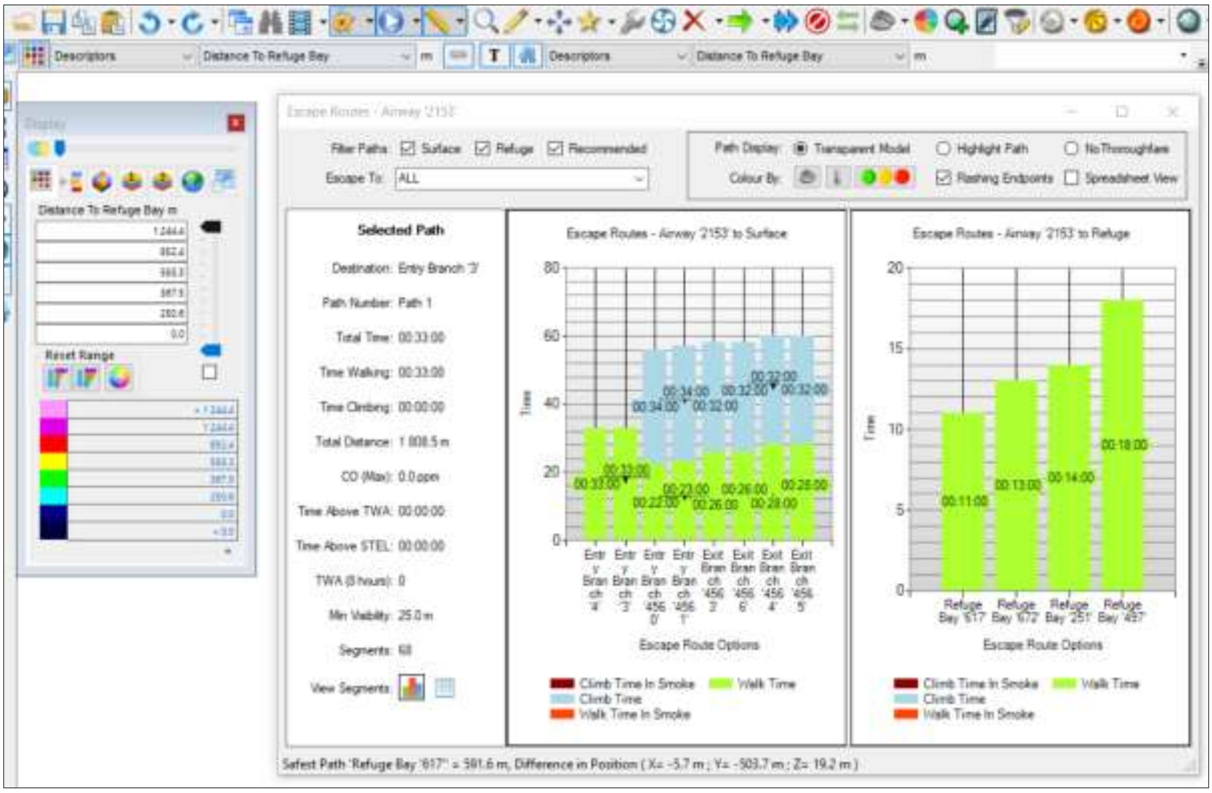

Figure 3.15: Escape route options

3.10 Power consumption

Power is one of the major cost drivers in mechanised mining operations hence monitoring and management of power consumption is essential. Various simulations or scenarios were carried out to optimise power usage. The projected power consumption for the life of mine was determined through empirical calculations and ventilation simulations. Figure 3.16 shows a typical fan power load from the simulation conducted for the greenfield project. The colours denote variation in air quantities as indicated on the legend. It can be seen that the minimum face air velocity is 0.8m/s and is adequate to dilute all contaminants. This research resulted in the design of a system that integrates projected power consumption from ventilation designs with actual power consumption through the application of fourth industrial revolution techniques. This was necessary to manage power consumption in real time thereby managing operating costs. Most platinum mines in the research area use negative pressure systems with main surface fans sitting on top of raise bore shafts. The mines use a hybrid of both axial and centrifugal fans. Refrigeration is not required based on shallow depths and simulation results. From the designed system, main surface fans will be driven by variable speed drives so that modulation of airflow will be activity-based. Main surface fans were regarded as primary constituents for the ventilation on demand system designed during this research.

Figure 3.16: Power consumption for main surface fans

To eliminate potential energy losses, a model was then designed to measure power in real time using smart sensors which will be linked with the Supervisory Control and Data Acquisition (SCADA) system. The designed system is expected to produce real time power trends from actual measurements and this will be cross-referenced against expected power consumption. The system will also flag and auto correct any anomaly in the system thereby managing ventilation power consumption. Figure 3.17 shows a typical power consumption report generated from the system.

Network Summary

File Edit

Main | Fans | Heat | Energy | Graphs | R Curve | Full | Heat Track

NETWORK SYSTEM SUMMARY	
Compressible Airflows	Yes
Natural Ventilation Pressure	Yes
Fan Pressure Simulation Type	Static Pressure Method
Stage	0: Stage 1
Airways	4792and 7 Excluded
Current Stage Segments	4422 and 6 Excluded
Total length	98 283.4 m
Total airflow intake	676.1 m^3/s
Total airflow exhaust	696.0 m^3/s
Total massflow	777.80 kg/s
Mine resistance (excluding duct)	0.00387 $Ns^2/m8$
Mine resistance (Including duct)	0.00387 $Ns^2/m8$
POWER SUMMARY	
AIR (friction loss) Power	1 249.2 kW Total
	283.2 kW Shaft
	966.0 kW Drive
	0.0 kW Vent Duct
Refrigeration Power Input	0.0 kW
INPUT Power Electrical	**1 938.8 kW**
Network Annual Power Cost	**$ 1 698 428**
Network Efficiency	**64.4 %**
Consisting of ..	
4 Fans	1 938.8 kW
0 fixed pressures	0.0 kW
0 fixed flows	0.0 kW
0 Refrigeration	0.0 kW

Figure 3.17: Underground network summary

System resistance was also considered during both the design and execution stages. The projected system resistance will be compared with the actual mine resistance through automated systems. As part of this research a system was designed to monitor system resistance so that any deviations will be automatically corrected. Figure 3.18 shows a typical mine resistance curve expected at full production for the greenfield mine.

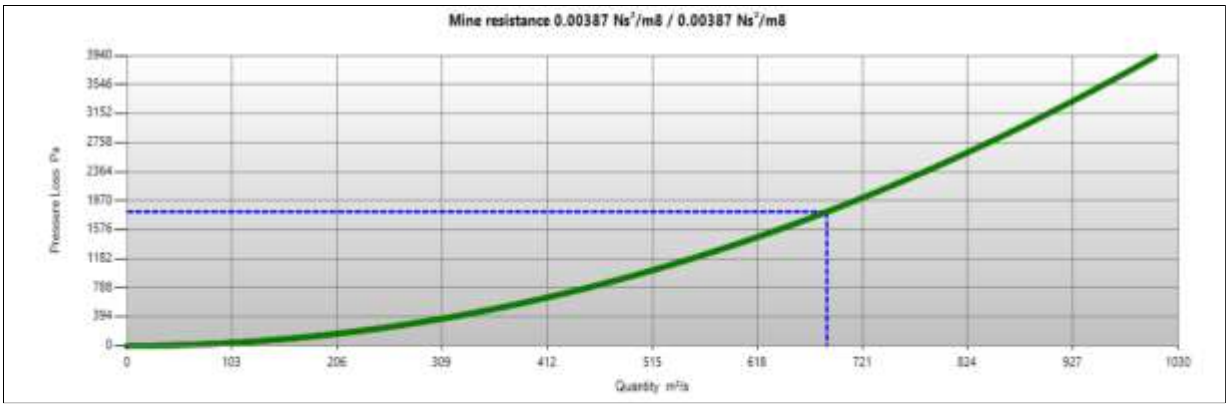

Figure 3.18: Mine resistance

Pressure loss is a function of system resistance hence it was incorporated during the design and execution stage. The author designed a system that monitors any pressure changes in the mine which allows the ventilation system to automatically adjust. If the system cannot adjust itself, for instance if there is a fall of ground or any obstruction in the main airway, the designed system will then flag this immediately so that remedial action will be put in place. Application of fourth industrial revolution techniques were mainly used in ventilation design and monitoring in order to optimise the mining key performance indicators of safety, productivity and costs. Figure 3.19 shows variations in barometric pressure for an underground set up. Yellow colour shows barometric pressures averaging 101.2kPa while the purple colour denotes the maximum barometric pressure of 103.2kPa. The barometric pressures increases with depth with lesser pressure readings closer to the declines and more pressure towards the syncline position with the greatest depth.

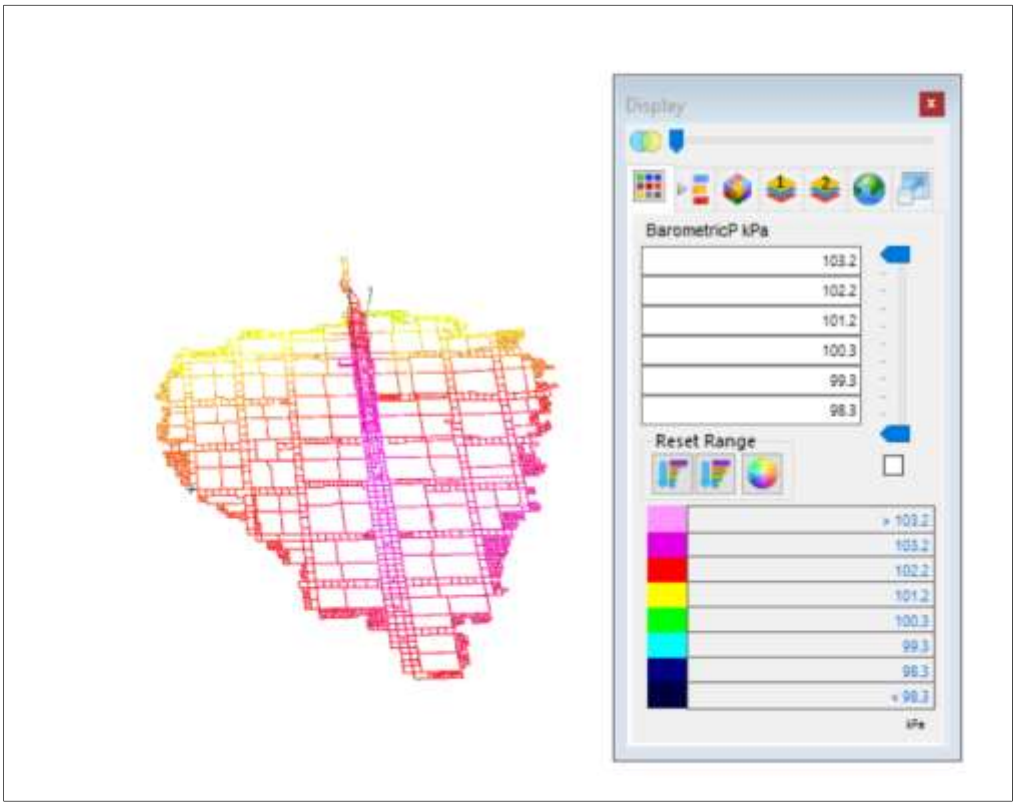

Figure 3.19: Pressure change in the system

Figure 3.20 shows the energy loss summary for the greenfield mine as designed by the author. Monitoring such critical parameters in real time was considered a necessity. It can be noted that drive wall friction losses contribute over 50% of the energy losses.

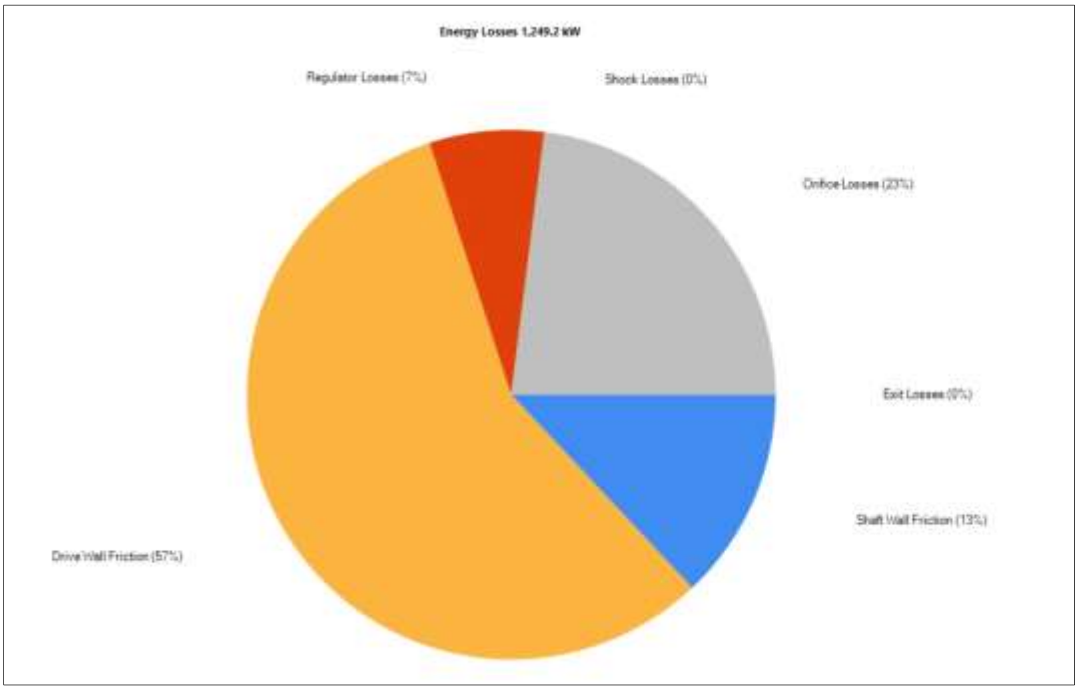

Figure 3.20: Energy losses

3.11 Chapter summary

In this research, both grounded theories and a practical approach were employed to achieve the research objectives. Initially, data was gathered from literature materials before collecting quantitative and qualitative data to achieve the aim and objectives of the research. Collected data was subjected to deductive and inductive reasoning with a view to identifying the key factors, issues and concepts that are pertinent to the research. Knowledge gained from leading best practices, literature and field observations was used to design and install a ventilation on demand based system using fourth industrial revolution techniques to review and improve current ventilation systems at one of the platinum mines operating on the Zimbabwe Great Dyke. The next chapter discusses ventilation design techniques which can be used in bord and pillar platinum mines.

CHAPTER 4 - CASE STUDY: VENTILATION DESIGN FOR A GREENFIELD UNDERGROUND HARD ROCK BORD AND PILLAR MINE

4.1 Introduction

Underground ventilation systems are crucial in mechanised platinum operations as they affect both efficiency and environmental conditions hence they constitute an integral part of the initial mine design. During the design stage, planners must strike a balance of creating a safe, healthy and conducive working environment by utilising cost-efficient ventilation systems. Numerous facets of ventilation systems are planned following a comprehensive baseline assessment as a mitigatory measure against all ventilation risks. Underground mines use large ventilation systems to maintain a safe and healthy environment for miners. Ventilation systems to meet both mining and engineering necessities should neither be overdesigned nor under designed since they have a direct bearing on mining key performance indicators of safety, productivity and costs (Watrant, 2008). It is against this background that ventilation systems need to be optimised in a logically structured and methodical manner. The mining industry is consistently changing from conventional to mechanised operations with some platinum mines already implementing digital transformation in their value chains. The design process to which ventilation systems are designed must incorporate all emerging exploitation techniques.

Dilution of diesel particulate matter (DPM) is often a key factor used to determine ventilation requirements in most mechanised platinum mines. Diesel emissions and exposure levels are highly variable depending on mine schedules and activities (Gangal and Grenier, 2002). Recent studies show that due to a lack of technology to continuously monitor levels, mine ventilation systems are often over-designed (De Souza, 2018). The main objective of this mine ventilation optimization thesis is to develop a sensible method for ventilation system control that minimizes the total cost attributable to mine ventilation. The fundamental principles for ventilation network optimization are highlighted and a multi-objective optimization model was established from the viewpoint of total cost of ownership. This thesis describes an optimised ventilation design approach for room and pillar platinum mines together with some power saving initiatives applicable to mine ventilation systems.

The mining method and exploitation sequencing determine quantitatively the required airflow for each stage of the mine that is from development to full production and lastly closure. The degree of mechanisation coupled with the required productivities often dictate the required air quantity at each stage. A case study mine on the Great Dyke of Zimbabwe was used to illustrate the modern design approach that can be used to determine air requirements in mechanised room and pillar platinum mines. The greenfield mine considered is required to produce 168 000 tonnes per month. Underground ore extraction will be carried out using a mechanised room and pillar mining method. Load- haul-dump (LHDs) and dump trucks will be used for ore conveyancing from the face to the underground tips where ore will be crushed and hoisted out of the mine by a series of conveyor belts.

Table 4.1 shows the key mining parameters for the case study area which were used for ventilation design.

Table 4.1: Mining parameters

Total production	168 000tpm
Number of fleets	8
Room width (m)	6
Mining height (m)	2.5
Advance per end per blast (m)	3
In situ density	3.20kg/m^3
Blasted ends per section per day	5
Total ends blasted per day	40
Section back length	300m
True dip	Up to 10°
Maximum strike distance	6000m
Maximum dip distance	2000m
Maximum vertical depth	250m
Shift cycles	2 per day, average 29 days per month

The mine design allows for two ventilation districts, one on either side of the decline system. Salient features and dimensions of the research area are illustrated in Figure 4.1.

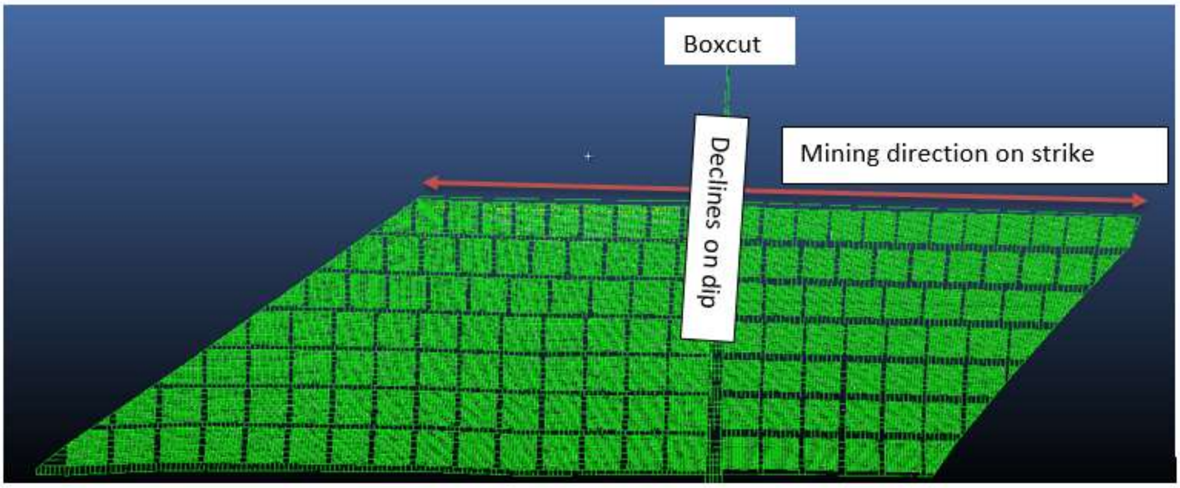

Figure 4.1: Case study footprint area

A sound ventilation design results in minimum occupational health diseases. The objective of this thesis is to improve occupational health of employees through a sound ventilation design and environmental monitoring by application of fourth industrial revolution strategies. Occupational Exposure Limit (OEL) means a time-weighted average concentration for an 8-hour workday and a 40-hour workweek which nearly all workers may be repeatedly exposed to without adverse health effects (Stanton, et al., 2014). Occupational Exposure - Ceiling limit (OEL-Ceiling) means an instantaneous value, which must never be exceeded during any part of the employee's exposure (Stanton, et al., 2014).

4.2 Ventilation design criteria

In order to provide acceptable occupational hygiene conditions for developing and mining of the case study area, occupational hygiene best practices, benchmarking information and current health and safety issues were considered. Table 4.2 shows the recommended design airway speeds as pointed out by Du Plessis and Biffi (2014).

Table 4.2: Main airway speeds *(Du Plessis & Biffi, 2014)*

Airway	Air speeds
Conveyor declines	1 -3m/s
Downcast shafts (equipped)	10 - 12m/s
Downcast shafts (unequipped)	18 - 22m/s
Up cast shafts	18 - 22m/s
Raise bored holes	15 - 25m/s
Footwall drives (personnel)	6 - 8m/s
Declines (personnel)	6 - 8m/s
Return airways (not utilized)	10 - 12m/s

Two access declines on either side will measure 6m wide x 3.2m high. Then the last two headings will form ledging declines and will measure 6m wide and 2.5m high. Figure 4.2 shows a typical mining layout for a particular section.

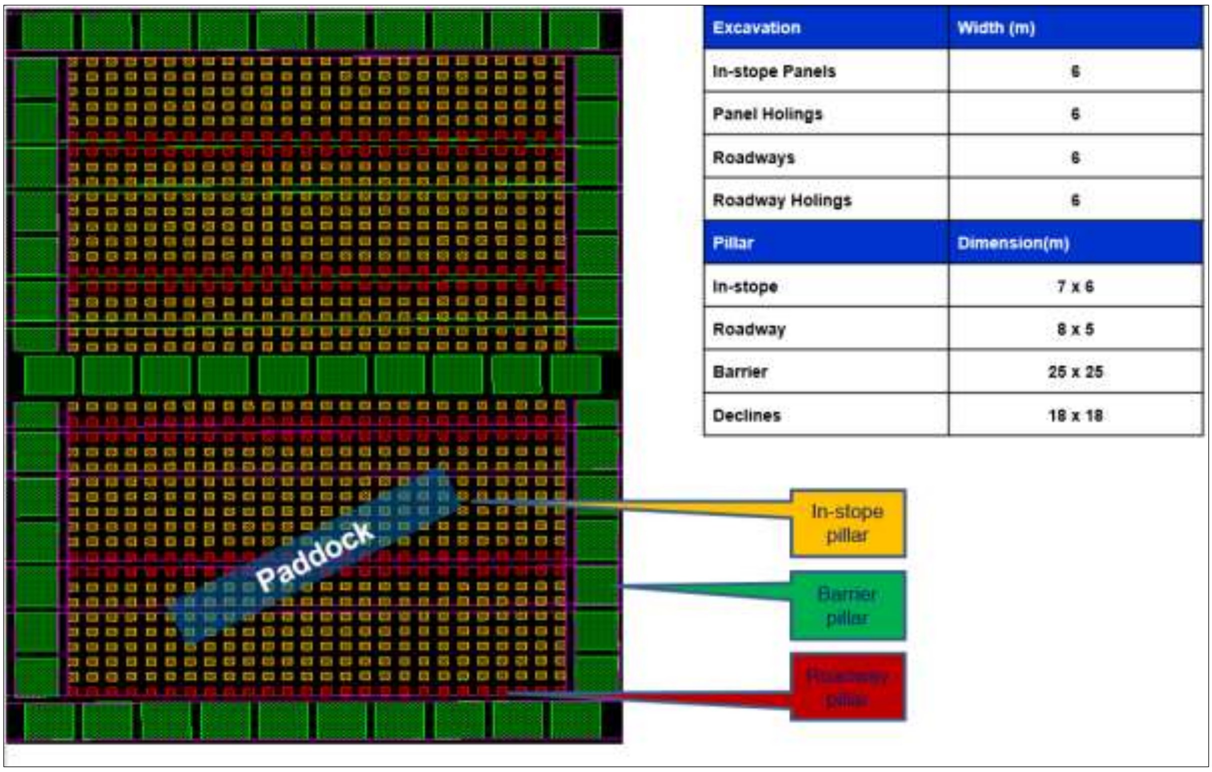

Figure 4.2 Mining layout

Table 4.3 shows the airway dimensions for the case study mine.

