

Improving the operational efficiency of deep-level mine ventilation systems

SW Hancock



orcid.org/0000-0002-0374-9047

Dissertation submitted in fulfilment of the requirements for the degree *Master of Engineering in Mechanical Engineering* at the North-West University

Supervisor:

Dr JF van Rensburg

Graduation: May 2019

Student number: 24409766

ABSTRACT

Title: Improving the operational efficiency of deep-level mine ventilation systems

Author: Mr SW Hancock

Supervisor: Dr JF van Rensburg

Degree: Master of Engineering (Mechanical)

Keywords: deep-level mining, ventilation, sustainability, optimisation, cost savings, improved operational efficiency, generic ventilation solution approach

Deep-level mines are faced with many challenges that influence and affect the gold production rate. Deep-level mines have unfavourable working conditions due to the extreme depths, additional heat sources, confined spaces and high temperatures. Ventilation of working areas is a challenge due to the intricacy of underground networks after years of mining and development. As a result, ventilation systems are outdated and lack optimised control.

Literature shows numerous studies about the aid of simulations in mine ventilation with regards to fan configurations, fan impeller improvements and theoretical approaches to improving the ventilation system. This is beneficial but requires implementation on the underground ventilation network to realise results. In order to do so, a comprehensive strategic approach is required.

Ventilation systems require effective planning and problem-solving techniques to ensure a prolonged sustainable ventilation network. A generic solution strategy was developed to identify the network inefficiencies, develop a suitable solution strategy with the aid of a simulation and implement the strategy in an effective manner.

The generic solution strategy was implemented on a South African gold mine – Mine X. Upon implementation of the strategy, the main inefficiency identified within Mine X's ventilation system, was numerous inactive working areas that still received ventilation. The solution developed aimed to reroute the air to the active working areas with the use of auxiliary ventilation components.

The concept of the solution was simulated which yielded an increased system resistance, airpower and better surface fan performance.

The actual results yielded an average increased airpower of approximately 57 kW, a decreased system resistance of 0.002 Ns²/m⁸ and an increase in surface fan efficiency of approximately 9%. As a result of the improved efficiency, the surface fan configuration was optimised. Instead of the typical three surface fans, only two were used to achieve the desired ventilation during the summer period. The new fan configuration sustained the working conditions and resulted in an additional electrical power reduction of approximately 20 400 kWh. This equates to R3.2 million p.a.

ACKNOWLEDGEMENTS

This page serves as a dedication to all my support and encouragement I received throughout my journey.

- I would firstly like to thank my Saviour and almighty God for all the love, guidance and strength He has given me. I would not have been in this position to continue my journey if it was not for His grace. I am blessed to have the talents to pursue my dreams and aspirations in life and for that I am grateful.
- I would like to thank my father, Norman Hancock, for the courage and the constant support throughout my life. You have taught me how to never back down from anything I embark on and commit myself 100% to everything I do.
- To my mother, Valerie Hancock, I thank you for the constant love and patience you have for me. For when I was weak you picked me up, you motivated me and believed in me.
- To my sister Lee-Jean van Wyk, “Steve”, you have been my inspiration from the beginning. You have always believed in me and made such an impact on my life for which I am grateful. I will never be able to thank you enough for your contribution, academically and as a sister.
- I would like to thank my brother Jan van Wyk, for all the support and motivation I received throughout this venture. You have been a rock and I appreciate the support.
- I would also like to thank ETA Operations (Pty) Ltd, Enermanage, and its sister companies for the resources, time and financial assistance to complete this study. Thank you to Prof. Eddie Matthews and Prof. Marius Kleingeld for the opportunity to complete this study.
- I would like to thank Dr. Johann van Rensburg, Dr. Johan Bredenkamp and Mr. Pieter Peach for the mentorship and assistance during my study. You have allowed me to grow in so many ways I never thought possible, as an engineer and a man.
- I would like to thank my colleagues who supported and motivated me throughout this venture. I am truly blessed and honoured to have had experienced this with all of you. I wish you the best of luck with the rest of your endeavours.

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LIST OF SYMBOLS

#	Denotes a mining shaft
%	Percentage
α_p	Density ratio
δ	Distance from layer
η	Efficiency
ρ_{Air}	Air density
$\rho_{Fan,curve}$	Original density from fan curve
ρ_{New}	Density from psychrometric chart
τ_s	Shear stress
A_c	Cross sectional area
AP	Airpower
d	Diameter
e	Exponential exponent
H_{AVE}	Average height
h	Head
h_e	Elevation
g	Gravitational constant
L	Mining level
m	Mass
N	Rotational speed
N_p	Number of points across diameter

n	Number of points
n_p	Number of points counted outwards from the centre
P	Electrical power
p	Pressure
p_{Friction}	Frictional pressure drop
p_{Head}	Pressure head or static pressure
p_{Kinetic}	Kinetic or dynamic pressure
$p_{\text{Potential}}$	Potential pressure or elevation pressure
p_{Static}	Static pressure on original fan curve
$p_{\text{static,adjusted}}$	Adjusted head or static pressure
p_{Tot}	Total pressure
Q	Volumetric flow rate
R	South African Rand
R_A	Atkinson's resistance
R_g	Specific gas constant
r	Radius
R_{Air}	Specific gas constant for air
T	Temperature
V	Volume
v_{air}	Velocity of air
W_{AVE}	Average height

LIST OF UNITS

°C	Degrees centigrade
K	Kelvin
kg	Kilogram
kg/m ³	Kilogram per cubic meter
kW	Kilowatt
J/kg.K	Joule per kilogram kelvin
m	Meters
m ³	Cubic meters
m ²	Squared meters
m ³ /s	Cubic meters per second
m/s ²	Meter per second squared
MW	Megawatt
Ns ² /m ⁸	Atkinsons
Pa	Pascal
RPM	Revolutions per minute
s	Seconds

LIST OF ABBREVIATIONS

GA	Genetic algorithm
GDP	Gross domestic product
KPI	Key performance indicator
MIP	Mixed integer programming
MV	Medium voltage
RAW	Return airway
PTB 3D	Process Toolbox 3D by TEMM International
FOG	Fall of ground
VOD	Ventilation on demand
VRT	Virgin rock temperature
VSD	Variable speed drive
VVPT	Virgin vertical rock temperature
DMR	Department of Minerals and Resources

CHAPTER 1: INTRODUCTION

1.1 South African gold mining and its role in the economy

Gold was discovered in the 19th century, in Johannesburg, later known as 'Egoli', the place of gold¹. This discovery of gold led to some towns starting near and afar, and later flourishing in the economy¹.

The South African gold mines stretch over a vast elliptical basin over an arc of 400km, navigating across three different provinces – Gauteng, North West and the Free State provinces ¹. This large gold reef is known as the Witwatersrand Basin and contains one of the world's most significant gold placer deposits ¹. Figure 1 shows the physical location of the mining operations across the basin in South Africa.

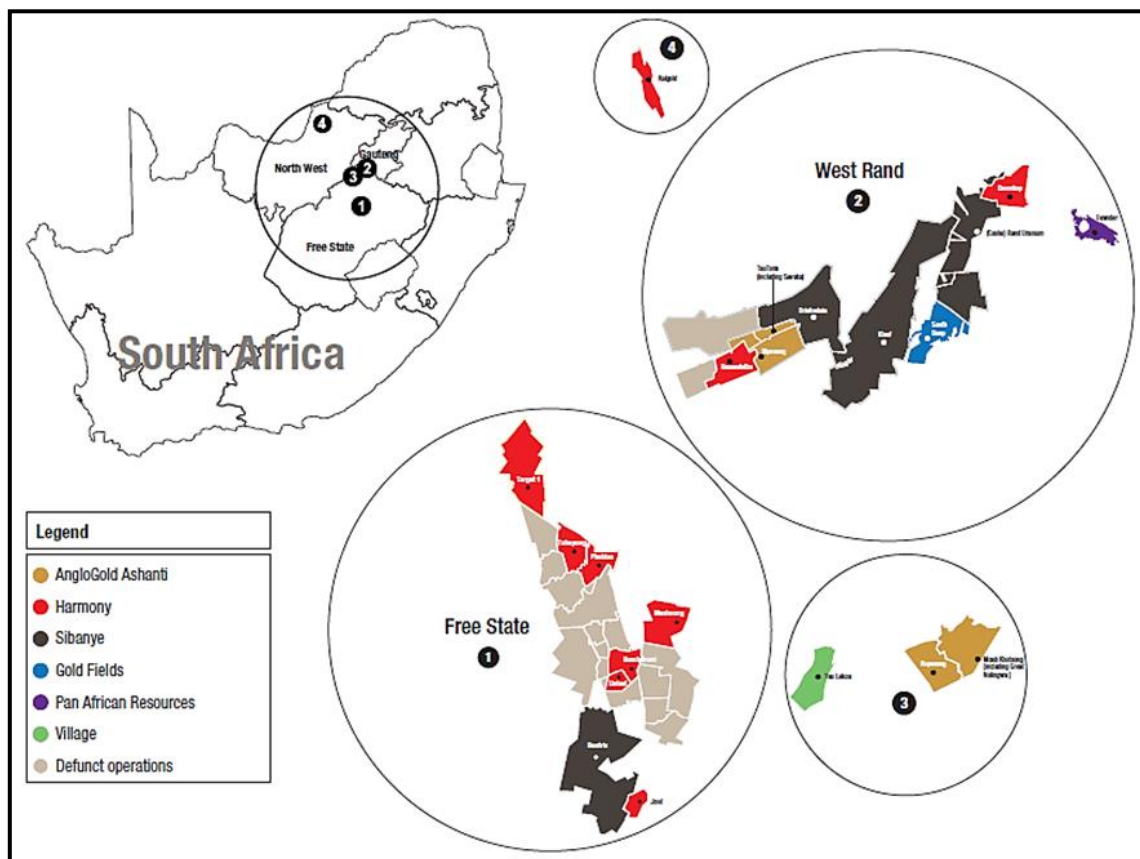


Figure 1: South African mining locations within the Witwatersrand basin [1]

¹ Chamber of Mines, "Gold - Chamber of Mines South Africa," *Chamber of Mines*, 2015. [Online]. Available: <http://www.chamberofmines.org.za/sa-mining/gold>. [Accessed: 15-May-2018].

The South African gold mining industry was one of the largest producers of gold in the early 1980's, however over the past 35 years, gold production has decreased significantly [2]. Gold production has decreased approximately 87% [2].

Figure 2 is a representation of the decline in gold production over the 35-year period.

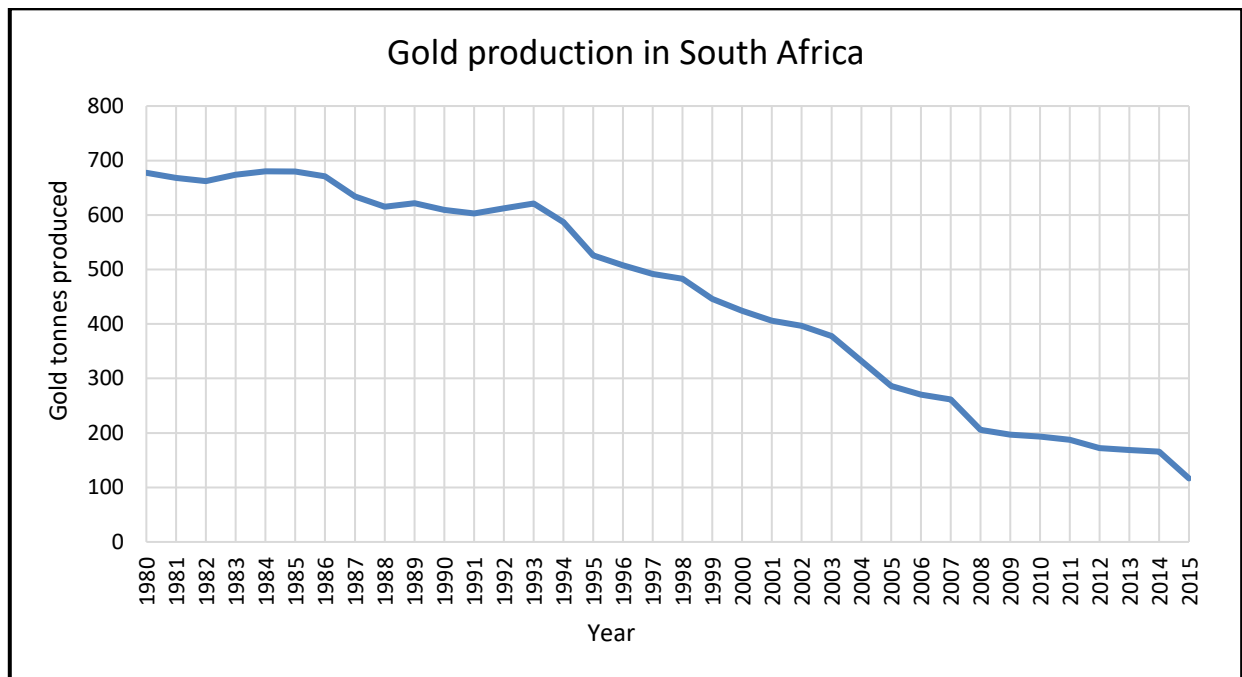


Figure 2: Gold production over 35 years [3]

Figure 3 illustrates the nominal shares and contribution of each sector to the Gross Domestic Product (GDP). Gold in the mining sector has experienced a decline from 3.8% (1993) to 0.7% (2016) ¹.

The holistic view of the mines challenges year on year reveals that mining is becoming more decentralised as operations occur further away from surface infrastructure, the electrical energy demand is increasing with increasing costs, and the use of mechanisation is increasing [4]. These challenges are represented in the external sector and may not have a direct impact on the production, however, do have an influence on the mining industry.

¹ "The state of the gold industry - Fact sheet July 2018," *This is Gold*, 2018. [Online]. Available: <http://www.thisisgold.co.za/component/jdownloads/send/2-fact-sheets/19-the-state-of-the-gold-industry>. [Accessed: 10-Oct-2018].

The production deterioration can be related to a production decrease over this period (1993 – 2013)¹. Gold's sales figures in the overall mineral sales has decreased from 67% in 1980 to 2.5% in 2014 and decreased a further 40%, from 2012 to 2016 ¹.

The above-mentioned information clearly indicates the waning gold mining industry due to challenges experienced in the sector. The challenges are further discussed in the following section.

Figure 3 depicts the contributors to the nominal GDP of 2017, third quarter ².

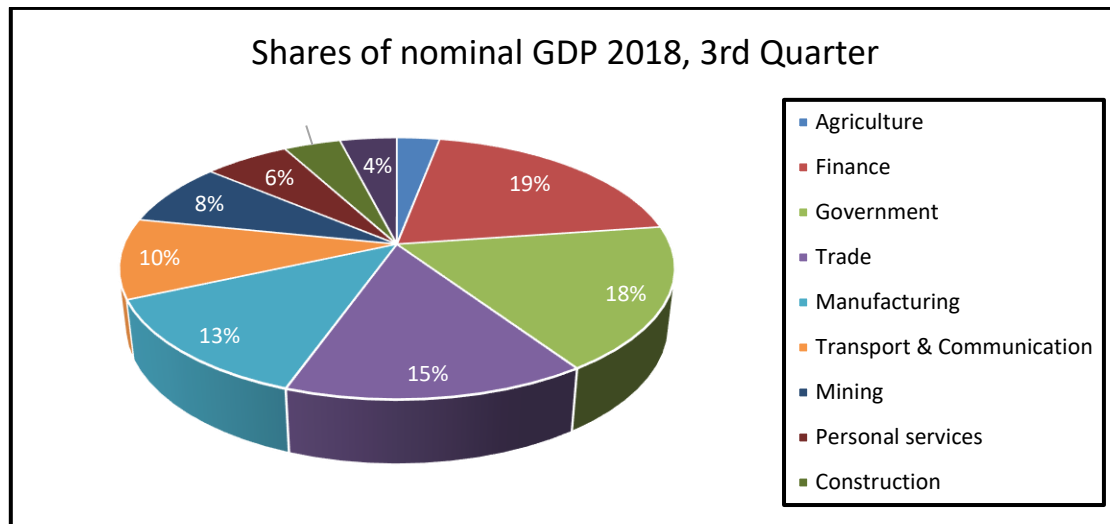


Figure 3: Nominal GDP 2017, 3rd Quarter ¹

Mining contributed 8% to the nominal GDP 2018, third quarter¹. Mining has a significant impact on the GDP, thus is important and critical mining flourishes in the sector. Gold mines employ thousands of people and supports millions of dependants and families ³.

¹ Chamber of Mines, "Gold - Chamber of Mines South Africa," *Chamber of Mines*, 2015. [Online]. Available: <http://www.chamberofmines.org.za/sa-mining/gold>. [Accessed: 15-May-2018].

² Statistics South Africa, "Gross Domestic Product 4th Quarter 2017. Embargo: 11:30," 2014.

³ "The state of the gold industry - Fact sheet July 2018," *This is Gold*, 2018. [Online]. Available: <http://www.thisisgold.co.za/component/jdownloads/send/2-fact-sheets/19-the-state-of-the-gold-industry>. [Accessed: 10-Oct-2018].

1.2 Systems within a deep level mine

Typical deep level mines are comprised of five key systems that work coherently and in tandem to ensure that the mine is operational [5]. The key systems are:

- Compressed air
- Dewatering
- Hoisting
- Ore handling
- Ore processing
- Ventilation and cooling

These systems are vital to the operation of the mine. Without any of the systems, the mine would not be operational. The key systems are the primary energy consumers and contribute to the total energy cost as shown in Figure 4 [5].

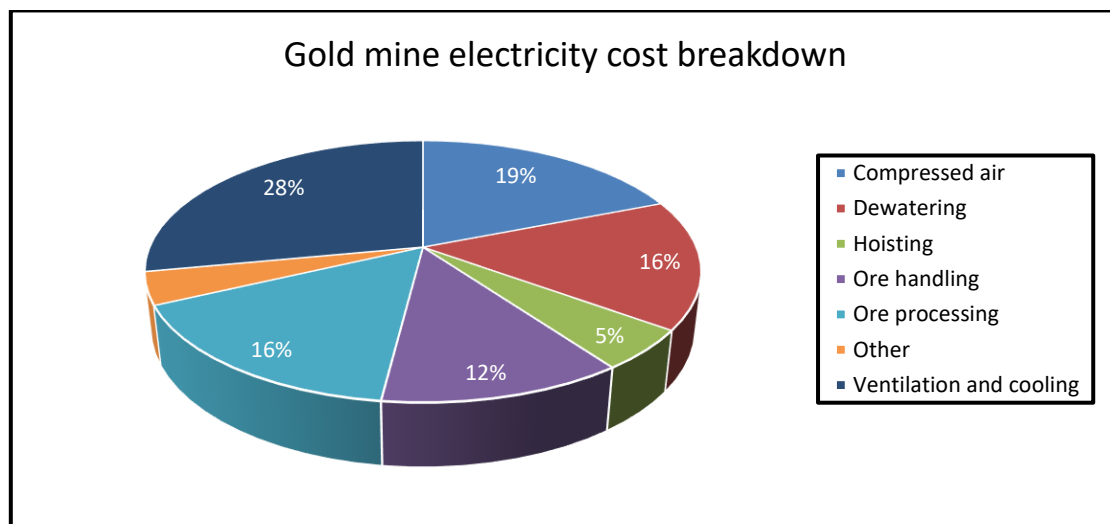


Figure 4: Gold mine electricity cost breakdown [5]

The major energy consumers are ventilation and cooling, compressed air and dewatering. The ventilation and cooling system is the highest as it is a combination of the ventilation and refrigeration system. These two systems are naturally interlinked when it comes to ensuring that the mine's underground temperatures are within the legal limit.

1.3 Challenges in the deep level mining industry

Challenges faced in the mining industry relate to technical, social, economic and operational challenges [2]. South Africa has set of unique challenges that are relatable to the country [2]. As a

result of the challenges faced, South Africa's gold mines are losing their competitive edge in the industry [2].

The loss of competitiveness is related to the decline in production with contributing factors such as the gold price fluctuations, escalating costs of production, depth and mining method, political, social and environmental issues, declining ore grades, labour issues (strikes) and reduced productivity [2].

A main concern for the South African gold mining industry is safety. Deep-level mining, especially in South Africa, has been rated as one of the deadliest forms of mining worldwide ¹. Miners constantly have to deal with injuries from FOG (Fall of ground), rock bursts and seismic activity ¹. Depending on the severity of the situation, miners may also face death as a result of the dangerous working conditions. Miners safety is considered as one of the greatest challenges yet ¹.

Figure 5 depicts the total yearly fatalities from 2004 to 2016 for the gold mining industry.



Figure 5: Gold mining fatalities from 2004 – 2016 ^{1 2}

¹ "Mine Fatalities in South Africa Rise First Time in Decade - Bloomberg," 2017. [Online]. Available: <https://www.bloomberg.com/news/articles/2017-12-07/mining-fatalities-in-south-africa-rise-for-first-time-in-decade>. [Accessed: 23-Jun-2018].

² Chamber of Mines, "Facts and figures 2016," 2016. [Online]. Available: file:///D:/Windows Libraries/Downloads/chamber-facts-figures-2016.pdf. [Accessed: 31-Oct-2018].

Fatalities have decreased significantly from 2004, however, it remains a major concern for mining companies and mine employees. Mining fatalities create a lot of controversy with the working conditions and standards of safety.

Wagner (1986) discusses the general underground challenges faced in the mining industry. His discussion is based upon the influence of hostile working environments, unfavourable stoping areas which restrict modernisation and the cost of constant deepening of mines [6]. As a result of the presented challenges, the production rate is affected negatively.

In addition to the safety concerns, due to the extreme temperatures and working conditions, miners also face heat cramps and exhaustion [6]. Hostile working environments, in terms of thermal comfort, are affected by the geometry and depth of the reef bodies.

The geometry and depth of the reef bodies are unfavourable in terms of high stresses and heat flows [6]. High stresses transpire in rock ahead of the working face which causes rock fracturing consequentially endangering the working environment and strengthening the need for more support systems [6]. The shape of the orebodies (Tabular) promotes heat flow into the working environment from the rock [6]. This creates a hostile thermal working environment and the need for more extensive and proficient cooling and ventilation systems [6].

The unfavourable working environment, restricted, hot and humid stopings have also prevented the large-scale mechanisation of stoping operations [6].

Mine planning and grade control are affected by the irregular distribution of gold in reefs, however is favoured by flexibility ¹. Mining is required to adapt in order to survive. Being able to adapt is key as the mining industry is irregular with new challenges daily.

Mines are also constantly developing and reaching new depths. With the new depths, new communication and transportation lines are required which are expensive and result in a loss of working time [6].

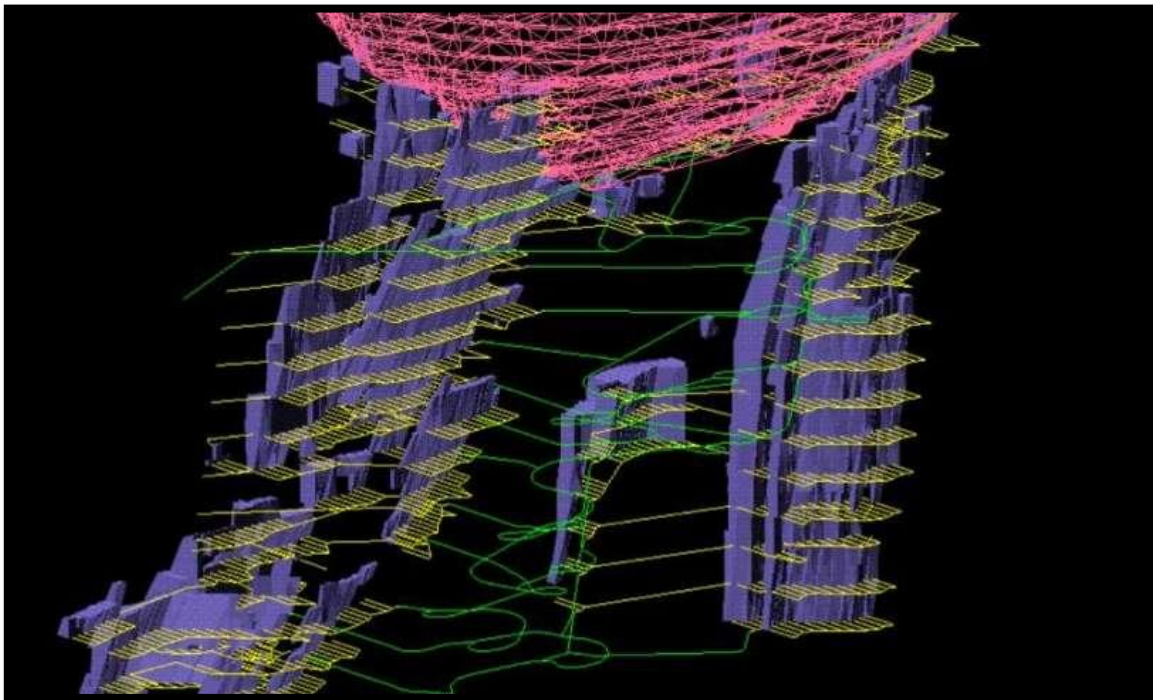
¹ G. Harrison, "Using maths to map mines deep underground," *Phys org*, 2017. [Online]. Available: <https://phys.org/news/2017-10-maths-deep-underground.html>. [Accessed: 15-May-2018].