Table 4.3: Airway dimensions

Mining Excavation	Dimensions
Access Decline from surface	6.0m x 3.2m
Conveyor Decline	6.0m x 3.2m
Access Decline Connections	6.0m x 3.2m
Vent. Holing: Access Decline to Conv. Decl.	3.0m x 3.0m
Loading Bays	6.0m x 3.2m
Switch Backs	6.0m x 3.2m
Declines on Reef (7 declines)	6.0m x 3.2m
Roadways	6.0m x 3.2m
Room Width	6.0m
Room Height	2.5m
Pillar Holing	6.0m
Pillar Holing Height	2.5m
Pillar Size (average)	6.0m x 6.0m wide
Phase 1: Intake Raise Bore Holes	2 x 4.3m diameter
Phase 2: Intake Raise bore holes (±1800m down dip)	2 x 4.3m diameter
Phase 1: Return Raise bore holes	2 x 4.3m diameter

Frictional pressure drop in a length of any airway is directly proportional to the frictional factor, the length of the airway and the square of the air velocity (Du Plessis & Biffi, 2014). Frictional factors can vary by an order of magnitude depending on the roughness of the perimeter of the roadway. Raise bore shafts have a smaller resistance compared to blasted airways because the raise borer leaves a smooth wall, circular opening. The following air friction factors shown in Table 4.4 were used to determine mine resistance and pressures in the research area:

Table 4.4: Friction factors *(Bluhm & Smit, 2014)*

Airway	Friction factor
Intake airways (irregular sides)	0.0158Ns^2/m4
Return airways	0.0158Ns^2/m4
Galvanized vent. Duct	0.004Ns^2/m4
Raise bore holes	0.004Ns^2/m4
Men & Material shafts	0.025Ns^2/m4

4.2.1 Leakage

Air leakage is a function of the type of seal, condition of seal and pressure across the seal. Over an average strike distance of 3km up to 200 seals are installed in a single roadway. In excess of ± 8000 strike and dip seals can be installed during the life of mine. Total airflow requirement grows exponentially with strike distance and leakage due to the compounding effects of higher pressure and more leakage paths. Typical results measured in South African (RSA) platinum trackless mining operations are as follows:

- Poor seal category leakage is 60% at a strike distance of 1.5km.
- Good seal category leakage is 30 to 40% at a strike distance of 1.5km.

The current seals utilized in the research area are considered average hence a leakage factor between 30% and 50% was applied for planning ventilation requirements.

In order to provide enough air quantity to the boundary limits (±3km strike distance from the declines) of the mining area, it is essential to install effective strike and dip seals. Figure 4.3 shows a typical shotcreted seal currently installed in the research area.

Figure 4.3: Example of a shotcreted pillar holing seal

4.2.2 Room and Pillar Stoping Ventilation

Stope headings which have advanced for more than 20m from the last through ventilation holing need to be ventilated by mechanical means (thus either using air-jet fans or scoop brattices) to ensure that pollutants are removed from the dead-end area and that a constant supply of air is available at the face. Table 4.5 shows the recommended air speeds for various advances.

Table 4.5: Recommended air Speeds *(Bluhm & Smit, 2014)*

	Air speed
Minimum air speed in last through road.	>1.0m/s
Stope room dead-end distance	
10 - 20m advance. (7.5 kW air-jet fan)	1.0m/s
10 - 40m advance. (l5.0 kW air-jet fan):	1.0m/s
10 - 50m advance. (45.0 kW air-jet fan):	1.0m/s

Table 4.6 shows the measured surface ambient and underground conditions in the research area.

Table 4.6: Surface ambient and underground design conditions

Summer average max. design wet-bulb temperature	20.0°C
Summer average max. design dry-bulb temperature	32.0°C
Barometric pressure	87kPa
Specific humidity	1.02g/Kg
Altitude	1272m
Surface density	1.03Kg/m^3
Geothermal gradient	20.7±1.3 K/km
Virgin rock temperature	28°C

Du Plessis and Biffi (2014) highlighted that,

Virgin rock temperature (VRT): VRT (°C) = 23.1 + [22.0 x Depth (Km)] (4.1)

This equation corresponds to the geothermal gradient in rocks of the main zone of the Bushveld Complex, which immediately overlie the platinum reefs. It was applied in the research area because of relatively comparable low thermal conductivity of rocks. Using the above equation, the VRT is 28.6°C for a maximum depth of about 250m for the case study mine. This was also verified through actual measurements in brownfield operations within the same domain.

Table 4.7 shows the geothermal properties in the research area. The production rock is pyroxenite and the development rock is gabbronorite.

Table 4.7: Rock properties

	Development rock	Production rock
Density	3220kg/m3	3200kg/m3
Thermal conductivity	4.65W/m°C	3.45W/m°C
Specific heat	0.9kJ/kg°C	0.9kJ/kg°C
Thermal diffusivity	1.9 x 10^{6}m^2/s	1.4 x10^{6}m^2/s

4.3 Empirical techniques and numerical modelling

It is imperative to effectively design mine ventilation systems so that sufficient air is supplied to areas where diesel machinery will be working (McPherson, 1993). The diesel dilution factor for South African mines ranges from 0.06 to 0.12 m^3/s/kW depending on engine selection and fuel used (Biffi, et al., 2007). This standard was adopted as best practice by all platinum mines operating on the Great dyke of Zimbabwe. Most mines use a general diesel dilution factor of $0.1m^3/s/kW$ which can be an overdesign or an underdesign depending on various circumstances (Hardcastle, et al., 2005). Overdesigning the ventilation system creates redundant air quantities which are often associated with a huge capital outlay mainly as a result of the required massive ventilation infrastructure such as raise bore shafts and main surface fans. Such ventilation systems will increase operating costs mainly driven by power consumption. A quantitative approach on ventilation design will also be described later in this chapter.

4.4 Determining ventilation requirements

The overall airflow requirements were historically based on mined tonnage (Bluhm & Smit, 2014). In this thesis overall airflow demands was based on diesel emission dilution, heat removal and clearance of blasting fumes and provision of a ventilation rate per 1000 tons mined per month which-ever is the greatest. The total air requirements were dominated by the provision of ventilation for diesel emission dilution. In order to apply the optimized diesel dilution factor for the case study mine, vane anemometers were used in conjunction with real time DPM monitors in the mine. Various LHDs from Tier 1 to Tier 3 (with the same power ratings of 170kW each) were allowed to run in a similar section using a different fuel selection. The same models were also tested based on the attained engine hours so that the effect of engine life could be evaluated. Air speeds were recorded in that heading while corresponding DPM emissions were also noted. The following results were recorded, and the optimum diesel dilution factor was deduced based on DPM emissions and quantity flowing.

Table 4.8: Measured air requirements for different engine specifications and conditions

Engine specification	**Brand new Tier 3**	**Tier 2**	**Tier 2**	**Tier 2**	**Tier 1**
Engine hours	<1000	<15 000	<15 000	>15 000	<15 000
Fuel selection	50ppm	50ppm	500ppm	50ppm	500ppm
TWA DPM (mg/m^3)	0.1	0.17	0.3	0.6	0.6
OEL DPM (mg/m^3)	0.16	0.16	0.16	0.16	0.16
Measured velocity to reduce DPM emission < $160mg/m^3$	0.7	0.9	1.1	1.4	1.4
Cross sectional area (m^2)	15	15	15	15	15
Quantity flowing in that end (m^3/s)	10.2	13.6	17	20.4	20.4
Calculated diesel dilution factor ($m^3/s/kW$)	0.06	0.08	0.1	0.12	0.12

Based on results shown in Table 4.8, a ventilation design rate of $0.08m^3/s$ per kW was used to determine air requirements which can dilute DPM generated by Tier 2 engines when using diesel 50ppm fuel. This was chosen as the optimum dilution factor since diesel 50ppm is readily available and tier 2 or tier 3 engines are already in use. The greenfield project will adopt the engine types currently in use. The overall air requirements were planned based on the number of vehicles to be used, total power rating as well as the optimised diesel dilution factor. Table 4.9 shows a complete fleet composition to be used at the case study mine, percentage utilisation and the corresponding power rating of each machine.

Table 4.9: Total Kilowatts from diesel fleet at the greenfield mine

	Max number	**Rated (kW)**	**Utilisation %**	**Total (kW)**
Drill Rigs	8	58	20	92.8
LHD's	8	186	80	1190.4
Bolters	8	55	20	88
DUT	8	298	80	1907.2
Sub-Total				**3,278**
Utility vehicles	8	40	20	64
Scissor lifter	4	70	20	56
Transporters	4	125	30	150
Grader	2	104	20	41.6
Compactor	2	104	20	41.6
Dust suppr Bowser	2	125	30	75
Personnel carrier	8	55	20	88
Scaler	2	125	20	50
Fuel Bowsers	2	60	20	24
Fresh Oil bowsers	2	60	20	24
Pick-ups	5	125	30	187.5
Sub-Total				**802**
Total utilised power				**4,080**

It is important to note that the main conveyor decline and underground workshops must be connected directly to the main return airway to mitigate the fire risk. Table 4.10 shows air requirements calculation based on fixed diesel dilution factors approved by the Mine Health and Safety Council. An alternative approach to determine air requirements is to consider a dilution factor determined through research by the CANMET (Canadian Regulatory Authority research organization) and the USA Mine Safety and Health Administration (MSHA) (Hardcastle, et al., 2005). This dilution factor considers specific, typical emission levels as scientifically measured for specific diesel engines operating under typical wear and application conditions.

Table 4.10: Primary air requirements using the CANMET approach

	Max number	Rated (kW)	Utilisation %	Residual kW utilised	CANMET Standard per engine, (m^3/kW)	Air quantity (m^3/s)
Drill Rigs	8	58	20	92.8	0.037	21
LHD's	8	186	80	1190.4	0.037	69
Bolters	8	55	20	88	0.037	20
DUT	8	298	80	1907.2	0.034	101
UVs	8	40	20	64	0.037	15
Scissor lifter	4	70	20	56	0.037	13
Transporters	4	125	30	150	0.037	23
Grader	2	104	20	41.6	0.037	10
Compactor	2	104	20	41.6	0.037	10
Dust suppr. Bowser	2	125	30	75	0.037	12
Personnel carrier	8	55	20	88	0.037	20
Scaler	2	125	20	50	0.037	12
Fuel Bowsers	2	60	20	24	0.037	6
Fresh Oil bowsers	2	60	20	24	0.037	6
Pick-ups	5	125	30	187.5	0.037	29
Total				**4080**		**365**

4.5 Optimized ventilation design

From the optimised diesel dilution factor of 0.08m^3/s/kW , the total air quantity required to dilute diesel emissions for the case study mine is therefore 326m^3/s (4080 x 0.08m^3/s/kW) before adding other commitments. The total air quantity for the mine will be based on the following:

- Diesel emission dilution;
- Ancillary air requirements for underground workshops, conveyor decline and crushers
- Leakage of 30% (assuming an air utilisation of 70% for good seals)

Table 4.11 shows the air requirements calculation at full production for the greenfield mine.

Table 4.11: Optimised air requirements

Air requirements	**Diesel dilution quantity (m^3/s)**	**CANMET quantity (m^3/s)**
Total ore production	2Mtpa	2Mtpa
Fleets	8	8
Air quantity required	0.08m^3/s/kW	<160 µg/m3
Air quantity (m^3/s)	326	365
Main w/shop 1 to return (m^3/s)	60	60
Main w/shop 2 to return (m^3/s)	60	60
Main conveyor decl. through ventilation (m^3/s)	40	40
Crushers dust extract. to return (m^3/s)	20	20
Leakage: (30%)	98	110
Total (m^3/s)	**604**	**655**

Another way of determining the overall air requirements is by applying a generic air supply ratio in m^3/s/kton/month to the overall mine production. Typical values range from 3 to 6 m^3/s/kton/month, depending on the depth of the mine, mining method used and the degree of mechanisation (Bluhm & Smit, 2014). Assuming an air tonnage ratio of 3.5 m^3/s/kton/month which is widely used by most mines in the same geological domain, the overall air quantity required will be 3.5 x 168 which gives a volume of 588m^3/s. A total volume of 600m^3/s will be used based on all three different approaches used to determine the overall air quantity.

4.6 Application of 4th industrial revolution techniques to monitoring

The application of 4th industrial revolution techniques to ventilation design entails the use of airflow sensors and DPM sensors in every section. There must be communication between DPM (or gas) smart sensors and main surface fans so that the correct air quantity can flow into the mine. The use of smart sensors will reduce DPM exposure because a decision will be made automatically to adjust the flow rate to effectively dilute all the airborne pollutants. DPM sensors also need to be fitted closer to trackless mobile equipment exhaust pipes so that the perceived level of engine maintenance and machine life is incorporated into the system. If the DPM emissions are greater than the threshold limits, the machine must send communication to the control room as well as warn the operator so that it can be taken for repairs instead of increasing power costs through the fans circulating excess air throughout the mine as a result of defective vehicles. It was observed that the use of older machines with engine hours greater than 15 000 hours resulted in greater emissions which require a diesel dilution factor of $0.1m^3/s/kW$ as opposed to $0.08m^3/s/kW$ (Table 4.10). A diesel dilution factor of $0.08m^3/s/kW$ is thus recommended for Tier 2 or Tier 3 engines using 50ppm diesel that is if the engine hours are kept below 15 000 hours. Tier 2 engines can run on 500ppm fuel however, this engine type is designed to run on 50ppm fuel hence mines should consider using the recommended fuel type. Where only 500ppm fuel is available, a minimum ventilation rate of $0.12m^3/s$ per kW is required (Nundlall, 2014).

Real time velocity sensors must be installed together with DPM monitors in each section so that when DPM levels go above the threshold value of $0.16mg/m^3$, the main surface fans will automatically adjust themselves if more air is required or ventilation controls will redirect existing air to reduce emissions to acceptable levels. This system will be coupled with gas sensors as well so that when gas readings go above the OEL, the system must automatically adjust itself until gas readings normalize. A typical example of such a set-up is shown in Figure 4.4.

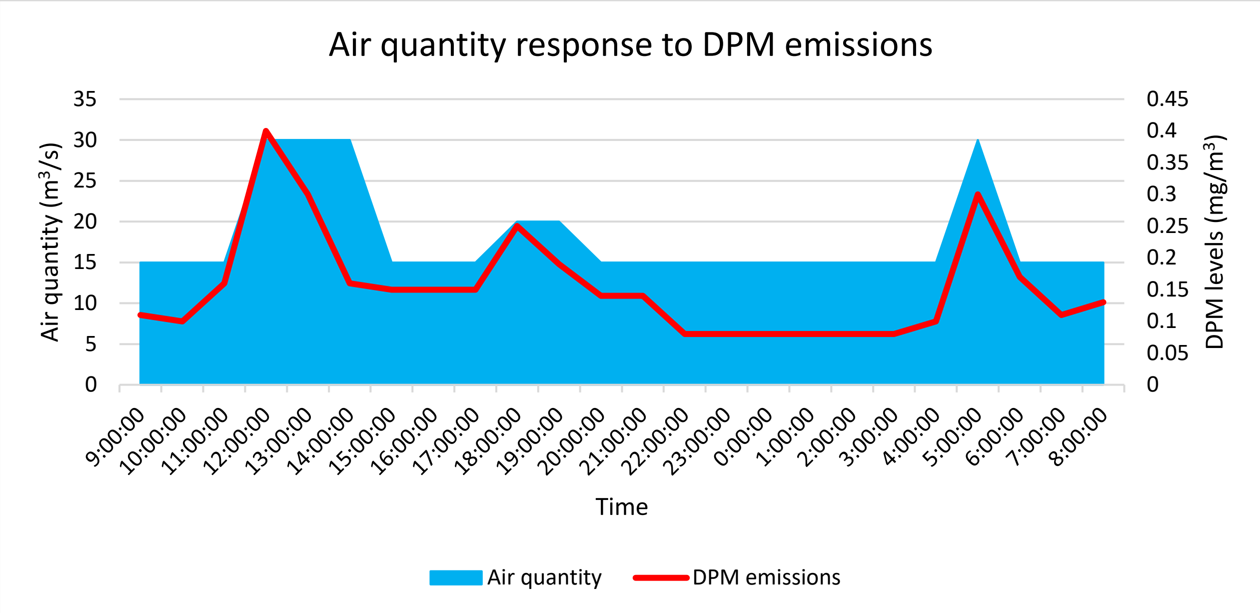

Figure 4.4: Gas bias

This system ensures that adequate air is supplied to where it is required and this reduces exposure levels thereby minimizing occupational hygiene hazards. The system will also plot the actual air supplied against the designed or budgeted air requirements. All diesel mobile machinery must be fitted with DPM sensors so that if emission levels are very high, then the machine can be sent to the workshop for engine repairs.

4.7 Estimate of heat load

Phillips and Rawlins (2005) noted that the heat in mechanised mines is normally generated from the following sources:

- Heat transfer from the rock strata and broken rock
- Auto-compression
- Auxiliary fans
- Diesel vehicles

4.7.1 Heat transfer from the rock strata and broken rock

The virgin rock temperature increases with depth below surface with a resultant increase in heat from this component (Phillips and Rawlins, 2005). At the research area, this component is not a major threat since most operations will be carried out at shallow depths (max of 250m) with a relatively low rock temperature (28.6°C).

4.7.2 Auto-compression

Auto-compression results in an increase in temperature of air as a result of the conversion of potential energy into enthalpy as depth below surface increases (Phillips and Rawlins, 2005). All platinum mines on the Great Dyke are operating at depths less than 350m hence the effect of auto-compression is minimal.

4.7.3 Auxiliary fans

The use of underground auxiliary fans is a favoured method to increase and control airflow in working areas (De Villiers, et al., 2019). Auxiliary fans in the thermodynamic sense do not do any useful work, and all electrical energy (input power) entering the fan driving motor is converted into heat (Bluhm & Smit, 2014). The design approach included auxiliary fans for ventilating development drives and secondary infrastructure such as crushers and workshops. Despite the use of fewer auxiliary fans, their heat contribution load was incorporated into the overall heat load of the mine.

4.7.4 Diesel vehicles

Diesel vehicles are a significant source of heat and their engines are typically 30% efficient hence a large percentage of the fuel combusted converts to heat (Phillips and Rawlins, 2005). It is important to note that 1.5 times the rated power will give the average heat load for LHD's and dump trucks operating in close proximity to production faces. This factor takes into account full engine load conditions during the shift. Drill rigs and bolters only utilize their engines when tramming from one face to another (normally 20% utilisation).

Table 4.12:Average heat load from Diesel fleet operating in rock temperatures <35.0°C

	Max number	Rated (kW)	Utilisation %	Heat load rated (1.5x rated)	Total kW
Drill Rigs	8	58	20	696	139
LHD's	8	186	80	2232	1786
Bolters	8	55	20	660	132
DUT	8	298	80	3576	2861
Utility vehicles	8	40	20	480	96
Scissor lifter	4	70	20	420	84
Transporters	4	125	30	750	225
Grader	2	104	20	312	62
Compactor	2	104	20	312	62
Dust suppr. Bowser	2	125	30	375	113
Personnel carrier	8	55	20	660	132
Scaler	2	125	20	375	75
Fuel Bowsers	2	60	20	180	36
Fresh Oil bowsers	2	60	20	180	36
Pick-ups	5	125	30	937.5	281
Total				**12,146**	**6,120**

It is important to note that 1.5 times rated power is the average heat load for LHD’s and dump trucks operating in close proximity to the production faces. This factor takes into account full engine load conditions during the shift. Drill rigs and bolters only start and utilize their engines when tramming from one face to another. Table 4.13 summarises the heat sink calculations at full production.

Table 4.13 :Heat Load and cooling requirement summary

Heat Source	**Heat load (MW)**
Surrounding and broken rock	0.5
Auto-compression [average]	2.4
Auxiliary fans	1.1
Vehicles (Average)	6.2
Other heat	1
Total heat load	15
Air cooling power with 600kg/s (20,0°C to 27,5°C WB, air density 1kg/m^3)	-13.2
Service water	-0.5
Additional cooling required	Nil
Total heat sink	-2.5

A negative heat sink indicates the cooling capacity of the air is sufficient to maintain temperatures below 27.5°C wet bulb in the workings whereas a positive heat sink indicates that in addition to the cooling provided by the ventilating air, additional cooling (refrigeration) will be required.

4.8 The main ventilation system for the case study mine

This chapter has given a detailed description of the designed ventilation system in order to produce 168 000 tonnes per month. Ore extraction is by mechanised Room and Pillar mining with LHDs and dump trucks which take the ore to the tips, strike conveyor belts and underground crusher situated above the main footwall conveyor belt. For the case study mine, the ultimate primary ventilation requirement is nominally 600 m^3/s of air as described earlier on. This requirement is based on detailed simulation models (to be shown later in this chapter), diesel dilution factor, underground equipment in use and air leakage. The ventilation design for the mine will allow for two separate ventilation districts that is one on either side of the declines. The production plan is to mine two mining sections with 72 strike headings on the north side and the same number on the south side of the access declines. The level of mechanisation for the research area has an average of 49 kW (rated diesel) per ktpm.

Although numerous high integrity ventilation walls have to be installed to ensure leakage within the air passages is kept as low as reasonably practical, losses of 30% of the initial section intake air quantity have been set aside to account for leakage. The conveyor belt, main workshops, refueling bays and tyre bay will be ventilated directly to returns.

4.8.1 Optimisation of shaft sizes and main fan selection

Having determined the overall air quantity for the mine, the next stage requires the need to optimise both shaft capacities and main fan duty. These must be strategically optimised for life of mine production through balance creation on the required environmental conditions and associated costs. This recommended air quantity can be achieved by using various options as shown in Table 4.14.

Table 4.14: Various diameter options

Key Performance Area	Option 1	Option 2	Option 3
Raise bore diameter (m)	4.1	4.3	4.6
Area(m^2)	13.2	14.5	16.6
Total air quantity (m^3/s)	600	600	600
Air velocities/ shaft (m/s)	22.7	20.7	18.1
Number of Intake raise bores	5	5	5
Number of Exhaust raise bores	2	2	2
Fan duty (m^3/s)	150	150	150
Number of fans required	4	4	4
Estimated operating pressure per fan (kPa)	2.8	2.7	2.6
Main fans absorbed power (kW)	2333	2208	2167

A trade off was done to select the optimum shaft size for both intake and return shafts. It is imperative to develop a software package which integrates the mining footprint, geological structures, fan size and quantity required. Ventsim software was used for this exercise to simulate airways and estimate costs and Vulcan software was used to establish geotechnical conditions which assist in optimizing shaft locations. The following assumptions were used to determine the net present cost values for the three different shaft options:

- Financial evaluation period - Life of mine
- Capital costs based on current quotations
- Operating costs - included electricity cost at the current rate of US$0.1292 per kWh

- Inflation rate at 2% per annum
- Assumed Weighted Average Cost of Capital of 20.4%
- Tax allowances at 25.75%

Table 4.15: Discounted cashflow

Description	**4.1m diameter**	**4.3m diameter**	**4.6m diameter**
	US$mil	**US$mil**	**US$mil**
Capex	**(6.67)**	**(6.85)**	**(7.62)**
Raise boring	*(3.90)*	*(4.08)*	*(4.85)*
Main Fans	*(2.77)*	*(2.77)*	*(2.77)*
Opex	**(17.18)**	**(16.27)**	**(15.97)**
Electricity	*(17.00)*	*(16.09)*	*(15.79)*
Conditioning monitoring	*(0.18)*	*(0.18)*	*(0.18)*
Tax allowances on capital outlay	1.59	1.63	1.81
Total cash outflow	**(22.26)**	**(21.49)**	**(21.78)**

From Table 4.15 above, 4.3m diameter shafts have the lowest net present cost which makes it the most viable option in this particular case. In addition to the total cost of ownership, 4.3m diameter shafts will have better geotechnical stability compared to 4.6m diameter shafts. Numerical modelling was also used together with empirical techniques to optimise the ventilation design. All three options were simulated to assess ventilation requirements, resistance and associated operating costs. Figure 4.5 shows a Ventsim simulation where changes in dry bulb air temperature throughout the ventilation system are reflected in a range of colours.