1.4 Ventilation challenges in deep-level mines

After approximately 120 years of excessive mining, depths of over approximately 4000m below surface level have been reached ¹. When extreme underground depths are reached, the virgin rock temperature (VRT) reaches approximately 50°C and the virgin vertical rock pressures (VVPT) increase to an approximate of 100MPa ¹.

Mining operations are also faced with deeper ore reserves which are hotter and further away from main ventilation and refrigeration systems [7]. As it is, ventilation is already a costly commodity required to travel to far distances via the complex network to shaft bottom [7].

Figure 6 is an example of a typical deep level mine system. The deeper the mine becomes, the more complicated the entire underground network system becomes. As the underground network becomes deeper, the system also becomes more complicated and difficult to direct the fresh air and successfully ventilate working areas ¹.



¹ Chamber of Mines, "Gold - Chamber of Mines South Africa," *Chamber of Mines*, 2015. [Online]. Available: <http://www.chamberofmines.org.za/sa-mining/gold>. [Accessed: 15-May-2018].

Figure 6: Example of deep level mine and haulages ¹

As the mine's progress deeper, the need for ventilation and refrigeration becomes more significant due to the ever-increasing VRT. As the underground temperature rises, more intense ventilation and refrigeration is required to match the demand for adequate refrigeration and ventilation systems.

Figure 7 shows the linear relationship between the depth of the mine and the average underground temperatures as the mine progresses deeper and the type of ventilation and refrigeration required to adequately ventilate and cool the mine.

With increasing depths, more satisfactory cooling and ventilation systems are implemented providing the mine with the opportunity to exploit deeper ore reserves, increasing production however increasing energy costs [6]. Although more intense cooling and ventilation systems are installed, thermal discomfort remains a reality [8].

¹ G. Harrison, "Using maths to map mines deep underground," *Phys org*, 2017. [Online]. Available: <https://phys.org/news/2017-10-maths-deep-underground.html>. [Accessed: 15-May-2018].

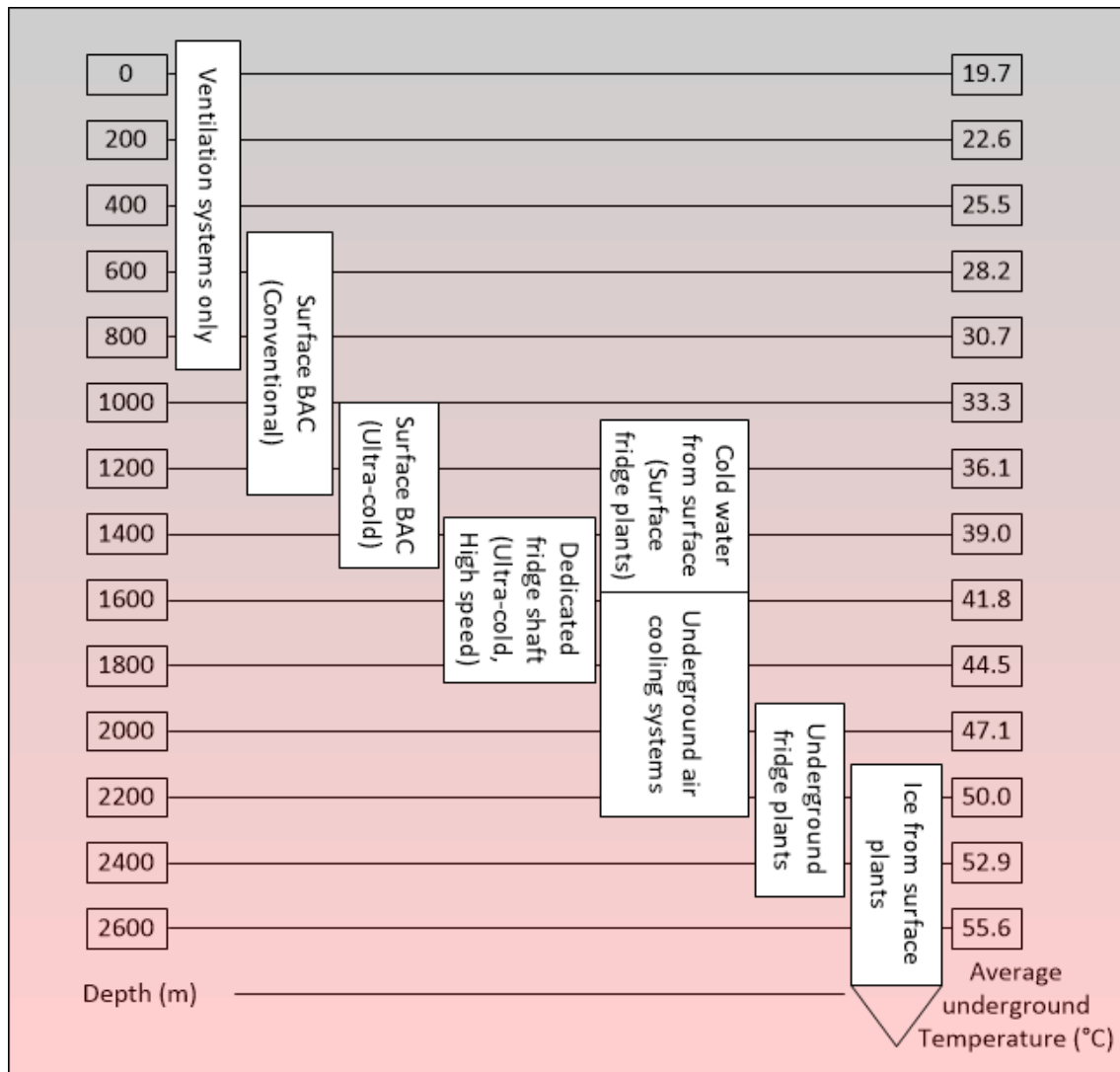


Figure 7: Linear relationship between depth and underground temperature [9], [10], [11], [12]

In addition to the extreme depths resulting in hot and humid conditions, Nixon, Gillies and Howes (1992) identified other contributing heat sources in deep level mines. They identified diesel powered equipment, electric powered equipment, explosives, broken rock, water and compressed air (depending on use) and rock surfaces as major heat source contributors [11]

Mine workers are subjected to heat stress and therefore experience serious health and safety implications [8] due to extreme depths and additional heat sources. As a result, the miners' productivity and morale are affected [8]. If conditions are too extreme, miners are also subject to heat exhaustion and cramps.

Maurya et al. (2015:491- 498) define heat stress as a significant challenge in the mining industry. Due to the ever-increasing depth of mines, the supply of adequate required ventilation to the active working areas is becoming increasingly difficult [13]. Ventilation systems are complex, as adequate ventilated air must maintain proper quality, temperature and pressure [13]. Therefore, to ensure that

ventilation adheres to laws that govern working conditions and overcome underground heat challenges, is no easy task [14].

Ventilation systems lack dynamic planning which can minimise long-term problems, building a sense of flexibility without exorbitant costs and reduce initial capital expenditure [15].

Pritchard (2008) explains that areas of focus in the ventilation system are the way in which ventilation is implemented, auxiliary equipment areas, intake and return airways, optimising development, alternate ventilation methods and the examination of airway utilisation [7].

1.5 The importance of adequate ventilation in a deep level mine

Many strict laws exist that govern the way the mine operates, to ensure a safe working environment for the employees. One of the laws that govern the ventilation requirements¹ for the stoping and station areas is to ensure the working temperatures in the stoping areas are below 32.5°C and 27.5°C wet bulb, in the station areas [16].

If the ventilation standards are not adhered to, a section 54 is issued, temporarily or permanently shutting down the working area at fault¹. A DMR (Department of Mineral Resources) representative inspects the working area and acts if standards are not adhered to¹. The working area shutdown then needs to be rectified and only after another inspection, re-opened if compliant¹. A section 54 can be issued to a single working area or an entire mine depending on the circumstance².

Ventilation's role in the mining sector is so critical to the success of mining and safety of miners yet the system is overlooked when operational and adhering to bare minimum standards. Adequate ventilation is becoming a major concern for South African deep-level gold mines due to the constant complication and excessive underground operations.

1.6 Problem statement

South African mines are complex systems due to the long-life span and intense operations. The complex and temperamental state of the mine only complicates the ventilation flow. With an ever-increasing depth, ventilation follows the same trend. Deep-level mines also face many contributing

¹ "MHS Act Section 54," 1986. [Online]. Available: http://www.klasslooch.com/mhs_act_section_54.htm. [Accessed: 15-May-2018].

heat sources as discussed earlier. Suitable and effective ventilation and heat extraction is required for the success of the mine due to governing ventilation laws and standards.

As mining operations progress, adequately ventilating a deep-level mine becomes increasingly difficult and ventilation inefficiencies accumulate, negatively effecting the airflow of the system. However, due to the nature of the mining industry, inefficiencies may accumulate and result in disaster due to neglect and a lack of resources to attend to the inefficiencies. Therefore, there exists a need for strategic planning when solving inefficiencies. Strategic planning will allow mine personnel to identify the inefficiencies and cause and develop a sustainable method to resolve the problem on a more long-term scale.

Strategic planning should be utilised when solving problems and developing suitable solutions for ventilation inefficiencies. Strategic planning will enable long-term solutions instead of resolving underground problems that are not effective over a long period. For effective ventilation, especially on complex network systems, proper strategic planning is required.

Strategic planning will allow dynamic changes in the air network system. As crucial system changes are made, it is vital that the ventilation system adapts and changes to accommodate the system change.

Deep-level mines require a generic strategic approach to identify and resolve ventilation inefficiencies as quickly as possible. Ensuring so will result in an updated network and have a positive effect on the operational efficiency of the ventilation system. As a result, this will positively affect the production and working conditions of the deep-level mines.

1.7 Objectives of the study

There is a lack of adequate structure, planning and implementation in the ventilation and problem-solving techniques of deep-level mines. A generic and suitable strategy is required to enforce a more structured network and manner in which ventilation inefficiencies are attended to. As a result of a more structured system, the overall system will operate more efficiently and effectively.

The most important factor of the study is to ensure sustained working conditions while re-configuring the ventilation network. Working conditions directly effect the production rate and may also result in production loss if not maintained.

The primary objective and focus of the study are to develop a generic strategy to optimise the ventilation system. A generic strategy will allow strategic planning to optimise the system over a long period and allow for dynamic ventilation changes as the mine evolves and grows.

The secondary objective of the study is to utilise a more dynamic system approach when resolving the inefficiencies. This will allow the ventilation system to adapt continuously with the ever-changing mine system. An added benefit of the optimised system is reducing operational costs. Operating efficiently will realise a energy cost saving.

The objectives can be defined in more detail as the following:

- Develop a generic solution strategy
 - A generic strategy will allow strategic planning
 - Strategic planning will ensure long-term fixes
- Optimise the ventilation network cost effectively
- Reduce the ventilation operational costs
- Ensure sustained working conditions
- Improve operational efficiency of the ventilation system

Ultimately, the primary goal of the study is to develop a generic strategic ventilation approach which can be used to analyse ventilation systems, identify the main inefficiencies and develop a suitable long-term solution. The developed solution should be aimed at resolving network-inefficiencies on a long-term basis. Ensuring a long-term solution will result in a more dynamic and adaptive ventilation network.

1.8 Study overview

Chapter 1

Chapter 1 briefly discusses the role of the mining industry in South Africa as well as the corresponding challenges that are faced. Challenges are becoming increasingly difficult to deal with due to the environmental, economic, social and political influences. An important, yet overlooked challenge faced in deep-level mining is ventilation. Chapter 1 provides an overview of the ventilation challenges as well as the importance of adequate ventilation.

Chapter 2

Chapter 2 subsequently breaks down the fundamental purposes of the ventilation system in a deep-level mine and how the ventilation strategy is implemented using various techniques to ensure safe working conditions.

Previous studies are scrutinised, analysing the validity of the study and improve the approach to improve the operational efficiency of the ventilation system.

Chapter 3

Chapter 3 incorporates the literature discussed in Chapter 2, to deduce a generic strategic approach when investigating the ventilation system. The approach defines the steps needed to ensure all aspects of the ventilation system are investigated and a suitable solution is identified for a dynamic long-term effect.

Chapter 4

Chapter 4 explains the implementation of the process on a deep-level mine in South Africa. The generic approach developed in Chapter 3 aims to identify the KPI's and corresponding inefficiencies, develop and simulate appropriate solutions and lastly, implement the strategy and validate the KPI's.

CHAPTER 2: VENTILATION IN A DEEP-LEVEL MINE

2.1 Introduction

Mine ventilation systems are complex systems comprised of many interconnected sections and branches [17], [18]. Typical mine ventilation systems are represented by intricate networks of airways and numerous branchings with a multitude of ventilation components [18]. This complex system has proven difficult to optimise air flow adequately [17], [18]. Without proper a properly designed ventilation system, the production cycle would fail [15]. Mines should adequately design and maintain ventilation systems in such a manner, that there is always a contingency available [15].

The complex ventilation system has the primary objective to supply sufficient quantity and quality airflow to dilute the contaminants and ventilate all mining, travel or working areas at minimum cost [7], [15], [17], [19], [20]. Even though the primary ventilation system may be well-designed, improper utilisation of the available air will result in a total failure of the system [15].

2.2 Ventilation in deep-level mines

Ventilation is defined as the control of fresh air supplied to active working areas and the removal of heat [15], [17]. Ventilation also plays a significant role in the removal of harmful natural gasses from underground. The amount, direction and movement of air underground are manipulated to achieve the required results in the necessary working areas [15]. The fresh air is manipulated with various ventilation components and machinery to achieve the desired results.

Ventilation does not contribute directly to production, however, ventilation does directly influence the worker efficiency, productivity, accident rates and absenteeism [15]. Ventilation is responsible for ensuring the active working area temperatures are within the legal limit [15], [16] and miners are able to work comfortably in underground conditions. Over-heated working areas will result in unproductive workers and extreme conditions may lead to heat-exhaustion and cramps [19].

Typical ventilation systems consist of suitable paths (airways) for the air flow down to the working areas via the intake shaft (down-cast shaft), into active working areas and up, the exhaust shaft (up-cast shaft) where the hot air is exhausted [15]. Basic ventilation throughout the mine is achieved with fans either on surface level and underground [15].

The main fans are generally centrifugal fans and are the primary source of inducing air flow throughout the mine, either in combination (Series or parallel) or singularly [15], [19]. The main fans are generally located on surface, exhausting air through the system or in the return airway forcing air into the system depending on the design of the ventilation system [15], [19].

Great care is taken with the design and installation of the main fan assemblage however, little interest is shown with the constant aerodynamic optimisation of the shaft collar design, ductwork configurations and the selection of fan isolation [21]. It has shown in previous studies, that poorly designed systems result in major pressure losses between the shaft and fan inlet [21].

2.2.1 Centrifugal fans

Fan affinity laws exist that govern the performance of the main centrifugal fans. The fan laws provide an indication of how the main fan will perform when the rotational speed is adjusted in a working environment [19]. The benefit of the fan laws is that an accurate prediction can be made on the performance of the main fans at different rotational speeds, without physically changing the speed [19], [22].

Equation 1, Equation 2, Equation 3 and Equation 4 express the fan affinity laws that apply to the centrifugal fan.

Equation 1 represents the volume flow capacity law in relation to rotational speed.

Equation 1: Centrifugal fan affinity law – Volume flow capacity [19], [22]

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2} \quad (1)$$

Q = flow rate (m³/s)

N = Speed (RPM)

Equation 2 represents the head or differential pressure law in relation to rotational speed.

Equation 2: Centrifugal fan affinity law – Head or differential pressure [19], [22]

$$\frac{h_1}{h_2} = \left(\frac{N_1}{N_2} \right)^2 \quad (2)$$

h = Head (m)

N = Speed (RPM)

Equation 3 represents the power consumption law in relation to rotational speed.

Equation 3: Centrifugal fan affinity law – Power consumption [19], [22]

$$\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3 \quad (3)$$

P = Shaft power (kW)

N = Speed (RPM)

Equation 4 represents all the affinity laws in relation to the rotational speed.

Equation 4: Fan affinity law [19], [22]

$$\frac{N_1}{N_2} = \frac{Q_1}{Q_2} = \sqrt{\left(\frac{h_1}{h_2}\right)} = \sqrt[3]{\left(\frac{P_1}{P_2}\right)} \quad (4)$$

From the above-mentioned equations, it can be seen that the volume flow has a linear relationship with the rotational speed, differential pressure or head (m), a quadratic relationship and power, an exponential relationship [22]. Therefore, as the rotational speed adjusts, so will the flow, pressure or head and power according to the relation. Figure 8 displays the fan affinity laws in relation with the rotational speed of the centrifugal fan adapted from the above-mentioned fan affinity laws.

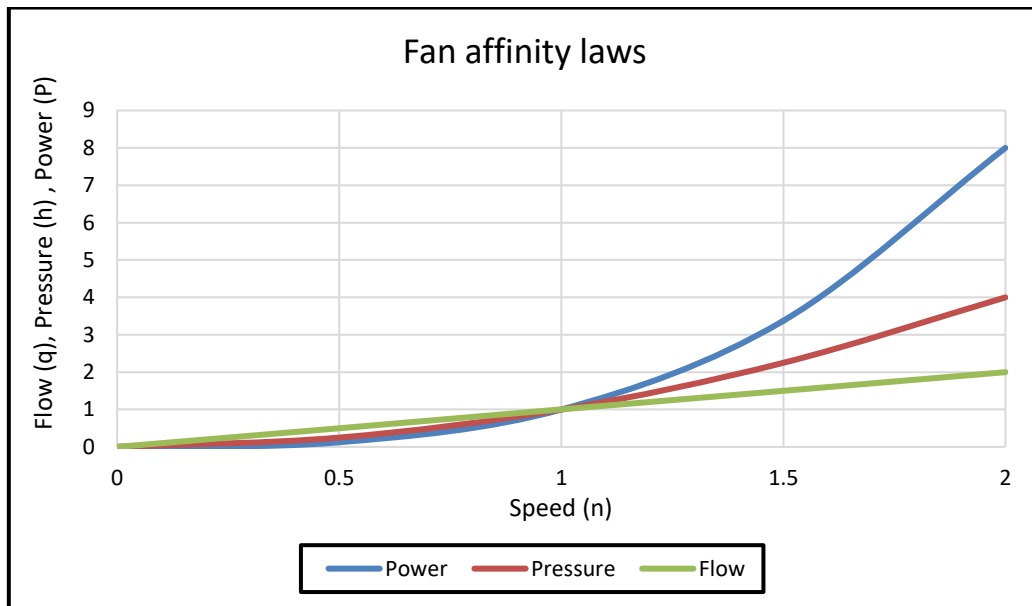


Figure 8: Fan affinity laws [19], [22]

The above-mentioned figure, re-iterates the fan law equations and graphically describes their relationship with the rotational speed of the impeller.

2.2.2 Main fan assemblages and network configurations

Two primary ventilation infrastructure configurations exist, where the main fan is either connected to the upcast shaft i.e. an exhausting system, as indicated in Figure 9 (a), or the downcast shaft i.e. blowing system, as indicated in Figure 9 (b) [19]. Figure 9 (c) illustrates a combination of the exhausting and blowing ventilation system. Two main fans are installed on surface and at two shafts to create the airflow [19].

The exhausting system induces a suction in the system, therefore creating a pressure below atmospheric (Negative pressure) while the blowing system induces a pressure above atmospheric (Positive pressure) [15], [19], [23], [24].

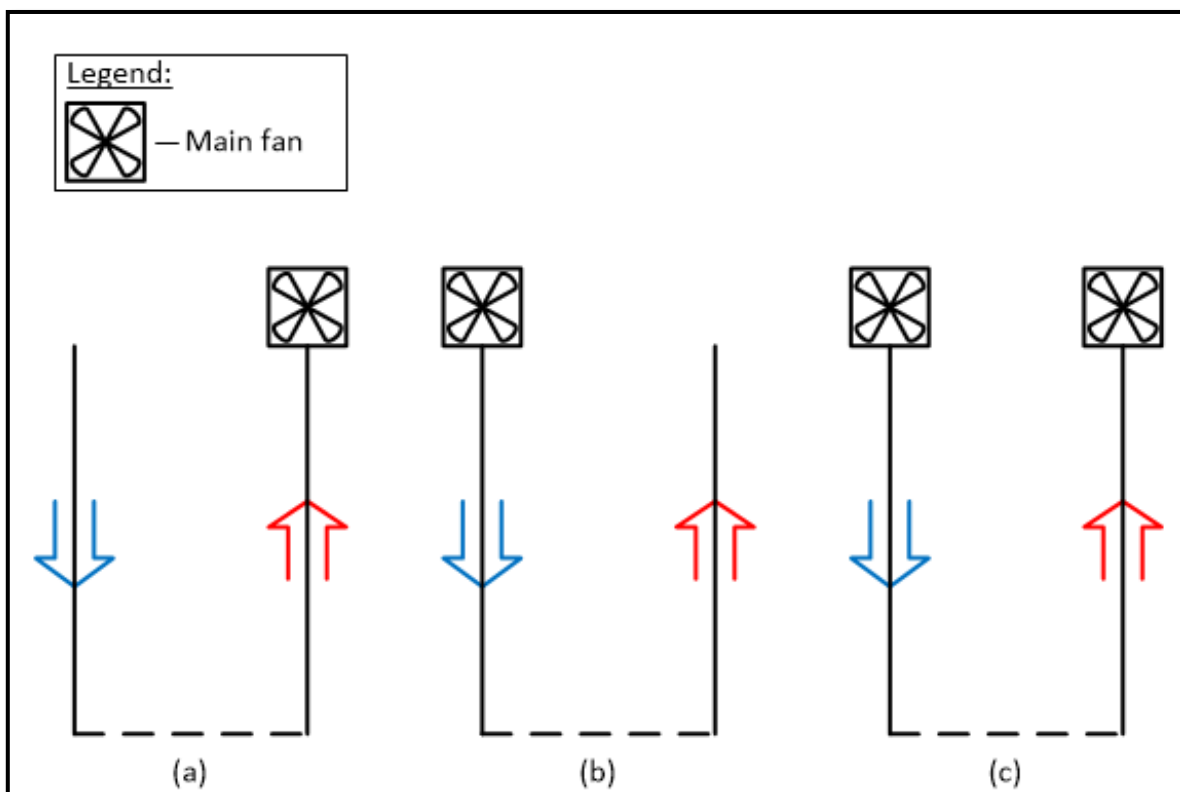


Figure 9: Various fan locations [19]

Furthermore, depending on the type and location (Local geology) of the mine, the ventilation layouts can be classified into two extensive arrangements, namely either a U-tube system or a through-flow system. In conjunction with the main fan location, the underground configuration can differ. The classification determines the direction of the airflow [15]. Fresh air enters the system via the intake, depicted with the blue arrows, travels through working areas where heat is absorbed, yellow arrows,

and is then returned to surface via the returns. The returned air is depicted by the red arrows symbolising contaminated and hot air. Figure 10 displays a basic U-tube arrangement which depicts the airflow towards and through the working area, returning via adjacent airways often separated by stoppings or long pillars [15].

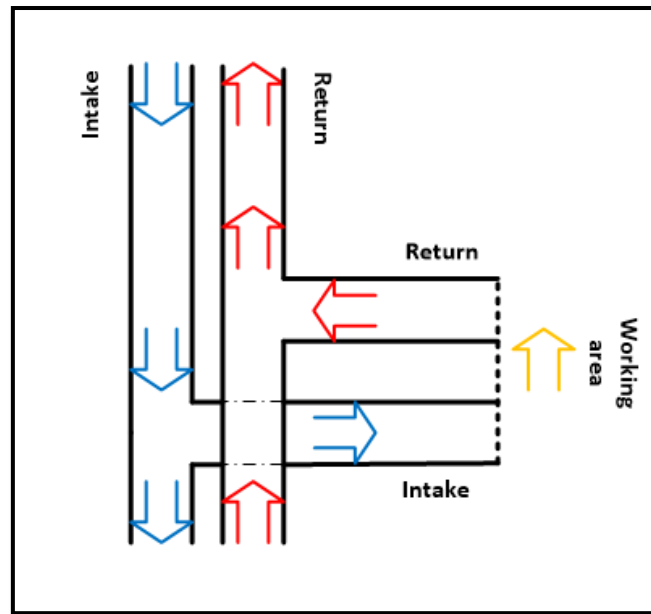


Figure 10: A simplified ventilation model – U-tube system [15], [25]

The U-tube arrangement can be beneficial to the mine for the following reasons [15]:

- As the main fans stop, the underground pressure builds up until it reaches atmospheric. This slows down the flow of harmful gasses to working areas,
- Traveling airways are ventilated ensuring fresh air, free of dust, gas and smoke, is supplied,
- In the event of an emergency, ventilation in the travelling allows for rescue work to proceed more swiftly,
- Intake airways serve as escape routes when stopping lines are well maintained and
- Scope for energy cost savings exists when mine openings are small due to the velocity pressure.