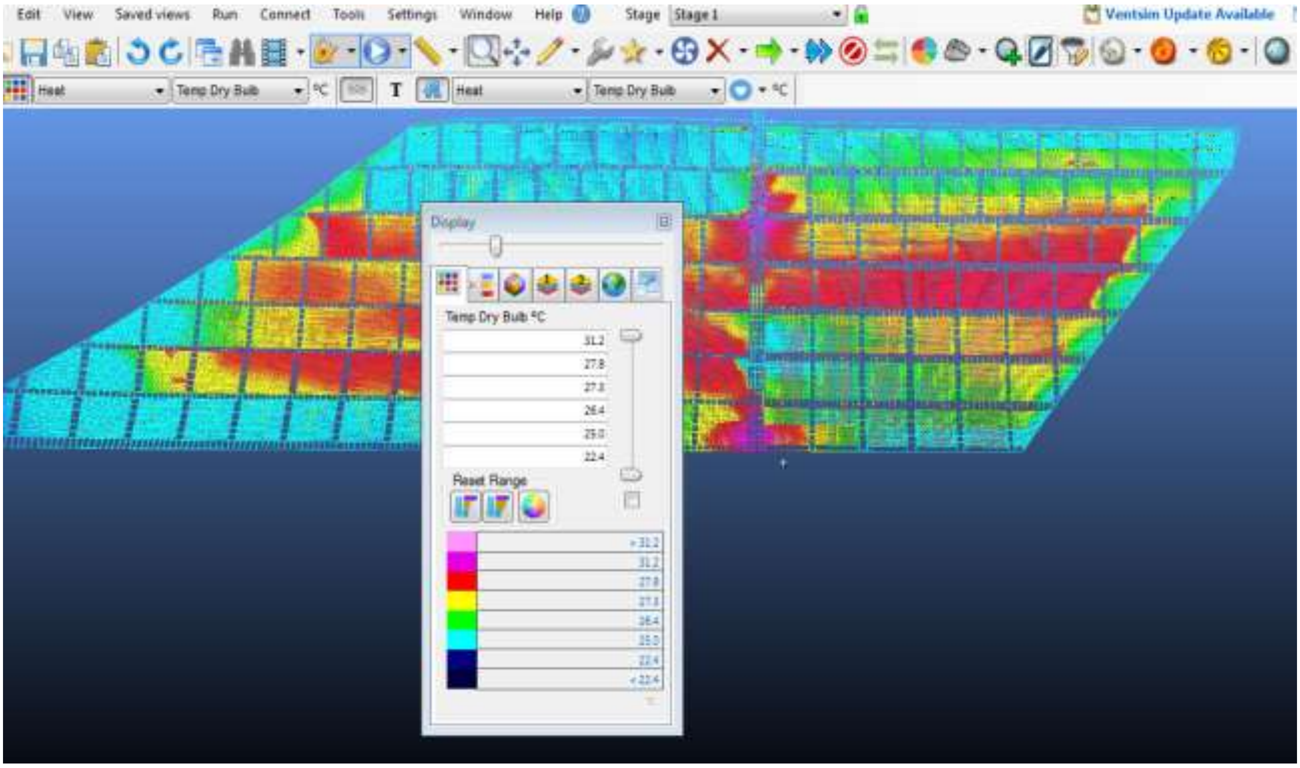

Figure 4.5: Ventsim simulation

The positions of all proposed and modelled shafts for life of mine (LOM) are shown in Figure 4.5. Figures 4.5 and 4.6 show the full extents of the mine though mining sequence will follow a Christmas tree as highlighted in previous figures. Figure 4.6 also shows the positions of two return shafts and five intake shafts described in Table 4.14

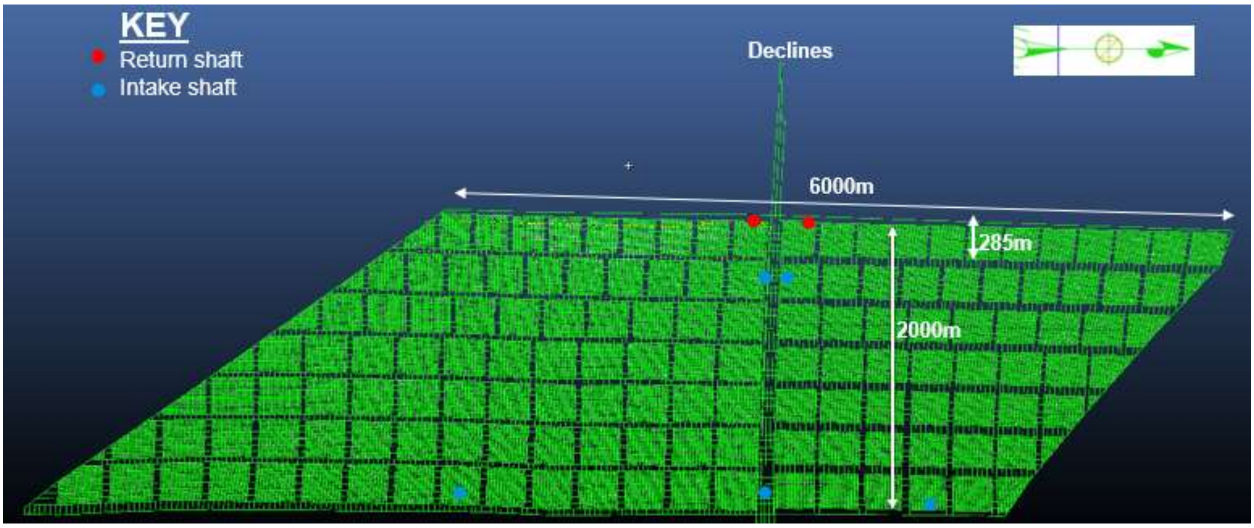

Figure 4.6: LOM ventilation design

4.8.2 Intake Airways

The mine will intake air from surface via the main declines and a series of Raise bore holes (RBH's). Seven access declines on the reef plane will be used for men and vehicular access. The conveyor decline will be mined 40m below the reef plane and will be equipped with a rock transport conveyor system. At a down dip distance of 300m from the portal area, the access decline splits into two. Two by 4.3m diameter downcast raise bore holes (RBHs) will connect with the declines on the reef horizon at a distance of ±400m down-dip from the 10° reef contour to supply ±370 m^3/s of additional intake air. Simulations indicate that an additional 4.3m diameter downcast RBH will be required to connect with the declines ±1800m down dip from the reef contour. This intake airway will provide additional cooling, reduce the system resistance with a resultant decrease in fan pressure, reduced power costs, air leakage and improvement in ventilation flow at the production headings.

The upper intake raise bore holes will have to be regulated to provide more cool air to the lower sections. In addition to providing intake air, these RBHs can be utilized as a second outlet to surface for personnel in the event of an emergency hence the shaft will be supported and equipped with a hoist and winder. Two additional intakes will be required on strike ±1500m to reduce the system resistance as well as to improve operational efficiencies. The conveyor belt decline will be independently ventilated with 120 m^3/s of air, which will be exhausted directly to a return airway. The 120 m^3/s includes 60m^3/s from the second workshop, 20 m^3/s from the crusher dust filtration units and 30 m^3/s for development through ventilation and surface leakage. This will ensure that the reef horizon will not be contaminated in the event of a conveyor belt fire Since the conveyor decline will not be used as an intake airway.

4.8.3 Return Airways

The mine will exhaust air by utilising two by 4.3m diameter RBHs placed above the uppermost ore drive. Two options were proposed to optimise main surface fans: Option 1 involves single fans that handle 300m^3/s at a static pressure of 2,8kPa, one each on either side of the mine and Option 2 comprises of two fans per RBH each exhausting 150m^3/s each. Option 2 comprising of multiple fans on one shaft was preferred mainly because of the economic viability with a reduced power consumption and improved operational efficiencies. The holes will be placed on either side of the access declines hence two ventilation districts will be established in the mine.

Room and pillar return airways leading ahead of the other room and pillar sections will be required at the top west limits of the mining foot print. Three uppermost drives (to be used as dedicated return airways) with an effective total area of $52.5m^2$ (3 x 7.0m x 2.5m) will be required on either side of the declines to allow ±$300m^3/s$ foul air to flow to the north and south return airway raise bore holes. No other additional RBH with fans will be required for the whole life of mine.

An optimised ventilation design strategy is necessary for reduced airflow resistance, fan pressure, absorbed power and improved airflow in the mine. In order to keep the system resistance as low as possible and without compromising airflow requirements, more pillar holings will be opened upstream since quantity increases going up-dip.

During development before one of the main fans is commissioned, booster fans ($160m^3/s$ at 2.7kPa) situated in the conveyor decline entrance will provide the required ventilation. The access decline will be utilized as the intake airway and the conveyor decline as the return airway. Figure 4.7 shows the life of mine air distribution for the case study area.

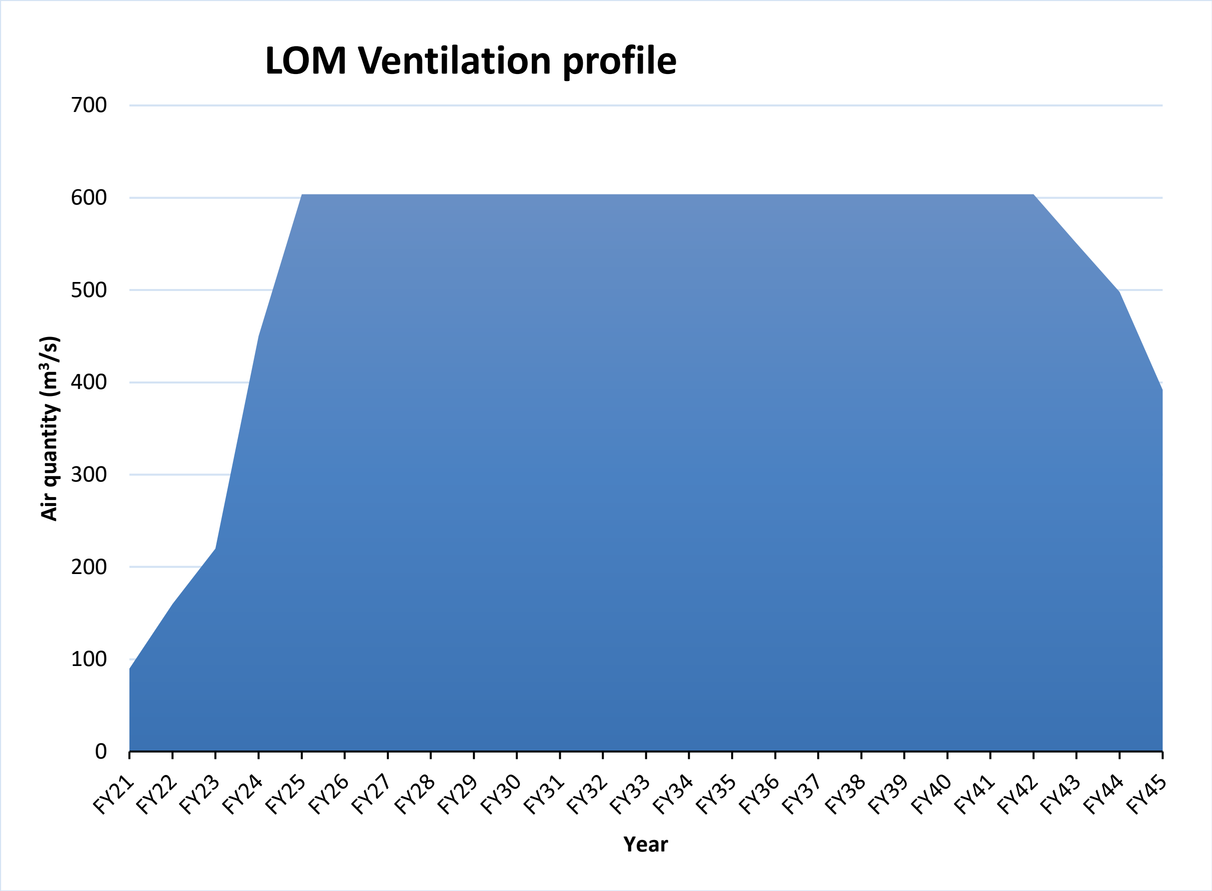

Figure 4.7: LOM Ventilation Profile

The problems of condensation and the possible accumulation of water droplets in an up-cast shaft can occur in deep underground mines (Biffi, et al., 2007). For this reason, the forbidden band for up-cast velocities where water can be suspended in a shaft is between 8 and 12m/s. Above 12m/s, water droplets are carried out to surface and below 8 m/s, water drops back out of the shaft (Bluhm & Smit, 2014). Condensation and accumulation of water droplets do not occur at shallow depths such as the research area unless significant amounts of ground water enter the shaft. The research area is generally dry with humidity levels below 80%.

4.8.4 Ventilation Power Requirements

Power requirements for the mine will vary at each stage of mining based on the number of teams operating underground. The total rated instantaneous power for main surface fans will be ±2300kW at full production. The secondary ventilation equipment will also absorb relatively large amounts of power. The total rated power of the secondary ventilation equipment will also vary during life of mine. Figure 4.8 shows average projected power consumption and the corresponding annual power costs until the mine reaches its full production.

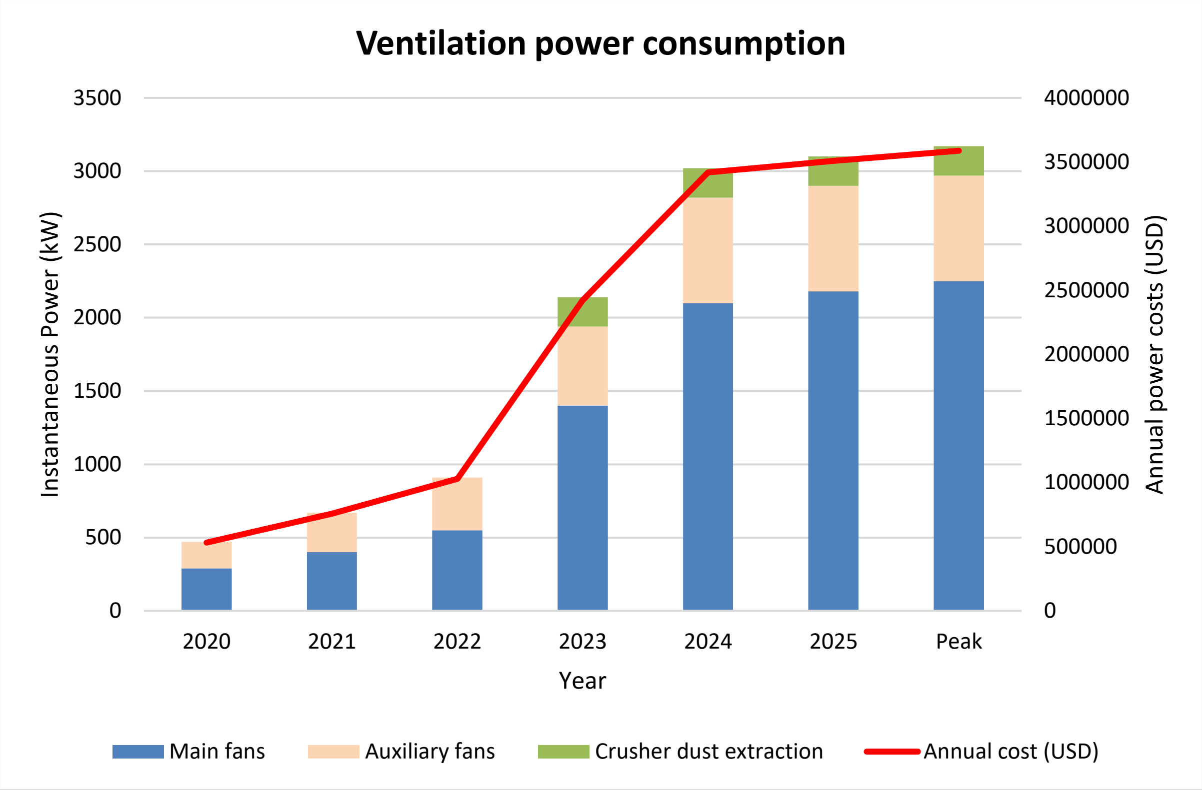

Figure 4.8: Ventilation power consumption

An average unit cost of 12.92c (USD) per kW/hour was used to calculate annual power costs in 2020.

4.8.5 Room and pillar ventilation

Stope headings advancing more than 10m from the last through ventilation position need to be ventilated by mechanical means (i.e. air-jet fans or scoop brattices) for the removal of blasting fumes before the expiry of the re-entry period. In addition to blasting fumes, flammable gas and diesel emissions have to be diluted and removed from the dead-end area. A constant supply of air should always be available at the face.

Figure 4.9 shows the recommended ventilation layout for regional pillar establishment or re-development where geological losses occur.

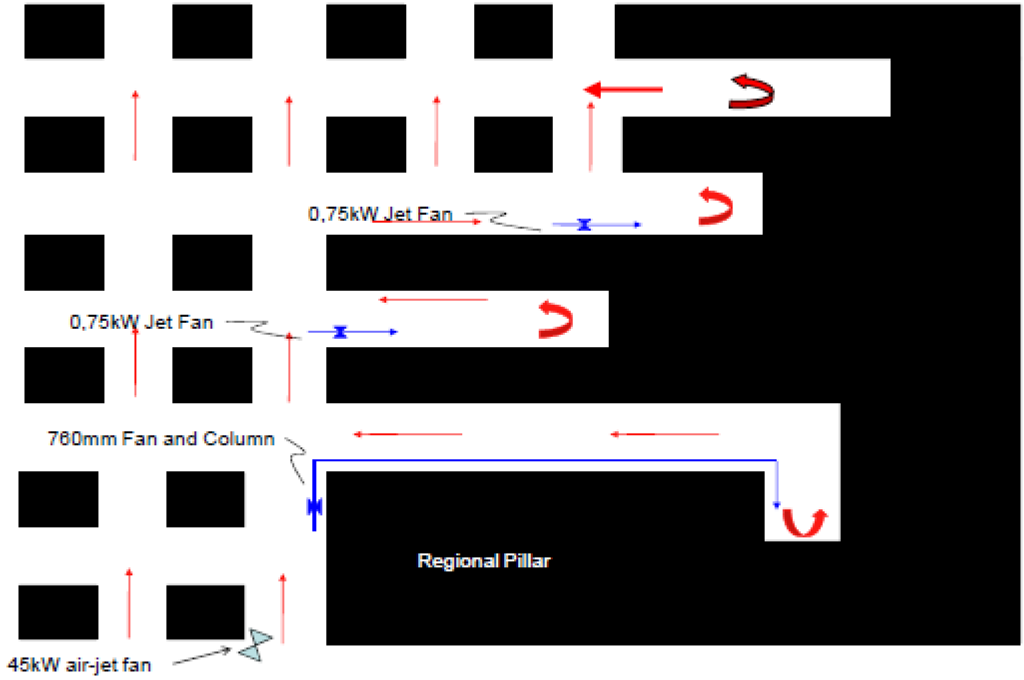

Figure 4.9 :Ventilation for strike roadways and last through roads

The minimum ventilation required by a dump truck at point of operation is $19m^3/s$ after applying a diesel dilution factor of $0.08m^3/s/kW$ to the rated power. In order to provide the required ventilation quantity, the roadway intakes need to be regulated and leakage paths are to be created through the worked out areas. In roadways where the required quantities are below the minimum requirement, 760mm (45kw) booster air - jet fans need to be installed at the roadway entrances.

The minimum air speeds required in the last through roads closest to the stope headings should not be less than 1m/s. In through roads where the minimum velocities are less than 1m/s, 45kW air-jet fans need to be installed in pillar holing openings closest to the stope headings.

Dust is also one of the greatest hazards in the mining environment. A fog nozzle water dust suppression and wet scrubber extraction system will be utilized for dust control at the underground tipping and crushing operations. Provision must be made for a ventilation quantity $10m^3/s$ for crusher ventilation.

The wet scrubber ventilation quantity of $\pm 8m^3/s$ will be discharged to the conveyor decline. A total quantity of at least $20m^3/s$ from the crushers will be added to the conveyor decline ventilation.

4.9 Power saving initiatives

Power is one of the major cost drivers in underground mining operations as shown in Figure 4.4. Main surface fans consume enormous quantities of energy therefore power saving initiatives must be considered in order to reduce energy consumption. The application of fourth industrial revolution technologies in the mining industry will reduce operating costs (Cawood, 2021). Autonomous mining operations, ventilation on demand and the adoption of electric vehicles will reduce ventilation requirements hence less power consumption.

4.9.1 Automating the value chain

If human beings are no longer required in working areas during production times, diesel particulate matter emissions will no longer be an issue during ventilation design and heat generation will then be used as a criteria for ventilation design. The effect of heat is more adverse in deeper mines hence platinum mines on the Great Dyke will not be so badly affected due to their shallow ore bodies (Hardcastle, et al., 2005). The design based on heat will be less demanding since the heat rejection temperature of machines is greater than that of humans. Hardcastle et. al (2005) pointed out that ventilation requirements for machines can be limited at a dry bulb temperature of 40^{o}C which is more than 35^{o}C for human beings. Apart from reducing the number of people underground, automation comes with an improved productivity hence less diesel vehicles will be operating underground. A reduction in the number of equipment items results in decreased ventilation hence less operating costs. Noone (2020) noted that an autonomous mine can reduce power by 20-50% depending on the degree of automation. Tele-remote operations also allows operators to control their machines from surface control rooms. Platinum mines on the Great Dyke should consider automating the whole value chain as this can improve safety performance by removing the man from the production environment and also reduces ventilation requirements since the number of personnel underground will be significantly diminished.

4.9.2 Reducing mine resistance

The mine system resistance can be reduced by increasing airway paths and or enlarging airway dimensions. One of the main power saving initiatives to be considered is to reduce the mine system resistance by increasing the intake and return airway paths and/or dimensions, thereby reducing fan operating pressure and absorbed power. Leakage is a function of the type of seal, condition of seal and pressure across the seal. In addition to power saving, leakage is less with fans operating at lower pressures.

4.9.3 Battery powered vehicles

As mining companies strive to reduce greenhouse gas emissions, many, particularly those with underground mines, are beginning to invest in battery-powered and electric-powered mining fleets (Nieto, et al., 2020). Electric vehicles also reduce ventilation requirements since they don't emit diesel pollutants. Such vehicles can only generate heat but their generation (typically 35%) is also less than diesel equipment (Bluhm & Smit, 2014). Varaschim and De Souza (2017) pointed out that battery electric vehicles have the potential to reduce power costs by 20-65%. In most underground mines, the required airflow to dilute an engine's exhaust is either based upon the worst operating condition or an average of multiple operating conditions. Electric vehicles can be adopted for minimal emissions and hence lower dilution air requirements (Nieto, et al., 2020).

4.9.4 Variable Speed Drives (VSD)

VSD systems offer considerable power saving while the efficiency is maintained. In the initial stages of production build-up, VSDs may be an option where there will also be a ventilation quantity and pressure increase. However, in the steady state production, the total planned ventilation quantity is to be maintained while the operating pressures will gradually increase as mining progresses towards the boundaries.

4.10 Control methods for centrifugal fans

Power is one of the major cost drivers in underground mining operations (Sottile, et al., 1996). Main surface fans consume enormous quantities of energy, and therefore, energy management considerations in air flow control is critical as this affects power consumption. This thesis seeks to compare the methods of air flow control in a bid to improve operational efficiencies as well as reducing energy costs. The analysis of electrical power savings achievable by variable frequency drive (VFD) versus the existing radial vane control (RVC) provides an opportunity for the adoption of new technology, with a short return on investment.

4.10.1 Method of Flow Control

Main surface fans are designed for 100% flow but in most cases, they operate with less flow (Hardcastle, et al., 2005). Main surface fans at one of the mines in the research area are currently set to exhaust 68% of the original fan duty using radial vane controls. De la Harpe (2014), highlighted that there are three main methods of controlling the output of a centrifugal fan namely:

- System dampers
- Inlet-vane control
- Variable speed of frequency(VFD) control

4.10.2 Comparative study of flow control methods

A VFD is the most expensive method of control because of huge capital outlay required as shown in Table 4.16. However, it provides the most energy efficient means of flow control with lower operating costs over the useful life of a fan, coupled with the smoother running of a variable speed fan over a wide range of duties. Consider the fan chart in Figure 4.10 for the 850kW fans currently utilised at one of the operations on the Great Dyke. All new mines will be equipped with energy efficient motors to reduce power consumption. The fan chart shows a comparison of fan power consumption for the design duty of 200m^3/s (no control) and the current duty of 150m^3/s. The 150m^3/s duty can either be achieved by using radial vane control at 50^o vane angle or by using variable frequency drives at 78% speed.