However, due to the arrangement of the exhausting system, some disadvantages occur as a result. These disadvantages are [15]:

- Fire detection is more difficult as air is directed out of the mine via the return airways,
- Dust produced in haulages, contaminates the air stream which is transported into working areas and

- Contaminated air flows through the main fan and corrosive particles settle on the blades, corroding the blades which can imbalance the blades.

The second arrangement, displayed in Figure 11, consists of either all intakes or returns, instead of the separated adjoined airway [15]. Additional booster fans may be required to control the airflow within the work areas, however, fewer stoppings and airways are required due to the geographical separation [15], [25]. This often results in less air leakages and air regulations [15], [25].

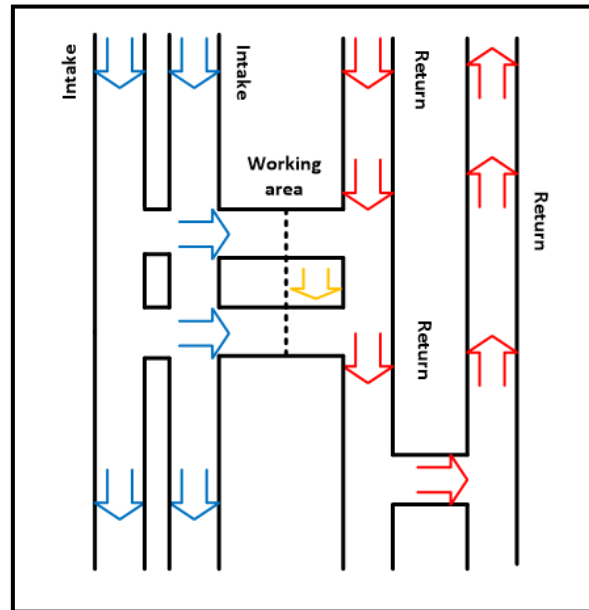


Figure 11: A simplified ventilation model - Through flow system [15], [25]

As a result of the through flow system, there are additional benefits such as [15]:

- A continuously decreasingly overpressure is created from the intake to the discharge airway, therefore preventing contaminating flow into working areas,
- Haulage travelling ways remain ice-free,
- A fire is soon apparent due to leakages and
- Non-corrosive air with a normal moisture content goes through the fan.

Although the configuration is advantageous, there are also some disadvantages to the configuration. These disadvantages are as follows [15]:

- Explosion products are carried into the neutral escapeway, this increases the difficulty of fire-fighting,
- Impurities are carried away from the face area along the haulage. Methane tends to accumulate in pockets along the roof causing minor explosions,

- Air flows from the working sections to the bottom of the shaft, therefore contaminants in the air accumulate at the bottom working areas,
- Shock losses are greater as greater distances are required to lose air velocity and
- Contaminants settle on fan blades.

Actual underground configurations could be a variation between the two systems or a combination of both [15]. This is known as a push-pull system illustrated in Figure 9 (c).

A push-pull system is more convenient in ventilating complicated networks. However, balancing the system is more complicated as there are more neutral spots in the mine [15].

The overall ventilation requirement is to provide a comfortable working environment which is safe due to the extreme temperatures at the high depths as explained in Section 0 [19]. This is based on ensuring a safe working environment for workers [7], [15], [17], [19], [20], [25]. The quantity and quality stipulated by law, may vary between the country and the countries mining history [19]. Governance of a specific country specifies the law for ventilation requirements in an underground mine [17], [26].

South African law stipulates stoping wet bulb temperatures are to be below 32.5°C and station areas below 27.5°C [16], [17]. As previously discussed, severe repercussions exist if these standards are not adhered to.

2.2.3 Auxiliary ventilation strategies in a deep-level mine

Fresh ambient air enters the ventilation system through one or either multiple downcast shafts, drifts (slopes) or other connections to surface [19]. The airflow is directed along the intake airways to the working areas or where required [19]. Fresh air may be required for removal of contaminants (Dust, toxic or flammable gasses etc.), heat, humidity or radiation [19]. The contaminated air is then flushed out of the system via the return airways [19].

Figure 12 depicts airflow underground and the essential components required within the subsurface ventilation facility for an exhausting system [19]. Airflow enters the ventilation system via the downcast shaft and is distributed to working areas via a series of control devices. The contaminated air is exhausted out of the system, due to a negative pressure created by the main fan assemblage, via the upcast shaft.

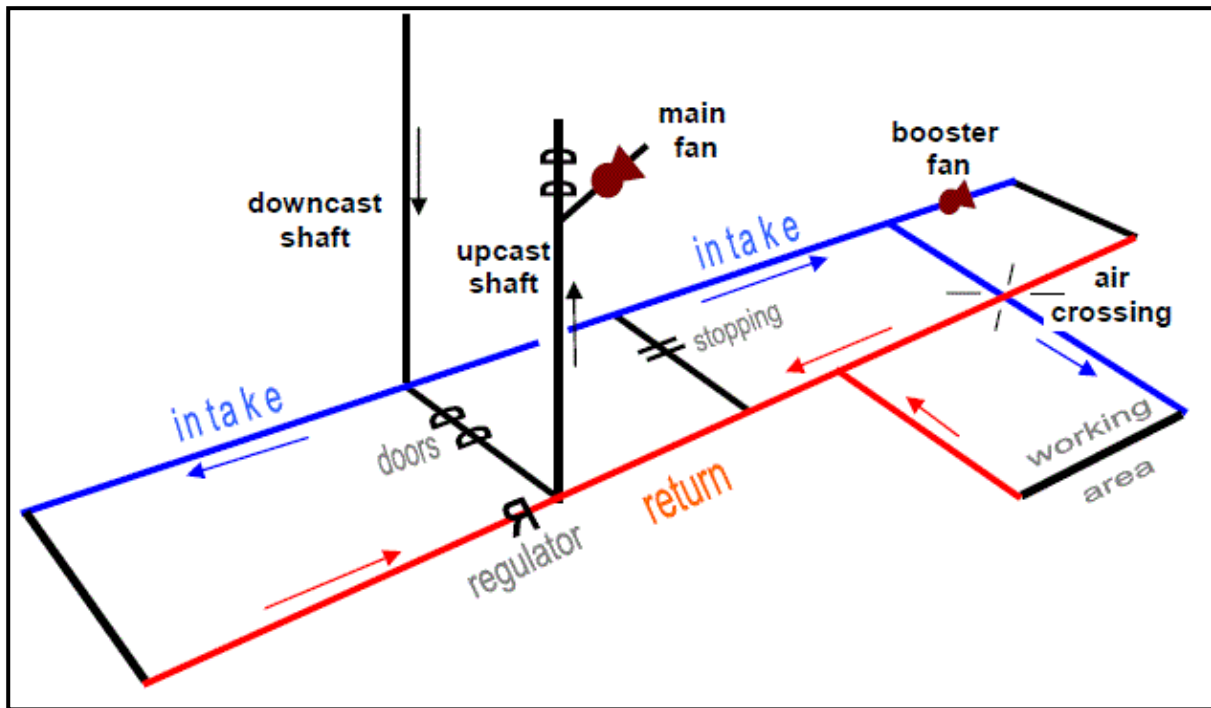


Figure 12: A typical ventilation system and main elements [19]

Table 1 lists the main elements found in a ventilation system, their corresponding description as well as their role within the ventilation system.

Table 1: Ventilation control devices [15], [19]

Component	Description
Stoppings – Temporary or permanent	Stoppings are air walls used to channel airflow for effective air distribution. Stoppings are generally made of masonry, concrete blocks, pre-fabricated steel etc. or any other material depending on the size of entries.
Overcast or undercast	Overcasts are air bridges which allow intake and return airways to cross without mixing.
Regulator	A regulator is used to reduce the airflow to an airway.
Man-doors	A man-door, also known as a 'ventilation door', is an access door normally between intake and return airways.
Air locks	An air lock is typically when access doors are required in the airways and two man-doors create a high-pressure difference.

Line brattice / vent tubing	Fire-resistant line brattices are attached to the roof, sides or floor to provide a temporary stopping when pressure differentials are low in the surrounding and active working areas.
Booster/ auxiliary fans	Booster fans enhance airflow beyond the achievable flow of an open system. Booster auxiliary fans enhance airflow in areas that are difficult to ventilate and redistribute the pressure pattern to reduce leakages and losses.
Machine-mounted water-sprays and scrubbers	Water-sprays are used to improve the flow of fresh air into the face areas or mining areas.

Although the primary ventilation source is the main fan assemblage, the auxiliary ventilation control devices are crucial for underground airflow control. The auxiliary ventilation control devices allow for further air manipulation and control in order to achieve a desired result.

2.3 Strategies to investigate and survey a ventilation system

Ventilation surveys are organised procedures of obtaining data to quantify the supply of airflow, pressure and air quality within a ventilation system [19], [27]. A major objective of ventilation surveys is to obtain pressure drops and corresponding airflows in branchings and other main working areas [19], [28]. The detail and quality of measurement required for the ventilation depends on the purpose of the survey [19].

Ventilation control parameters that should be measured and monitored within safe regulations are [19], [29], [30]:

- Air quantity
- Toxic gasses present
- Dust levels
- Thermal air quality

Air quantity is crucial for safe underground working conditions, ensuring the environment is ventilated free of harmful gasses and dust, in turn improving the general productivity of the workers [19].

Toxic gasses present underground pose a huge health and safety risk for underground workers [29], [31]. Sufficient ventilation is required to evacuate the gasses, especially from the main working areas [29], [31]. These toxic gasses include carbon oxide, carbon dioxide, methane from diesel machinery, sulphide gasses and nitrates of oxide [29], [31].

Dust levels are especially associated with Silicosis, lung disease and Tuberculosis [32]. The main culprit is the silica dust [32]. Therefore, ventilation is used to transfer the dust via the auxiliary ventilation systems, to surface.

Thermal air quality is defined as the thermal comfort of employees [33]. Thermal comfort is affected by the underground temperature and humidity in the specific working area. This is not only a health and safety issue but is directly related to the productivity of the employees [33]. The thermal comfort negatively affects the employees with increasing temperature and humidity.

Prior to ventilation strategies being prepared, the micro-ventilation scene such as the stopes, haulages etc. should be assessed, involving:

- a comprehensive layout and design study with regard to principles of ventilation and cooling [27],
- understanding the airflow requirements [27] and
- understanding desired temperatures entering and exiting the working areas [27].

Ventilation surveys should be conducted in all underground facilities of concern and required by law [19]. Sufficient routine measurements should be taken with a great regard to safety [19], [29]. The objective of routine measurements is to:

- ensure working areas are ventilated and receiving sufficient airflow in an effective manner [19],
- ensure an up to date ventilation record [19] and
- verify distributions, quantities and ventilation infrastructure are maintained and of adequate standard [19].

Ventilation surveys conducted at each traverse station, should include the following parameters [19]:

- Name, date and barometer identification
- Number and station location
- Time
- Barometer reading
- Wet and dry bulb temperatures
- Cross-sectional area of airway at traverse location
- Anemometer reading at the traverse location

From detailed ventilation surveys, the following parameters can be calculated:

- Distribution of airflow, pressure drops and leakages [19]
- Dimensions of airways [27]
- Airpower losses [19]
- Volumetric efficiencies [19]
- Branch resistances [19]
- System resistances [19]
- Natural ventilation effects [19]
- Friction factors [19]
- Air control facilities [27]

Regular routine measurements of airflow and pressure differentials are required across access doors and stoppings to ensure direction and prescribed limits are maintained [19]. Regular measurements are required for incremental adjustments of ventilation controls [19]. Major ventilation amendments are required throughout the life of the mine due to constant development and excessive mining [19].

2.3.1 Volumetric airflow

The volumetric airflow rate is defined as the rate at which a fluid flows through a cross sectional area - Equation 5. Volumetric airflow is the product of the mean air velocity and the cross sectional area of the airway [19].

The volumetric airflow rate is required to calculate the airpower or fluid power (Equation 15) and efficiency (Equation 16) of the surface fan. The volumetric flow rate is also used to calculate the system resistance of the ventilation system (Equation 17).

Equation 5: Volumetric flow rate [34]

$Q_{air} = v_{air}A_c$		
Q_{air} – Volumetric flow of air		[m ³ /s]
v_{air} – Velocity of air		[m/s]
A_c – Cross-sectional area through which the air flows		[m ²]

However, the air velocity and cross-sectional area are obtained from the ventilation survey. The air velocity can be measured by several techniques depending on instrument availability, accuracy and reliability.

Available air velocity measurement instruments available are as follows [19]:

1. Rotating vane anemometers
2. Swinging vane anemometer (Velometer)
3. Vortex-shedding anemometer
4. Smoke tubes
5. Pitot-static tube and digital manometer
6. Hot body anemometers
7. Tracer gases

Figure 13 displays typical instruments used for ventilation surveys and investigations.

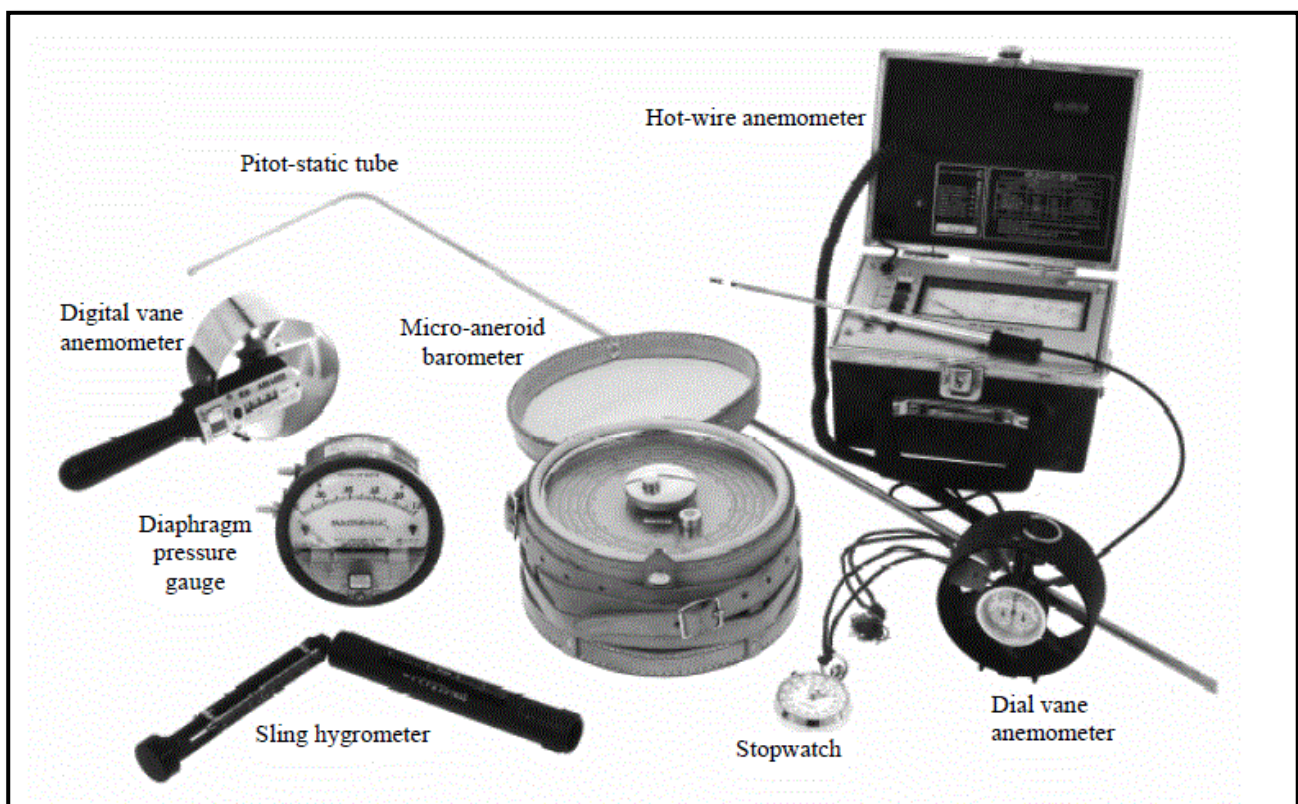


Figure 13: Selection of ventilation survey equipment [19]

Measurement location selection

It is important to consider the laminar and turbulent flow of air when selecting a measurement location. Measurements are typically taken in fully developed turbulent regions [19]. Figure 14 demonstrates the typical flow over a plate as well as the characteristics thereof.

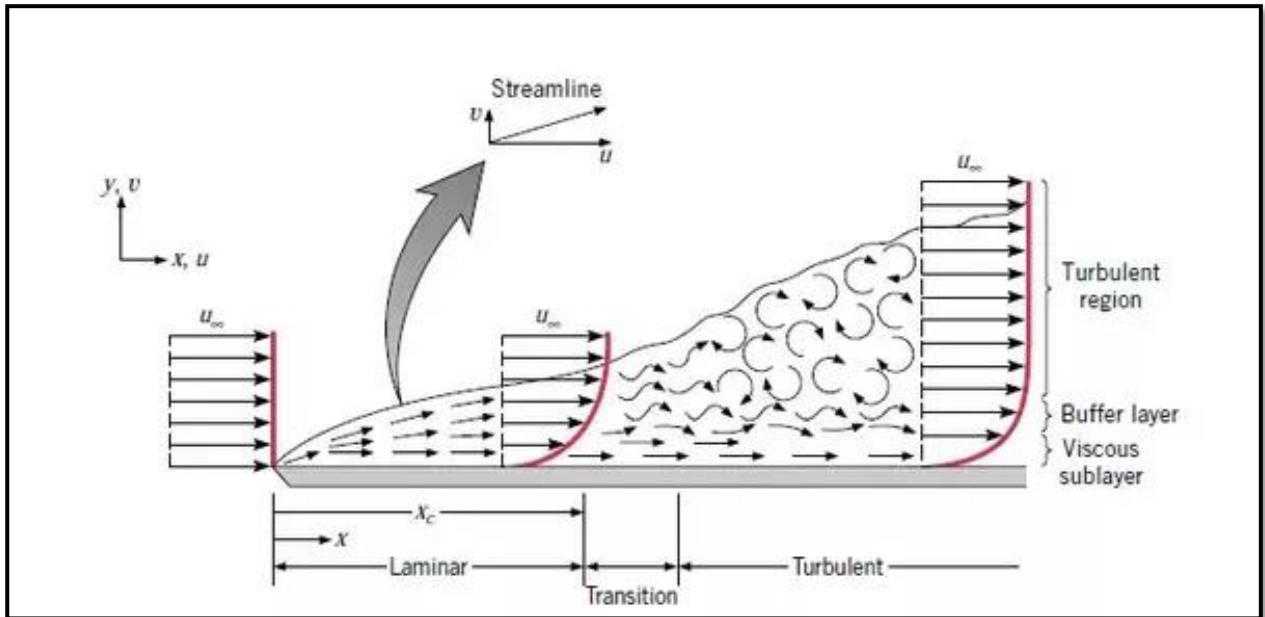


Figure 14: Velocity boundary layer development on a plate [35]

In the above figure, the laminar flow precedes the turbulent flow section [35]. For either condition, the fluid motion is characterised by the velocity components in both the x and y directions [35].

Fluid motion away from the surface is necessitated by the slowing of the fluid near the wall as the boundary layer grows in the x-direction [35]. Within the laminar section, the streamlines are highly ordered and is easy to identify the particles line of motion [35].

When the particles contact the surface, the velocity is reduced significantly relative to the fluid velocity upstream [35]. These particles act to retard the motion of the particles in the next layer. At certain distance from the surface (δ), the effect becomes negligible [35]. This retardation of the fluid motion is associated with the shear stresses (τ_s) acting in the planes parallel to fluid velocity [35].

It is also noted that with increasing distance in the x-direction, the shear stress (τ_s) decreases [35]. The highly ordered behaviour continues until a transition zone is reached [35]. The laminar flow converts to turbulent flow [35]. Typically, measurements should be conducted in fully developed turbulent airflow.

Air velocity measurement technique and method

A variety of velocity measurement techniques exist that correspond with the different air velocity measurement instruments. The available methods that can be used to measure the air velocity for this method are [19], [28]:

1. Fixed point measurement

2. Multiple fixed-point measurement
3. Continuous traverse measurement

Fixed point measurement

Centre point

The fixed-point measurement technique provides an estimate of the airflow in the airway [19]. An anemometer is placed in the centre of the airway at a known and well-established location [19]. The fixed-point method is generally compared with several traverse methods to obtain a “fixed point” correction factor due to the single measuring point [19]. This method is typically used for routine checks, however, should be adjusted with calibration and the correction factor [19]. Ensuring the airflow is fully turbulent developed, will result in the correction factor remaining near constant as the airflow varies [19].

Multiple points

An alternative fixed point method that can be used with multiple points is the multiple point method. The airway is divided up into either nine or sixteen equal parts. The measurement is then taken in the centre of each part [19]. The grid method allows for a more suitable average velocity [19]. The measurement instrument is then placed in the centre of each section for a period of time or until the instrument value stabilises [19]. The more measurement points, the more accurate the average value is [19]. Figure 15 depicts a nine-point grid of air velocity measurement positions.

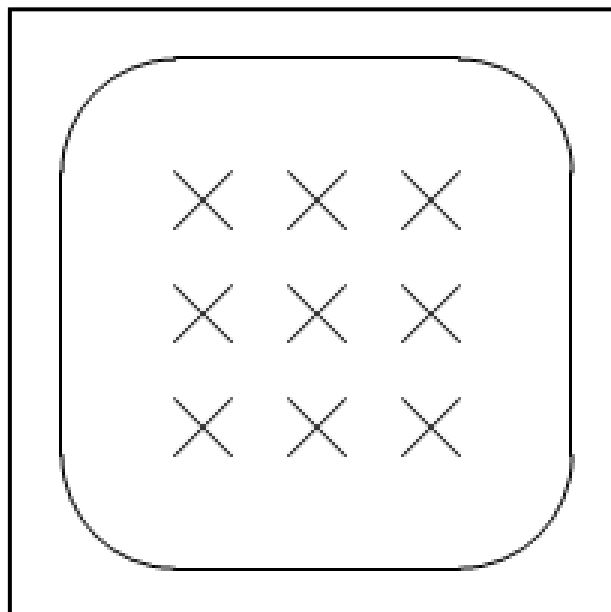


Figure 15: Example of nine point air velocity measuring grid [28]

The measuring instruments used for the fixed-point method are [19]:

- Pitot static tube and manometer
- Rotating vane anemometer
- Hot body anemometers

Multiple fixed-point measurement

The multiple fixed-point method involves taking several readings at different points in the airway to find the mean air velocity [19]. This method assumes the airflow is distribution across the airway is uniform and does not vary with time [19]. There are three different methods to perform the fixed-point traverse method [19].

Equal area method

The airway is divided up into equal subsections and instrument placed in the centre of each [19]. Depending on the area, the number of points for a rectangular airway is defined in Equation 6.

Equation 6: Fixed-point traverse method - Number of points for rectangular airway [19]

$n = 100e^{\frac{-8}{A_c}} + 23$	
n = Number of points	
e = Exponential exponent	2.7183
A _c = Cross sectional area	[m ²]

Figure 16 displays the fixed-point traverse method for a rectangular airway divided into equal sections.

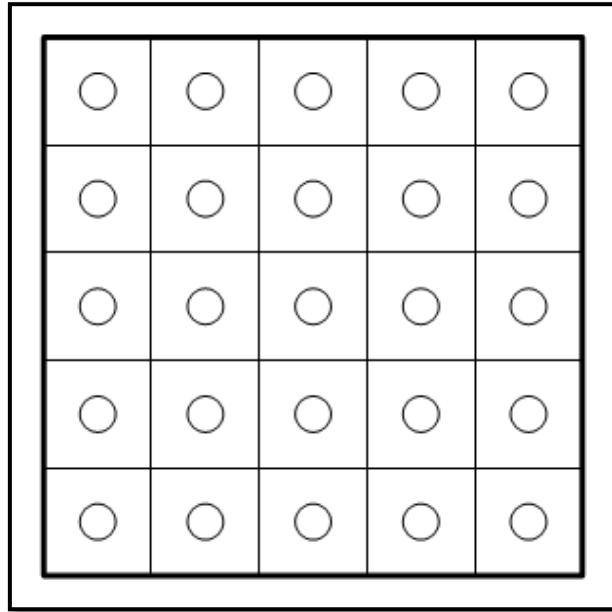


Figure 16: Fixed point traverse method for a rectangular opening [19]

Equation 7 determines the number of points required to evaluate the airflow within a circular airway.

Equation 7: Fixed-point traverse method - Number of points for circular airway [19]

$$r = d \sqrt{\frac{2n_p - 1}{4N_p}}$$

Where,

r = Radius [m]

n_p = Number of the point counted outwards from the centre

d = Diameter of the airway [m]

N_p = Number of points across the diameter

Figure 17 displays the measurement points for the fixed-point traverse method for a circular airway.

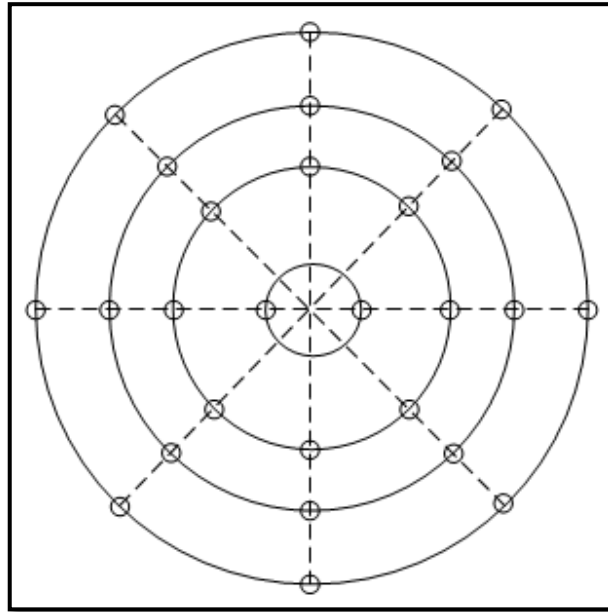


Figure 17: Fixed traverse method for a circular opening [19]

Velocity contours

The velocity contour method helps quantify the airflow by constructing velocity contours to gain a better understanding of the airflow [19]. A scaled sketch is drawn-up of the contours and replicated with wires in the airway to define points of measurement [19]. The greater the number of measurement points, the more accurate the reading [19]. This method is very time consuming, thus is not favourable.

The available methods that can be used to measure the air velocity for the fixed-point traverse method are [19]:

1. Pitot-static tube
2. Rotating vane anemometer
3. Hot-body anemometer

Continuous traverse measurement

An alternative, preferred method when measuring the velocity within a cross-sectional area, is the continuous traverse method. The continuous traverse method involves activating the clutch and traversing the vane anemometer in an continuous motion across the entire cross sectional area [19], [28]. Either a vertical, up and down traverse movement or a horizontal, side to side traverse movement may be used to quantify and determine the direction of the airflow [19], [28]. Typically a time integrated vane anemometer and a stopwatch is used for this method [19], [28].

The vane anemometer uses the kinetic energy from the airstream to drive the impeller [28]. The impeller's rotation is proportional to air velocity [28]. The translation of the impeller rotation speed will give a measure of the air velocity [28].

The traverse movement is timed as the vane anemometer traverses and accumulates a measure of air speed [19], [28]. The accumulated value is then divided by the time value obtained [28]. The process should be repeated until three values are obtained within 5% from each other [19]. The continuous traverse method is displayed in Figure 18 (Vertical) and Figure 19 (Horizontal).

The measuring instrument used for the continuous traverse method is the rotating vane anemometer [19]. As the instrument is traversed across the airway, the velocity is accumulated as a measure of speed.

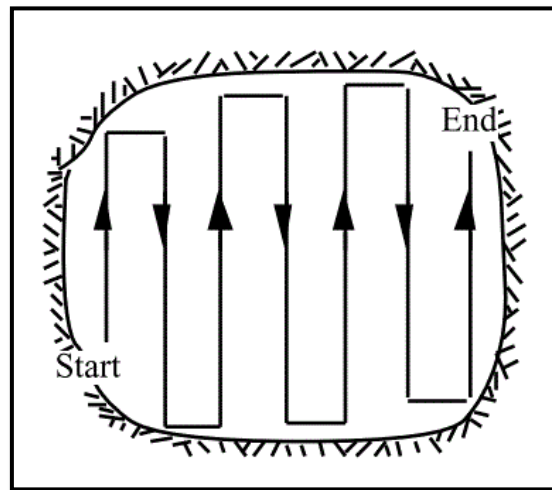


Figure 18: Illustration of the vertical continuous traverse method [28]

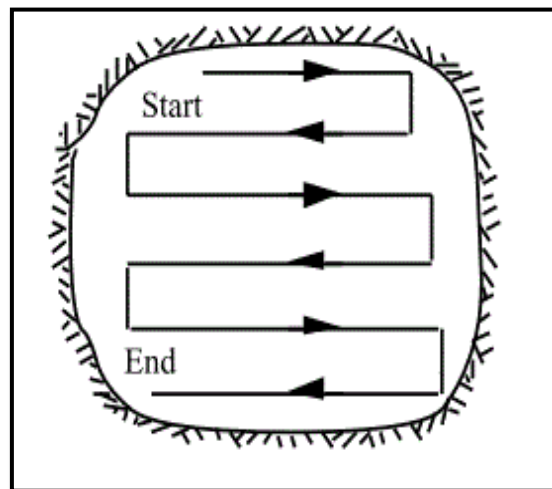


Figure 19: Illustration of the horizontal continuous traverse method [28]

Airway cross-sectional area (m²)

The cross-sectional is used to determine the volumetric airflow rate (Equation 5), as the volumetric flow rate is a product of the mean air velocity and cross sectional area [19].

Three locations are measured for both the height and width to determine a more accurate average. Three measurement locations allows for a more accurate cross sectional area reading as the underground haulages are not uniform and even [28]. A well defined airway profile is favourable in this case [19]. In cases where the cross sectional areas are not uniform and even, multiple measurements in different locations are required to obtain a representative area [28].

Equation 8 represents the formula used to calculate the cross-sectional area of a rectangular shaped airway.

Equation 8: Cross sectional area for a rectangular shape airway

$A_c = H_{Ave} W_{Ave}$	
Where,	
A_c = Cross-sectional area	[m ²]
H_{Ave} = Average Height of airway	[m]
W_{Ave} = Average Width of of airway	[m]

Figure 20 depicts the width and height measurement locations for a rectangular cross-sectional area.

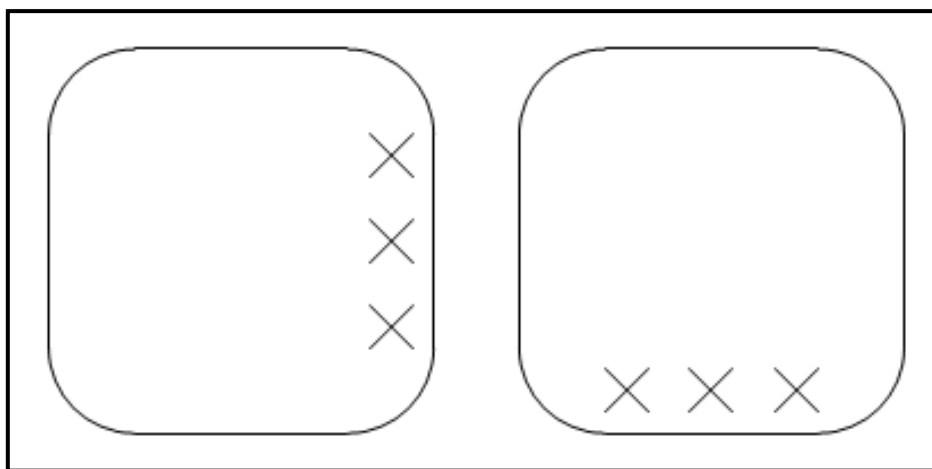


Figure 20: Width and height measuring points (Rectangular cross-sectional area)

In other cases where the airway is circular, the procedure is applied with the same objective, however, the radius of the of the airway is measured and used in Equation 9. Equation 9 represents the formula used to calculate the cross-sectional area for a circular airway.

Equation 9: Cross sectional area for a circular shape airway

$A_c = \pi * r^2$	
Where,	
A_c = Cross-sectional area	[m ²]
r = Radius of drift area	[m]

2.3.2 Air temperature

When measuring temperatures, it is important to measure both the wet-bulb and dry bulb temperature. Generally, a sling psychrometer is used. A sling psychrometer uses the airflow past wet-bulb and dry-bulb thermometers to measure the temperature [36]. The sling psychrometer is a mechanical mechanism that uses two thermometers, one naked thermometer (Dry bulb) and a cotton wick covered thermometer (Wet bulb) [36]. The sling psychrometer also contains a reservoir, with the thermometers, mounted on the frame, which is rotated manually about the handle.

Figure 21 depicts the location of temperature measurement in a airway.

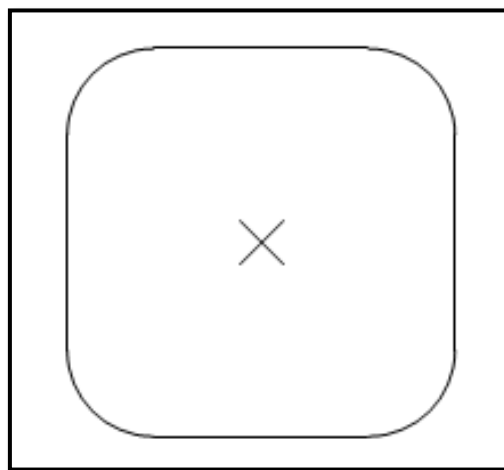


Figure 21: Temperature measurement point within the airway

The sling psychrometer should be whirled at approximately 200 rpm for 30 seconds before reading the temperature values can be read. This process should be repeated until a constant temperature value is obtained.

2.3.3 Air pressure

The main purpose of conducting pressure surveys is to determine the frictional pressure drop (p) that corresponds with the airflow (Q) [19].

The Bernoulli equation is the sum of the pressure head, velocity head and elevation head and is used to determine the total pressure in a streamline [37]. Equation 10 represents the Bernoulli equation used to determine the total pressure in a streamline [37]. It is not always necessary to calculate the total pressure depending on the sought outcome of the survey.

Equation 10: Bernoulli's equation [19], [36], [37]

$P_{Tot} = P_{Head} + P_{Kinetic} + P_{Potential}$	
Where,	
P_{Tot} = Total pressure	[Pa]
P_{Head} = Pressure head	[Pa]
$P_{Kinetic}$ = Velocity head	[Pa]
$P_{Potential}$ = Elevation head	[Pa]

Pressure head

The pressure head term, represents the height of a column of the fluid that is required to produce the pressure [37]. The pressure head is expressed further in Equation 11.

Equation 11: Bernoulli's equation - Pressure head (Static) [19], [36], [37]

$P_{Head} = \text{Static air pressure}$

The pressure surveys can be conducted in a manner of ways. Pressure surveys may be conducted with the following instruments [19], [37]:

1. Pitot-static tube and digital manometer
2. Barometer
3. U-tube manometer

Pitot-static tube and digital manometer

The pitot-static tube and digital manometer can be used to determine the static pressure in an airway using the same method described in Section 2.3.1 (Equal area method) [19].

Barometer

Generally, the barometer is used to measure the barometric pressure within an airway or on surface. The barometer is a glass tube, closed at one end and open at the other which immersed in a container filled with mercury [37]. When using the barometer, two measurement points are required to determine the pressure loss in the airway [37]. The measurement should be conducted at the beginning and at the end of the airway [37].

The pressures are dependent on the following factors [37]:

- Air velocities
- Elevation difference
- Frictional pressure drops between stations

The barometer is placed in the respected area and the barometric pressure reading is read off and noted.

A digital barometer, which is much simpler and easier to use, can also be used to determine the barometric pressure difference and drop in airways.

U-tube manometer

The U-tube manometer widely used, consists of a tube shaped as a U, filled with a gage fluid. Typically, the manometer consists of two rubber tubes which is inserted into the different contained areas [37]. The difference obtained on the manometer is then a measure of pressure difference measured in Pa.

Figure 22 is a visual representation of the proper use of a U-tube manometer [19], [37]. The height difference between the levels, represents the differential pressure (h).

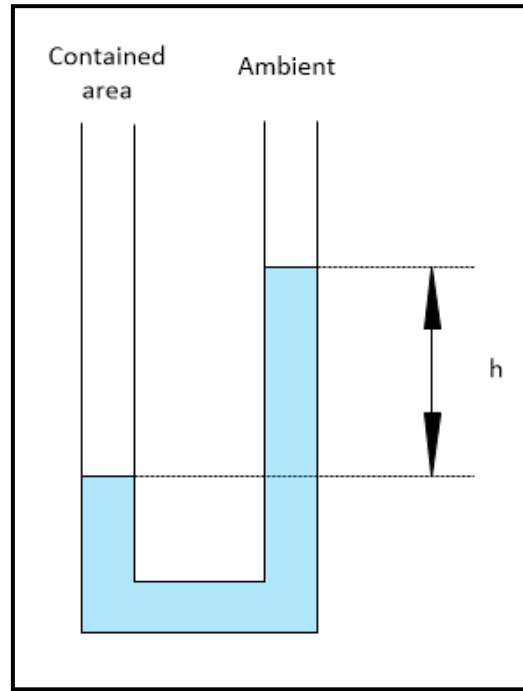


Figure 22: U-tube manometer representation [37]

The left limb, as described in the above-mentioned figure, is connected to the contained area while the other end remains open in the ambient conditions. The pressure difference between the two areas is then denoted by h , generally in Pa.

Pressure measurement technique

Considering the level duct in Figure 23, three types of gauge pressure measurement techniques exist, while conducting pressure surveys.

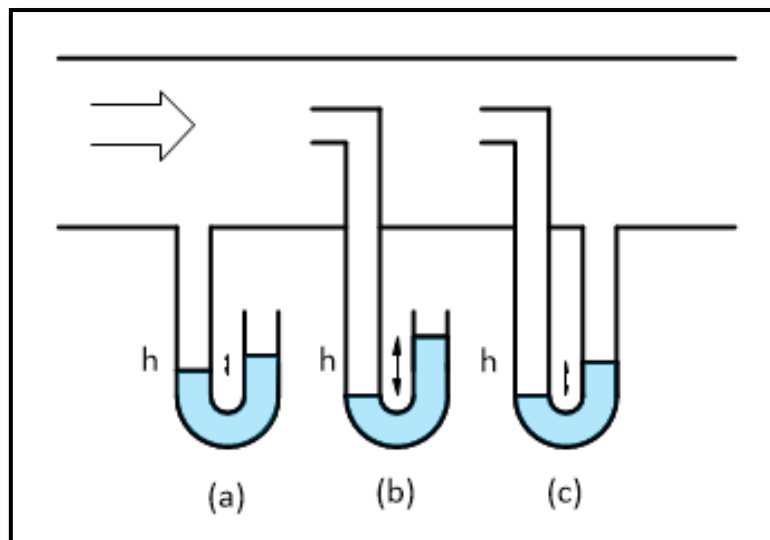


Figure 23: Different gauge pressure measurements [19]

The pressure measurement technique demonstrated in position (a), Figure 23, displays the static pressure measurement technique [19]. One limb is connected perpendicular to the duct while the other limb is open in ambient conditions [19].

Position (b) in Figure 23, demonstrates the total pressure measurement technique [19]. One limb is connected to the duct, extending into the airway against the flow [19]. This gauge pressure measurement is a measure both, the dynamic and static pressure values [19]. The second limb remains open in ambient conditions [19].

Position (c) in Figure 23, demonstrates the technique used to measure the velocity pressure head [19]. Implementing the same technique as position (b), however, connecting the second limb to the duct, provides a measure of the velocity pressure [19].

Velocity head

While the velocity head represents the vertical distance required for the fluid to fall freely, to reach the velocity V [37]. The velocity head is expressed further in Equation 12 [37].

Equation 12: Bernoulli's equation - Dynamic pressure (Kinetic energy) [19], [36], [37]

$P_{Kinetic} = \frac{1}{2} v_{air}^2 \rho_{air}$	
Where,	
ρ_{air} = Air density	$[kg/m^3]$
v_{air} = Air velocity	$[m/s]$

The air velocity obtained from the volumetric airflow rate measurement, explained in the Section 2.3.1, is used in the above-mentioned equation to determine the velocity head.

In order to calculate the dynamic pressure, the density is required. Density can be calculated with the ideal gas law, expressed in Equation 13 providing the fluid is an ideal gas.

Equation 13: Ideal gas law for air [36]

$pV = mRT$		
Where,		
p = Pressure		[Pa]
V - Volume		[m ³]
m - Mass		[kg]
R _g – Specific gas constant		287 [J/kg.k]
T – Absolute temperature		[K]

The ideal gas law (Equation 13) can be remodelled to determine the density of the fluid at the different conditions and parameters.

However, air is considered as an imperfect gas [38]. A psychrometric chart, located in Appendix A, is used with two parameters, either the dry bulb, wet-bulb or humidity to determine the density of the air [38].

Elevation head

The elevation head represents the potential energy the fluid possesses at the elevation, h [37]. The elevation head term is expressed further in Equation 14 [37].

Equation 14: Bernoulli's equation - Head pressure (Potential energy) [19], [36], [37]

$P_{Potential} = \rho_{air}gh$		
Where,		
ρ_{air} = Air density		[kg/m ³]
g = Gravitational constant		9.81 [m/s ²]
h _e = Elevation		[m]

When calculating the air density with Equation 13, the static air pressure should be used. With Bernoulli's equation, the total pressure may be calculated as well as the different contributing energy components. The total pressure and other components can be used to determine performance statistics and indicators required when conducting a ventilation survey.

2.3.4 System performance analysis

System performance analysis after the ventilation system survey is completed, is crucial as additional information is provided describing the performance of the airflow throughout the airway at a specific location [19]. The fluid power and system resistance may be calculated after the ventilation survey to evaluate the performance.

Fluid power

Fluid power is defined as the product of airflow and air pressure [19]. Fluid power is a measure of the mechanical energy content as per the supplier machine [19]. The fluid power between points provides the airpower loss over a branch or airway [19]. Fluid power provides a good indication of the fluid's key performance indicators. Generally, fluid power is calculated to determine the losses over branchings and or airways.

Equation 15 expresses the equation used to calculate the fluid power in the system.

Equation 15: Fluid power [19]

$AP = Q_{air}p_{air}$	
Where,	
$AP = \text{Airpower}$	$[\text{kW}]$
$Q_{air} = \text{Volumetric airflow}$	$[\text{m}^3/\text{s}]$
$p_{air} = \text{Air pressure}$	$[\text{kPa}]$

Results from all three surveys explained in Section 2.3.1, 2.3.2 and 2.3.3 (Volumetric airflow, Air temperature and Air pressure) is used to determine the airpower at certain locations [19].

Using the airpower value obtained from the calculation in Equation 15, the efficiency may be calculated. Although the airpower of any branching or airway may be calculated, the efficiency calculation is focussed at the main fans.

The airpower of the main fan needs to be calculated from volumetric, pressure and temperature surveys performed in the main fan airway. Thereafter, the overall efficiency may of then be calculated using Equation 16 [19].

Equation 16: Fan efficiency [19]

$\eta = \frac{AP}{P}$	
Where,	
η = Efficiency	[%]
AP = Airpower	[kW]
P = Electrical power of fan	[kW]

The overall fan efficiency is an indication of the overall performance of the main fan [19]. This value may be plotted on an Efficiency vs Airflow graph to indicate performance and objective airflow.

System resistance

Resistance in the ventilation system is defined as the size, number of openings and manner in which they are connected [19], Mine resistance is significantly reduced and environmental circumstances enhanced, when airways to working areas are split [19].

The ventilation resistance may be calculated with obtained from the pressure survey, Section 2.3.3, and ventilation survey, Section 2.3.1.

Equation 17 expresses the formula used to calculate the system or Atkinson's resistance.

Equation 17: Atkinson's resistance [19]

$R_A = \frac{P_{static}}{(Q_{air})^2}$	[Ns ² /m ⁸]
--	------------------------------------

The Atkinson' resistance is an indication of subsurface airflow and pressure performance. The resistance is directly proportional to the static pressure and indirectly proportional to the airflow [19].

The system performance as per the ventilation surveys should be compared with the supplied main fan curves. Identified operating points can be plotted on the curve, however, the fan curve needs to

be adjusted to correspond with the calculated air density due to temperature and pressure differences although the different densities may not differ significantly. Two curves exist on a fan curve, a curve for the pressure and a curve for the power against the airflow rate.

The fan curve is defined by a plot of the static pressure and power over a range of generated airflow. It is important to understand this ratio when sourcing or designing a fan system¹. Figure 24 is a typical example of a fan curve that is supplied with a fan from the supplier ¹.

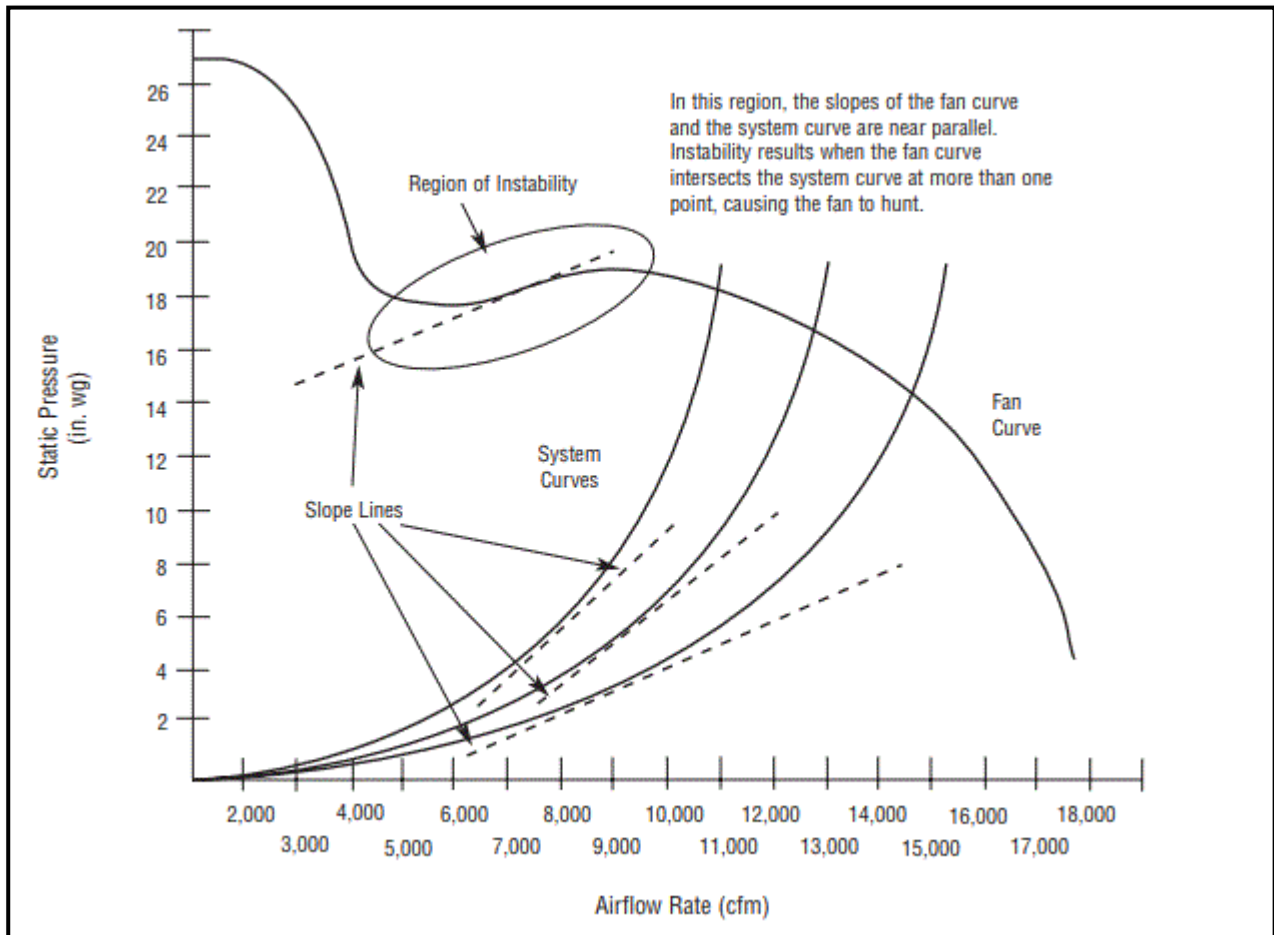


Figure 24: General fan curve ²

The fan curve depicts different stages that a fan encounters when starting up and when operational¹. The fan undergoes a region of instability when started up due to the extreme vibrations and frequencies on the motor¹. The fan curve also demonstrates the system curve as well as the slope

¹ Lawrence Berkeley National Laboratory Washington DC, "Improving Fan System Performance," 1989.

lines which indicate the position of the guide vanes. Guide vanes can be controlled to gain a certain output from the fan ¹.