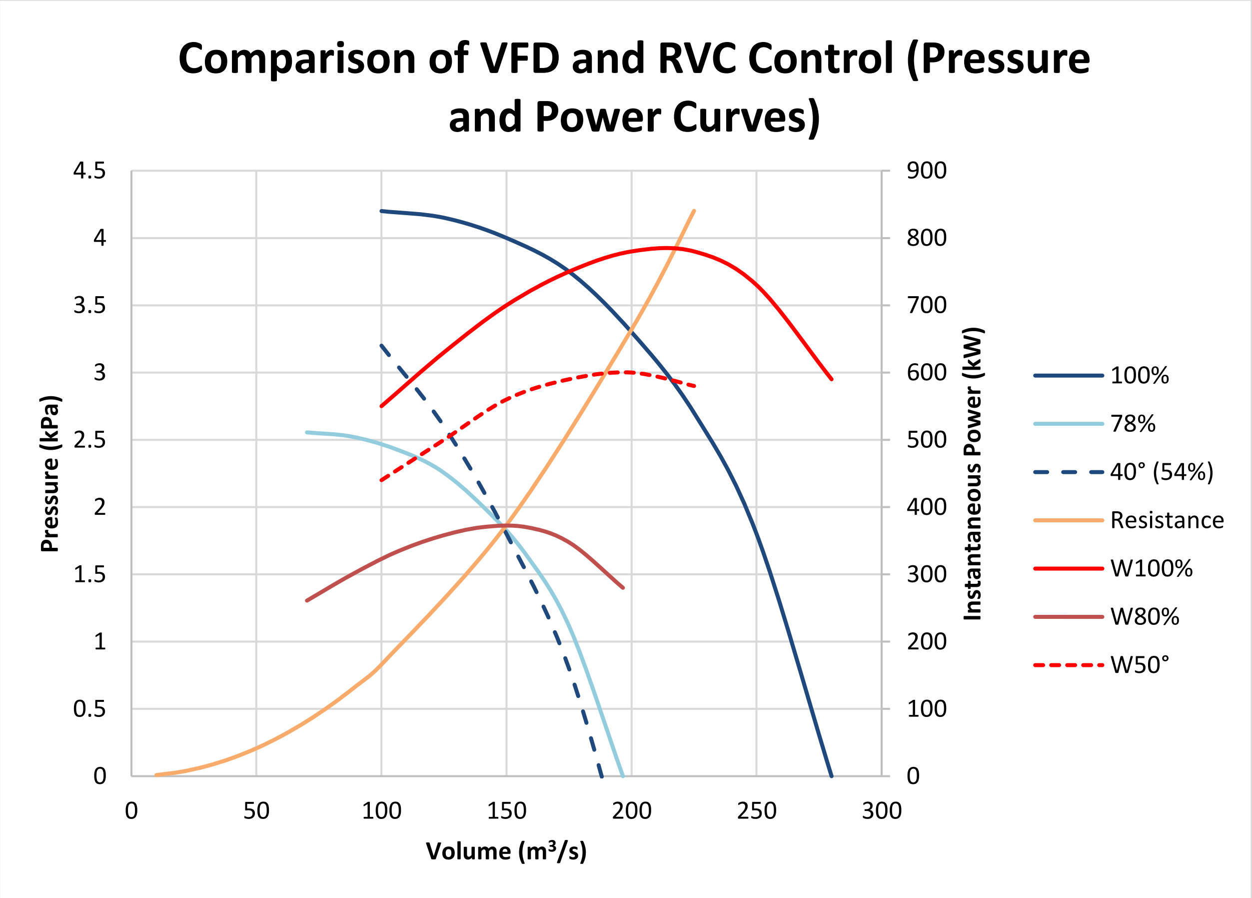

Figure 4.10: VFD vs RVC for 850kW fans

The RVC's main purpose has been to control flow according to the required production needs, up until peak life of mine (LOM), where the vanes will be fully open. In this way, RVC's are currently saving some power compared to a constant volume without any flow control measure. However, significantly more power savings will be achieved by using VFDs as shown in Table 4.16. These savings were based on 4 fans operating at one of the mines.

Table 4.16: Financial evaluation on methods of flow control

	Quantity/fan	**Power/fan**	**Annual electricity costs (for 4 fans) (USD)**	**Capital costs (USD)**
	(m^3/s)	(kW)		
Constant volume	200	780	(2,459,808.00)	-
RVC (currently in use)	150	560	(1,766,016.00)	(133,333.30)
VFD (78%)	150	370	(1,166,832.00)	(534,145.90)
RVC savings vs Design (no flow control)			693,792.00	(133,333.30)
VFD savings vs Design (no flow control)			1,292,976.00	(534,145.90)
VFD savings vs RVC case			599,184.00	(400,812.50)

The payback period of VFDs is one year which presents a strong business case for platinum mines on the Great Dyke.

4.10.3 Advantages of VFDs

Globally, VFDs are used across several end-use sectors, including infrastructure, industrial, power generation, and oil and gas (Vijay, 2018). Growing concerns regarding energy efficiency worldwide coupled with rising awareness about benefits of these drives are boosting their adoption across these sectors. Varying the fan frequency is the best method of flow control and the VFD motor speed control will give superior performance due to the following merits (Vijay, 2018):

- Lowest power consumption
- Lowest installation cost.

- Least maintenance (reduced mechanical wear and tear).
- Reduced power "demand charge" because the motor is started softly with no inrush current.
- Highest (near unity) power factor.

In addition to these benefits, the installation of VFDs will allow for the implementation of ventilation on demand and thus greater control over fan speed at more frequent intervals throughout the day, as well as a higher degree of speed reduction and thus power reduction.

4.11 Chapter summary

Although the research reported in this chapter was undertaken as part of my routine work, the literature search and the analysis of data was for the purpose of writing this thesis. Optimum ventilation design for the case study mine was achieved through integration of empirical techniques and numerical modelling. A ventilation design rate of 0.08m^3/kW was used based on the current engine specifications as well as the current use of 50ppm fuel. The total cost to provide 4.3m diameter shafts instead of 4.1m raise boreholes for the 50ppm design, result in a saving of US$3.5milion over the life of mine. In terms of the Ventsim network analysis, when mining at the extremities (worst case), a fan duty of 600m^3/s at 2.8kPa will be required. The mine will exhaust air through two 4.3m diameter raise boreholes placed above the uppermost roadways. The holes will be on either side of the access declines. Fans will be located on surface above each raise bore hole with an operating quantity of 300m^3/s per raise bore hole. Application of fourth industrial revolution techniques such as the use of smart DPM and airflow sensors is recommended for optimum ventilation design based on the current fleet. A conceptual model which deduces the optimum shaft size based on actual inputs against net present value (NPV), power consumption and shaft integrity has been developed. The concept design was given to software developers for modification and integration with existing ventilation software. In addition, trendlines which show the actual measurements against design parameters must be automatically generated with an automatic response plan to airborne pollutants. Chapter 5 focuses on the application of 4IR technologies to environmental monitoring systems and ventilation optimisation.

5.0 APPLICATION OF 4IR TECHNOLOGIES TO ENVIRONMENTAL MONITORING SYSTEMS AND VENTILATION OPTIMISATION

5.1 Introduction

The mining industry is increasing its adoption of digital and technology solutions. However, very little emphasis has been placed on techniques that could be applied to reduce power consumption and subsequent operational costs for ventilation (Noone, 2020). The current operational philosophy of the ventilation system in the research area is based on the provision of the full ventilation capacity around the clock irrespective of operational and diurnal cycles. The current underground ventilation systems are designed more towards the “worst-case-scenario” with respect to airflow demand, which usually occurs well into the future of a mine’s operating life. As a result, in the early stages of operation, the mine’s intake air volume could be well in excess of its actual ventilation demands. Such ventilation systems are inefficient and wasteful and this design approach needs to change if Zimbabwean mines are to remain competitive while attempting to reduce the adverse health effects of emissions. The concept of setting up a VOD system, will address such redundant use of air in mines as well as improve underground conditions. VOD is based on providing ventilation to various mining areas as and when desired. This model is required to reduce operational costs, improve productivity as well as to improve the health and safety of underground employees. Different activities in a mining cycle require different amount of air for each process being undertaken. VOD encompasses an automated control system capable of altering environmental conditions within a defined ventilation district in accordance with an effective and safe control strategy.

5.2 Ventilation on demand architecture

Underground VOD is the ability to direct air in an underground mine to the area that requires it, at the quantity needed for the local activities and ambient conditions at the time (Acuna and Allen, 2017). There are five control strategies that are considered for VOD as described in Chapter 2. The five identified strategies can be used singularly or in tandem. This research will focus more on manual control and time of day scheduling since the other levels have not yet been reached and are still under investigations. Ventilation is an absolute necessity for underground mining and is becoming increasingly expensive (Wang et al, 2014). Prevailing trends within the global mining industry, including greater depth, are generally demanding a significant air quantity not only for ventilation but also for cooling purposes, which has the consequence of higher power consumption at the main fan station. The drive to minimise greenhouse emissions increases the importance of managing power consumption in the mining industry (Hardcastle and Kocsis, 2001).

The current ventilation mechanism at most mines operating on the Great Dyke entails the use of a negative pressure system. Figure 5.1 shows the ventilation system layout for a typical mechanised board and pillar operation. A VOD model was developed by the author and applied to a mine that uses four by 850kW primary surface fans as well as underground auxiliary fans. Foul air is being exhausted out of the mine through upcast shafts (two by 4.5m diameter) and intake air is being drawn into the mine via a series of declines and intake raise bore holes (two by 4.5m diameter). Figure 5.1 shows a schematic layout where there VOD model was installed. Ventilation walls are built along roadways which are mined at every 10th stope panel. Intake air is being controlled into each section by means of regulators which are normally placed in each roadway. Currently, the mines are using brattices to regulate air flowing into any section. Such brattices were replaced with automatic doors during the VOD trial. The louvers open accordingly, depending on sectional demand which depends on the number of people and operational equipment in any section. The designed and installed ventilation on demand system comprises of a communication backbone, tagging and tracking system, variable speed fan drives and air quality stations.

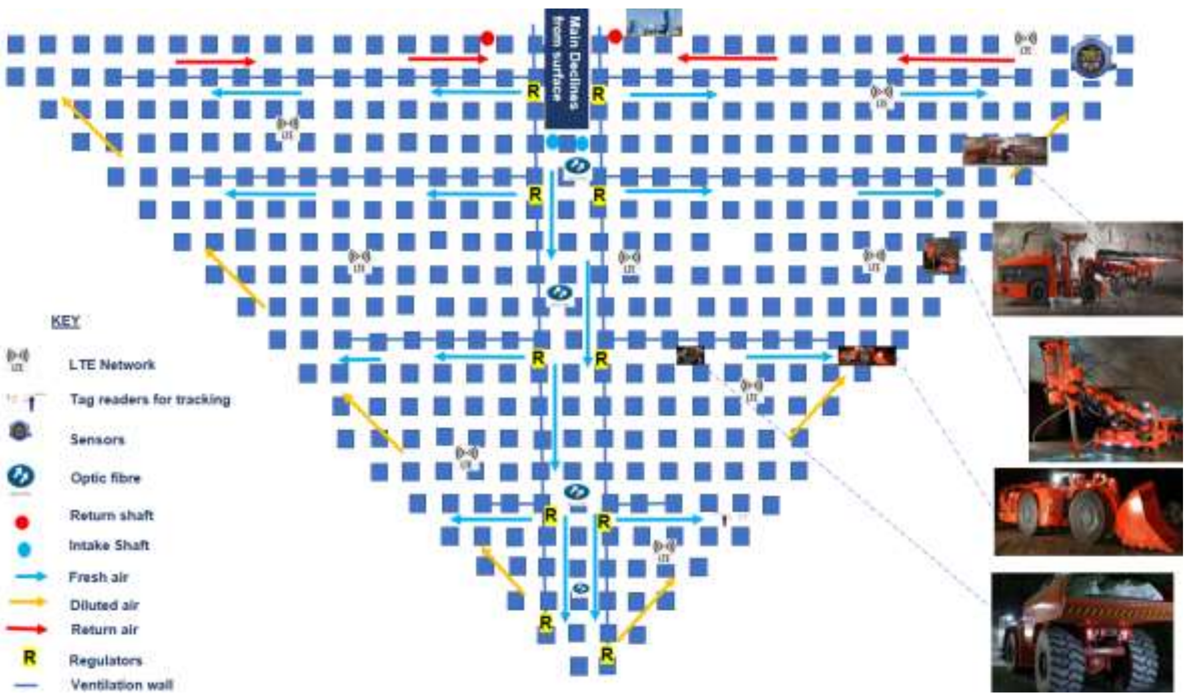

Figure 5.1: Typical ventilation layout for a bord and pillar operation

Energy efficiency of mine ventilation systems including automated ventilation control is achieved by means of an algorithm for optimal ventilation control, controlled recirculation and dynamic assignment of airflow lower limits in real time mode. VOD has several levels which starts from manual scheduling to ventilation optimisation. During this research, an optimised VOD model was designed which links tagging and tracking systems and environmental monitoring stations to primary and auxiliary ventilation fans. The amount of air drawn into a section was automatically determined from operating diesel equipment in a section, the heat load, the number of people working in a section and other exceptional airborne pollutants.

The ventilation on demand system designed and trialed as part of the research undertaken for this thesis comprises of key components shown in Figure 5.2. In addition to minimizing power, the VOD system was developed to ensure a healthy working environment underground through:

- Dilution of hazardous substances which affect the health and safety of employees
- Climate control through modulation of airflow
- Quicker evacuation of blast gases thereby improving productivity
- Better utilisation of existing infrastructure thereby resulting in better capital and operating expenditure control
- Producing accurate and consistent ventilation survey measurements
- Validation of new ventilation layouts and control strategy in simulated environment which enables optimal investment decisions

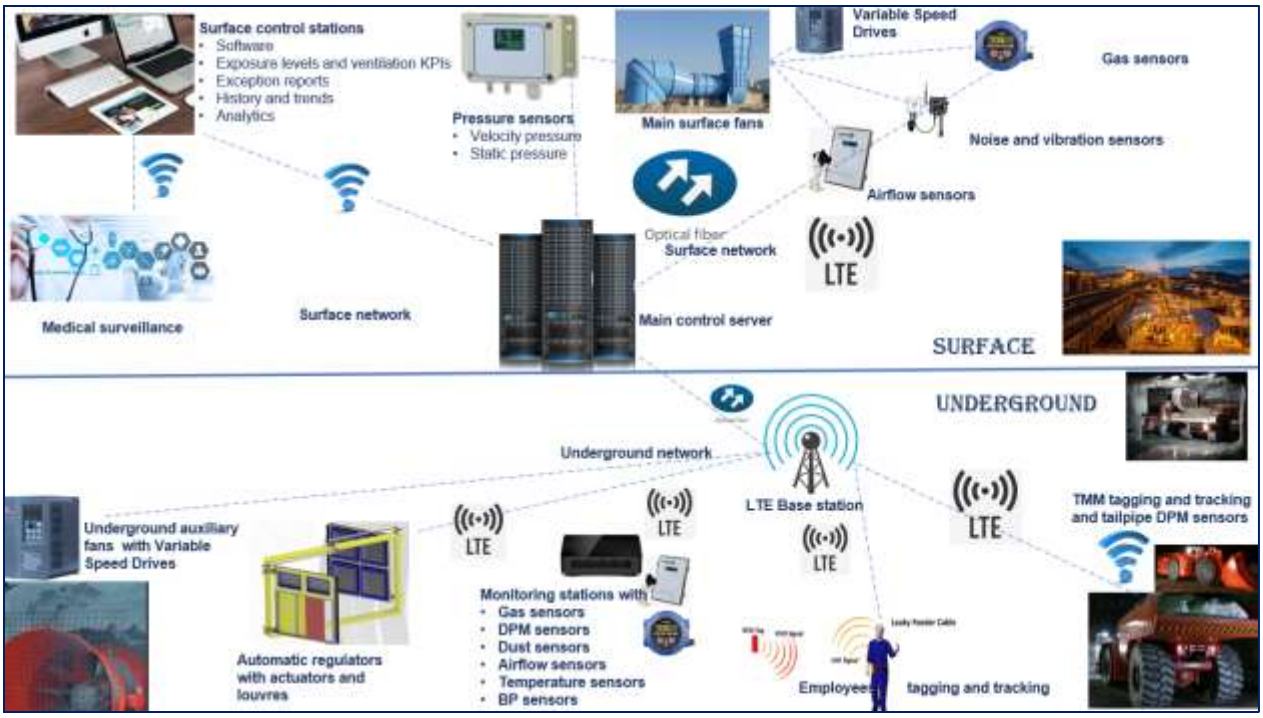

Figure 5.2: VOD model developed during this research

The VOD system utilises airflow sensor feedback to perform an online optimization process of main ventilation fans and underground auxiliary fans. Some of the system components incorporated into the VOD structure include:

- ***Variable speed drives (VSDs)*** – All primary and auxiliary fans were equipped with variable speed drives so that they can allow fans to run at different speeds based on the actual demand. The airflow delivery being controlled through rotational speed of the fans. VSDs were supplied by WEG through Airblow.

- ***Automated ventilation doors***- these are installed in all roadways for each section and ventilation district. Each automatic door is equipped with sensors so that the quantity of air entering a section can be controlled and is primarily dependent on the type and the number of operational equipment as well as available personnel in that particular zone. Automated doors were procured from UVVS of South Africa.

- ***Main surface fans*** – these form the basis of the system since the air quantity for each fan is being controlled by utilising VSDs and environmental monitoring stations. The mine has both Howden and Airblow fans.

- ***Tagging and tracking system*** – to selectively deliver appropriate air volumes to the production workings according to various mining activities undertaken, it is essential to know where, when and for how long these air volumes are needed. In mechanized board and pillar mines, this means knowing the location of production, development and service vehicles together with their characteristics. This is being achieved through the use of a vehicle identification and tracking system. All vehicles and cap lamps are equipped with Becker chips for tracking which subsequently inform the desired quantities to dilute heat and other pollutants. The tag readers are located at strategic points throughout the mine so that the tagging system can give live readings throughout the shift.

- ***Monitoring system*** **-** environmental monitoring systems ensure that an activity based ventilation system provides and maintains adequate working conditions within all production workings. Firstly, the required air quantity to all working faces must be maintained. For this reason, non-intrusive ultrasonic airflow sensors were installed along the main haulages and inside fan drifts. Secondly, the quality of air delivered to all working areas must also be monitored and for this reason, gas sensors, DPM sensors and dust sensors were installed in all sections. To ensure the equipment operators are always exposed to safe underground environmental conditions, DPM sensors were also installed on dump trucks and load haul dump machines (LHDs).

- ***Data management and communication systems*** – this includes the process logic of ventilation control systems by which information is processed and outcomes determined. The VOD system requires a communication backbone which runs from surface to underground operations. Optic fibre cables and a Long-term evolution (LTE) network were installed in both surface and underground operations. The software to integrate all system components is being configured and this will be maintained annually through a license key. One key design variable that has largely been ignored in control structure design is passive damping. There will be need for passive damping in the variable frequency drive feedback loop to improve nominal performance, stability and fan performance robustness.

- ***Operator workplace*** – all data will be integrated into one server so that reports and trends can be pulled out using any connected device that can either be on surface or underground. Data being collected and analysed by the system sensors include ventilation KPIs such as quantity, airflow, airborne pollutants and pressure readings. Other information to be graphically displayed includes:

- Mine ventilation overview layout
- Details regarding performance of main surface fans
- Ventilation layout for each section
- Rate of change alarms and advanced alarm statistics for mine ventilation
- Production statistics displays –current and historical trends
- Overall mine ventilation KPI's
- Total energy consumption , run-time, energy statistics per fan and mode of operation
- Trends and logged data for all important data sets

The VOD control philosophy entails the capability of a system to alter environmental conditions in a ventilation district in accordance with smart sensors and control servers. There are five levels of VOD but so far the mine is operating on level 2 and is in the process of trialling level 3.

5.2.1. User control or manual control

User control strategy is the first level that allows for manual control or setting of operational points for the different components of the ventilation system. Usually this can include:

- *Main and secondary fans:* Main fans can be connected to start directly online or be equipped with soft starters or variable frequency drives (VFD) to save energy (Tran-Valade, T and Allen, C, 2013). It is more common to operate auxiliary fans direct online by switching on or off, however, soft starters should be considered for energy savings and safety when considering flexible tubing. All main fans (4 by 850kW in size) were equipped with VFDs replacing Radial Vane Control (RVC) valves which were previously installed. This was considered as the first step towards automation and the mine reduced its instantaneous energy consumption by 36%.

- *Regulators and doors:* Regulators are used for controlling airflow by increasing the airway resistance thereby decreasing the air quantity flowing (Du Plessis & Biffi, 2014). The mine installed automated ventilation doors to prevent the flow of air while still allowing travelling and transport to take place. The doors are efficient, economical and require minimum maintenance. Figure 5.3 shows typical automatic doors installed at the mine.

Figure 5.3: Automatic doors

- *Manual operational point settings* can be divided into two subcategories:
    - Fixed setting: For fans these settings correspond to the on or off, or in a case where a VFD is available, to fix the operational speed or frequency of the fan drive in an attempt to deliver just the airflow required (Tran-Valade and Allen, 2013). For regulators and doors, the fixed settings correspond to a percentage of the opening from 0 to a 100%.
    - Proportional Integral Derivative (PID) Control loop: This is a feedback control loop to achieve a desire set point based on a measured process variable (Tran-Valade and Allen, 2013). In this case, the set point is the opening of the regulator or door and the measured process variable is the airflow volume. This capacity is not available at the manual or first level, but in the second or third levels.

5.2.2. Time of day scheduling

The second control strategy is "Time of day scheduling" which refers to the concept of triggering different set points of the fans, regulators and doors based on the time input to follow a certain schedule (Tran-Valade and Allen, 2013). Assuming that the sensor deployment in the mine is fairly limited or non-existent as could be the case for this level, then the logical extension of the level 1 "user or manual control" is to couple it with a timer to trigger sequences of changes in the set point of the ventilation system such as fans, doors and regulators in a semi-automated way (Tran-Valade and Allen, 2013). This application is actually a limited version of the main concept behind level 2, which from a broader point view should be called the “action trigger”. If the “action trigger” concept is constrained to act based on a timer only, the result is effectively the “Time of day scheduling”. If the “action trigger” could be adapted to use with other environmental variables or data as triggers, the opportunity for different applications and savings could be even further enhanced. However, this also requires a more extensive deployment of sensors underground. The mine programmed all main surface fans to run at different set points depending on time of the day. This will be described later in this thesis.

5.2.3. Event based strategy

The third control strategy is the “Event based strategy” and, as indicated by Tran-Valade and Allen (2013), it is the “automatic trigger of prescribed actions in reaction to configured events”. This control strategy can be summarized as the “action trigger” function based on alternative inputs other than the timer and the environmental variables, as each one of them has its own category. Just like the “Time of day scheduling”, this control strategy uses the same principle of the action triggers but based on any variable available that could be conveyed to the software making the decision. In particular it could potentially be a combination of variables with a certain logic. The potential for applications of this control strategy is significant, for example: optimize blast fume clearance and mine fire response. Additionally, the “Event based strategy” can also be used to trigger cascade use of fans, for example turn a booster fan on if an auxiliary fan is turned on, to secure the supply of fresh air across the main drift (Nie and Wei, 2017).

5.2.4. Tagging

The fourth control strategy is the “Tagging” which represents a major step in both the capacity to understand where people and equipment are located, and also in terms of infrastructure required to locate them. This control strategy requires the implementation of a tag and tracking system, and its associated communication integrated with the ventilation software. The airflow distribution of the mine is generated based on the location of the personnel and equipment and is also based on rules to calculate the airflow that has to be assigned to each. The “Tagging” control strategy is commonly associated with the concept of ventilation on demand as the airflow volumes can be allocated across the mine according to the location data, in real time, of both personnel and equipment (Wang et al., 2014). As a result of knowing where the airflow demand is located, then the ventilation system set points can be adjusted to provide the airflow required at minimum energy and cost for both the auxiliary and main ventilation systems. Figure 5.4 shows a snapshot of the tag reader interface at the mine. At the moment, the tagging and tracking system was commissioned but will be linked to the VOD system, however, that integration will be the next step towards the optimisation of underground ventilation systems.