Equation 18 can be used to calculate the air density ratio which is then applied to the original fan curve.

Equation 18: Adjusted static pressure [36], [37]

$$\alpha_{\rho} = \frac{\rho_{New}}{\rho_{Fan,curve}}$$

Where,

α_{ρ} = Density ratio

ρ_{New} = Density from psychrometric chart [kg/m³]

$\rho_{Fan,curve}$ = Original density obtained from supplied fan curve [kg/m³]

The ratio is multiplied with the static air pressure values to obtain the new adjusted curve. However, the above obtained ratio may also be applied to the power vs airflow curve to obtain a similar result.

Equation 19: Static pressure adjustment [19]

$$P_{static,adjusted} = \alpha_{\rho} P_{static}$$

Where,

$P_{static,adjusted}$ [kPa]

α_{ρ} = Density ratio

P_{static} = Fan curve static pressure [kPa]

Once the fan curve has been adjusted with the density ratio, the operating points may then be plotted on the curve to analyse the results.

General ventilation survey information

Detailed logs of ventilation data obtained from the surveys is imperative to monitor improvements and deterioration of the operational efficiency of the ventilation system. An easy way to monitor the efficiency of the system is to firstly, monitor the surface fan performance and secondly, monitor individual branchings and cross-cut performance.

Furthermore, a colour coded map may be used to identify problematic branchings which are expensive and difficult to ventilate. These areas may then be specifically focussed on, to improve the efficiency of ventilation throughout the area.

2.4 Simulation techniques and strategies

Simulation software serves the purpose of solving complex problems that occur in the ventilation networks [39]. Due to the extensive underground networks and large quantities of data, computing technologies are required to solve the problems [39]. The objective of ventilation simulation software's are to ensure the optimal repartition of airflows at the individual levels [39].

Different ventilation simulation software is widely available today, that have developed significantly over the past few decades [39]. Available simulation software is:

- VentSim [24], [39],
- VUMA [40],
- PTB 3D and
- Environ.

VentSim

VentSim simulation software was designed as an aid to view and alter ventilation networks [39]. Simulation software imports mine layout files (DXF formats) including all information regarding lines and line string data which then creates a 3D model of the mine network [24].

VentSim typically focusses on underground ventilation development however, is disadvantaged when fixing airflow in a more complicated system. The simulation produces inaccurate results; therefore, the auxiliary ventilation system is unable to be simulated realistically [24].

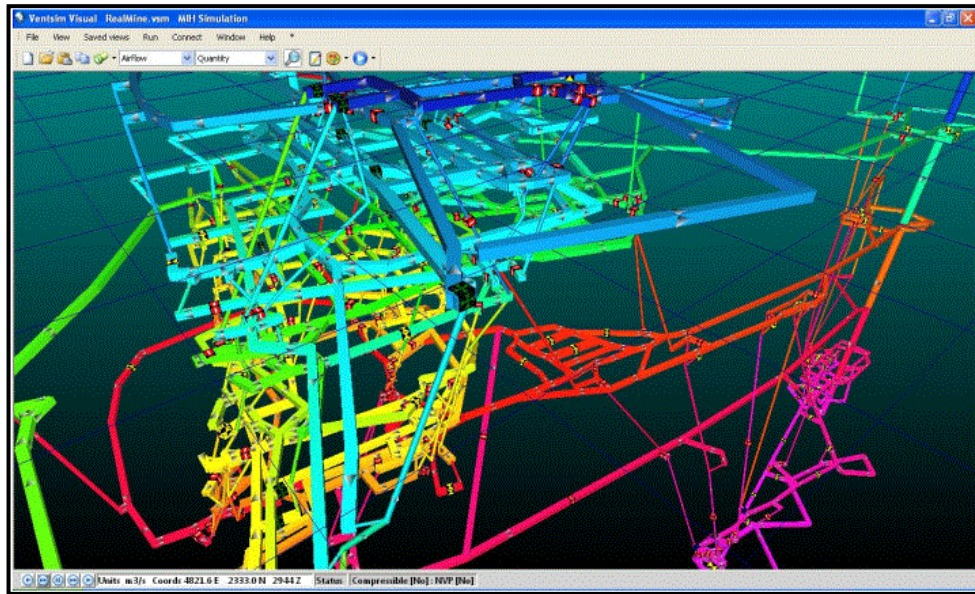


Figure 25: Example of VentSim simulation software mine layout [24]

VUMA

The simulation software, VUMA, is specifically designed for underground ventilation assistance in terms of planning, designing and operation [40]. VUMA is a collaborative program that simulates airflow, gas behaviour, dust suppression and thermodynamic control simultaneously [40], [41].

VUMA is comprised of the following main design criteria [40]:

- Designed specifically for mining industry
- Compatible with all Windows platforms
- Incorporates majority of mining methods
- Simultaneous and interactive simulation

This software is mainly used to optimise the refrigeration and ventilations requiring large amounts of input data for a more accurate result [1] and requires experienced personnel to operate the software [40].

Process Toolbox (PTB 3D)

Process toolbox (PTB 3D) is a three dimensional thermal hydraulic simulation package software which is used to simulate the mines refrigeration, ventilation and dewatering system [1]. The software determines the optimal operating points of the equipment [1]. PTB can also be used to design, analyse and optimise systems [1].

PTB enables a Graphical User Interface that enables a drag and drop system [1]. Systems are comprised of different components (nodes, pipes, tunnels etc.) to calculate the flow and required parameters [1].

Previous studies by Oberholzer [9], Vermeulen [42], Mare [43] and Peach [1], on the refrigeration systems proved the accuracy of the simulation software, PTB. Simulated and actual results corresponded between simulations and measured results.

ENVIRON

ENVIRON, is one of the most commonly used simulation software's in the industry [41]. Although the software is concentrated on the design side, it still solves underground ventilation strategies. The software is not a dynamic or integrated software [1], [41].

The different simulation software's were evaluated according to the advantages and disadvantages when using the software on a mine. The results obtained are depicted in Table 2.

Table 2: Simulation software packages comparison

	Advantages	Disadvantages
VentSim	• Auxiliary ventilation systems are simulated • New ventilation design can be simulated	• Complicated networks make it difficult to simulate •
VUMA	• Simultaneous simulation • Analyse underground thermodynamic properties	• Large amount of input data is required • Requires experienced personnel to operate
PTB (3D)	• User-friendly • Able to calculate costs savings • Accurate simulation results • Determines optimal operating points	Large amount of input data is required
ENVIRON	• New ventilation design can be simulated	Lacks integration

	• Auxiliary ventilation systems are simulated	
--	---	--

It is evident from the summary in the table above that PTB 3D is more advantageous when simulating an existing ventilation system as it is more user friendly and accurate. The VUMA model requires an experienced or trained person to build the simulation. This is not always possible due to resource constraints and limitations thus making PTB 3D the more suitable choice for ventilation simulations.

2.5 Previous studies on deep-level mine ventilation optimisation

Literature has revealed several studies performed on ventilation systems:

Study A [17]

Author:	A.J.H Nel
Title:	Mine ventilation characterisation through simulations
Overview and objectives:	The author aimed to analyse, optimise and quantify mine ventilation characterisation to produce improved operational efficiencies and decision-making capabilities with the aid of simulation software packages.
Outcomes:	• A method was developed with simulation packages to properly evaluate mine ventilation systems, in turn, which improved the decision-making capabilities operational efficiencies and profitability. • A model was created to effectively quantify the financial benefit of energy efficiency projects in the mining industry. • An integrated simulation planning procedure was developed in which ventilation evaluation, selection and implementation of the primary access and ventilation network is studied, to achieve the most feasible method. • The author also developed an innovative velocity on demand (VOD) airflow profile using MV (medium voltage) VSD's.
Shortcomings:	The author focussed mainly on theoretical applications and quantitative methods on ventilation systems, no actual implementations on the ventilation system were implemented.

Study B [44]

Chapter 2

Authors:	S. Maleki, F. Sotoudeh and F. Sereshki
Title:	Application of VENTSIM 3D and mathematical programming to optimise underground mine ventilation network: A case study
Overview and objectives:	The study aimed at determining the optimal location for fans and regulators. The study also focussed on minimising costs using VentSim simulation software.
Outcomes:	Ventilation equipment and machinery position selection resulted in a reduction in exit pressure. This increased the overall efficiency and optimised ventilation network structure by reducing the number of regulators. As a result of the improved ventilation network structure, cost savings were realised.
Shortcomings:	The study focussed on the optimal fan and regulator locations however failed to analyse the optimal locations and performance of underground auxiliary ventilation strategies.

Study C [7]

Author:	C. Pritchard
Title:	Methods to improve mine ventilation system efficiency
Overview and objectives:	Pritchard focussed on the methods to improve the ventilation efficiency cost effectively. The study focussed at improving operations because of deeper and hotter conditions.
Outcomes:	The study yielded areas to be focussed on are shop ventilation methods, auxiliary equipment areas, intakes and returns, airflow utilisation and alternative ventilation methods. The study also identified alternative methods to ventilate the mine with no extra capacity available and contaminants that need to be diluted for a safer environment.
Shortcomings:	Use of simulation models to determine consequences and effects of system changes on emergency and evacuation strategies. Pritchard also mentions adjusting the fan blade setting for cost savings should be investigated further.

Study D [45]

Authors:	W.M. Marx, Prof JJL du Plessis, D. Hoffman and R. van der Westhuizen
Title:	Optimising ventilation and cooling systems for an operating mine using network simulation models
Overview and objectives:	The objective of the study is to describe an interactive network that can be used to design a ventilation and cooling model to optimise thermal conditions in working areas cost effectively. This aims to improve worker health, safety, productivity and profitability.
Outcomes:	• VUMA-network is an accurate simulation software program for design purposes. • Results from VUMA can be viewed graphically to readily identify inefficiencies. • The effect of changes can be assessed easily. • Benefits derived from the use of VUMA are airflow and fan power requirement optimisation and strategic placement of ventilation equipment.
Shortcomings:	The optimisation of the ventilation and cooling systems was mainly focussed on achieving cost savings, neglecting operational improvements.

Study E [46]

Author:	R. Els
Title:	Potential for load shifting in ventilation and cooling systems
Overview and objectives:	Els investigated the potential for a load shift on the ventilation and cooling systems on deep level mines. The objective of the study was to develop a control strategy to perform a load shift on the ventilation and cooling system for a continuous period during a day.
Outcomes:	The study identified scope for a load shift of approximately 19MWh sustained for five continuous hours in a day for deep-level mines.
Shortcomings:	The main focus was on the energy consumption during of peak periods. The author neglected the service delivery of the ventilation system.

Study F [21]

Author:	A. Haghighat
Title:	Analysis of a ventilation network in a multiple fans limestone mine
Overview and objectives:	The author developed a strategy to improve the ventilation network of the mine with consideration to the source of losses in the network and design with multiple fans with the aid of simulations. He also focussed on the optimum blade angles of the booster fans, fire analysis (Including toxic gasses) and the elbows louvers as a major source of pressure losses.
Outcomes:	• The solution strategy resulted in an increased efficiency of 34% by utilising two surface fans and booster fans for optimum ventilation. This also resulted in an increase in the air quantity through all working faces on a case study. • The study also analysed the effect of changing the angles of the elbows and louvers to minimise the pressure losses. He found that in a 0° angle, the pressure losses were minimal with optimum flow. • The author determined that natural ventilation is an important factor during fires and the best method of controlling a fire.
Shortcomings:	The study mainly focussed on shallow mines and neglected underground operational improvements in terms of performance due to auxiliary ventilation strategies. The geographical and physical characteristics of limestone mines (shallow) cannot be compared to deep-level mines.

Study G [47]

Author:	E.I. Acuna Duhart
Title:	Multiple period mine ventilation and fan selection optimisation
Overview and objectives:	The author presented a genetic algorithm (GA) to optimise single period main ventilation systems and application of linear mixed integer programming (MIP) to optimise the selection of fans for multiple period auxiliary mine ventilation systems.

The objectives of the studies were to develop, with a genetic algorithm and ventilation solver, a series of potential fan configuration solutions consisting of multiple and single period. The second objective was to optimally select fan units to supply airflow and pressure to the development ends or “dead ends” for multiple periods.

Outcomes:

- The study concluded the addition of regulators in a system implemented correctly is a novel contribution to the field and can solve a broader problem than the case where regulators are installed in fixed quantity branches.
- The MIP algorithm presented considerable capital and energy cost savings. The MIP algorithm also allow various fan operational efficiencies instead of assuming fixed values.
- The obtained solution is near optimal with the use of the algorithms (GA & MIP), however, cannot be guaranteed feasible as it is not easily implemented.

Shortcomings:

The study recommends further research in extending the input data for the algorithms to include costs parameters. He also recommends testing the optimisation technique with larger ventilation networks.

Table 3 is a summary of the previous studies discussed in this section, that cover previous work performed on the ventilation system. Various forms of studies were performed either analysing the effect of improving or optimising the system and some informative of areas lacking improvement.

Table 3: Previous studies summary and comparison

	Study						
Criteria	A	B	C	D	E	F	G
Use of simulations to improve operational efficiency	✓	✓		✓	✓	✓	✓
Theoretical operational efficiency improvement approach	✓		✓				

Chapter 2

Improvement of ventilation operational efficiency in a shallow mine						✓	
Use of algorithms to optimise ventilation network structure							✓
Auxiliary ventilation network optimisation with the use of simulations		✓					
Optimising the ventilation and cooling systems for cost savings		✓		✓			
Identifying potential load shifts and energy efficiency on ventilation and cooling systems					✓		
Analysis of ventilation systems (Identify areas for improvement)			✓				
Mine ventilation and fan selection optimisation		✓				✓	
Improving the operational efficiency of deep-level mine ventilation systems							

From the above-mentioned table, it is noted that there are many studies performed with the aim of improving the operational efficiency with the aid of simulations. Simulations are used as a preliminary source to validate the solution strategy prior to implementation. This is valid and should be performed to ensure a successful initiative.

There is lack of academic literature regarding the improvement of the operational efficiency of a ventilation with the aid of simulations although a study was performed on the operational improvement of a shallow mine, it cannot be compared to a deep-level mine.

A theoretical approach using different models was developed however, this was implemented on the ventilation network, thus supporting the need for the study.

2.6 Conclusion

Chapter 2 summarises the main concepts and operations of a deep-level mine ventilation system. It is necessary to understand the concepts of ventilation as well as the components and purposes in the network before an accurate and realistic solution strategy may be developed.

Ventilation survey techniques and purposes were discussed as it is part of the initial step to understanding the workings of a ventilation system. To completely understand the airflow within a deep-level mine, the airflow rate, temperatures and pressures need to be investigated in areas of concern. Accompanying formula and measurement technique for the key parameters is explained in detail as the data obtained from the surveys is vital for decision-making and subsequently, solution development.

Currently, modern technology has become an important factor and should not be neglected when developing solutions as it is advantageous. Simulation software packages can be used to mimic actual systems and implement changes without physically changing the system. This is very advantageous as solution strategies may be tested without resulting critical consequences. Different simulation software packages are briefly discussed to determine the most applicable software to use when simulating ventilation systems.

Previous studies regarding ventilation systems are discussed and critically analysed to highlight the outstanding literature gap applicable to this study. The literature revealed a lack of attention in improving the operational efficiency of deep-level mine ventilation systems. The information discussed in Chapter 2 was used to develop a generic strategic approach to identify, develop and resolve ventilation inefficiencies.

CHAPTER 3: DEVELOPING A GENERIC STRATEGIC APPROACH TO OPTIMISE THE VENTILATION OPERATIONAL EFFICIENCY

3.1 Introduction

The information obtained in Chapter 2 was used to develop a generic solution strategy to optimise the operational ventilation efficiency at a deep level mine. Figure 26 depicts the generic solution development process.

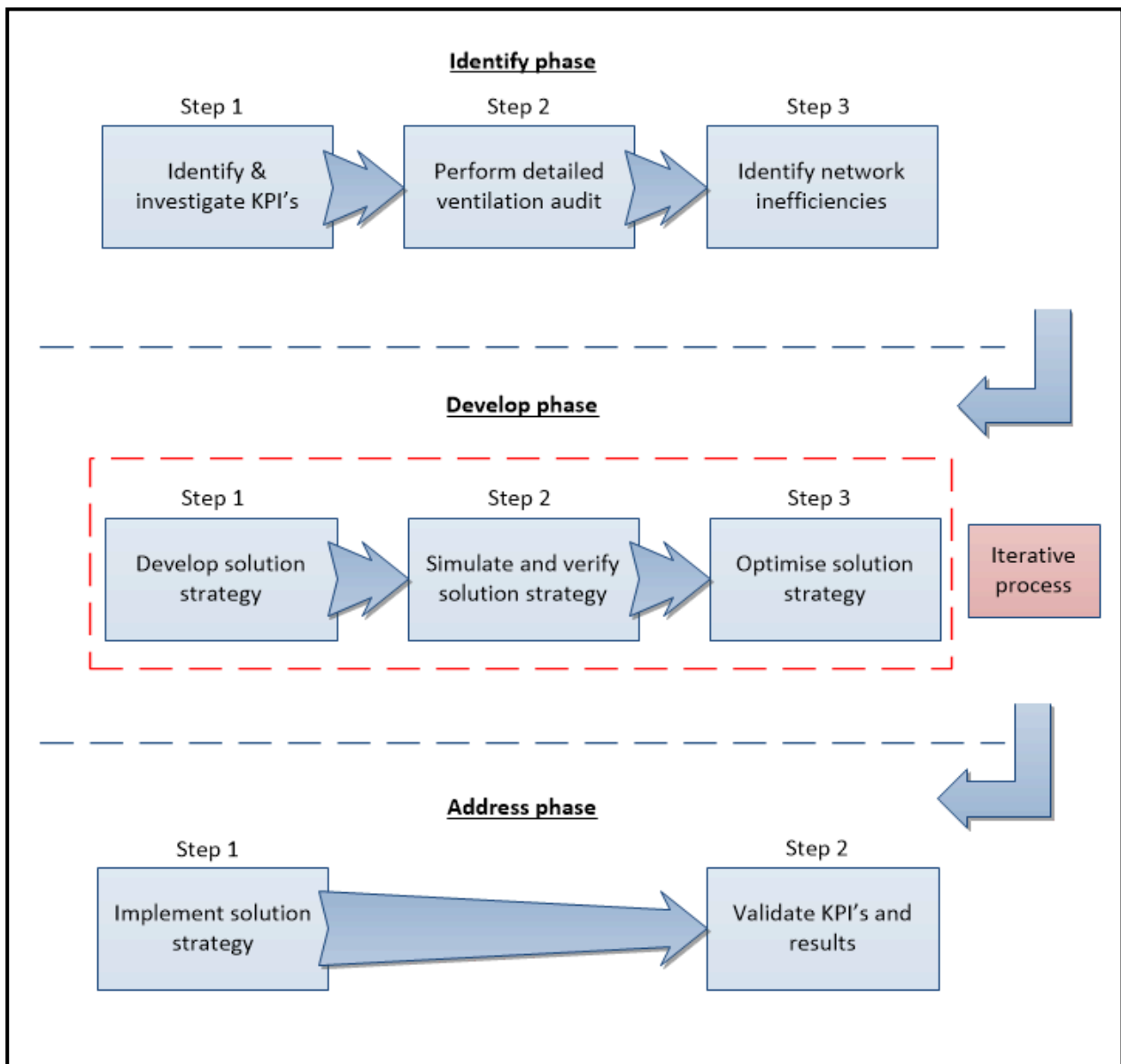


Figure 26: Generic solution strategy

The generic process in Figure 26 comprises three important sections, namely identify, develop and address. The process is adapted from the original six step process to develop an effective problem-solving process¹. The original involving six step process is as follows¹:

1. Identify the issues
2. Understand everyone's interest
3. List the possible solutions
4. Choose most suitable solution to be implemented
5. Implement the solution
6. Monitor the performance

Table 4 compares the two different process used in the study and demonstrates how the two processes are inter-linked with one another as the generic strategy used is an adaptation of the original process.

Table 4: Problem-solving process comparison

Six step process	Adapted generic solution strategy
Identify the issues	Identify phase
Understand everyone's interests	
List possible solutions	Develop phase
Most suitable solution implemented	
Implement solution	Address phase
Monitor the performance	

The developed process aims to identify the network inefficiencies, develop a suitable solution strategy and address the network issues.

The solution strategy aims to not only to rectify the network inefficiencies but also to accommodate dynamic changes within the deep-level mine. Within the ever-changing mine, it is important to ensure the ventilation system adjusts and accommodates the systems changes. Due to the nature of deep-level mines, system changes frequently occur, therefore, affecting the structure and operational efficiency of the underground ventilation.

¹ R. Halabi, "Six Steps to Develop an Effective Problem-Solving Process," 2017. [Online]. Available: <https://www.potential.com/articles/six-steps-develop-effective-problem-solving-process/>. [Accessed: 09-Oct-2018].

The first step is to identify the KPI's (Key performance indicators) and perform detailed ventilation audits on the mine. From the investigations, it will be possible to identify the network inefficiencies.

The development section (Step 2) is an iterative process. Development of the solution strategy should be repeated until suitable solutions are developed. It is necessary to simulate and optimise the solution strategy to ensure the solution will be sufficient. After that, it is necessary to implement the strategy and validate the KPI's (Step 3) ensuring the implemented strategy fulfils the goal set out.

The generic solution strategy is iterative. The process should be applied to the network until a solution is implemented successfully in rectifying the shortcomings identified. The solution development process is explained in more detail in the sections below.

3.2 Identify key factors

It is of critical importance to ensure a good understanding of the ventilation networking system before being able to develop a suitable solution strategy to implement, in order to optimise the system.

The purpose of the 'Identify' step is to gain a better understanding of the ventilation network. A better understanding of the ventilation network will enable an individual to identify the KPI's correctly, and as a result, classify the network inefficiencies accordingly. Correctly identifying the inefficiencies will result in a more streamlined problem-solving process.

Figure 27 illustrates the identification section of the solution strategy process.

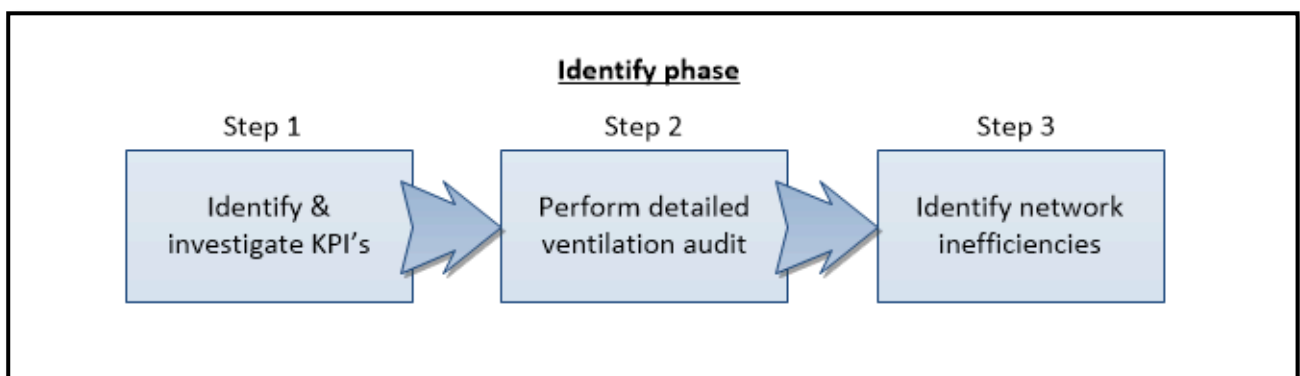


Figure 27: Identify phase

3.2.1 Identify and investigate KPI's

Identifying the KPI's is one the most key actions in the solution development process. Incorrectly identifying the KPI's will result in a delay in the development and implementation of the suitable strategy.

Individuals need to understand the ventilation networking system before being able to identify the inefficiencies and provide solutions. Correctly identifying the KPI's will result in a comprehensive understanding of the system.

It is also necessary to investigate the performance of the KPI's as this will indicate the operational efficiency.

Table 5 lists typical examples of KPI's in the ventilation system. The KPI's listed below play an important role in the operation of the ventilation system and should be monitored and noted in the surveyance section.

Table 5: Typical KPI's of a ventilation system

Location	KPI
Ambient surface conditions	• Temperatures (Wet and dry bulb) • Barometric pressure
Surface fan assemblage	• Fan pressures (Static, Dynamic and Total) • Airflow rate • Fan efficiency • Airpower
Underground auxiliary components (location and effect)	• Seals, • Access doors • Regulators • Auxiliary fans • Overcasts/ undercasts • Airlocks • Stoppings • Vent tubing • Water sprays

Underground parameters (Traveling ways, active working areas, inactive working areas and main haulages)	• Airflow • Pressure • Temperatures
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Once the KPI's have been identified, a thorough investigation is required to determine the operating performance. The operating performance of the KPI's will give a clear indication of the problematic areas. The problematic areas may then be investigated further to determine the cause.

The development of further work areas underground is considered non-applicable to this study due to the time period in which the study is performed and the rate at which areas are being developed. Generally further expansion of the mine would be considered however due to the time frame, the size of the mine is considered constant to focus on the effect at the current work areas.

3.2.2 Perform detailed ventilation audits

Detailed ventilation audits are very advantageous and should be performed across the focus areas. Detailed audits supply valuable information when determining the inefficiencies. Detailed audits are based on analysing the underground air temperatures (Dry and Wet bulb), static pressures, barometric pressures, volumetric air flows and ventilation component locations and effects.

The aim of the detailed ventilation audits is to identify the critical measurement locations to gain a comprehensive understanding of the air flow within the mine network. Once the ventilation audits have been performed, inactive working areas still receiving air flow may be identified as well as the active working areas that require air flow. The air flow will give an indication of air flow within cross-cuts leading to the stoping areas.

Ventilation audits should be performed after significant changes are made to the ventilation network. This constant updating of the flow of the ventilation network will allow dynamic system changes to be made. As a ventilation audit is completed, it is necessary to document and note all data for a thorough investigation.

Equation 5 is the generic equation for the calculation of volumetric flow (m^3/s). The volumetric flow is the product of the air velocity (m/s) and the area (m^2). Equation 8 and Equation 9 are the generic equations used to calculate the cross sectional area of the airway either for a rectangular shaped or circular shaped airway. The shape of airways differ from mine to mine. The correct equation should be used upon the shape of the airway.

Measurement location

Figure 28 illustrates a typical underground network system. In the figure below, the blue arrows represent the air flow from the downcast shaft into the main haulages and cross-cuts. The red crosses represent the measurement locations. In the figure below, it can be noted that a measurement location occurs after a split from the main haulage.

Determining the measurement points requires strategic planning. Measuring points need to be critically placed for optimum results. Incorrectly placed measurement points will result in unreliable measurements and an unbalanced system flow. It is important to ensure the airflow is fully turbulent in the measurement location before the measurement is taken [19]. To ensure this, measurements are generally taken away from bends and airway restrictions.

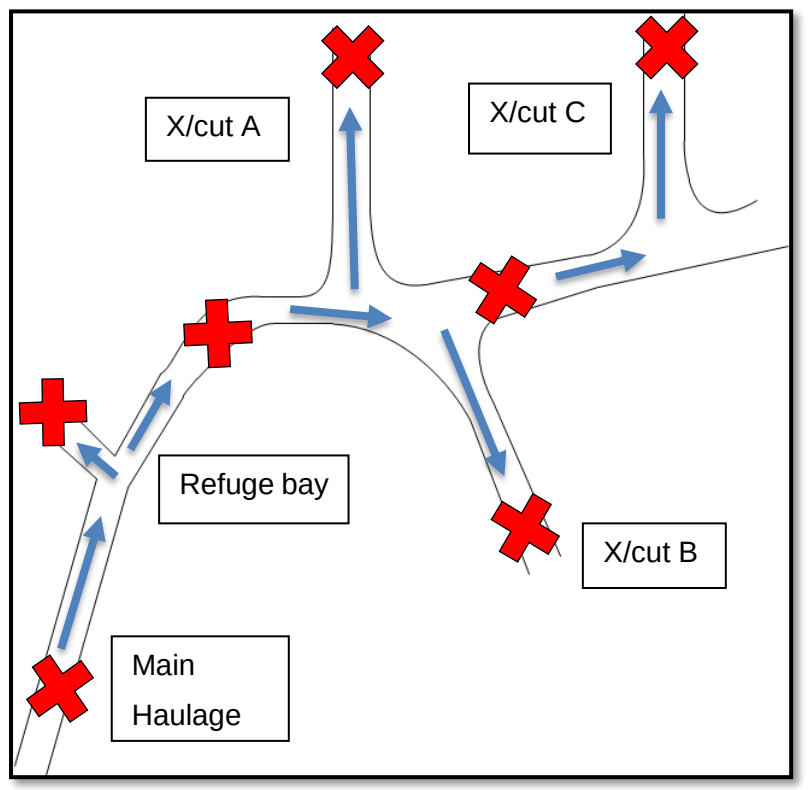


Figure 28: Measurement location identification

¹ Drawn by Shaun Hancock

Ventilation symbols

When performing the ventilation audit, it is necessary to ensure that all ventilation related equipment and tools are included in the network. It is also important to note all factors that have a role on the ventilation.

There are various influences on the system, thus the importance of denoting the factors with a well worked out legend.

Table 6 is a list of general symbols used to denote the different ventilation factors.

Table 6: Ventilation symbols

Description	Symbol
Section break	N
Seal/ Wall (broken/ leaking)	
Seal/ Wall with duct:	
Open duct	⊥
Closed duct	⊥
Ventilation doors:	
Open door	⌋
Closed door	◐
Underground fan	
Fan on	←●●
Fan off	←○

Air duct:	
Closed air duct	
Open air duct	
BAC/ Cooling cars:	
BAC on	
BAC off	

Measurement technique and equipment

The proper measurement technique with the correct equipment is required when performing the ventilation audit. The equipment requires adequate calibration before use to ensure accurate and reliable results. Uncalibrated or faulty equipment will result in misleading or inaccurate results.

The instruments required to be based upon the purpose of the data when measuring the KPI's. Therefore, measurement instruments are chosen according to the accuracy and required accuracy for the given purpose.

Data capturing

The data obtained from the ventilation audits needs to be concise and neatly recorded to avoid confusion. Table 24 in Appendix B demonstrates the ventilation sheet used to audit the different locations. The sheet includes all aspects such as the velocity of the air [m/s], the cross sectional area [m²] and temperatures.

Table 25 located Appendix B, demonstrates the sheet used to audit the surface fan. The sheet includes the air speed [m], the cross sectional area [m²], static pressure of the surface fan [°C], instantaneous power [kW], time [s], ambient temperatures [°C] and barometric pressures [kPa].

The two sheets listed in Appendix B, are to document and track the performance of the KPI's throughout the investigation. This allows for easy progress tracking.

Processing the ventilation data

All data obtained from the ventilation audits needs to be processed and documented for further use and comparison after the project is completed. This data can then be used to evaluate the performance of the project after completion.

It is important to ensure the data is processed in such a manner that may be easily read and understood. The easiest manner to do so, is to tabulate and plot the results.

From the data obtained throughout the investigation, Equation 15, Equation 16 and Equation 17 mentioned in Section 2.3.4 , may be used to determine the fundamental values used for further analysis, comparison and decision making.

While processing the results, the surface fan curve must be included in the comparison as this is the design specification of the fan. Comparing the measured results to the design specifications will give a good indication of the performance of the fan and opportunities for improved performance may exist.

The comparison will provide a complete overview of the performance and may highlight the areas in which the system is lacking. The comparison is very advantageous in providing vital information for critical decisions that need to be made in the solution development process.

3.2.3 *Identify network inefficiencies*

Section 3.2.2 discussed the procedure of how general ventilation audits are performed to achieve the most reliable and accurate results for decision making.

From the processed ventilation data obtained from the initial ventilation audit, it will be evident where the network inefficiencies lay. The network inefficiencies may be identified by scrutinising the information and ensuring a good understanding of the network.

By understanding the flow of the network, it will be evident where the ventilation network system is lacking.

Possible network inefficiencies that may arise within a ventilation system may be:

- Re-circulation of air
- Inactive cross cuts receiving air
- Active cross cuts not receiving air
- Redundant ventilation machinery operating

- Ventilation components ineffective due to negligence and discipline
- Incorrectly placed ventilation components

From all the information gathered throughout the investigation, it will be possible to identify the network inefficiencies in the ventilation network.

3.3 Develop and verify a suitable solution

When developing a suitable solution strategy for the identified problematic issues in the ventilation network, it is key to incorporate the KPI's to address the inefficiencies. The KPI's are the factors that will indicate whether the solution is viable.

The purpose of the 'Develop' step is to analyse possible solutions continuously until all the requirements are satisfied. Developing a strategy is an iterative process and should be applied until a suitable solution is identified and verified.

Figure 29 illustrates the development section of the solution strategy process.

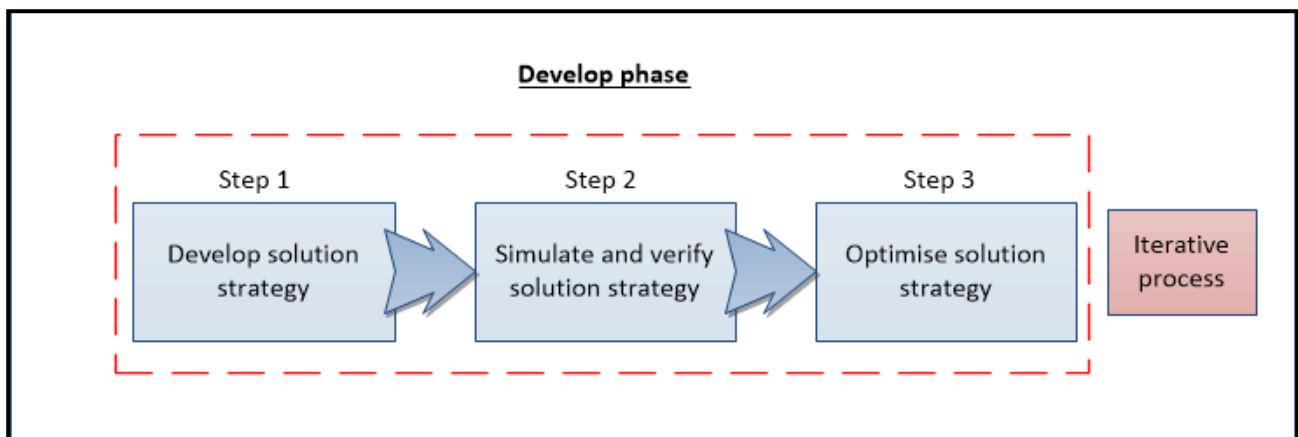


Figure 29: Develop phase

3.3.1 Develop a solution strategy

The solution strategy development should be based on the information found in Section 3.2, the identified network inefficiencies. The solution developed should be aimed at resolving the network inefficiencies for a long-term base instead of the common short-term fix.

While developing the solution strategy, the strategy should be well thought out considering all impacts it will have on the system. When developing the solution strategy, the following factors should be considered:

- What is the root cause of the inefficiency?
- How will the strategy be implemented?
- Is it possible to implement it?
- What is the estimated time of implementation?
- What are the long-term and short-term effects?
- What are the costs involved with implementation?
- Is there enough man-power to implement the solution without compromising other important work?
- Are the employees skilled enough to implement the solution?
- Are there contingency plans in place for implementation failure?

It is vital to ensure the 'root cause' is taken into consideration when developing a new solution strategy as this will mitigate implementing past strategies which led to the ventilation inefficiency. When all the factors have been taken into consideration then an adequate solution strategy may be developed and planned out to solve the network inefficiencies. The main concern is to ensure the network inefficiencies and all aspects of the above-mentioned factors are addressed before the strategy is completed.

Table 7 explains possible inefficiencies and corresponding solutions that may be applied to rectify the issue at hand.

Table 7: Possible inefficiencies and corresponding resolutions

Inefficiency	Solution
Inactive cross-cuts receiving ventilation	• Determine the purpose of the cross-cut (e.g. Travelling way etc.) • Find suitable solution for the cross-cut (A travelling way still requires some ventilation – Regulator) • Install the applicable solution • Validate results and installation
Active cross-cuts not receiving ventilation	• Investigate the entire ventilation network (Perform ventilation audits) • Analyse the results and determine the cause of the ventilation shortfall (e.g. Inactive cross cuts receiving ventilation) • Develop suitable solution (e.g. Seal off inactive areas)

Chapter 3

	• Implement solution and validate results to determine if the problem resolved
Re-circulation of air at certain areas	• Investigate the entire ventilation network (Perform ventilation audits) • Find a suitable solution (e.g. Install a booster fan to ensure air flow through the problematic area) • Install the suitable solution • Evaluate ventilation flow after installation to ensure problem is resolved.
In-effective ventilation equipment	• Investigate ventilation equipment and performance (determine the purpose of the equipment and reason for unfulfillment) • Develop a solution (e.g. Relocate ventilation equipment) • Execute solution strategy • Evaluate implemented strategy performance
Insufficient surface fans operating	• Investigate ventilation network system • Analyse ventilation results • Develop a solution (e.g. Investigate all other options to optimise air flow – if all else fails commission a surface fan) • Implement the solution • Investigate ventilation network • Evaluate the solution strategies performance
Restrictions in RAW (return-airway)	• Investigate root cause for the inefficiency • Develop a suitable immediate solution (e.g. clear RAW or blast a new RAW) • Implement the solution • Re-evaluate the performance

Table 7 highlights possible inefficiencies that may arise in the ventilation network and corresponding resolutions. The problem-solving process used to address the inefficiency follows a similar trend.

Figure 30 illustrates a holistic process used to investigate and address problems.

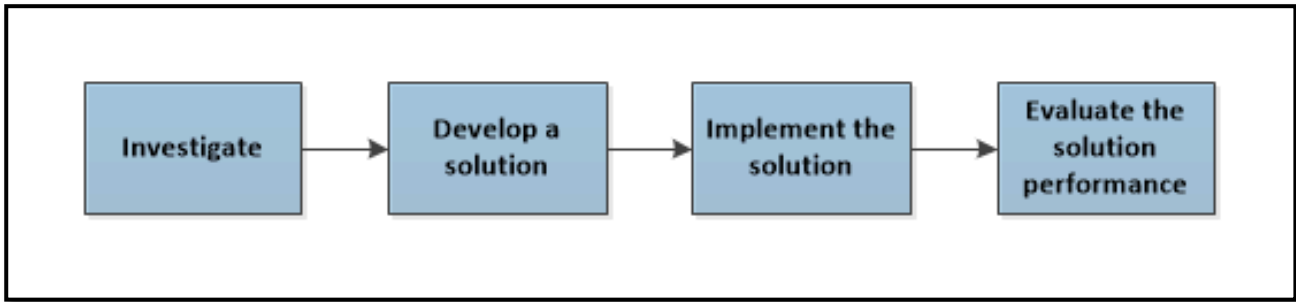


Figure 30: Generic problem-solving process

The above-mentioned problem-solving process is brief summation of the complete process and highlights the most important points. Firstly, investigating a problem, to gain a full comprehensive understanding of the problem. Developing a suitable solution to resolve the issue. Implement the solution strategy and then evaluate the performance of the system thereafter to determine whether additional actions are required.

3.3.2 *Simulate and verify solution strategy*

Simulating a system is an imitation of a process using computer software. This is advantageous as the system may be replicated and various scenarios may be applied without physically changing the system.

Simulating the solution strategy can be a helpful tool in determining whether the solution strategy is viable, however, it is not always possible to simulate accurately. Simulating an underground haulage or an intricate piece may prove difficult due to the underground physical conditions (e.g. uneven walls etc.).

Therefor simulations are not always performed on solution strategies depending on the conditions of the system. Some system's do not require simulations as the solution strategy is simple and the outcome is imminent. Simulations are more commonly used on systems that require a more complicated and comprehensive approach.

However, the verification of the solution strategy is vital. Ensuring the solution strategy will be effective in resolving the ventilation inefficiencies is critical. Therefor the necessary steps and actions need to be taken for a suitable and effective solution plan.

Steps that can be taken to ensure this is as follows:

- Ensure strategy is aimed at resolving the inefficiencies
- Ensure the strategy is implemented correctly

3.3.3 Optimise solution strategy

Simulations can be used to optimise the solution strategy ensuring the most effective strategy to be implemented. Optimising a strategy will also confirm a more long-term solution.

Optimising the solution strategy without the use of simulations may be more complicated, however requires more in-depth scrutiny and a comprehensive understanding of the network as well as the solution strategy obtained to rectify the inefficiencies.

Optimisation is a recurring process and should be applied until the solution is optimal and can provide the desired outcome. The purpose of the optimisation of the strategy is to enhance the strategy to be most effective.

3.4 Address network inefficiencies and evaluate performance of the KPI's

The 'Address' step involves implementing the solution. Once implemented, it is necessary to validate and evaluate the KPI's to ensure the implemented solution has satisfied the required outcomes set out.

The aim of the 'Address' step is to not only implement the developed solution strategy but to ensure the strategy is implemented in an effective manner to avoid future complications. Post implementation validation is critical ensuring the success of the strategy.

Figure 31 illustrates the execution section of the solution strategy process.

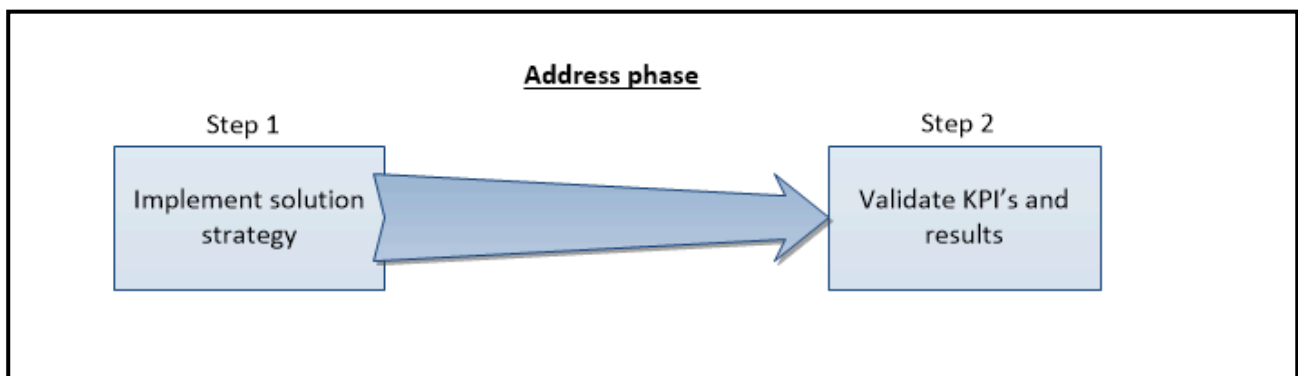


Figure 31: Address phase

3.4.1 *Implement the solution strategy*

The implementation of the solution strategy is the execution of the developed plan. Prioritising the planned actions is imperative. Prioritised actions will result in problematic areas being addressed first. Whilst executing the plan, proper documentation and recording of data should be exercised.

The execution of any strategy requires more than adequate planning. The biggest possible challenge that may arise is following the schedule. Due to the nature of the mine, other issues may arise that take preference setting the project back.

3.4.2 *Validate KPI's*

The evaluation of the KPI's mentioned in Section 3.2.1 is the performance measurement of the strategy. Detailed ventilation audits post solution strategy implementation is required to confirm the results which then can be compared to the initial and simulated results.

The performance measurement will give an indication of the success of the project. The results can be analysed to determine the effect of the strategy as well as possible short-comings the solution strategy failed to identify.

The development section of the solution process should be conducted again to address the shortcomings taking the new information into account. It is not necessary to repeat the entire process as the additional information of the shortcomings will only affect the type of solution.

The entire generic strategic approach should be re-iterated providing the validation of the KPI's is completed and performance indicators have shown a negative impact. This means the developed solution strategy has failed and a new solution is required, however to do so, basic information must be collected again to omit any discrepancies when the solution is developed again.

3.5 Conclusion

Chapter 3 describes a generic methodology developed in order to survey ventilation systems, identify the inefficiencies, develop a solution, simulate an appropriate solution and implement the solution. The generic solution strategy aims at analysing the ventilation system as a whole and identifying the problematic areas which requires immediate action.

The generic strategic solution approach is based upon the objectives stated in Chapter 1, which is to develop a generic ventilation approach to improve the operational efficiency of the ventilation

system, sustain working conditions, ensure long-term strategic ventilation planning to create a sense of dynamicity and reduce ventilation costs.

The generic strategic approach can be divided into three main steps; Identify, Develop and Address. A critical step in the methodology is correctly identifying the inefficiencies based upon the ventilation surveys data. Inaccurate data will result in false identified inefficiencies, leading to incorrect solution strategies being developed and implemented. Special care and time should be devoted to the identify step in the process.

Chapter 4 is based upon the actual implementation of the methodology described in Chapter 3. The methodology was implemented on one case study.

CHAPTER 4: CASE STUDY A

4.1 Introduction

Ventilation is critical for the operational success and health and safety of miners on a deep level mine. There are laws that govern the underground temperatures ensuring the workplace is safe and cool enough to operate within. The law states that wet-bulb temperatures in stoping and station areas are to be below 32.5°C and 27.5°C [1].

Ventilation systems are volatile and should adapt dynamically with the ever-changing underground network. Adapting continuously with the system changes implemented by the mine would result in effective ventilated working areas.

The nature of the mining sector does not allow for constant attention to the necessary components and configurations of the ventilation. Mines lack adequate workforces to implement projects, therefore, delaying projects.

Therefore, the ventilation system lacks optimisation for improved operational efficiency. Scope exists for an improved ventilation network which may potentially result in improved working conditions and energy efficiency.

Due to the depth of Mine X, no refrigeration is required as of yet. However, due to the configuration and design of the mine, it will not be possible to add refrigeration systems, motivating the need for an updated ventilation system.

Mine X is approximately 1.3km deep. Mine X consists of three 1MW surface fans on the upcast shaft. The main fan assemblage is configured as depicted in Figure 9 (c). The surface fans extract the heat from the stoping areas via raise boreholes and airways. Mine X also uses a U-tube ventilation configuration and an exhaustion type auxiliary system.

Traditionally the heat extracted from the stoping areas is exhausted via the RAW, however, because of the design constraints, there is no dedicated RAW at Mine X. The heat is thus exhausted via travelling ways and chairlifts sections. The lack of the dedicated RAW further complicates the way in which the mine is ventilated.

It is critical for the surface fans and the ventilation network to operate efficiently as the surface fans are the primary source used to ventilate and extract heat from underground. Due to the nature of the mine, short-term fixes are implemented to solve the immediate problems.

Deep-level mining does not allow for dynamic changes to be implemented on the volatile ventilation system. Network inefficiencies do exist throughout the ventilation system. It is necessary to investigate the ventilation network and identify the inefficiencies, evaluate the system and address the major issues.

The primary objective of the initiative is to improve the operational efficiency of the ventilation system. By improving the operational efficiency, this may result in improved air-flows, better underground temperatures and safer working conditions. Because of the improvement, a possible energy efficiency may realise.

A generic solution strategy is required to ensure that the challenges in the ventilation sector are rectified on a long-term basis. The solution should be dynamic to accommodate system changes in the underground network.

The solution developed for evaluating the ventilation system and addressing the key inefficiencies is a repetitive process. The process is explained in more detail below.

4.2 Identify main network inefficiencies

4.2.1 Identify KPI's

It is critical to identify the key performance indicators and to investigate their role within the system. The key performance indicators identified are as follows:

- Surface fan performance
 - Temperature
 - Static pressure
 - Volumetric air flow
 - Fan efficiency
- Airways (Active, inactive, travelling ways, escape routes etc.)
 - Temperature
 - Static pressure
 - Volumetric air flow
 - Fan efficiency
- Ambient conditions (Temperatures and pressure)
- Atkinson's resistance (System resistance)

Once the key performance indicators are identified, detailed ventilation audits on the various levels need to be performed to form an understanding of the ventilation network system. The detailed ventilation audits will highlight the problematic areas which require optimisation.

4.2.2 Perform detailed ventilation audits

Detailed ventilation audits were performed on the active mining areas as this is the main concern for improvement. The active mining areas are situated on 117L, 121L and 129L. Figure 48, Figure 49, Figure 50 are detailed representations of the active mining levels obtained from the initial ventilation audits, as seen in Appendix E.

The equipment required for the underground ventilation audits are as follows:

- Rotating vane anemometer
- Laser distance meter
- Sling psychrometer
- Digital barometer
- Mechanical pressure manometer

The purpose as well as the correct measurement technique of the various measurement instruments has been discussed in detail, in Section 2.3. Various different methods for the proper use of the measurement equipment has been discussed, however, only few are most suitable for the case. Table 8 explains the different KPI's that require investigation and the most suitable method to investigate the parameters of the KPI.