Figure 5.4:Tagging and tracking system

5.2.5. Environmental

The fifth control strategy is "Environmental" and considers the automatic control of the ventilation system based on real-time environmental data, which could be a number of sensor inputs such as gas, dust, DPM, temperature (heat stress) for example, assuming that such sensors could work underground and provide real-time information. Real time dust and DPM sensors were installed in main haulages. Environmental control can be used in two ways, as a failsafe in case of flammable or noxious gas exceeding safe limits or as the ultimate control strategy (Du Plessis & Biffi, 2014). Coupled with any of the control strategies, the environmental strategy acts as a failsafe in case of an environmental variable going outside of the pre-set boundaries, for example high CO or high temperature. This could be referred to as the quantity and quality approach of the environmental control strategy. As a stand-alone strategy the environmental control strategy allows the ventilation system to distribute the airflow according to the environmental variables, for example the gas or dust concentration (Wang et al., 2014). This control strategy is expected to provide the largest amount of savings. Figure 5.5 shows a typical gas sensors interface at the mine. The gas detection system was commissioned but will be configured and linked to the main ventilation system. Each monitoring station is equipped with six sensors for monitoring carbon monoxide, oxygen, methane, carbon dioxide, nitrous fumes and hydrogen sulphide as shown in Figure 5.5. there are no additional methane and carbon dioxide sensors in 77B to avoid double dipping of gases already measured in 77A.

Figure 5.5: Real time gas monitoring at the mine

5.3 Results

The mine has since achieved both Level 1 and Level 2 stages of VOD. Preliminary results over the past 6 months showed some significant power savings and an increased productivity as a result of increased face time by utilising a portion of the of the re-entry period as shown in Table 5.2 and Table 5.3. At the last optimisation stage, changes in the modulation of airflow will be initiated by one or more of the following :

- Increased airflow demands due to additional vehicles or personnel entering a ventilation district. For this reason, all vehicles and employees are being monitored by a tagging and tracking system.

- Environmental conditions within a particular ventilation district. Such conditions are currently monitored using real time air quality monitoring stations comprising of gas, DPM, dust, airflow and temperature sensors. When any of the aforementioned parameter is above the OEL, the system will automatically adjust itself to ensure that airborne pollutants are diluted and reduced to concentrations below OELs.

- Timing parameters - less air quantity is required when employees are travelling into and out of the mine at the start and end of shift respectively. Other timing parameters include blast clearance periods, maintenance, holiday periods and other non-production activities such as safety talks and machine check-ups. Modulation of airflow will also be set to be time based.

Table 5.1 shows a typical shift cycle time currently adopted at the mine

Table 5.1: Shift cycle time

Blasting time	04:00	
Blast clearance	04:00	08:00
Arrival of employees and changing	07:30	08:00
Travelling to waiting places	08:00	08:30
Safety talk	08:30	09:00
Machine set up and making safe	09:00	09:30
Production time on the face	09:30	17:00
Travelling to surface	17:00	17:30
Incoming shift travelling to workplace	18:00	18:30
Safety talk and machine checks	18:30	19:30
Production time on the face	19:30	03:00
Travelling to surface	03:00	03:30
Clearance for blasting	03:30	04:00

It can be noted that for some activities in Table 5.1, the flow can be reduced to 40% of the normal requirements through the use of variable speed drives because of low air demands. As a starting point, the flow was reduced to 50% during non-productive periods as shown in Figure 5.6. The fans were programmed to run at full speed during the first two hours of re-entry to allow for a quicker blast clearance before being reduced to 50% until peak production times when all machines are now at the faces. Since the mine has not reached its full production, the VSDs are currently set at a maximum speed of 85% during production face times to supply the required total flow of $700m^3/s$. Figure 5.6 shows how airflow varies when there is no control, when control is by means of radial vanes (RVCs) and through time of day scheduling (VOD Level 2 control).

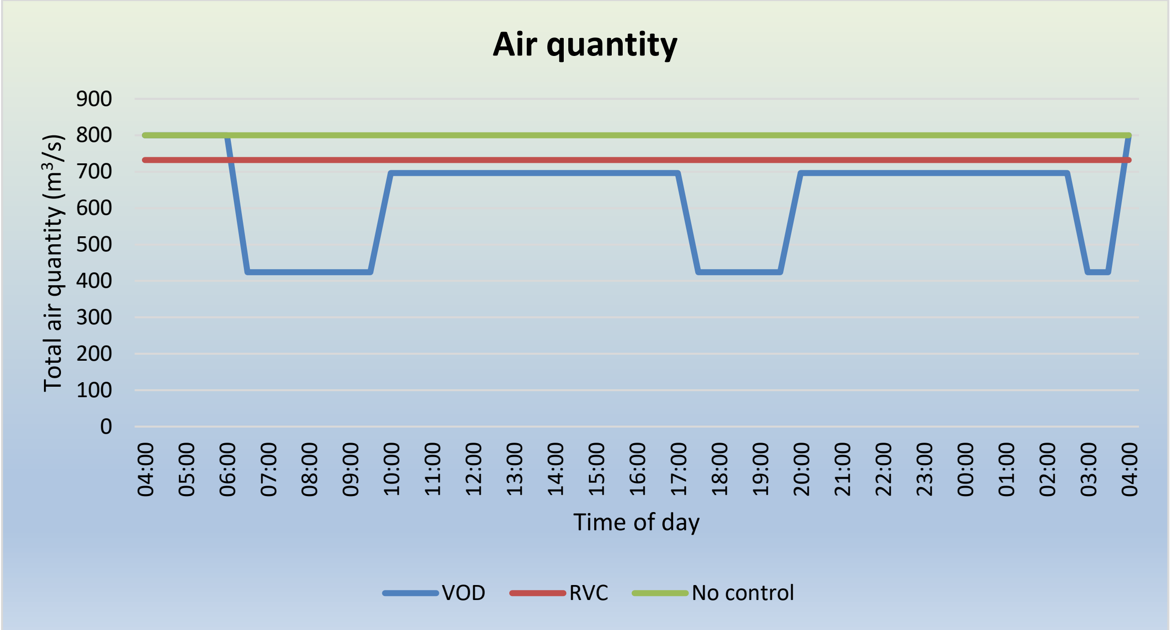

Figure 5.6: Planned air flow modulation per day

Power measurements were taken directly from the system and results obtained demonstrate significant power savings. Each 850kW fan was equipped with RVCs and was consuming an instantaneous power of 671kW at 85% RVC setting to give a flow of 175m^3/s as shown in Figure 5.7.

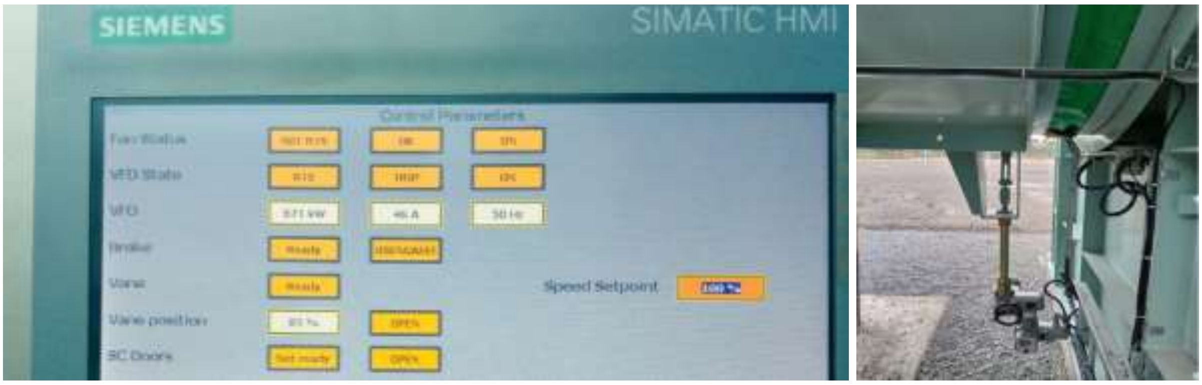

Figure 5.7: Airflow regulation by RVC

RVCs were then replaced with variable frequency drives (VFDs) to start the implementation of VOD and for the same quantity, the instantaneous power reduced significantly from 671kW to 426kW as shown in Figure 5.8. This shows a 36.5% power reduction which will translate to 2.1MWh per year per fan (obtained from (671-426) × 24 × 365) thus a combined annual power cost saving of US$1.1 million (assuming 4 fans running and an average unit electricity cost of US$0.1292/kWh). This is before ramping up to full production.

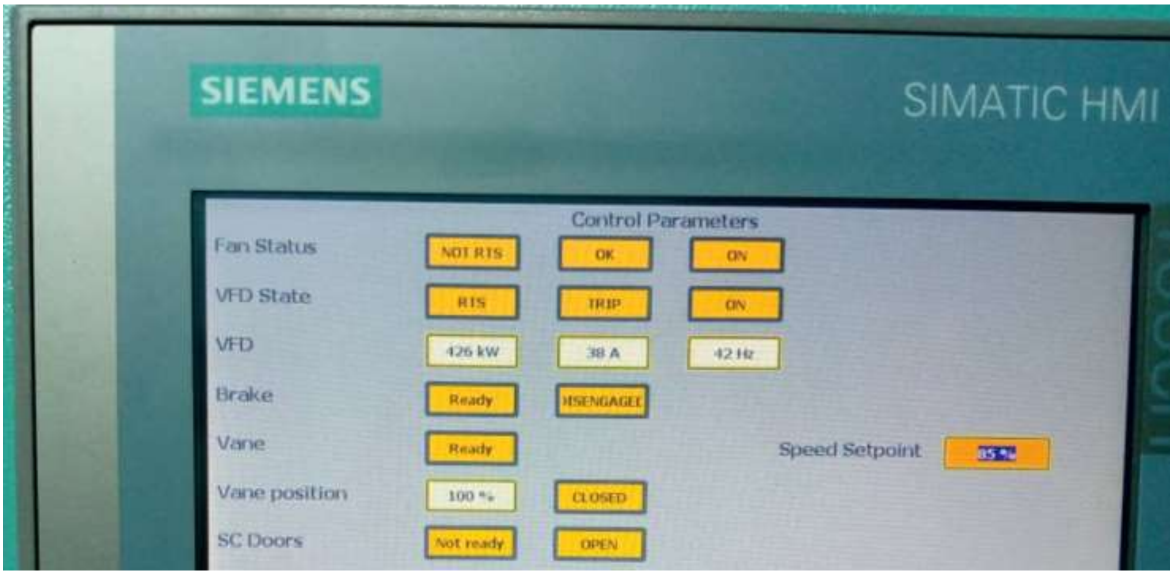

Figure 5.8: Airflow regulation by VFD

At full production, the fans will be opened to 100% and other levels of VOD will kick in such as time of day scheduling. The system is designed to monitor both air quantity and air quality in real time. For time of scheduling, main surface fans were programed to modulate airflow as shown in Figure 5.6 and the total predicted instantaneous power varies as shown in Figure 5.9.

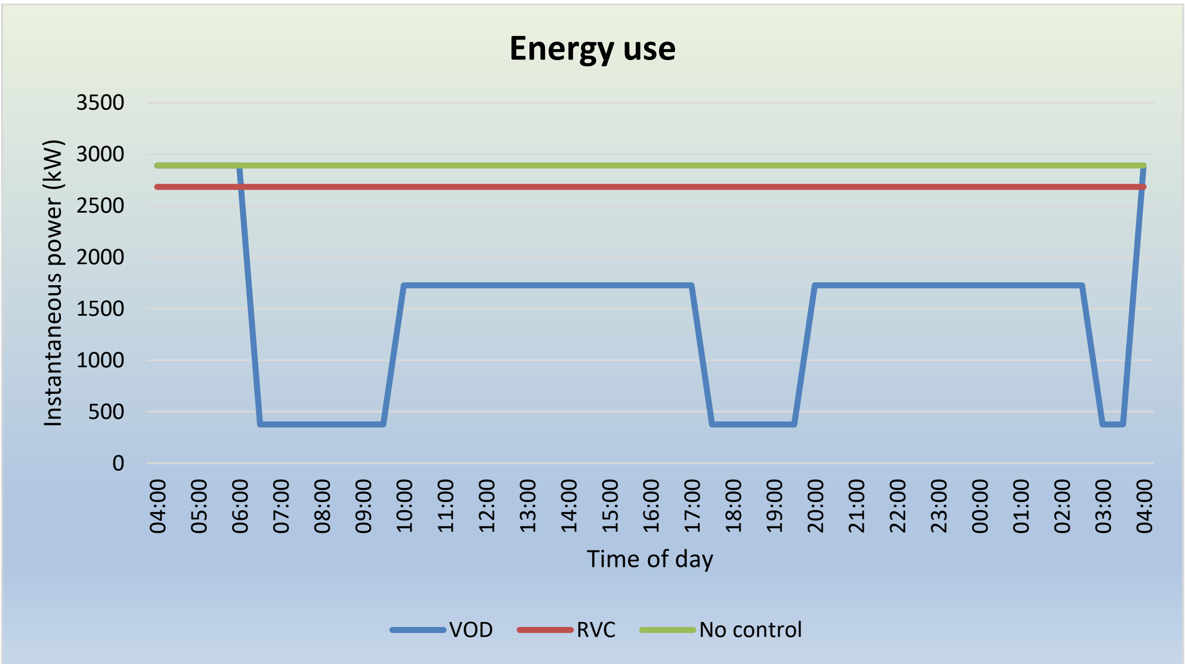

Figure 5.9: Instantaneous energy consumption per day

The overall energy gains of the VOD level 2 were derived from zero base and Table 5.2 shows the assumptions used in deriving the predicted energy gains for the mine. Each main surface fan has a rated motor capacity of 850kW with a duty of 200m^3/s and a static pressure of 3.1kPa.

A total of four fans are used to ventilate a brownfield mine which will require a total quantity of 800m^3/s at full production. The mine is equipped with four (850kW each) centrifugal fans. The base case does not include VOD and represents the current set up at all operations in the research area. It assumes 100% airflow supply throughout the year without any airflow modulation and 96% utilisation to cater for maintenance periods. It can be seen that by rolling out full VOD systems to the trialed mine, power savings of approximately US$ 0.5 million will be achieved on an annual basis for primary fans with a combined power load of 3.4MW. It is important to note that there are larger mechanised operations in the same geological domain with a fan power load of over 7MW. Such larger operations can save more power if this ventilation optimisation concept is extended to their operations.

Table 5.2: VOD Energy gains

	Base case	**VOD**
Total power for main fans (kW)	3,400	3,400
Main fans utilisation	96%	82%
Total auxiliary power	450	450
Auxiliary fans utilisation	80%	30%
Total nominal power	3,715	3,238
Annual operational days	365	365
Daily hours	24	24
Annual power consumption	32,541,648	28,367,508
Energy difference (kWh)		4,174,140
Unit cost (US$/kWh)		0.1292
Power savings (US$)		**539,299**

In addition to reduced power costs, the VOD structure significantly increases productivity by increasing face time as well as creation of favourable underground working conditions which promotes men to work at optimum levels. The re-entry time for the mine was four hours which conforms with the Zimbabwean legislation. Real time monitoring of blasting fumes was used for three months to establish the actual time required to clear all blasting fumes, which was later on used as the “true” re-entry period. Upon blasting, gas concentrations increase up to a peak value and thereafter, the gas concentrations decrease gradually depending on the type of explosives used and the ventilation capacity. Figure 5.10 shows how carbon monoxide concentrations varies with time in a 24 hour period which includes the blast window at the mine. Real time monitoring of gases reduces the risk of sending underground employees to poorly ventilated areas which haven't been cleared from gases.

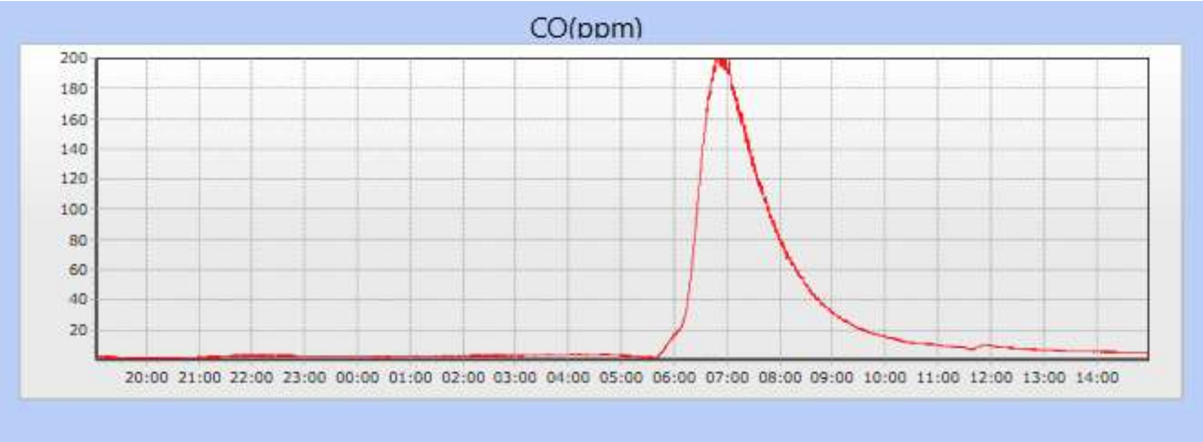

Figure 5.10: Actual Carbon monoxide concentration on 11.02.21

VOD systems improves the safety performance of an organisation by monitoring and management of pollutants such as gases, DPM, dust and heat. This will eliminate potential incidents which may arise due to employee fatigue and heat exhaustion. The VOD system was designed in such a way that when gas concentration levels exceed the OEL, the system will automatically adjust itself until gas readings normalize as shown in Figure 5.11 below. When gas levels exceed the OEL, communication will be send to main surface fans and auxiliary fans to channel more air to areas of demand. As the concentration of air borne pollutants decreases to acceptable values, there will be an automatic modulation of airflow through VSDs.

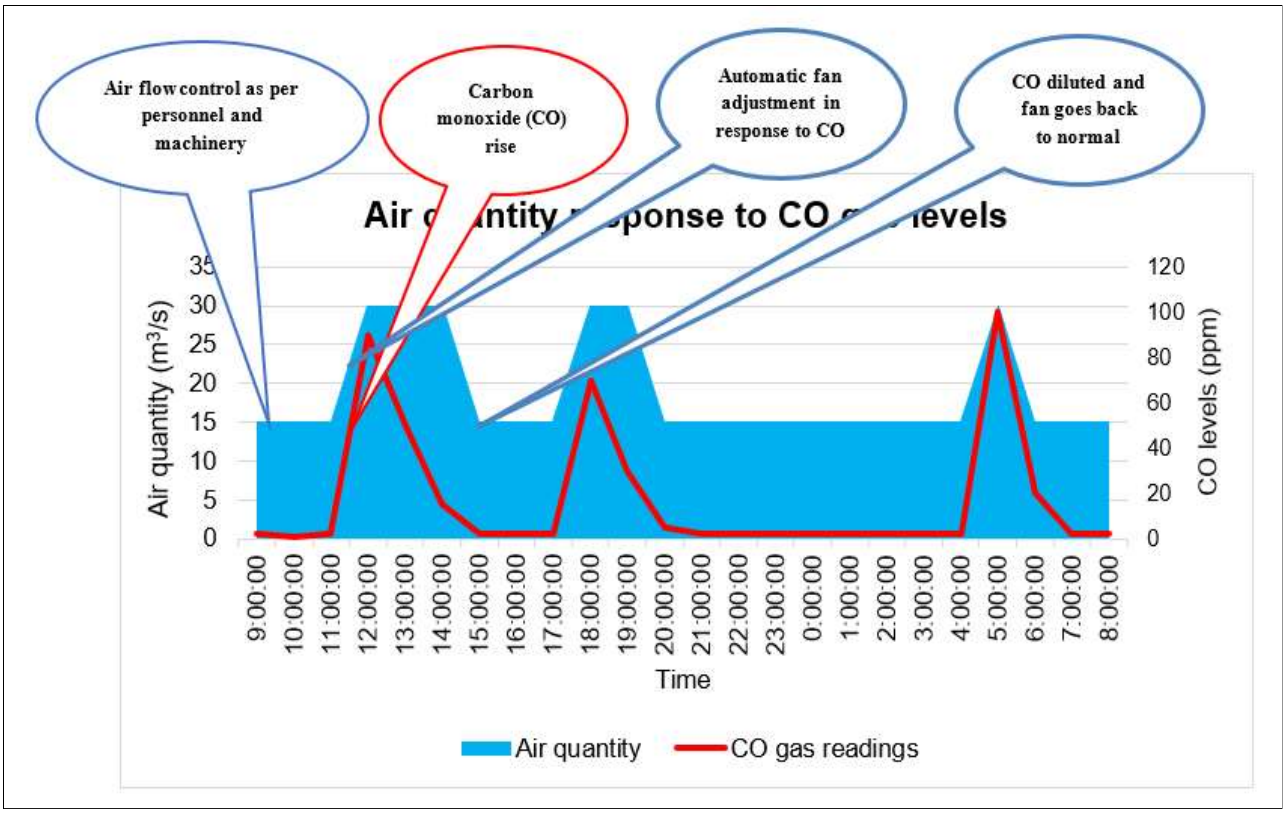

Figure 5.11: Air quantity response to gas concentration levels

VOD systems allow mines to clear blasting fumes and dust faster than the projected time by allowing fans to run at full speed thereby diluting foul air in the shortest possible time. The trialed mine was simulated and simulation results revealed that the mine will clear in two hours. The re-entry time exemption from four hours to two hours was approved by the Ministry of Mines in Zimbabwe. Shortening the re-entry time significantly increased face time. The mine utilised the two hours gained by reducing re-entry time and converted it into face time as a productivity enhancement strategy. This however increased operating cost in form of additional labour and incentivizing the current employees through paying overtime. Table 5.3 shows the annual projected production gains in the trialed mine.

Table 5.3: Peak production gains

Total annual production	2Mtpa
Daily production target (t)	5,523
Hourly production (15 hours per day face time)(t)	368
Increase in daily production due to VOD (t)	736
Increase in daily tonnage with efficiencies (due to VOD) (t)	552
Annual production gains from VOD (t)	201,600
6E grade (g/t)	3.48
Pt grade (g/t)	1.582
Annual cost of mining additional tonnage (US$)	6,048,000
Milling costs of additional tonnage (US$)	3,024,000
Other additional costs (US$)	1,935,360
Total costs for addition tonnage (US$)	11,007,360
Revenue from additional ounces (US$)	12,902,400
Yearly Profits (US$)	1,895,040
Assuming 15% of additional revenue (US$)	**1,806,336**

*6E metals – Platinum, Palladium, Gold, Rhodium, Ruthenium , Iridium**

Production gains were only achieved through increasing the speed of surface fans and accurate monitoring of air quality. The mine managed to reduce the re-entry period from four hours to two hours. The additional production time gained improved productivity which amounts to an additional revenue of USD1.8milllion.

5.4 Financial evaluation

A bankable feasibility study was conducted before carrying out a trial on VOD. The VOD system runs from underground operations to surface system servers which will also be linked to an employee database in future. The financial evaluation for the designed system was based on actual quotations and invoices requested from various suppliers of each individual component. The associated benefits of this system include improved health and safety of underground workers, increased productivity and reduced power costs . The cost breakdown structure of the system is shown in Table 5.4.

Table 5.4: VOD Cost breakdown

VOD component	Total cost (USD)
VSDs for main surface fans (four)	654,668
VSDs for auxiliary fans (eight)	490,656
Tagging and tracking system	179,974
Airflow and gas monitoring stations	166,266
Dust and DPM monitoring systems (two each)	144,000
Pressure and temperature sensors	31,650
Automatic Doors (six)	230,384
Engineering services	132,432
Annual Software fee	47,362
Additional communication backbone	532,000
Condition monitoring	114,532
Annual operating costs	113,136
Total cost for the system	**2,837,060**
Contingency (10%)	**283,706**
Total cost for the system with contingency	**3,120,766**

NB: Capital cost estimates in 2020 monetary value

From the annual gains (both productivity and energy gains), it can be concluded that the payback period of the VOD system is 1.5 years. A ten year financial analysis of the system is shown in Figure 5.12. A financial evaluation undertaken showed a positive net present value (NPV) and an internal rate of return (IRR) of 62% which is greater than the hurdle rate of 20.4% hence the project is acceptable with a lower risk margin on capital investment.