Table 8: KPI and chosen measurement technique

KPI	Instrument	Measurement technique
Underground haulage air flow	Rotating vane anemometer Laser distance meter	• The continuous traverse method was used. • The six point distance method was used to determine the cross sectional area.
Underground haulage temperatures	Sling psychrometer	The single point method was used.
Underground stoping temperatures	Sling psychrometer	The single point method was used.

Surface fan air flow	Rotating vane anemometer	- The continuous traverse method was used. - The six point distance method is used to determine the cross sectional area
Surface fan static pressure	Mechanical pressure manometer	The static pressure measurement technique was used explained in section 2.3.3.
Ambient conditions (Pressure and temperature)	Digital barometer Sling psychrometer	- The single point method was used. - The single point method was used.

The KPI's, instruments and techniques discussed in the above-mentioned table are the most suitable options chosen due to the case and the performance.

The detailed audits were performed several times throughout the implementation of the solution strategy. The initial and post implementation results are discussed and compared in the validation section of the entire strategic approach to enable a comprehensive comparison and understanding.

4.2.3 Identify network inefficiencies

After the detailed ventilation audits were performed, a comprehensive performance analysis of the results revealed that the major network inefficiencies that exist on the active mining levels are:

- Inactive working areas receiving ventilation
- Re-circulation of air

Table 9 lists the inefficiency at the investigated area as well as the purpose of the cross cut. This analysis will help determine a suitable solution for each of the inefficiencies. The purpose of the cross cut determines the type of solution required.

Table 9: Identified inefficiencies on focus levels

Level	Cross-cut	Inefficiency	Purpose of area
117	Main haulage	Air is re-circulating in the haulage	Travelling way
129	W6A	Inactive area receiving ventilation	Travelling way

129	E3	Inactive area receiving ventilation	Travelling way
129	E5	Inactive area receiving ventilation	Travelling way
129	E6	Inactive area receiving ventilation	Travelling way
129	E7E	Inactive area receiving ventilation	Travelling way
129	E7A	Inactive area receiving ventilation	Travelling way
129	E8	Inactive area receiving ventilation	Travelling way
129	Main haulage before E8	Air re-circulation	Travelling way

Further investigation yielded that some of the above cross-cuts are not active mining areas however are used for other purposes such as travelling ways and safety purposes. Detailed ventilation audits were performed on the remaining levels within the mine to identify more inefficiencies on the higher levels. Table 10 lists the inefficiencies and the purpose of the level.

Table 10: Inefficiencies identified on remaining levels

Level	Cross-cut	Inefficiency	Purpose of area
60	Station	Inactive area receiving ventilation	None
90	Station	Inactive area receiving ventilation	Travelling way
110	Main haulage	Inactive area receiving ventilation	Travelling way

The identified inefficiencies are used in the next phase of the strategy to develop a suitable solution. It is crucial to ensure the inefficiencies are identified correctly, as the solution strategies are based upon the results obtained in this section.

4.3 Develop and simulate a suitable solution strategy

4.3.1 Develop a solution strategy

The solution development is aimed at developing a suitable cost-effective solution for the identified inefficiency. It is important to ensure the correct solution is chosen for the inefficiency of the given location. The solution must still accommodate the purpose and use of the located area while

resolving the ventilation inadequacy. The solutions mentioned in Table 11, are based on the investigated purpose mentioned in Table 9 and Table 10.

Table 11: Developed solutions for inefficiencies

Level	Cross-cut	Inefficiency	Solution
60	Station	Inactive area receiving ventilation	Seal off level
90	Station	Inactive area receiving ventilation	Seal off level
110	Main haulage	Inactive area receiving ventilation	Install two ventilation doors
117	Main haulage	Air is re-circulating in the haulage	Install a ventilation door Install two booster fans (45kW)
129	W6A	Inactive area receiving ventilation	Seal off cross cut
129	E3	Inactive area receiving ventilation	Install a ventilation door
129	E5	Inactive area receiving ventilation	Install a ventilation door
129	E6	Inactive area receiving ventilation	Install a ventilation door
129	E7E	Inactive area receiving ventilation	Install a ventilation door
129	E7A	Inactive area receiving ventilation	Install a ventilation door
129	E8	Inactive area receiving ventilation	Install a ventilation door
129	Main haulage before E8	Air is re-circulating in the haulage	Install a ventilation door Install two booster fans (45kW)

4.3.2 Simulate and verify solution strategy

PTB 3D simulation software was used to build a simulation as the simulation software is the most suitable. As discussed in Section 2.4, PTB 3D software can be used on an existing system to simulate the ventilation network. PTB 3D is the preferred simulation software for ventilation analysis due to the easy use and accurate results. PTB 3D has proven to be accurate and useful in previous studies regarding complicated network configurations.

Two different case simulations were performed to illustrate the effect of the increased resistance on the performance of the surface fan. The initial simulation was based on the initial results obtained from the initial ventilation audit (Underground and surface fan). The verification simulation is based upon the concept of increasing the system resistance and improving surface fan performance when re-routing airflow and sealing off inactive working areas.

A traditional U-tube mine layout was used with the various ventilation components. The simulation chosen is a simple mine ventilation structure consisting of the surface fan, air tunnels and haulages and air pressure boundaries.

The simulation layout, details and inputs are discussed in further detail in Appendix C. Both simulation results are discussed in more detail in Appendix D. Table 12 is an overview of the main results obtained from the two simulation cases. The results are focussed on the performance of the fan and the underground ventilation resistance (Door fraction). The door fraction is the underground air tunnel regulator which regulates the amount of air passing through the air tunnel. The air flow through the air tunnel is manipulated with the door fraction to achieve the desired result. The air flow control mimics the developed solution strategy, although the developed solution strategy effect can't be quantified in terms of system resistance.

Table 12: Comparison of surface fan simulation results

Description	Initial simulation	Verification simulation	Difference
Door fraction	0.8	0.5	-0.3
System resistance	0.033	0.042	+0.009
Static air pressure (Surface fan)	2.05 kPa	2.39 kPa	+0.34 kPa
Volumetric air flow (Surface fan)	249.01 m ³ /s	238.66 m ³ /s	-10.35 m ³ /s
Fan power (Surface fan)	843.6 kW	902 kW	+58.4 kW
Airpower	510.45 kW	570.41 kW	+59.96 kW
Fan efficiency (Surface fan)	61%	63%	+2 %

Increasing the door fraction in the verification simulation led to an increased system resistance. This increase effects the performance of the surface fan as the static pressure increases whilst the

volumetric air flow decreases. The surface fan efficiency also increases because of better performance. Ultimately, manipulating the airflow from inactive to active areas, increases the system resistance and offers better surface fan performance.

Therefore, the simulation substantiates the developed solution strategy and action required at the inactive working areas.

4.3.3 Optimise solution strategy

Generally, the simulation is used to optimise the solution strategy, ensuring via the iterative process, the most suitable solution is obtained. The simulation should be altered and adjusted until the desired result is achieved prior to implementation.

However, in this case, due to time limitations and constraints, the concept of the solution strategy was simulated and proved positive. Mine X required immediate action to resolve the inefficiencies at hand due to weak ventilation performance and governing laws.

4.4 Address network inefficiencies

4.4.1 Implement the solution strategy

The final step in the strategy approach is to implement the developed solution discussed in Section 3.4.1. The actions presented in Table 11 were implemented by mine personnel. Detailed tracking sheets and audits during the implementation was noted on both the levels and the surface fan performance.

Table 32 and Table 33 located in Appendix E, shows the actions completed at the certain levels, the dates of the actions completed, and which levels were audited out of the focus levels to see the effect on them. Initial and post-audits were performed to serve as a comparison and validation of the solution strategy. The results are compared prior to and after implementation in the above-mentioned tables.

As seen in Appendix E, the corresponding detailed layouts of the active levels after the implementation have been updated with the appropriate ventilation symbols at the installed locations. Figure 51, Figure 52 and Figure 53 illustrate the validation audit of the implemented solution strategy. In these figures, it can be noted the solution strategy was implemented at the identified inefficiencies with substantial ventilation network updates.

4.4.2 Validate KPI's

Evaluating the results after the developed solution is implemented is necessary to ensure the success of the initiative. Detailed ventilation audits will be required again to ensure the success of the initiative. The key performance indicator identified is the stoping temperatures. The purpose of the initiative was to optimise the ventilation system – to ensure a safe working environment.

Underground results

Figure 32 displays the stoping wet bulb temperatures over the past eighteen months. It is noted that similar stoping temperatures were experienced in the two contrasting summer periods (December to March).

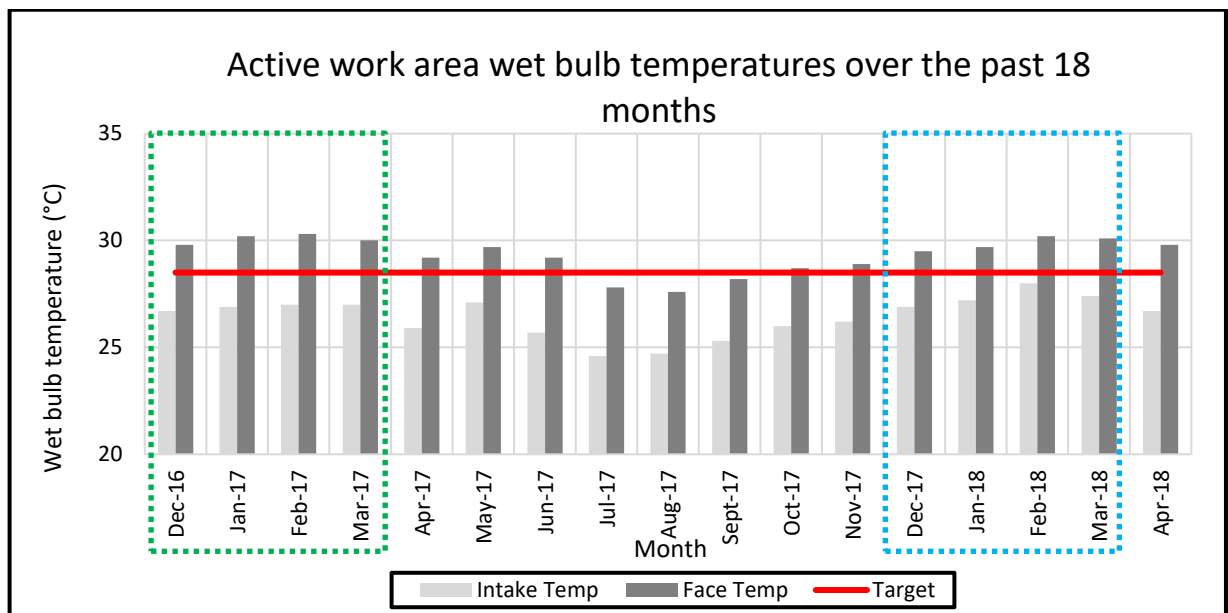


Figure 32: Comparison of wet bulb temperatures in the stopes

In the 2016-2017 summer period, three surface fans were utilised. The 2016-2017 summer period is depicted in Figure 32 by the green dotted frame and the 2017-2018 summer period is depicted by the blue dotted frame. The intake and face temperatures measured are significantly similar between the two periods. Due to the similarity, it can be noted that working conditions were sustained although the fan configuration was altered by reducing the number of fans running in the summer period. This was caused by the optimised underground ventilation network.

¹ Graph provided by Fidelis Mufara – Occupational hygienist Mine X

After the ventilation network was optimised, two surface fans were operated in the 2017-2018 summer period. This therefore resulted in an energy efficiency over the summer period.

Surface ambient results

The underground and surface temperatures (wet bulb and dry bulb), volumetric air flows, surface fan pressures and volumetric air flows were audited systematically after implementation of the solution.

Ambient conditions have a very significant role on the ventilation system because of the network configuration. Therefore, it is important to monitor the ambient conditions. Figure 33 illustrates the increase in ambient temperatures prior to the summer months.

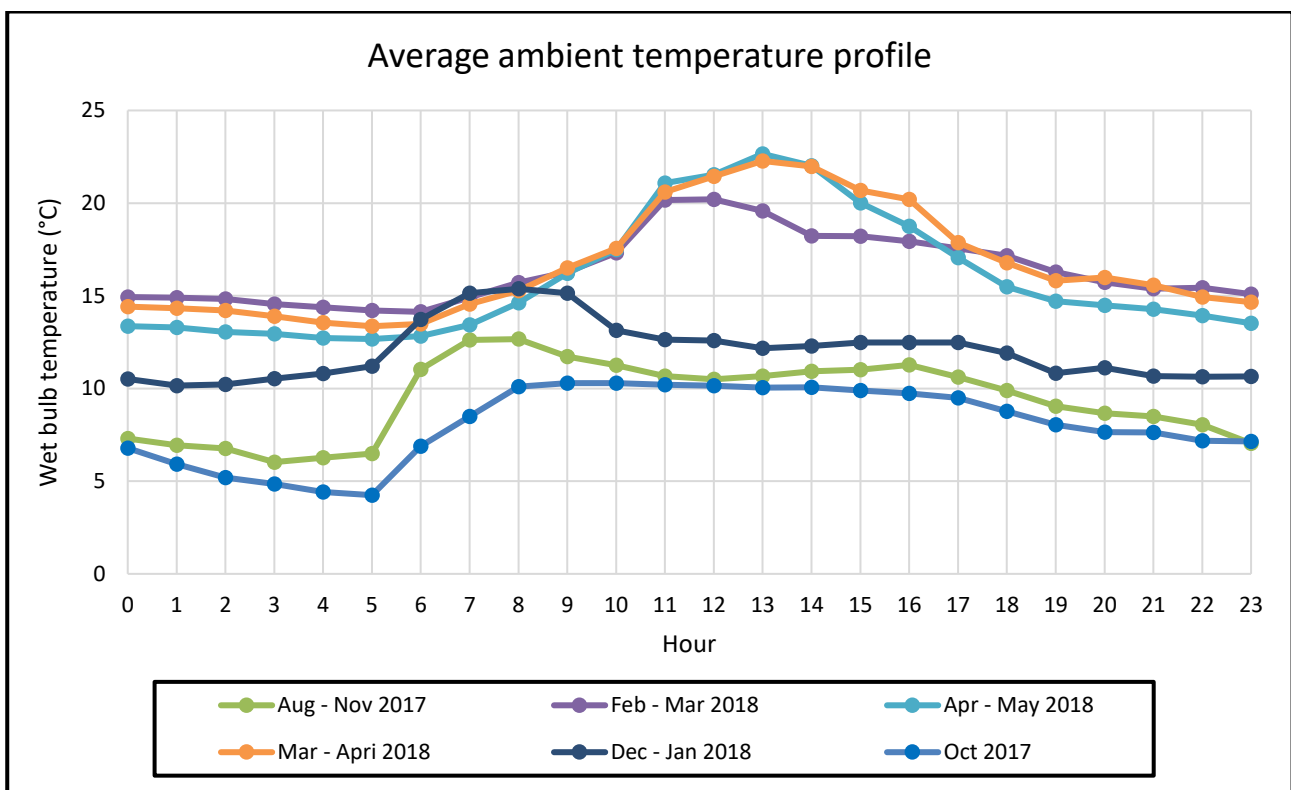


Figure 33: Average surface wet-bulb temperatures over project implementation

The graph depicts the change in wet-bulb temperature during the investigation period. The graph depicts an average monthly profile of measured values throughout the investigation period. It is notable that there is a significant difference between the months leading up to summer and the months during summer. The temperature increases over the period and due to the configuration of the ventilation system, ambient surface air is introduced into the mine. Therefore, ambient surface air is a key factor and needs to be monitored. The values also indicate a cooler summer period especially in the November and December months.

Surface fan performance results

Surface fan pressure (static pressure), air velocity, drift area and volumetric air flow were measured and calculated throughout the implementation of the initiative to monitor the surface fan performance. The same measurement point was maintained for the surface fan air velocities, static pressures and areas throughout the investigation.

The surface fans cross-sectional areas were measured accordingly. The surface fan assemblage consists of three main airways of the same structure and size. The information obtained follows in Table 13.

Table 13: Surface fan cross-sectional area parameters

Description	Value [m]
Average width	4
Average height	4.67

From the information in the above-mentioned table, the cross-sectional area at the measurement point is 18.68 m² using Equation 8, as the shape of the airway is rectangular. The cross-sectional area obtained may be used to determine the volumetric airflow rate for all three surface fans.

The surface fan audit results are tabulated in Table 34 located in Appendix E. The results include the surface fan performance before and after the initiative implementation. Table 14 is a summary of the surface fan KPI's obtained from the initial and validation audit. The table shows the surface fan performance increase.

Using Equation 5, discussed in section 2.3.1, the volumetric airflow may be calculated using the measured air velocity and calculated cross-sectional area.

The static pressure for all three fans increased over the investigation period as expected from the fan affinity laws discussed in section 2.2.1 and the simulation performed. The static pressure was measured and monitored, to correspond with the pressure type used on the original surface fan curves. The volumetric airflow rate also increased, although it was expected to decrease. The surface fans maintained a 100% open guide vane position throughout the investigation period.

Chapter 4

Table 14: Surface fan performance results prior and after initiative implementation

Surface fan audit											
			Fan 1			Fan 2			Fan 3		
	Date	Barometric pressure (kPa)	Static Pressure [kPa]	Air velocity [m/s]	Volumetric airflow [m ³ /s]	Static Pressure [kPa]	Air velocity [m/s]	Volumetric airflow [m ³ /s]	Static Pressure [kPa]	Air velocity [m/s]	Volumetric airflow [m ³ /s]
Initial audit	10 Aug-17	85.2	2.09	11	206	2.06	12.05	225	2	12.5	240
Validation audit	8 May-18	86.4	2.16	12	224	2.25	12.52	234	2.3	13.5	252

Ambient surface temperature and pressure readings were taken during the surface fan audit for both the initial and validation audit. Table 15 lists the air parameters used to calculate the air density to adjust the surface fan curve to the new calculated density. The air parameters remained relatively constant over the investigation period.

Table 15: KPI measurements during surface fan audits

	Barometric pressure (kPa)	Temperature - Dry bulb [°C]	Temperature - Wet bulb [°C]
Initial audit	86.5	22	17.9
Validation audit	86.5	25	18.5

Table 16 lists the surface fan instantaneous power consumption before and after the initiative implementation. Different surface fan configurations are run. Throughout the investigation, the running configuration is changed to rotate the surface fans and ensure an equal running hour count.

Table 16: Instantaneous power of surface fans before and after initiative implementation

	Fan 1	Fan 2	Fan 3
Instantaneous power before implementation [kW]	849	803	892
Instantaneous power after implementation [kW]	856	705	888

The measured results of the surface fan prior, during and after the investigation (Pressure, Velocity and Volumetric flow) from Table 14, are plotted in the following graphs. From Figure 34 and Table 33, trends of the three-surface fan's performance can be deduced.

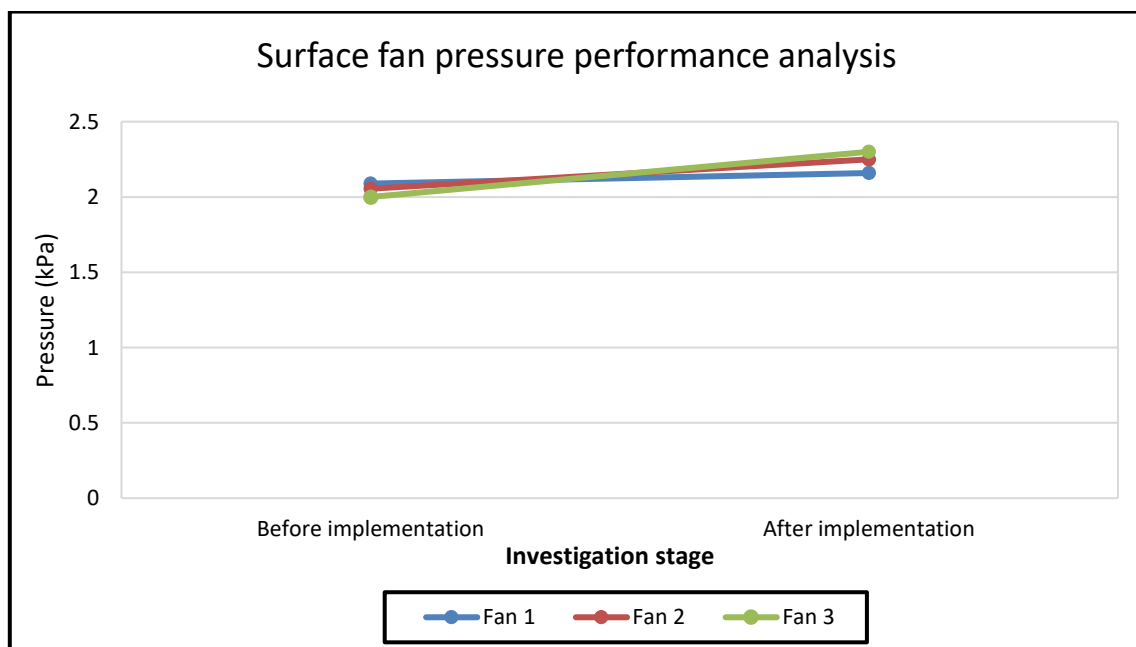


Figure 34: Surface fan static pressure graph

It was expected to see an increase in the static pressure of the surface fan after the initiative has been implemented according to the fan affinity laws. Figure 34 demonstrates the pressure change

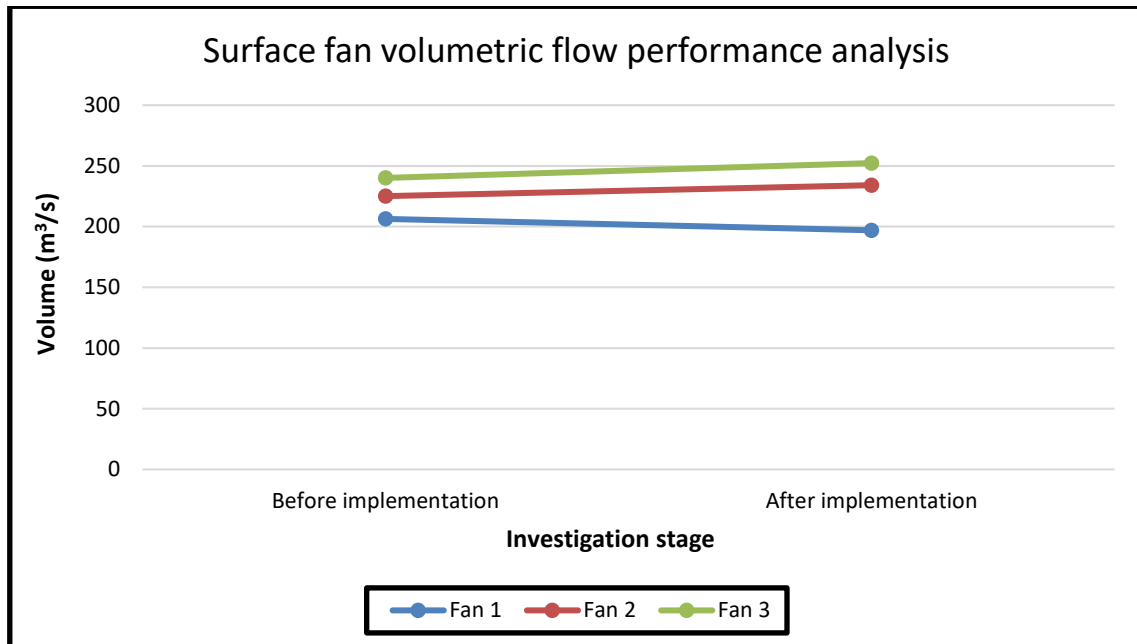


Figure 35: Surface fan volumetric flow graph

Because of the increase in the static pressure, according to the fan affinity laws explained in the previous sections, the volumetric air flow is supposed to decrease. In Figure 35, the volumetric air flow for fan 3 decreased. The remaining two fans experienced a slight increase in volumetric air flow. Possible reasons for the slight increase of the volumetric air flow may be measurement technique, underground network shifts etc.

Using the results obtained from the ventilation audits and surveys prior and post solution implementation, the surface fan performance may be calculated. The airpower and Atkinson's resistance of the surface fans may be calculated using Equation 15 and Equation 17 discussed in Chapter 2.

Table 17 compares the airpower of the surface fans prior and post solution implementation.

Table 17: Surface fan performance comparison - Airpower

	Initial airpower [kW]	Current airpower [kW]
Fan 1	431	484
Fan 2	463	482

Fan 3	480	580
Average	458	515

The average airpower of the system has increased due to the increased static pressure of the surface fan although the airflow decreased slightly.

The Atkinson's resistance was calculated and tabulated in Table 18 using Equation 17.