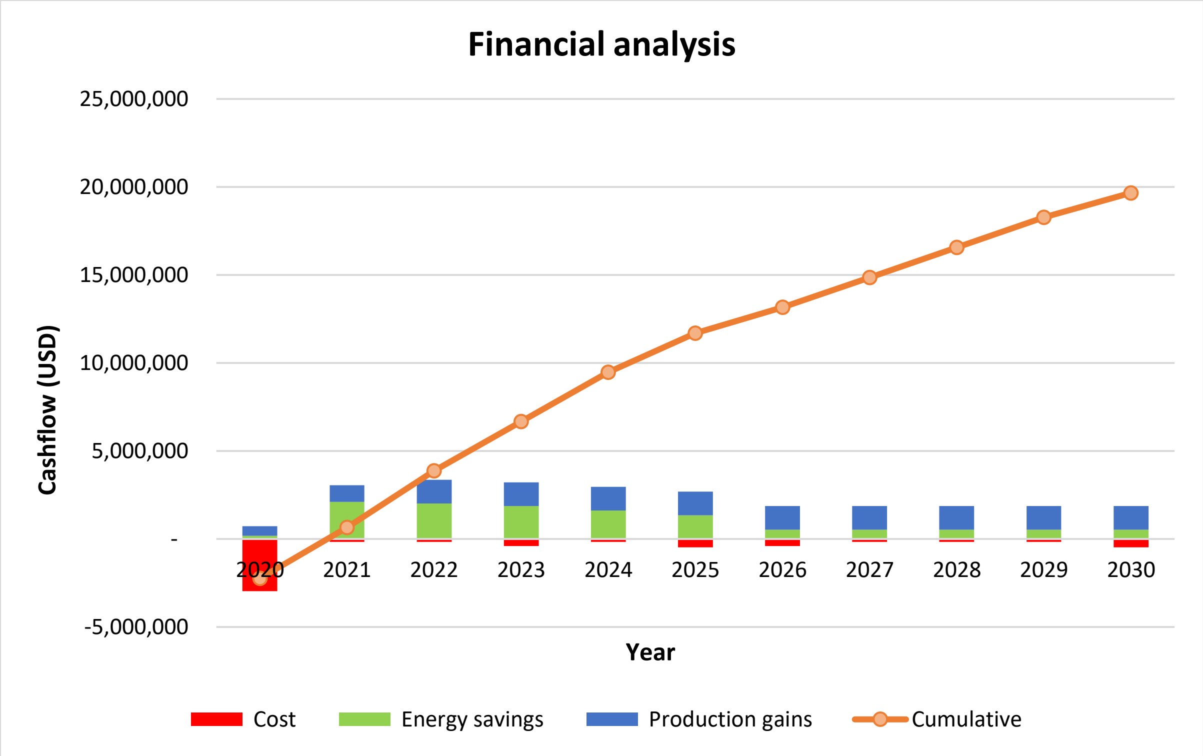

Figure 5.12: VOD financial analysis

It is important to note that the installed ventilation infrastructure was designed to ventilate the sections at full production. VOD systems will improve power consumption as the mine ramps up to full production. Production gains will be harnessed over the life of mine.

Table 5.5: Financial analysis for Ventilation on demand

YEAR		FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30
VOD capital and operating costs	**$4,072,209**	**2,837,060**	**161,894**	**161,894**	**401,601**	**161,894**	**474,918**	**401,601**	**161,894**	**161,894**	**714,625**	**283,703**
VSDs for main surface fans		654,668										
VSDs for auxiliary fans		490,656										
Tagging and tracking system		179,974										
Airflow and gas monitoring stations		166,266			111,600			111,600			111,600	
Dust and DPM monitoring systems		144,000			96,457			96,457			96,457	
Pressure and temperature sensors		31,650			31,650			31,650			31,650	
Automatic Doors		230,384					313,024				313,024	
Engineering services		132,432										
Software fee		47,362	47,362	47,362	47,362	47,362	47,362	47,362	47,362	47,362	47,362	47,362
Communication backbone		532,021										121,809
System maintenance & critical spares		114,532	114,532	114,532	114,532	114,532	114,532	114,532	114,532	114,532	114,532	114,532
Total Expenditure	**$4,072,209**	**2,837,060**	**161,894**	**161,894**	**401,601**	**161,894**	**474,918**	**401,601**	**161,894**	**161,894**	**714,625**	**283,703**
Gains												
Energy gains	**$2,098,245**	408,523	408,523	408,523	408,523	408,523	408,523	408,523	408,523	408,523	408,523	408,523
Productivity gains	**$6,903,025**	1,344,000	1,344,000	1,344,000	1,344,000	1,344,000	1,344,000	1,344,000	1,344,000	1,344,000	1,344,000	1,344,000
Total gains	**$9,001,270**	**1,752,523**	**1,752,523**	**1,752,523**	**1,752,523**	**1,752,523**	**1,752,523**	**1,752,523**	**1,752,523**	**1,752,523**	**1,752,523**	**1,752,523**
Net cash flow before tax	**4,929,061**	**(1,206,347)**	**1,590,628**	**1,590,628**	**1,350,921**	**1,590,628**	**1,277,604**	**1,350,921**	**1,590,628**	**1,590,628**	**1,037,897**	**1,590,628**
Tax	**25.75%**	-	**(409,587)**	**(409,587)**	**(347,862)**	**(409,587)**	**(328,983)**	**(347,862)**	**(409,587)**	**(409,587)**	**(267,259)**	**(409,587)**
Net cash after tax	**3,349,194**	**(1,206,347)**	**1,181,041**	**1,181,041**	**1,003,059**	**1,181,041**	**948,621**	**1,003,059**	**1,181,041**	**1,181,041**	**770,639**	**1,181,041**
Discounted net cash flow	**3,349,194**	(1,206,347)	980,931	814,727	574,708	562,030	374,939	329,282	322,018	267,457	144,948	184,502
Discount factor	**20.4%**	0	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
IRR	**62%**	1.00	0.83	0.69	0.57	0.48	0.40	0.33	0.27	0.23	0.19	0.16

The mine has since achieved just level 2 VOD. At full production that is at FY2025, power gains will average US$0.5 million as compared to the ramping up period from 2021 to 2024 where there are huge power savings. The average annual savings are projected to be 23% if the full VOD system is rolled out as shown in the waterfall chart in Figure 5.13. The blue bars show the total annual costs while green bars in the waterfall reflect power savings and the red color reflects an increase in power costs.

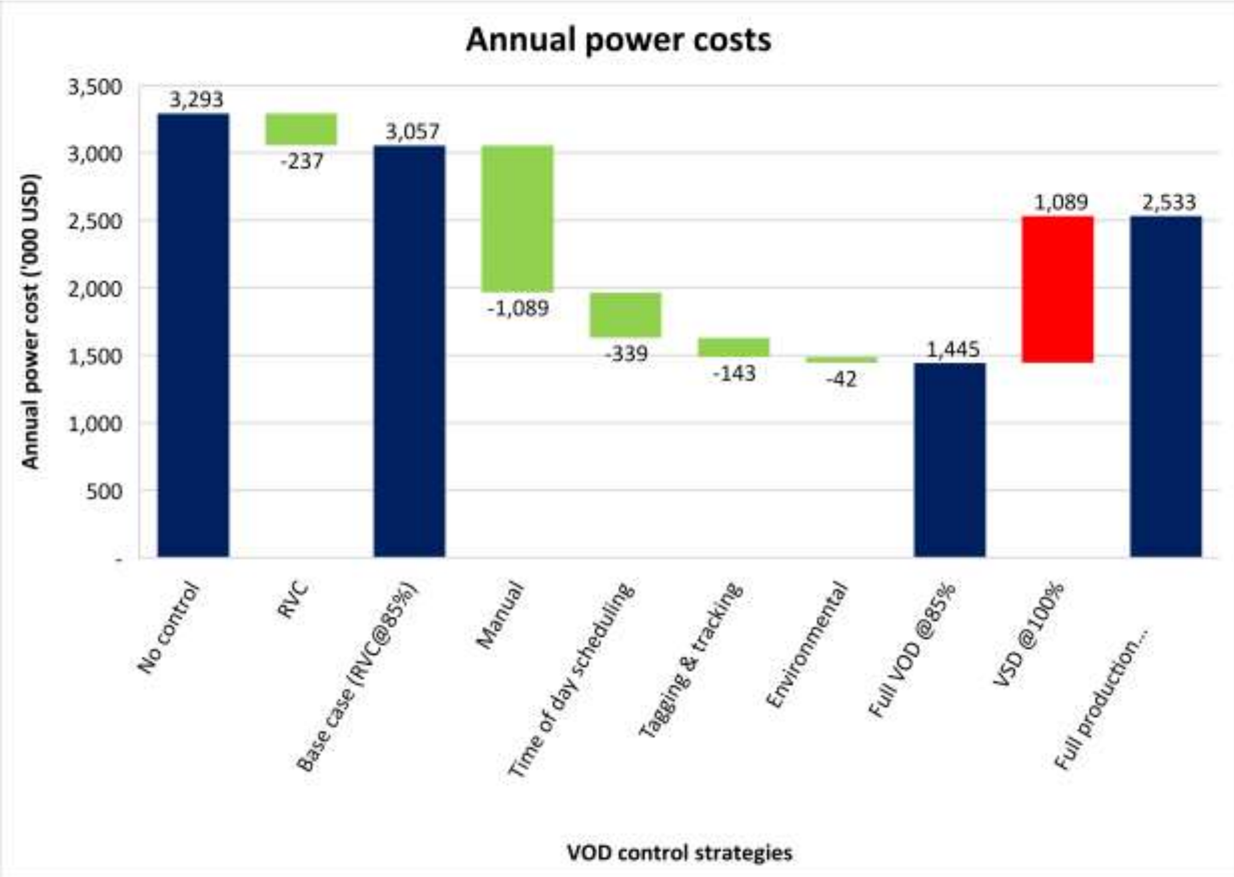

Figure 5.13: VOD control strategies annual power costs

5.5 How does the designed system work ?

It is important to ensure that the health and safety of workers is safeguarded at all times to ensure sustainability of mining operations. Real time monitoring of ventilation key performance indicators forms the basis of sound operational philosophy as opposed to the current monitoring strategies of monthly ventilation surveys. The application of artificial intelligence through VOD application, allows the system to automatically adjust airflow requirements thereby reducing airborne pollutants to desired levels less than OELs. In simple terms, this would entail monitoring production areas for the presence of activity and mining equipment, based upon which, appropriate air volumes would be delivered accordingly. The tags on the mining equipment carry information such as equipment identification number, power (kW) and required air volumes based upon diesel exhaust dilution requirements, information which is transmitted to a tag reader as soon as the mining equipment arrives within a tag reader's zone of influence. This information is processed by the VOD software into air volume requirements and transmitted to the main programmable logic controller (PLC) which controls primary and auxiliary fans together with associated regulators. Table 5.6 shows an ideal ventilation dashboard which includes most ventilation key performance indicators that are used to assess the effectiveness of any ventilation system. Sensors to give the parameters will be installed in a section where mining activities will be taking place. Information under the plan column is used as a reference so that any readings outside the plan which are recorded under actual column will be regarded as exceptional measurements which will therefore prompts an automatic response to the ventilation system.

Table 5.6: Ventilation key performance indicators for January 2021

	Actual	**Plan**			
Return quantity	601m^3/s	600m^3/s		*Gases*	
Intake quantity	600m^3/s	600m^3/s		CO	0ppm
Wet bulb	22ºC	27.5ºC		NO_2	3ppm
Dry bulb	27ºC	35ºC		O_2	20.9
Humidity	76%	90%		CH4	2%
Heat stress index	96W/m^2	115W/m^2		H_2S	0ppm
Respirable Dust	1.2mg/m^3	5 mg/m^3			
Air utilisation	68	70%			
Leakages	20%	30%			
Wet kata	25	18			
DPM	0.13mg/m^3	0.16mg/m^3			
Face Velocity	1m/s	0.8m/s			
BP	90.12kPa				
10.02.2021	15:28:31				

The graphical representation of the information in Table 5.6 will display in a dashboard designed during this research as shown in Figure 5.14. The system will measure air quality, air volume and air pressure changes in selected branches of a ventilation network. The data will be transmitted to a ventilation program, which in turn simulates real-time airflow distribution through all other branches of the ventilation network. The system will ensure accurate reporting, allow early response and will generate exception reports in real time. All health and safety risks will be addressed accordingly thereby eliminating potential fatal gassing incidents.

Traditional sampling techniques will be used as a parallel check to ensure that the system is well calibrated. The designed dashboard will show live parameters in colours with green representing desired levels, yellow representing warning and lastly red signalling danger.

TONDERAI VENTILATION DASHBOARD

Return air quantity	601m^3/s
Intake air quantity	600m^3/s
WB temperature	22^{o}C
DB temperature	27 ^{o}C
Humidity	76%
Heat stress index	96W/m^2
Respirable Dust	1.2mg/m^3
Air utilisation	68%
Leakages	20%
Wet kata	25
DPM	0.13mg/m^3
Face Velocity	1m/s
Barometric Pressure	90.12kPa

Gases

CO	0ppm
NO_2	3ppm
O_2	20.9
CH4	2%
H_2S	0

Engineering dashboard

Fan 1	
Bearing temp	30^{o}C
Vibration	1mm/s^2
Noise	110dB
Static Pressure	1.2kPa

10.02.2021 *15:28:31*
Date *Time*

Figure 5.14: Designed ventilation screenshot

The engineering screenshot in Figure 5.14 will be used as a predictive asset management strategy. In addition to exception reporting, the system will be equipped with rate of change alarms to ensure early responses and this will be linked with telemetry and cloud reporting. The desired air quantities should not be significantly exceeded at any given point in time to maintain the budgeted costs. However, where airborne pollutants are emitted to levels above OELs, it should be anticipated that air requirements will increase to reduce pollutants to acceptable values less than OELs, for example following blasting operations. The system will be configured with OELs and it will be programmed to give exception reports as well as auto adjustment techniques to reduce any airborne pollutant existing above the OEL. Figure 5.11 shows a typical gas monitoring dashboard for carbon monoxide and the modulation of air quantity in response to actual gas readings recorded in real time. It can be noted that the system responds when carbon monoxide levels are recorded above the maximum permissible concentration. When the carbon monoxide concentration goes back to normal values (less than OEL), the fans also respond by reducing the air quantities to the desired values which will be coupled to the demand. The designed system will improve the health and safety of all underground workers by establishing a conducive working environment. This can also improve worker productivity since all employees are more productive when they are operating under favourable working conditions. A reduction in the number of explosions and gassing incidents will also reduce all costs attributable to infrastructure resuscitation and litigation costs.

Diesel particulate matter has been classified as carcinogenic by the World Health Organisation (WHO) and IRAC. It is thus critical to monitor and manage DPM emissions throughout the shift. Although there is no legislation for DPM measurements in Zimbabwe, it is imperative to ensure that DPM levels are maintained below the acceptable limits of 0.16mg/m^3 as stated by the Australian and American standards. DPM sensors will be installed in all sections as part of the air quality monitoring stations and when DPM readings exceeds 0.16mg/m^3, the system will automatically adjust itself by running fans at increased speeds thereby exhausting more air to quickly disperse the pollutants until the readings go back to normal. Figure 5.15 shows the daily modulation of airflow in response to DPM emissions. The system will be calibrated annually to consider transient response times.

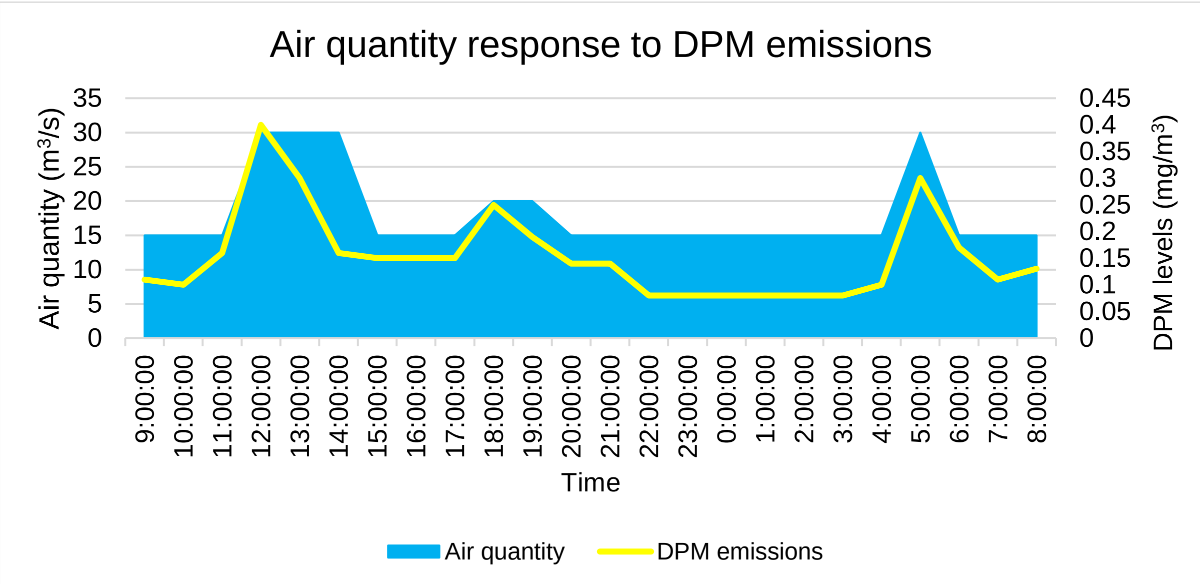

Figure 5.15: Air quality response to DPM on 11.03.21

This real time monitoring and automatic adjustment of airflow in response to DPM will assist ventilation systems by identifying high risk areas, high leakage areas and will also be used to monitor engine status of operating vehicles. In addition, all trackless mobile equipment (TMM) will be equipped with DPM sensors closer to exhaust pipes so that when the machine starts to emit exceptional DPM, an early response system will be triggered for remedial action plans to be put in place such as sending the machine to the workshop for repairs. Canada Centre for Mineral and Energy Technology (CANMET) has set limits for undiluted engine exhaust emissions not to exceed 150mg/m^3 (Nundlall, 2014). Any engine which exceeds that threshold limit value will automatically be rejected for use in underground mines. With the application of smart sensors, the level of maintenance and engine condition can be monitored thereby reducing the risk of worker exposure to DPM. If excessive DPM readings obtained are attributable to deteriorating engine condition, the company will save costs by replacing or repairing the machine instead of increasing the airflow continuously to allay DPM.

Air quantities can be effectively monitored and managed through real time ventilation surveys as opposed to the current monthly survey results. This allows the mining team to address high risk areas identified in the ventilation system within a reasonable time. Anomalies of air quantities can be analysed and corrected as they affect both safety of employees and power costs. Figure 5.16 shows a typical air quantity trend recorded throughout the month. It can be seen that the budgeted air quantity was capped at 600m^3/s and any anomalous readings identified will be analysed and prompt remedial action be put in place.

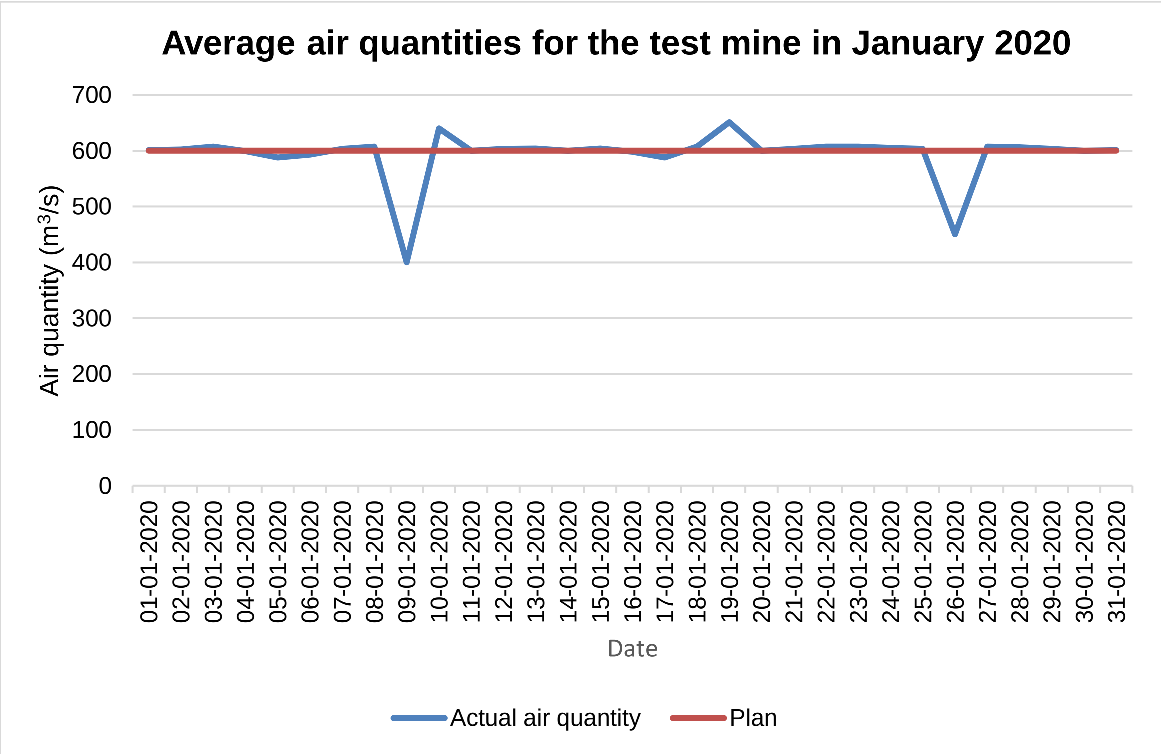

Figure 5.16: Variation of air quantities in a month

Such surveying techniques are more accurate as they give a monthly representation of both air quality and air quantity. Average monthly readings will be extracted from daily figures and such trends will assist in identifying areas with high resistance and excessive leakages. With VOD techniques, exception reports will be generated and areas of concern will be automatically highlighted for remedial work to be conducted .

In addition to air quantity measurements, pressure measurements are also key fundamentals in underground ventilation systems. Pressure surveys are conducted to prepare specifications for the specification of a new fan, investigate abnormalities in the ventilation flow, audit the ventilation system, determine the ability to cope with future production plans and to enable ventilation network analysis (Du Plessis and Biffi, 2014). The volumetric efficiency in advancing bord and pillar operations tends to decrease as the mine extends further along strike and dip, requiring higher pressure differentials and mined out excavations to be sealed inbye. The importance of this can be assessed by estimation using the main fan's static pressure, fan's efficiency and electrical power wastage over a specific period. Figure 5.17 shows a typical fan static pressure trend for one of the fans.

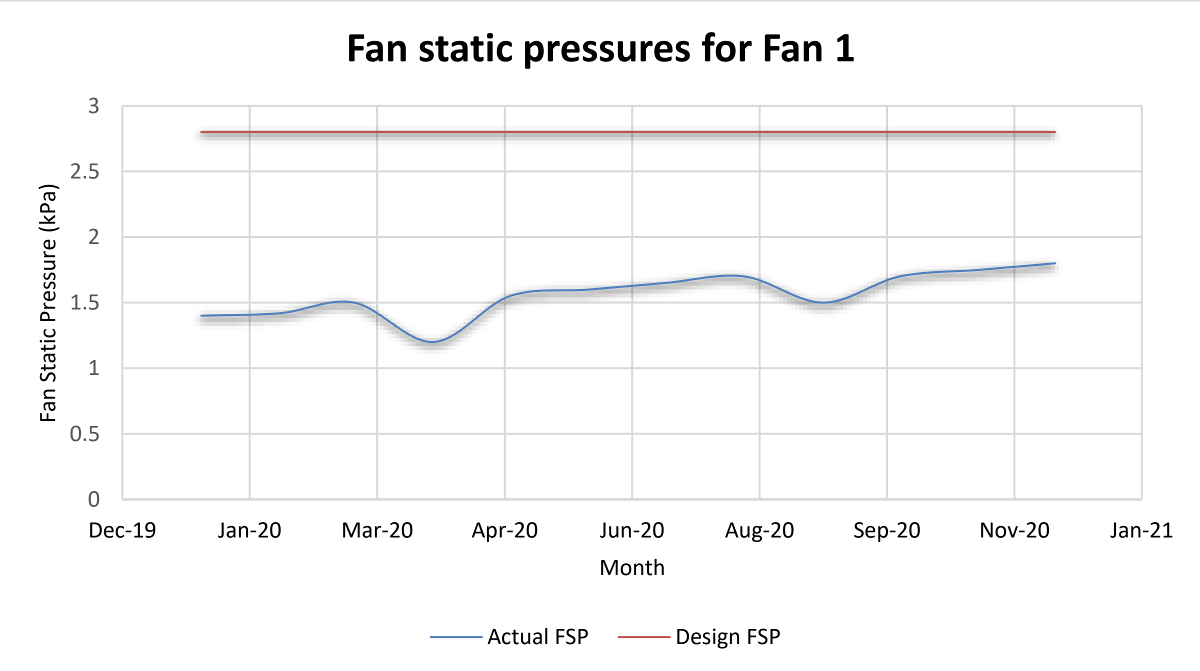

Figure 5.17: Fan static pressure trends

The fan static pressure is expected to increase as mining progresses due to increased resistance. All seals, ventilation doors and air crossings should be constructed to adequate standards and should be maintained in good working order. However, in most underground operations, ventilation doors can be kept open at times and several blockages in the ventilation system should also be expected. Main return airways must be accessible and maintained regularly to prevent accumulation of rocks through falls of ground. In addition, unplanned stowage of waste material and obsolete equipment in airways also increase airway resistance which limits the amount of air reaching working faces. Such instances will significantly affect air quantity at the face hence they must be managed without any time delay. It is against this backdrop there is the need to implement a system that monitors airflow and pressure differentials. This will detect deteriorating atmospheric conditions including excessive leakages in real time so that all unsafe conditions are corrected. The designed system will also be used to deduce differential pressures across doors, ventilation walls and fans. Environments sensors to monitor gases, DPM, temperature, airflow and dust will be installed on all critical ventilation controls with interlocking systems to improve the health and safety of employees. One example is the conveyor decline where gas sensors installed at all head and tail assemblies along the conveyor decline will be interlocked with fire doors along the conveyor decline. When gas sensors, placed along the conveyor decline, record high levels of gas concentrations, all fire doors along that conveyor decline will automatically shut to prevent contaminants from spreading to working areas as well as stopping oxygen feed to burning structures. Trapped employees will then use man doors on each automatic doors when escaping to safety.

Both air quantity and fan pressure affect the power consumption of a mine hence they should be monitored and managed properly. The designed system will also constitute smart sensors which can collect fan data such as power consumption readings from real time measurements of voltage, current and power from the motor control centre (MCC) and link the gathered data to main servers. Monitoring of daily power consumption assists in implementing cost management strategies for future production planning. Any exceptional power consumption readings apart from the expected trend will be flagged so that control measures can be checked and corrected. Figure 5.18 shows a typical power consumption trend obtained from 850kW rated centrifugal fans.

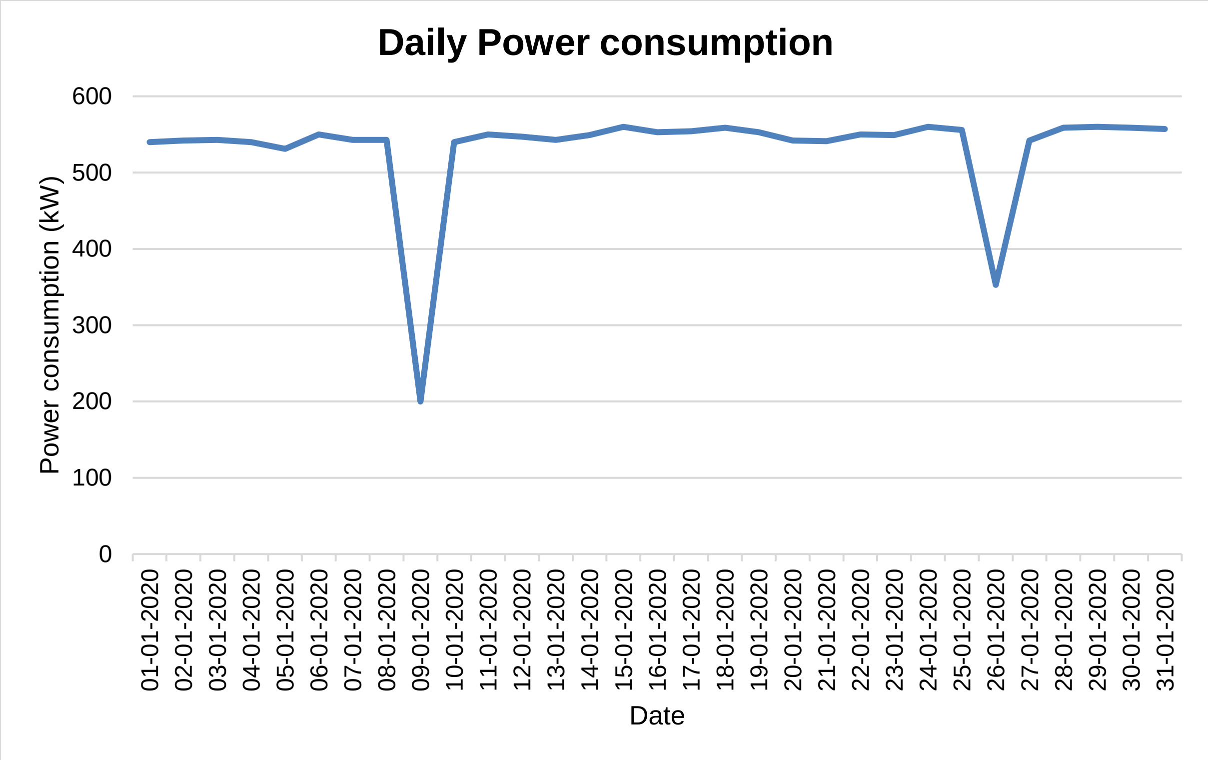

Figure 5.18: Fan power consumption trend

It is well understood that for a given airway, the airflow relationship can be defined as:

$$P = RQ^2 \quad \text{(Pa)} \qquad (5.1)$$

The parameter R (kg/m^7) is the resistance of the airway and it is the factor that governs the amount of airflow Q (m^3/s), which will pass when this airway is subjected to a given pressure differential P (Pa). The frictional pressure drop (ΔP) along this airway is a function of its length. This is because the resistance of the airway (R) is defined by:

$$R = k\frac{LC}{A^3} \quad \text{(kg/m}^7\text{)} \qquad (5.2)$$

Where k = friction factor (kg/m^3), L = airway length (m), C = airway perimeter (m) and A = cross sectional area (m^2). Furthermore, the fan power needed to overcome the frictional pressure losses along the airway can be defined as:

$$FP = \Delta PQ = RQ^3 \quad \text{(W)} \qquad (5.3)$$

Equation (5.3) shows that the fan power (FP) is linearly proportional to the resistance of the airway (R), and hence the length of the airway (L). In general C, A, and k are constants for any particular airway. More importantly this equation shows that there is a cubic relationship between the fan power (FP) and the passing airflow (Q). If there is a high resistance in the system such as blockages in airways, the static pressure will increase and subsequently increase the power consumption. Very low power consumption can be attributable to high air leakages in the system which can also be investigated and corrected immediately. Power is one of the major cost drivers in any mechanised mining operations, hence it must be monitored in real time.

Production performance will be integrated with ventilation conditions in real time to determine the adequacy of ventilation as well as to assist in future planning. Information from the production dashboard will include the number of blasted faces, blasted tonnages and the fleet composition. The system will automatically compute the air/tonnage ratios in real time as well as diesel dilution factors at any point of operation. Such smart sensors will assist in correcting any anomalous readings which can affect the health and safety of employees.

5.6 Dust management

Excessive dust generation will affect worker health and impact negatively on employee productivity and other performance indicators impacted by visibility as described in Chapter 3 (the literature review). Ensuring adequate precautions against harmful dust is a requirement of the Mine Health and Safety Regulations (Brouwer & Rees, 2020). Figure 5.19 shows a typical respirable dust variation that was generated at a crusher station. A real time dust monitor (Trolex) was used to measure respirable dust inside the rock breaker cabin of the underground crusher. The crusher chamber was earmarked as a high dust area hence the trial was conducted inside the chamber to protect the operator.

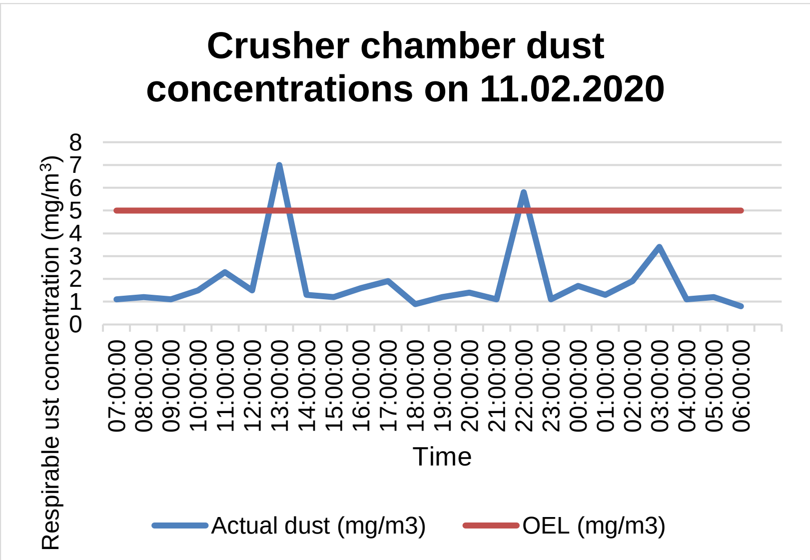

Figure 5.19: (a)Real time dust concentration trends **(b) Real time dust monitor**

Various mechanisms will be employed to ensure that dust remains below OELs. These abatement methods include modulation of auxiliary fans, automatic activation of dust suppression systems in hauling roadways and automatic activation of water-blasts in blasted ends. Figure 5.20 shows a typical dust management system designed as part of this research to allay dust in addition to the primary ventilation system discussed earlier on.

Figure 5.20: Underground dust management system

This system will be linked to the employee database which will be used for medical surveillance and screening. Currently, all employees are subjected for annual medical check-ups, however there are some employees who have greater dust exposures and may require frequent check-ups due to the increased risk. The system will automatically flag when an employee is due for a medical check-up based on actual exposures deduced by sensors in the employee's working environment. This system will substantially reduce the number of medical fatalities as well as the number of occupational diseases which have wreaked havoc in the mining industry.

5.7 Smart cap lamp

In addition to the VOD system, an ideal cap lamp shown in Figure 5.21 was specified to the manufacturer which can be used by all underground employees. Early indications show that the price of such cap lamp will be averaging ZAR4 350. The cap lamp comprises of sensors to monitor underground conditions and give warning to underground employee the moment atmospheric conditions become unsafe. Such sensors will be measuring carbon monoxide, methane, temperature, respirable dust, DPM and noise. All these sensors will be linked to the supervisory control and data acquisition (SCADA) system and will automatically generate exception reports and possibly direct the employee for medical check-ups if the exposure levels are adverse. This will ensure adequacy in recovery periods for exposed employees based on real time exposure measurements. A displaying screen will be attached to the battery and will be showing similar measurements as those reported to the SCADA system. In addition to visual warnings, the cap lamp will be fitted with audible alarms as well as by means of vibration to warn employees in the event of danger. Figure 5.22 shows an ideal cap lamp specified by the author and how it can become part of the 4IR concept for future mining.

Figure 5.21: Underground smart cap lamp

5.8 Optimised medical database

The primary objective of medical screening and surveillance is to prescribe baseline and periodic evaluations of workers exposed to various types of occupational hazards such as dust and noise by performing screening and diagnostic examinations. In most mines, there is a gap between exposure and the frequency of such medical examinations. Employees from different workplaces must be examined at a different frequency rate based on the nature of activities undertaken or exposure levels. Highly exposed employees must be examined more frequently than employees who are subjected to low dust exposures. With the application of fourth industrial revolution techniques in environmental monitoring, both screening and medical surveillance processes will be improved by :

- Creating a baseline to assess changes in health conditions of an individual that may develop in future
- Detecting abnormalities that may have been caused by occupational hazards and deciding when corrective measures can be put in place
- Reducing the number of pneumoconiosis cases
- Identifying potential hazardous atmospheric conditions and underscoring the need for improvements in ventilation systems

In order to have accurate information regarding the health of workers, an employee database must be established and information in the database must be aligned with employee workplace daily conditions. Currently, the medical team relies on monthly surveys and not necessarily real time conditions hence the need for a more reliable system which can bridge that gap. The individual data collected in the system relating to exposure risks can be used to measure exposure trends and the effectiveness of the controls in place. Good ventilation design and environmental monitoring will ensure sustainability of mining operations through a reduction in the number of occupational related diseases.

5.9 The future

For inaccessible, abandoned, poorly ventilated or high risk areas, all ventilation key performance indicators can be measured using a ventilation drone. This current research has included considering the use of a ventilation drone which can be linked to the main server. The drone will need to be controlled remotely by an operator, who is far away from all exposure risks and the drone will be equipped with a number of sensors to determine underground conditions. Such sensors include gas sensors, dust sensors, temperature sensors, velocity sensors, DPM sensors and humidity sensors. Figure 5.22 shows the design configuration for the ventilation drone and its principle mode of operation.

Figure 5.22: Drone for conducting ventilation surveys in inaccessible parts of the mine

Fixed environmental sensors described in the VOD model will be placed at a safe distance from the faces to avoid being damaged by fly rock and concussion from blasting operations. The application of ventilation drones will assist in gathering accurate and reliable results from unsupported areas and blasted faces and also improves the health and safety of underground employees by eliminating personal exposure to airborne pollutants. Autonomous dump trucks, automated LHDs and remote controlled rock breakers should also be considered as they remove workers from occupational risks.

The mining industry consumes approximately 11% of global energy (De Souza, 2018). This energy is mainly supplied from diesel, natural gas and grid electricity. Mine sites are often in remote areas and typically depend on diesel-generated power plants which can be costly and pose challenges for transport and logistics. Loss of power can be catastrophic for mining companies as seen in 2016 when a 24-hour state-wide blackout in South Australia halted production at BHP’s Olympic Dam mine for nearly two weeks (De Souza, 2018). There is an opportunity for companies to use renewable sources of energy, differentiating them on the basis of sustainability. Companies have begun to utilise renewable energy, in particular solar and wind, resulting in a reduction in the amount of diesel used and CO_2 emissions and consequent cost savings. An integration of a solar electricity system and grid electricity can be incorporated to power main surface fans. The system will automatically switch to solar energy in summer seasons particularly during the day due to high radiant areas in Zimbabwe. This will reduce mine power consumption which is known to be one of the major cost drivers in mechanised mining operations. With automation, there will be less ventilation requirements due to decreased demands as well as higher heat rejection temperatures of machines as opposed to human beings. To date, it has been shown that future ventilation systems would need to be designed primarily to combat equipment "heat stress," which can occur at ambient air temperatures exceeding 40°C (Schneider, 2016).

5.10 System maintenance

Sensors used during the VOD trial are robust, resist concussion, heat resistant and water resistance and were compatible with underground conditions. These sensors will be calibrated by the Original Equipment Manufacturer (OEM) annually. This will be done to ensure that all readings obtained are accurate to an acceptable degree. Bump tests will be conducted on each sensor on a monthly basis by instrument technicians at the mine. The budget for condition monitoring of the designed system was covered in the full financial evaluation analysis shown in Table 5.5. With technological advance the system will be upgraded to meet any new technical specifications. All sensor heads will be leapfrogged closer to working faces as mining progresses. A representative of each system will be resident onsite to ensure a smooth running of the system through maintaining desired availabilities. Replacement costs for certain system components are also shown in the cashflow in Table 5.5. Remote assistance will be provided by various OEM. Critical spare parts will also be stored on site because of long lead times associated with other system components. Periodic training on use and maintenance of the system will be carried out by the relevant authorities.

5.11 Safety and occupational hygiene risk assessment

The emergency preparedness of any mining operation should address detection and early warning systems, communication systems, mine evacuation, rescue and response capabilities, fires and explosion prevention (Du Plessis and Biffi, 2014). A robust system is therefore required for the prevention and detection of fires to combat the devastating effects regarding gases and underground fires. Major fire sources identified in the research area include trackless vehicles, conveyor belts and electrical substations.

5.11.1. Trackless vehicles

Safety features and devices must be installed on each item of underground mobile equipment. Various safety features must be attached to all trackless equipment which include a tagging and tracking system and automatic fire suppression systems to cool hot exhaust gases. Haulage roadways where trackless vehicle operate will be equipped with automatic dust suppression systems to combat the risk posed by respirable dust. A back up system will be installed where an operator can press an emergency switch linked to the main server.

5.11.2. Conveyor belts

Conveyor belt fires are fairly common in Southern African mines (Bluhm and Smit, 2014). The Northam platinum fire which occurred in September 2004 resulted in nine fatalities while the Impala incident which happened in 2014 claimed five lives and luckily the Mimosa incident which occurred in 2012 had no fatalities (Casey, 2020). If conveyor belts are left unmonitored, frictional heat can cause a significant mix of toxic combustion gases and smoke. An automatically activated water dowsing or foam fire suppression system will be installed in all conveyor belts excavations. Gas sensors will be installed along the entire length of the belt particularly at all head and tail assemblies. These gas sensors will be interlocked with all conveyor ventilation doors to reduce worker exposure to fumes in the event of an underground conveyor fire. No combustible material should be stored in all conveyor excavations and CCTV cameras should be installed along the belt to monitor the accumulation of such material which increases the mine fire load index.

5.11.3. Electrical sub-stations

Sub-station fires are infrequent but regular events in underground mining operations. In order to reduce the fire risk , sealed dry-type transformers should be the choice for underground use. The Soma mine disaster where 301 mine workers perished was attributable to an oil filled transformer that caught fire (Ünver & Ünal, 2018). Bund walls should be constructed where oil-filled transformers are currently installed.

5.11.4. Early warning systems

In addition to early warning systems along conveyor belts, there is also a risk of other fire, explosion and/or toxic gas release that could lead to an irrespirable atmosphere in the reef plane workings. An early warning system or systems should be considered at all working places as described earlier on. All mines should consider monitoring their systems with early warning systems around the clock including during off-shift periods. Employees working in high risks areas such as raises, steep orebodies and crusher stations should be issued with cap lamps that can detect various occupational hazards as described under section 5.6 on smart cap lamps. Flammable gas should be expected particularly when mining across geological structures such as dykes and faults, hence all drill rigs must be fitted with an interlocking system which deactivate all operations and alerts the operator upon intersecting any gas pocket during the drilling process.

5.11.5. Control room and communication

All mines in the research area should have a well-established 24-hour manned control room where all the aforementioned parameters will be monitored. The parameters to be monitored in each control room include and are not limited to fire detection systems, main surface fans, ventilation key performance indicators and blasted tonnages. There will be a need to upskill the current C1 control room operators to cope with emerging technologies. In addition, there is need for regular simulation of emergencies via automated systems.

5.11.6. Escape and rescue strategy

A risk assessment is always required for escape and rescue procedures related to explosions, fires, flooding and accidents (Phillips, et al., 1997). All persons entering the mine should be adequately trained on health and safety risks and control measures. Refuge chambers serve as an alternative option when escape is not possible. Refuge chambers must be provided within 500m walking distance from the furthest working places. Refuge chambers must be equipped with environmental monitoring systems similar to the ones described in the VOD model structure. This can assist in monitoring the exact number of people in the chamber as well as monitoring of atmospheric conditions. A risk assessment done in the research area identified a worst case scenario where an accident can lead to a loss of electricity and compressed air. This necessitated the need for a self-sustaining refuge camber in all mining operations. In order to minimize the risk, portable self-sustaining refuge chambers ventilated by compressed air cylinders inside the chamber can be considered. A maximum of 30 people can survive for 48 hours in one of these refuge chambers.

5.12 Chapter summary

A VOD system was designed and installed in a bord and pillar platinum mine to minimize the redundant use of air in underground operations. Fourth industrial revolution techniques were employed to monitor the mine environmental systems thereby optimizing its airflow demands.

The findings of the research reveal that the mine managed to reduce its annual power consumption by 23% through the implementation of manual control and time of day scheduling levels of the ventilation on demand concept. There was also a 6% productivity improvement mainly attributable to a significant reduction in the re-entry period. The research benefits can be extended to other mines which are in the same geological location, mining the same type of deposit and using the same mining method.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

This thesis has provided a brief overview of the ‘perspective’ on optimised ventilation design for mechanised room and pillar platinum operations. This research has provided an insight on ventilation design aspects. For optimum ventilation design, it is important to integrate empirical techniques with numerical modelling. Ventilation demands can be reduced by the application of fourth industrial revolution techniques such as automating the mining value chain and the adoption of ventilation on demand. Monitoring of DPM is critical and can be used as a measure of ventilation efficiency. It allows ventilation systems to be adjusted based on the actual demands. Ventilation is a major cost driver of any mechanised operation hence cognisance must be taken during the design stage to optimise the ventilation system. The integration of air requirements in a technical mine design for life of mine production has been highlighted in this thesis. Ventilation inefficiencies through overdesigned systems or under designed systems need to be eliminated as these can increase operating power costs or result in creating a harmful underground environment. The challenge in mechanised operation remains the provision of a healthy and safe working environment that is effective and cost-efficient throughout the life of mine operations.

Current mining trends, including an increased degree of mechanisation, would generally require that more air is required and consequently more power consumed. Power usage is not only a cost issue but is increasingly becoming an environmental issue when, worldwide, industry is trying to reduce greenhouse gas emissions. For Zimbabwean platinum mines, it is believed that by reviewing the way ventilation systems are designed and exploring future technologies that reduce energy demands, considerable savings can be achieved. Optimised ventilation systems in mechanised bord and pillar mines remain challenging, however, the application of fourth industrial revolution techniques will mitigate ventilation from being cost prohibitive. In order to have a sustainable operation, there must be a balance in profit, safety and social responsibility. This research was carried out to improve mine safety and productivity. The research covers extensive work on one mine on the Great Dyke but the research benefits can be extended to other mines which are in the same geological location, mining the same type of deposit using the same mining method. Efficient ventilation systems will optimise mining key performance indicators. Sickness absenteeism and medical retirement due to health problems at the mines lowers production. The employer is obliged to exercise a high level of care to all workers. Additional medical bills and compensation claims will increase the company costs hence this will affect the profit margins. A more efficient and effective ventilation system will improve health and productivity of the mine. A higher production will result in high revenue generation, hence economic growth.

6.2 Key findings and research contribution

From the analysis of results, the current ventilation systems needs to be optimised to manage costs and manage the health risk. It is therefore essential to implement the ventilation systems designed during this research, taking into account the cost benefit analysis to minimise unplanned costs that may arise. The key performance indicators in the mining industry are safety, health, production and costs. The optimisation of these KPIs in relation to this research is described in this chapter.

6.2.1 Health and safety

Listed herein are health related benefits deduced from the major findings of the research.

- Monitoring of airborne pollutants in real time
- Modulation of airflow in response to airborne pollutants
- Automated medical surveillance systems

In addition, the adoption of VOD will improve the safety performance by creating a thermally acceptable environment thereby reducing fatigue and heat exhaustion related accidents. The implementation will also contain underground fires through automated systems. Emerging risks such as trapping underground employees will be addressed by the use of man doors installed adjacent to automated doors which can be used in the event of a fire. The required minimum velocity will be maintained through the use of airflow sensors which will trigger a response if the actual readings are less than the desired quantities

6.2.2 Production

The adoption of VOD systems will reduce re-entry which will directly increase face time. Productivity increased by 6% following the utilisation of additional face time. The research findings and recommendations will also improve production because of the creation of a conducive working environment which will enable employees to produce optimally.

6.2.3 Costs

Mining companies must remain in the lowest cost quartile of similar mines in a bid to provide business growth and also to produce superior returns to all stakeholders. The following points from this research pinpoint the cost cutting initiatives:

- Apart from improved safety, the VOD system will reduce power costs by US$539 299 per year (23% of the current operating cost).
- There will be fewer litigation costs and compensation claims as a result of reduced number of pneumoconiosis cases and gassing incidents.
- Less capital will be required in retrofitting main surface fans.

The findings of this research together with the proposed recommendations will integrate health and safety measures, value addition and economic benefit to the mines on the Great Dyke. Mining is the backbone of the Zimbabwean economy. The benefits of this research are in line with the global mine key performance indicators of production, safety and costs. The results of this study will therefore give long lasting benefits to the platinum mines on the Great Dyke as they can safely extract the remaining resources at a minimum power cost. The study will therefore meet the vision of many companies of remaining in the lowest cost quartile of platinum producers and to provide superior returns to the stakeholders..

6.3 Research limitations

The research was only limited to diesel operated equipment. An impact of electric vehicles on ventilation was not practically assessed due to limited availability of such machinery in the market. Battery powered equipment is still under research and development. The model of smart drones was also not tested on the ground since the system is also still under research and development. This may be recommended as future work.

6.4 Recommendations for Future work

Since mine ventilation engineering system is an important enabler in mine health and safety, this research area is of continued importance by many in the past and into the future. There is still room for improvement to optimise mining key performance indicators of safety, productivity and costs by maintaining the required airflow in working areas based on the nature of activities undertaken. A full automatic ventilation optimisation system can be developed to maximise the projected benefits. For inaccessible, abandoned, poorly ventilated or high risk areas, all ventilation key performance indicators can be measured using a ventilation drone. Such systems can be further investigated and designed. Other future considerations in the mining industry include the use of electrically powered vehicles to replace diesel vehicles due to their low ventilation demands as well as reduction in carbon emissions. Future research can also consider the applicability of continuous miners to hard rock platinum mines to replace drilling and blasting techniques due to a reduction in fumes generation.

REFERENCES

Abrahamsson, L., Johansson, B. & Johansson, J., 2009. Future of metal mining: Sixteen predictions. *International Journal of Mining and Mineral Engineering*, 1(3), pp. 305-311.

Acuna, E. & Allen, C., 2017. *Totten mine ventilation control system update: implementation and savings achieved with Level 1 user cintrol and future plans.* Colorado, Colorado school of mines.

Acuña, E. I., Álvarez, R. A. & Hardcastle, S. G., 2014. *A theoretical comparison of ventilation on demand strategies for auxiliary mine ventilation systems.* Johannesburg, Mine Ventilation Society of South Africa.

AMS Haden, 2020. *AMS Haden technology solutions.* [Online]
Available at: https://www.amshaden.co.za/products/#environmental-monitoring
[Accessed 29 January 2020].

Baiden, G. R., 2001. *Autonomation of underground mining using teleremote systems.* Proc. 6th Int. Symp. Mine Mech. Autom, The Southern African Institute of Mining and Metallurgy.

Belle, B., 2018. How relevant are engineering samples in the management of personal dust exposure. *International Journal of Mining Science and Technology,* 28(4), pp. 707-712.

Biffi, M., Standton, D., Rose, H. & Pienaar, D., 2007. Ventilation strategies to meet future needs of the South African platinum industry. *The Journal of The Southern African Institute of Mining and Metallurgy,* 107(1), pp. 59-66.

Blekhman, I. I., 2012. *Wear and tear of nominally fixed joints affected by vibration and percussive impacts.* [Online]
Available at: https://www.ipme.ru/ipme/conf/APM2012/2012-PDF/2012-043.pdf
[Accessed 28 June 2019].

Bliss, M., 2018. *How Technological Innovation is Impacting the Mining Sector.* [Online]
Available at: https://www.igfmining.org/technological-innovation-impacting-mining-sector
[Accessed 14 May 2021].

Bluhm, S. & Smit, H., 2014. Planning ventilation and refrigeration requirements. In: *Ventilation and Occupational Environment engineering in Mines.* 3 ed. Johannesburg: Mine Ventilation Society of South Africa, pp. 773-804.

Bohanek, V., Dobrilovic, M. and Skrlec, V, 2013. Influence of the Initiation Energy on the Velocity of Detonation on ANFO explosives. *Central European Journal of Energetic Materials,* 10(4), pp. 555-567.

Bonsu, J., van Dyk, W., Franzidis, J. P. & Peter, F., 2017. A systemic study of mining accident causality: an analysis of 91 mining accidents from a platinum mine in South Africa. *Journal of the Southern African Institute of Mining and Metallurgy,* 117(1), pp. 59-66.

Brouwer, D. H. & Rees, D., 2020. *Can the South African Milestones for Reducing Exposure to Respirable Crystalline Silica and Silicosis be Achieved and Reliably Monitored.* [Online]
Available at: https://www.frontiersin.org/articles/10.3389/fpubh.2020.00107/full
[Accessed 14 October 2020].

Casey, J. P., 2020. *Mining in Zimbabwe: time to use it or lose it.* [Online]
Available at: https://www.mining-technology.com/features/mining-in-zimbabwe-time-to-use-it-or-lose-it/
[Accessed 15 August 2020].

Cawood, F. T., 2019. *Mining Review Africa - Beyond 2020: The future of mining in a world of technology.* [Online]
Available at: https://www.miningreview.com/central-africa/future-mining-technology/
[Accessed 23 May 2020].

Cawood, F. T., 2021. *Mining's year ahead will demand deep innovation.* [Online]
Available at: https://www.bizcommunity.com/Article/196/723/211911.html
[Accessed 1 March 2021].

Chaumba, J., 2017. Hydrothermal Alteration in the Main Sulfide Zone at Unki Mine, Shurugwi Subchamber of the Great Dyke, Zimbabwe: Evidence from Petrography and Silicates Mineral Chemistry. *Geochemistry and Mineralogy of Hydrothermal Metallic Mineral Deposits,* 7(7), pp. 127-142.

Chifurira, R., 2018. *Modelling Mean Annual Rainfall for Zimbabwe.* Bloemfontein: University of the Free State.

Cosbey, A., 2019. *Seven ways new technology will impact the mining sector.* [Online]
Available at: https://www.iisd.org/articles/insight/seven-ways-new-technology-will-impact-

mining-sector
[Accessed 15 September 2019].

Creamer, M., 2018. *Exciting new mining research thrust.* [Online]
Available at: https://www.engineeringnews.co.za/article/exciting-new-mining-research-thrust-2018-04-27
[Accessed 15 October 2020].

De la Harpe, J. H., 2014. Basic fan engineering. In: *Ventilation and occupational environment engineering in mines.* Johannesburg: Mine Ventilation Society of South Africa, pp. 111-144.

De Souza, E., 2018. Cost saving strategies in mine ventilation. *Canadian Institute of Mining, Metallurgy and Petroleum,* 9(2), pp. 1-7.

De Villiers, D. J. et al., 2019. Evaluating the impact of auxiliary fan practices on localised subsurface ventilation. *International Journal of Mining Science and Technology,* 29(6), pp. 933-941.

Develo, E., Pillalamarry, M. & Garab, E., 2016. Improving the ventilation system at. *Journal of the Sothern African Institute of Mining and Metallurgy,* April, 116(04), pp. 301-305.

Dhillon, B. S., 2010. *Mine safety- A modern approach.* [Online]
Available at: https://www.springer.com/gp/book/9781849961141#
[Accessed 17 August 2019].

DMRE, 2019. *Department of mineral resources.* [Online]
Available at: https://www.dmr.gov.za/mine-health-and-safety/mine-accidents-and-disasters
[Accessed 18 December 2019].

Drager, 2018. *Drager gas detection equipment.* [Online]
Available at: https://www.draeger-mo.com/en/catalog/safety-equipment/gas-detection-equipment-portable/multi-gas-detection-equipment/drager-x-am-r-5600/groups/g+c+p+a+view
[Accessed 14 April 2019].

Du Plessis, J. & Biffi, 2014. Ventilation and Occupational Environment engineering in Mines.. In: 3 ed. Johannesburg: Mine Ventilation Society of South Africa, pp. 237-306.

Du Plessis, J. J. & Belle, B. K., 2014. Sampling of airborne dust and diesel particulates. In: *Ventilation and occupational environment engineering in mines.* Johannesburg: Mine Ventilation Society of South Africa, pp. 255-277.

Du Plessis, J. J. & Beukes, J. J., 2014. Gases encountered in mines. In: *Ventilation and occupational environment engineering in mines.* Johannesburg: Mine Ventilation Society of South Africa, pp. 533-554.

Edgecombe, R., 1990. Dannhauser (1926) and Wankie (1972)—Two Mining Disasters. *Journal of Natal and Zulu History,* 29 January, 13(1), pp. 71-90.

Emetere, M. E., Agubo, O. & Chikwendu, L., 2021. Erratic electric power challenges in Africa and the way forward via the adoption of human biogas resources. *Energy Exploration & Exploitation,* 39(4), p. 1349–1377.

Gangal, M. & Grenier, M., 2002. *An Overview of Regulations to Control Diesel Emissions in Canadian Mines.* Ontario, Kingston.

Grau, III R.H., Robertson S.B., Krog R.B., Chekan G.J., Mucho T.P, 2004. *Raising the bar of ventilation for large-opening stone mines.* s.l., Mine ventilation: Proceedings of the 10th U.S./North American Mine Ventilation Society.

Hardcastle, S.G. and Kocsis, C.A, 2001. *Ventilation designs for an automated underground metal mine.* Krakow, 7th International Mine Ventilation Congress, pp. 779-786.

Hardcastle, S. G. & Kocsis, C. A., 2004. *The ventilation challenge.* Ontario, Natural Resources Canada.

Hardcastle, S. G., Kocsis, C., Bissiri, Y. & Baiden, G., 2005. *Optimizing Mine Ventilation Through the Use of Life-Cycle Production Models.* Brisbane, AUSIMM, Carlton, Victoria,.

Hardcastle, S., Schmitz, B. & Drummond, J. A., 2014. Measurement of airflow. In: *Ventilation and occupational environment engineering in mines.* Johannesburg: Mine Ventilation Society of South Africa, pp. 33-60.

Harris, A. M., 2020. *Implementing a Root Cause Analysis Program.* [Online]
Available at: https://pubmed.ncbi.nlm.nih.gov/31978526/
[Accessed 14 December 2020].

Hemp, R. & Rawlins, C. A., 2014. Sources of heat in mines. In: *Ventilation and occupational environment engineering in mines.* Johannesburg: Mine Ventilation Society of South africa, pp. 407-439.

Hermanus, M., 2017. Mining redesigned - innovation and technology needs for the future. *The Journal of the Southern African Institute of Mining and Metallurgy,* 117(8), pp. 811-818.

Holding, G., 2010. *Training manual for production personnel in the principles of strata control.* Great dyke geological succession: s.n.

Howes, M. J., de Koker, M. J. & Edwards, A. L., 2014. Noise control for hearing conservation. In: *Ventilation and occupational environment engineering in mines.* Johannesburg: Mine Ventilation Society of South Africa, pp. 749-772.

IARC, 2012. *International Agency for Research on Cancer - Diesel engine exhaust carcinogenic.* Press release: World Health Organization.

Implats, 2016. *Fire at Impala Rustenburg 14 Shaft.* [Online]
Available at:
www.implats.co.za/implats/downloads/2016/Implats_SENS_14_Shaft_Fire_25_January_2016.pdf
[Accessed 14 January 2019].

Jacobs, J., 2016. *Creating a technology map to facilitate the process of modernisation throughout the mining cycle.* Pretoria: University of Pretoria.

Jenkins, M. C. & Mungall, J. E., 2018. Genesis of the Peridotite Zone, Stillwater Complex, Montana. *Journal of Petrology,* 59(11), p. 2157–2189.

Jones, M. Q., 2018. Virgin rock temperatures and geothermal gradients in the Bushveld Complex. *The Journal of the South African Institute of Mining and Metallurgy,* 118(7), pp. 671-680.

Khawaja, S., 2022. *Digitalisation and its impact on the mining industry.* [Online]
Available at: https://www.mining-technology.com/sponsored/digitalisation-and-its-impact-on-the-mining-industry/
[Accessed 28 January 2022].

Kumar, S., Tiwari , P. & Zymbler , M., 2019. Internet of Things is a revolutionary approach for future technology enhancement: a review. *Journal of Big data,* 111(6), pp. 1-21.

Kurlenya, M. V., 2017. Methane Explosions and Causes of Their Origin in Highly Productive Sections of Coal Mines. *Journal of Mining Science volume,* 53(1), pp. 862-867.

Liedtke, S., 2019. *Mining sector's pursuit of 'zero harm' continues.* [Online]
Available at: https://www.miningweekly.com/article/mining-sectors-pursuit-of-zero-harm-continues-2019-04-19
[Accessed 23 August 2019].

Lilic, N., 1997. An Expert System for Mine Ventilation. *Mining technology,* 79(915), pp. 295-302.

Loow, J., 2022. Understanding technology in mining and its effect on the work environment. *Minerals Economics,* 35(1), pp. 143-154.

MacNeill, P., 2008. *International Mining Fatality Database.* [Online]
Available at: www.resourcesandenergy.nsw.gov.au/miners-and-explorers/safety-and-health/incidents/international-mining-fatality-review
[Accessed 20 January 2019].

Maranda, A., 2011. ANFO Detonation Parameters. *Central European Journal of Energetic Materials,* 8(4), pp. 280-291.

Marx, W. M. & Butterworth, M. D., 2014. PC-based planning tools. In: *Ventilation and occupational environment engineering in mines.* Johannesburg: Mine Ventilation Society of South Africa, pp. 805-821.

Mather, W., 1997. *Bulk Explosives.* [Online]
Available at: https://miningandblasting.files.wordpress.com
[Accessed 13 December 2014].

Matthews, C., 2020. *Miningmx higher grade.* [Online]
Available at: https://www.miningmx.com/news/markets/40120-zimbabwes-chitando-says-countrys-mining-sector-has-entered-new-heights/
[Accessed 14 January 2021].

McPherson, M. J., 1993. *Subsurface Ventilation and Environmental Engineering,.* s.l.:Chapman & Hall.

Mkhabela, M. & Manzi, M., 2017. Detection of potential methane gas pathways in deep South African gold mines. *Journal of Geophysics and Engineering,* 14(4), pp. 960-973.

Ndlovu, R., 2021. *Zimbabwe Faces Lengthy Power Outages After Surge Hits Plants.* [Online] Available at: https://www.bloomberg.com/news/articles/2021-06-28/zimbabwe-faces-prolonged-power-outages-after-surge-hits-plants
[Accessed 18 July 2021].

Nicolson, G., 2016. *Mining Fatalities: 'Zero Harm' is just not enough.* [Online] Available at: https://www.dailymaverick.co.za/article/2016-01-27-mining-fatalities-zero-harm-is-just-not-enough/
[Accessed 16 June 2019].

Nie, X. X. and Wei, X., 2017. Optimization and practice on the reform schemes of ventilation system in the Jinqu Gold Mine. *Mining Research and Development*, 37(8), pp. 86-89.

Nieto, A., Schatz, R. C. & Dogruoz, C., 2020. Performance analysis of electric and diesel equipment for battery replacement of tethered LHD vehicles in underground mining. *Mining Technology,* 129(4), pp. 1-8.

Nixon T, R., Deakin , J. J. & Ralph, A., 1983. *Ventilation analysis for mine planning and operation.* Southern Queensland, Australasian Institute of Mining and Metallurgy.

Noone, G., 2020. *What does the future hold for automation in the mining industry.* [Online] Available at: https://www.nsenergybusiness.com/features/automation-mining-industry-future/
[Accessed 16 January 2021].

NSSA, 2019. *Occupational diseases surveillance through one stop shop.* [Online] Available at: https://www.nssa.org.zw/occupational-safety-health/health-services/
[Accessed 7 December 2019].

Nundlall, A. R., 2014. *Development of a regulatory mechanism for the control of exposure to DPM in the South African mining industry.* Johannesburg: University of the Witwatersrand.

Nundlall, A. R., 2014. Diesel emission. In: *Ventilation and occupational environment engineering in mines.* Johannesburg: Mine Ventilation Society of South Africa, pp. 872-898.

Oberthür, T., Melcher, F., Buchholz, P. & Locmelis, M., 2012. *The oxidized ores of the main sulphide zone, great dyke, zimbabwe: turning resources into minable reserves.* [Online] Available at: http://www.saimm.co.za/Conferences/Pt2012/647-672_Oberthur.pdf [Accessed 14 April 2015].

Odendaal, N., 2019. *SA mining adopting, driving 4IR as its transformation journey continues.* [Online]
Available at: https://www.engineeringnews.co.za/article/sa-mining-adopting-driving-4ir-as-its-transformation-journey-continues-2019-06-21
[Accessed 5 November 2020].

Phillips, H. R., Kielblock, A. J. & Rose, H. J., 1997. *An Integrated Approach to Post Incident Survival Strategy.* Calgary: 11th International Conference on Coal Research.

Phillips, H. R. & Rawlins, C. A., 2005. *Underground mine ventilation planning and design with regards to heat load and cooling mechanisms.* Brisbane, Eighth International Mine Ventilation Congress.

Ping, C. & Guang, X., 2017. A review of the health effects and exposure-responsible relationship of diesel particulate matter for underground mines. *International Journal of Mining Science and Technology,* 27(5), pp. 831-838.

Prendergast, M. D., 1989. The Wedza-Mimosa platinum deposit, Great Dyke, Zimbabwe. In: *Magmatic Sulphides-the Zimbabwe volume.* 1 ed. London: Institution of Mining and Metallurgy, pp. 43-69.

Schneider, S. M., 2016. Heat acclimation: Gold mines and genes. *Temperature,* 3(4), pp. 527-538.

Sensing precision, 2014. *PCE.* [Online]
Available at: https://www.pce-instruments.com/english/measuring-instruments/test-meters/anemometer-kat_40038.htm
[Accessed 26 January 2019].

Shahzad, Y. et al., 2020. Internet of Energy: Opportunities, applications, architectures and challenges in smart industries. *Computers & Electrical Engineering,* 86(1), pp. 1-4.

Shtokal, A., 2016. *People Killed In Coal Mine Explosions And Fire, Russia Says.* [Online]
Available at: https://www.npr.org/sections/thetwo-way/2016/02/29/468533153/36-people-died-in-coal-mine-explosion-and-fire-russia-says
[Accessed 15 August 2019].

Sottile, J., Wala, A. & Yingling, J., 1996. Estimating and reducing electrical energy consumption in underground coal mines. *Mineral Resources Engineering,* 5(1), pp. 57-77.

Stanton, D. W., Du Plessis, J. J. & Belle, B. K., 2014. Occupational exposure limits for airborne pollutants. In: *Ventilation and occupational environment engineering in mines.* Johannesburg: Mine Ventilation Society of South Africa, pp. 238-279.

Tapia, C., 2020. *The importance of partners in mining digital transformation.* [Online]
Available at: https://miningglobal.com/technology/importance-partners-mining-digital-transformation
[Accessed 6 January 2021].

Tekin, A., 2022. Assessment of vibration exposure of mine machinery operators at three different open-pit coal mines. *The Journal of the Southen African Institute of Mining and Metallurgy,* 122(5), pp. 235-242.

Tran-Valade, T and Allen, C, 2013. *Ventilation-On-Demand key consideration for the business case.* Toronto, Canadian Institute of Mining (CIM).

Ünver , B. & Ünal, M. S., 2018. Analysis of a possible root cause and mechanism for Soma mine disaster. *Journal of Mining and Environment,* 4 December, 10(1), pp. 1-26.

Varaschim, J. & De Souza, E., 2017. *The economic potential of electric mining equipment.* [Online]
Available at: https://www.airfinders.ca/wp-content/uploads/2015/06/Economics-of-Diesel-Fleet-Replacement-by-Electric-Mining-Equipment.pdf
[Accessed 24 August 2019].

Vijay, A., 2018. *A growing emphasis on boosting energy efficiency and meeting energy requirements are increasing demand for variable frequency drives.* [Online]
Available at: https://www.controleng.com/articles/vfds-six-benefits-energy-efficiency/
[Accessed 7 October 2019].

Wallace, K., Prosser, B. & Stinnette, J., 2015. The practice of mine ventilation engineering. *International Journal of Mining Science and Technology,* 25(2), pp. 165-169.

Walters, D. M. & Roman, W. N., 2014. Ventilation of Mechanised mines. In: *Ventilation and occupational environment engineering in mines.* Johannesburg: Mine Ventilation Society of South Africa, pp. 901-914.

Wang, H. N., B. Peng, B. and Peng J. L, 2014. Analysis of commonly existing ventilation problems and the optimal approach to deal with them in large-size mines. *Journal of Safety and Environment,* 14(3), pp. 24-27.

Watrant, E., 2008. *Mine ventilation Design criteria" for underground metal mines based upon "life cycle" airflow demand schedule.* Washington DC, IEEE.

Wilson , A. H. & Prendergast., M. D., 2001. Platinum-Group Element Mineralisation in the Great Dyke, Zimbabwe, and its Relationship to Magma Evolution and Magma Chamber Structure. *South African Journal of Geology,* Volume 104, pp. 320-340.

Wilson, K. S., Naicker, N., Kootbodien, T. & Ntlabi, V., 2019. *Usefulness of occupation and industry information in mortality data in South Africa from 2006 to 2015.* [Online]
Available at: https://bmcpublichealth.biomedcentral.com/articles/10.1186/s12889-019-7177-3
[Accessed 13 September 2021].

Wood, D., 1987. *Support in underground hard rock mines.* [Online]
Available at: https://rocscience.com
[Accessed 10 December 2014].

Wu, X., Topuz, E. and Karfakis, M, 1991. *Optimization of ventilation control device location and sizes in underground mine ventilation systems.* s.l., s.n., pp. 391-399.

Zeal, 2019. *Whirling pattern hygrometer.* [Online]
Available at: https://www.zeal.co.uk/whirling-pattern-hygrometer.html
[Accessed 15 February 2019].

Zheng, M., 2015. *Characterization of Exhaust Gas Recirculation for Diesel Low Temperature Combustion.* [Online]

Available at: https://www.sciencedirect.com/science/article/pii/S2405896315018832
[Accessed 28 June 2019].

APPENDICES A

SUMMARY OF PAPER ABSTRACT ON THE RESEARCH

The publications listed below have originated from this thesis so far:

Paper 1

Part of Chapter 5 was compiled and published as the paper: Chikande, T., Phillips, H. R. and Cawood, F.T (2021). Ventilation optimisation through digital transformation. Journal of Southern African Institute of Mining and Metallurgy

Abstract

Underground mines require electricity to operate both main surface fans and auxiliary systems. According to De Souza (2018), primary ventilation systems typically account for approximately 40 to 60% of the mines' overall electricity consumption. The primary reason for this considerable expense is that most underground ventilation systems are designed for the peak demand regardless of the actual demand, which is commonly dictated by diesel equipment usage. Most platinum mines on the Great Dyke tend to operate their ventilation systems at this peak level, despite the mine's air volume being well in excess of the "true" ventilation needs due to a lack of appropriate ventilation controls. The authors designed and installed a ventilation on demand system at one of the bord and pillar platinum mine to minimize the use of redundant air in underground operations. Fourth industrial revolution techniques were applied to environmental monitoring and tracking systems thereby optimizing airflow demands. The mine managed to reduce its annual power consumption by 23% through the implementation of manual control and time of day scheduling levels of the ventilation on demand concept. There was also a 6% productivity improvement mainly attributable to an increased face time as a result of the significant reduction in the re-entry period. This paper introduced a novel concept of ventilation optimisation through digital transformation targeting mainly room and pillar platinum mines. A system was designed, installed and commissioned though there is currently an ongoing optimisation process to harness the full benefits of VOD.

KEY WORDS : mine ventilation, ventilation on demand, internet of things, power savings, ventilation optimisation

Paper 2

Parts of Chapter 4 and 6 were compiled, and accepted as the paper Chikande, T., and Phillips, H. R. (2021). Optimised ventilation design for mechanised bord and pillar platinum mines *Journal of the Southern African Institute of Mining and Metallurgy*.

Abstract

Mine ventilation plays a pivotal role in underground mining operations. It is required to dilute and remove dust, gases, diesel contaminants and to remove heat thereby creating a thermally acceptable conducive working environment. Most platinum mines on the Great Dyke of Zimbabwe are highly mechanised as they utilize trackless diesel equipment during the extraction process. De Souza (2018) pointed out that in highly mechanized platinum mines, primary ventilation systems accounts for 40-60% of the mines' energy consumption hence cognizance must be taken during mine design. The ever increasing geological complexities, higher degree of mechanization and the espousal of more stringent health regulations have generally influenced more air demands in underground operations. Such increases in air quantity result in augmented energy consumption due to the cubic relationship of quantity and power. As a result, to mitigate prohibitive ventilation costs, underground mines must optimise their ventilation systems during designing and must explore cost cutting initiatives through digital transformation technologies. The adoption of electric vehicles, autonomous vehicles and ventilation on demand systems must be implemented in room and pillar platinum mines to reduce operating costs and to enhance safety and productivity.

***KEY WORDS** : mine ventilation, ventilation design, room and pillar mines, automation, ventilation optimisation, shaft, main fans*