Table 18: Surface fan performance comparison - Atkinson's resistance

	Initial resistance [Ns^2/m^8]	Current resistance [Ns^2/m^8]
Fan 1	0.049	0.049
Fan 2	0.041	0.037
Fan 3	0.034	0.036
Average	0.041	0.039

The average of the Atkinson's resistances decreased by 0.002. The significantly constant airflow rate is the root cause of the decreased value. According to the developed simulation, the resistance is supposed to increase.

The efficiencies of the surface fan increased due to better underground networking and pressures. As a result of the increased static pressure, the surface fan efficiencies increased. The surface fan efficiencies can be calculated using Equation 16. The results of the are displayed in Table 19.

Table 19: Surface fan performance analysis - Efficiency

	Initial efficiency	Current efficiency
Fan 1	0.51	0.57
Fan 2	0.58	0.68
Fan 3	0.54	0.65
Average	0.54	0.63

It is noted that the efficiencies have increased significantly over the initiative period. This is beneficial to the mine as it will result in an improved operational efficiency and lead to better ventilated working areas. The system resistance and pressure provide an indication of the extraction of heat from the working areas. An increase in the overall system pressure will result in better extraction of warm air from working areas. According to the fan laws, as the pressure increases, the airflow rate decreases which is not considered a negative attribute provided heat is being extracted from the correct areas.

The surface fan results obtained can be compared with the surface fan curve. It is important to compare both the static pressure and power of the surface fan with the surface fan curve. However, before the surface fan curves can be plotted, it is necessary to ensure the air density is determined and the fan curve is adjusted according to the determined density.

The surface fan curve, initially, was plotted with an air density of 1.0 kg/m^3 on the original fan curve. To accurately adjust the curve for the measured results, the current air density is required. The curve adjustment is the product of the original adjustment and the relation between the calculated and original density.

The air density for the different audits can be read of the psychrometric chart located in Appendix A using the information obtained from the ventilation audit, listed in Appendix A. The determined densities are listed in Table 20.

Table 20: Calculated air densities

	Initial audit	Verification audit
Air density	1.044	1.038

The air densities are then used to calculate the adjusted fan curve. The relations can then be calculated using Equation 18 for the curve adjustments. Table 21 depicts the air density relations that are multiplied with the pressure specified on the original fan curve to adjust the curve to measured conditions.

Table 21: Air density relations

	Initial audit	Verification audit

Air density relation	1.044	1.038
-----------------------------	-------	-------

Equation 19 can be used to adjust the static pressure on the fan curve. The adjusted static pressure is then used to plot the adjusted fan curve. The 100% guide vane curve is adjusted on the original fan curve due to the position of the guide vanes during the investigation.

The surface fan curves in Figure 36, Figure 37, Figure 38 and Figure 39 has been adjusted according to the air density relationship equation in Section 2.3.4.

Figure 36 and Figure 37 display the surface fans performance prior to and after the initiative based upon the un-edited surface fan curves, located in Appendix E for further reference.

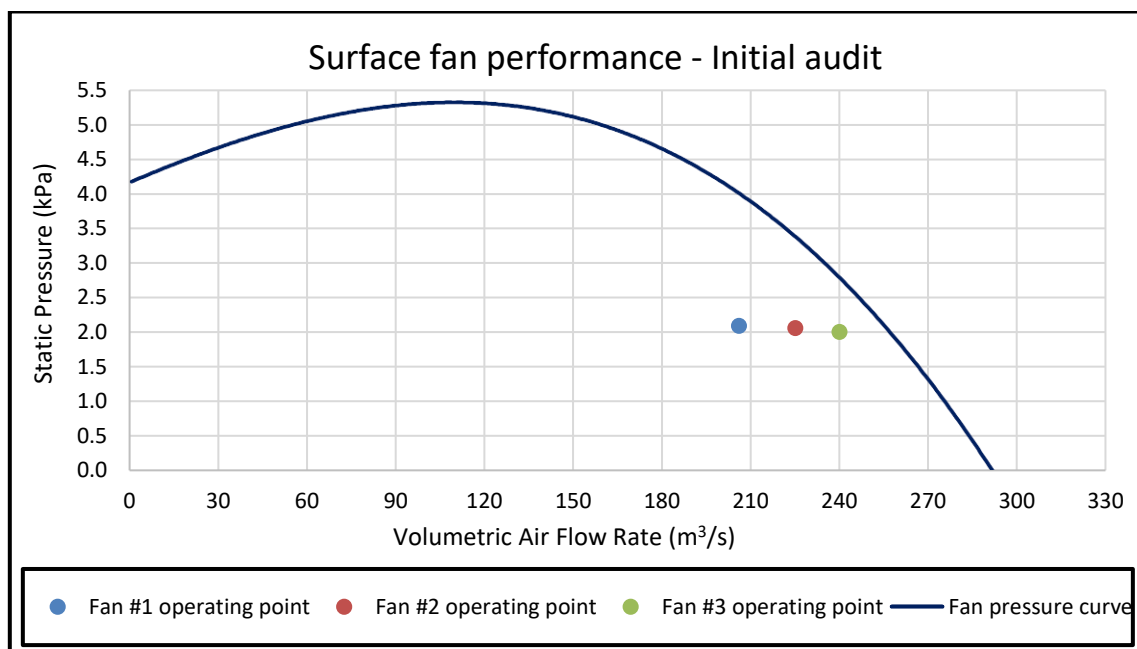


Figure 36: Surface fan performance – Initial audit

The operating points in the above-mention graph are near the curve. This is an indication of the performance and possible performance of the fan according to the design specification.

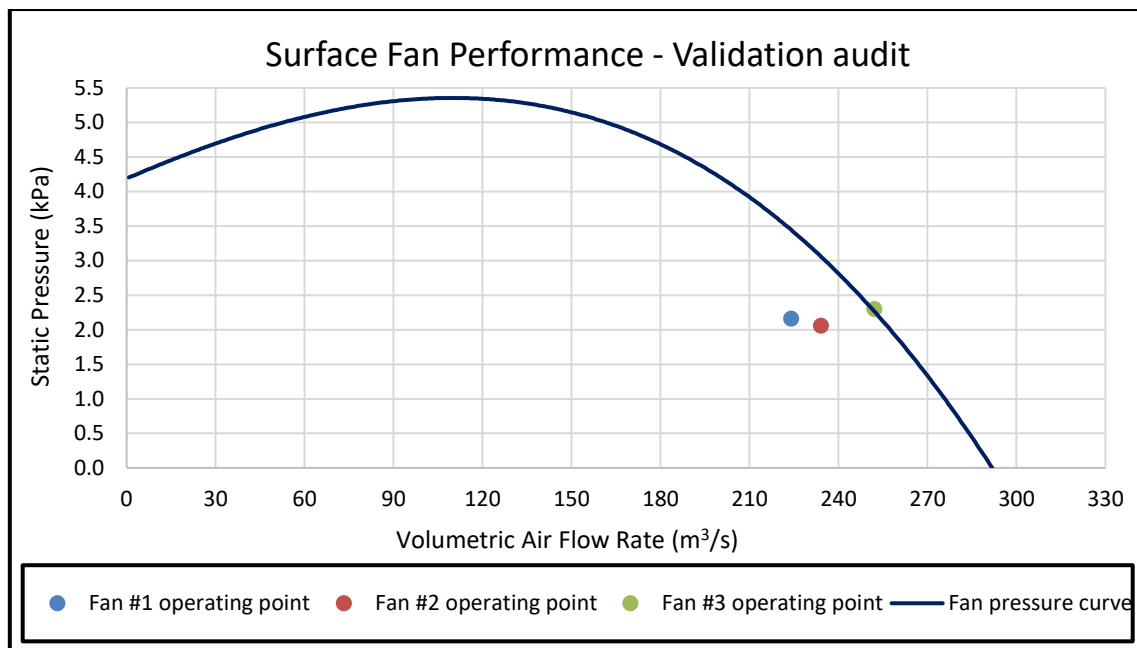


Figure 37: Surface fan performance – Validation audit

The validation audit graph depicts the operating points after the implementation of the solution. The operating points have shifted closer to the design specification of the surface fan. This was expected due to the increased airpower of the system and surface fans.

Figure 38 and Figure 39 display the surface fan's efficiency shift. As the performance of the surface fan increases, the efficiency of the fan increases. Figure 38 shows the performance analysis of the surface prior to the implementation of the initiative. Figure 39 shows the performance analysis of the surface fan after the initiative had been implemented.

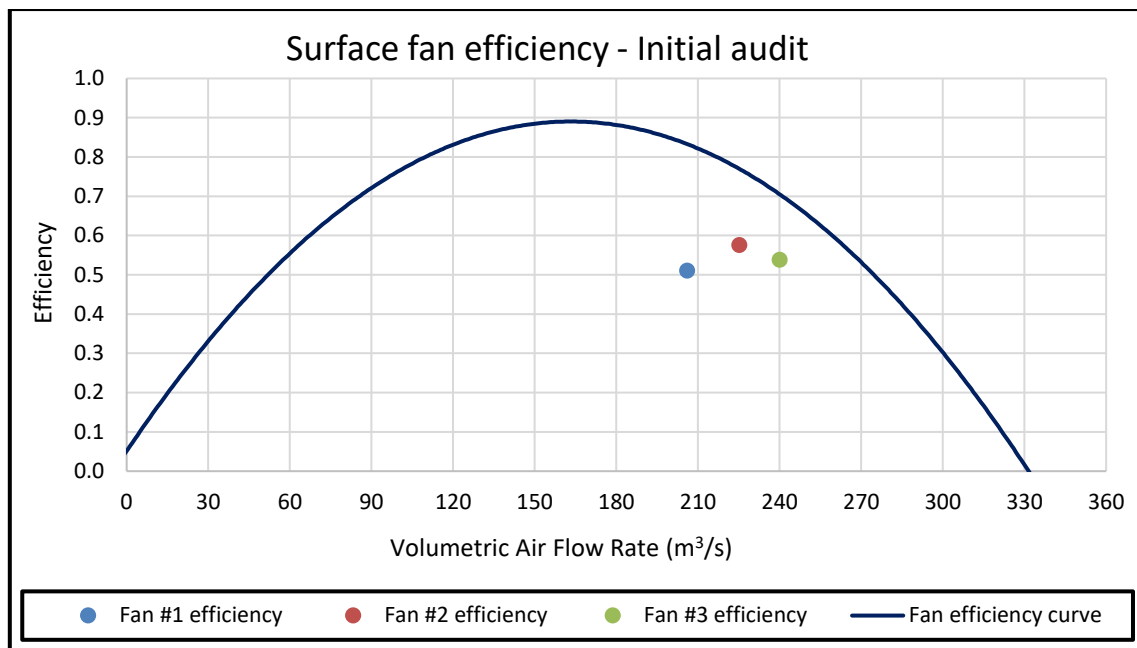


Figure 38: Surface fan efficiency curve – Initial audit

The operating points in the above-mention graph are near the curve. This is an indication of the efficiency of the of mentioned operating points prior to the implementation of the solution.

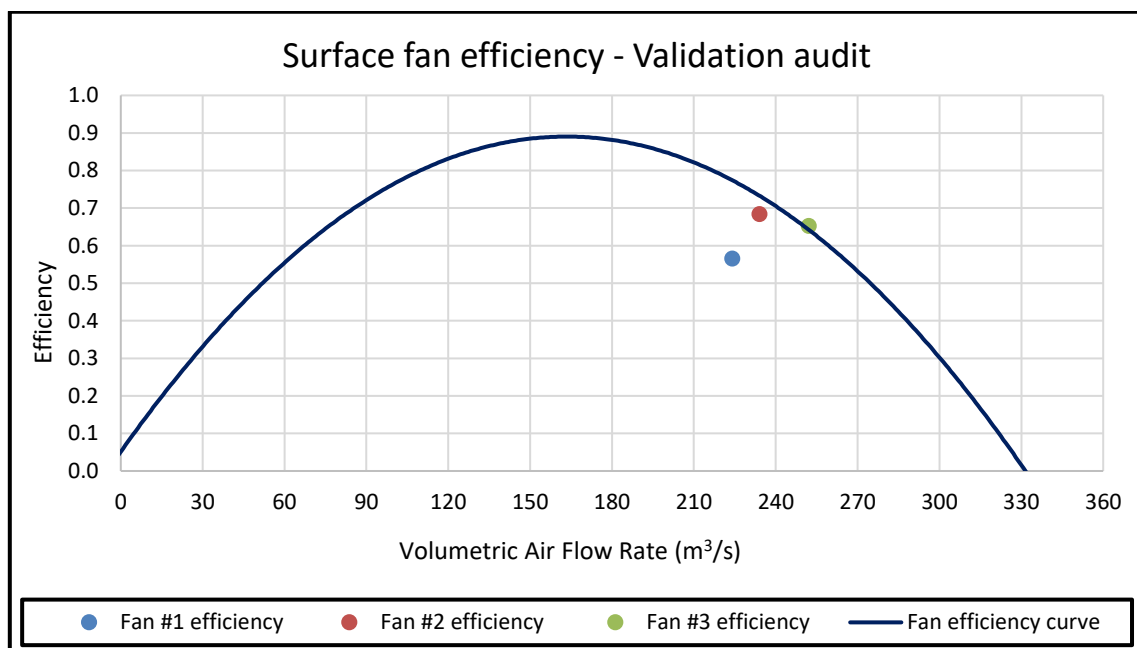


Figure 39: Surface fan efficiency curve – Validation audit

The validation audit graph depicts the efficiency of the operating points after the implementation of the solution. The operating points have shifted closer to the design

specification of the surface fan and have experienced an increase in performance and efficiency.

An increased fan system performance was realised due to the increased the system changes. The operating points experienced an increase in static pressure and as a result, an overall increased system resistance. This led to an increased surface fan performance and efficiency, thus an overall increased operational efficiency. The increased overall operational efficiency assisted with the optimised fan configuration.

Energy efficiency results

The optimisation of the ventilation network allowed for sustained working conditions during the summer 2017/2018 summer period although the third fan was not operational. During this summer period, two surface fans were utilised instead of the traditional three.

The shutdown of a surface fan resulted in a saving of 850kW which equates to R 3.2 million over the 2017-2018 summer period according to the Eskom MegaFlex 2017/2018 tariffs.

Figure 40 is a graph comparing the difference in power profiles between the summer period in 2016-2017 and 2017-2018. The baseline represents the summer 2016 – 2017 summer period (Three surface fans) while the actual line represents the optimised system (Two surface fans).

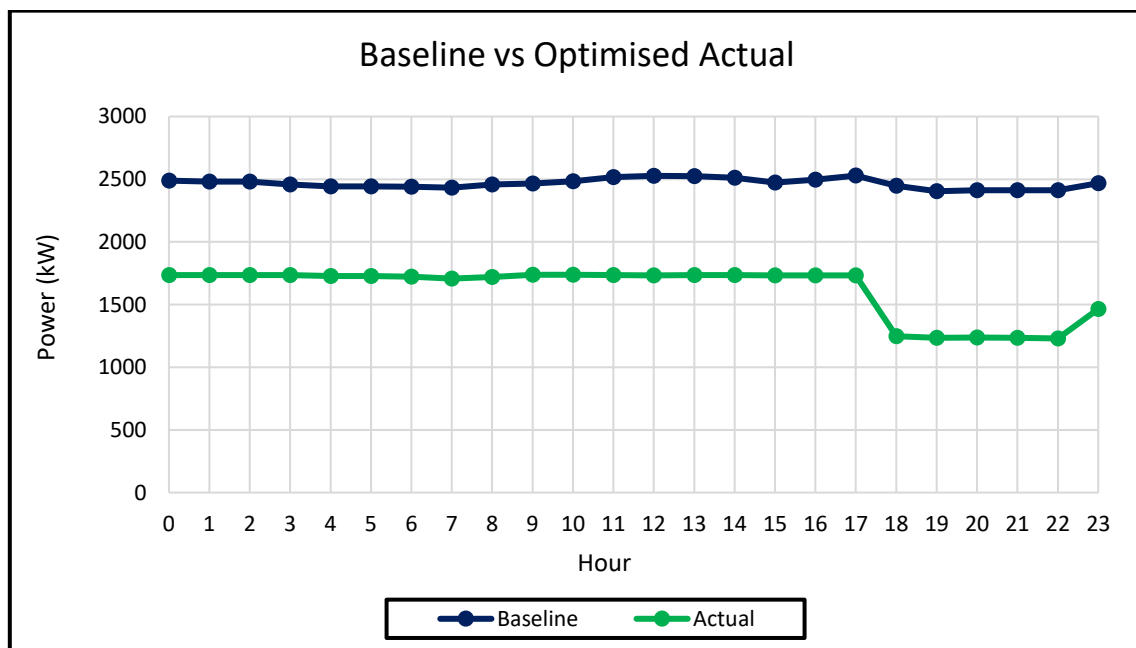


Figure 40: Surface fan power profile comparison

An added benefit, due to the optimised surface fan configuration, is a third surface fan is available as a back-up in this period especially when all three fans usually operate. This is beneficial as this is a crucial period where ventilation is most needed, especially as the main fan assemblage is the primary source of ventilation.

4.5 Conclusion

A ventilation audit was performed at Mine X to identify the network inefficiencies and implement a solution strategy to improve the operational efficiency. Because of the improved operational efficiency, the surface fan configuration may be optimised. A fan re-configuration may lead to a possible energy efficiency.

The solution strategy developed entailed rerouting the air to the active working areas. Ventilation doors, regulators and seals were installed in the old working areas according to their use and status. Some areas are still being used as traveling ways etc. therefore still need to be accessed. The solution for the specific inefficiencies is determined by the purpose and use of the haulage. Although stopings may be inactive, the airway and haulage may still be used depending on the location and purpose, therefore not all inactive areas will be sealed off.

The generic solution approach described Chapter 3 was followed during the study. The ventilation system was critically analysed to gain a full and comprehensive understanding of how the system operates and to identify the major inefficiencies. Correctly identifying the major inefficiencies is key in this procedure. The major inefficiencies identified were mainly inactive working areas being ventilated unnecessarily. Secondary inefficiencies identified include the circulation of air near development ends.

Network inefficiencies were analysed to determine the most suitable solutions. This process is re-iterated until a viable solution is obtained which will ensure objectives are met. A simulation was built to verify the developed solution. The simulation revealed an increase in the system resistance when inactive working areas are sealed, and airflow is channelled to the required areas. An increase in the system resistance results in a reduction in the airflow rate and an increase in the pressure. This ultimately results in better surface fan performance.

The solution strategy was implemented at the identified inefficiencies and brought forth the following benefits:

- Improved surface fan assemblage performance

- Sustained working conditions
- Improved ventilation operational efficiency
- Optimised surface fan assemblage configuration during summer months
- Energy efficiency

Ensuring the surface fan was kept off during the summer period led to a energy efficiency of 850kW, which equates to R3.2 million.

The optimised ventilation network yielded sustained working conditions with an added benefit - energy efficiency.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Gold mining production in South Africa has declined significantly over the last few decades. There are numerous challenges that the mining industry faces that influence the production negatively. One of the main challenges faced in the industry is extreme working conditions. Working conditions are unfavourable due to the increasing depths, confined spaces, high temperatures and humidity especially in deep-level mines. There are also additional heat sources that contribute to the heat load and overwhelm underground working conditions. As a result of the conditions that the workers are subjected to, health and safety is a major concern.

On the other hand, ventilation is faced with its own challenges such as complicated network systems which increase the difficulty of adequately ventilating working areas. The constant extensive development and excessive mining makes continuous ventilation updates tough to implement and remain on par with system changes. Ventilation systems lack dynamicity and long-term solution planning which can adapt with major system changes.

Therefore, this study focussed on developing a generic strategic approach to analyse ventilation systems, identify the main inefficiencies and develop a suitable long-term solution. The aim of the generic solution approach is to ensure network inefficiencies are identified quickly and a suitable solution is developed and implemented to ensure a long-term effect. This results in eliminating outdated ventilation systems and an adaptive nature within the ventilation system. The generic strategy is an iterative process which can constantly be applied to a system.

The generic strategic approach can be divided into three main steps, namely identify, develop and address. A critical step in the strategic generic approach is correctly identifying the inefficiencies based upon the ventilation surveys data. Inaccurate data will result in false identified inefficiencies, leading to incorrect solution strategies being developed and implemented. Special care and time should be devoted to the first step in the process.

The developed strategy was implemented on one gold mine in South Africa (Mine X). The strategy was implemented to determine the major ventilation inefficiencies and develop a suitable solution to rectify the problems. The implemented solution was not only implemented

for this reason, however, also achieve a dynamic system which may adapt with system changes.

Upon implementation of the strategy, the main inefficiency identified within Mine X's ventilation system was numerous inactive working areas still receiving ventilation unnecessarily. The solution developed aimed to reroute the air to the active working areas with the use of auxiliary ventilation components.

The developed solution strategy was simulated using PTB 3D to verify the validity of the solution. The concept of the solution was simulated, increasing the underground resistance to better fan performance and the operational efficiency. Table 22 depicts the results obtained from the simulation.

Table 22: Generic strategy result validation

Description	Initial simulation	Verification simulation	Difference
System resistance	0.033	0.042	+0.009
Static air pressure (Surface fan)	2.05 kPa	2.39 kPa	+0.34 kPa
Volumetric air flow (Surface fan)	249.01 m ³ /s	238.66 m ³ /s	-10.35 m ³ /s
Airpower	510.45 kW	570.41 kW	+59.96 kW
Fan efficiency (Surface fan)	61%	63%	+2 %

It can be noted from the obtained simulation results, the surface fan performance increases as the system resistance increases. An increase in the static air pressure is also noted as the volumetric airflow rate decrease. According to the fan affinity laws discussed in Chapter 2, the relation between pressure and volumetric airflow is indirectly proportional. As the volumetric airflow decreases, the static pressure increases. The simulation verified the developed solution strategy.

The solution was implemented on the ventilation system, either sealing off working areas, installing access or ventilation doors and installing regulators. Some of the areas were not active, however, were still used for travelling purposes etc.

The surface fan performance was monitored throughout the investigation to validate the performance. The three surface fans performance prior to the investigation and after the investigation is listed in Table 23.

Table 23: Mine X's surface fan performance - Efficiency

	Initial efficiency [%]	Current efficiency [%]	Percentage difference (%)
Fan 1	0.51	0.57	11.8%
Fan 2	0.58	0.68	17.2%
Fan 3	0.54	0.65	20.4%

After the implementation of the solution strategy, the surface fan performance increased. The surface fan assemblage experienced an increased efficiency, airpower and a slight decrease in system resistance due to system changes implemented throughout the study.

The solution strategy was implemented at the identified inefficiencies and brought forth the following benefits:

- Improved surface fan assemblage performance
- Sustained working conditions
- Improved ventilation operational efficiency
- Optimised surface fan assemblage configuration during summer months
- Energy efficiency

As a result of the improved operation efficiency of the system, during the summer period, only two fans were required to achieve the same user requirement achieved with three surface fans. The optimised fan configuration resulted in an additional energy savings of approximately 850 kW which equates to R3.2 million annually.

The generic strategic solution approach is based upon the objectives stated in Chapter 1, which is to develop a generic ventilation approach to improve the operational efficiency of the ventilation system, sustain working conditions, ensure long-term strategic ventilation planning to create a sense of dynamicity and reduce ventilation costs.

The optimised ventilation network yielded sustained working conditions with an added benefit - energy efficiency.

5.2 Recommendation for future work

During the investigation and implementation of the solution strategy, a new challenge arose. The challenge included the lack of discipline and co-operation from miners regarding ventilation auxiliary components, especially access doors and air locks. During shifts, underground employees fail to follow prescribed ventilation protocol, by not properly closing the components. This results in a disruption in the ventilation system performance.

A wider simulation study with more auxiliary ventilation detail would be optimal when it comes to decision-making. The study would be able to examine performance parameters of the auxiliary components for an in-depth overview.

For future work, the following recommendations are advised:

- Further study to improve the ventilation commitment and co-operation from miners
- More comprehensive simulation study
- Assess optimal auxiliary control devices location
- Implementation of VSD's on the main surface fan assemblage after major system changes

Ventilation discipline is major issue underground, miners neglect adhering to ventilation protocol such as ventilation doors that need to remain closed, however are left open. The neglect results in system changes that affects the whole ventilation network negatively as the system does not work coherently anymore.

A more comprehensive simulation study will provide more detail in terms of flows and losses in haulages. A simulation model may also be used to develop several different cases which may be implemented without changing the physical network and provide detail in terms of which case suits the mine better.

Control devices such as booster fans are installed underground at locations which seem best, however no validation of the installation location is performed. Validating and optimising control device locations may result in improved operational outputs such as the working conditions.

The entire fan configuration has been optimised in the study, however it is possible to further optimise the airflows of the surface fans by implementing VSD's. VSD's can be beneficial although are initially expensive in terms of capital.

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Appendices

Appendix A: Ventilation literature

Figure 41 displays the psychrometric chart for air.

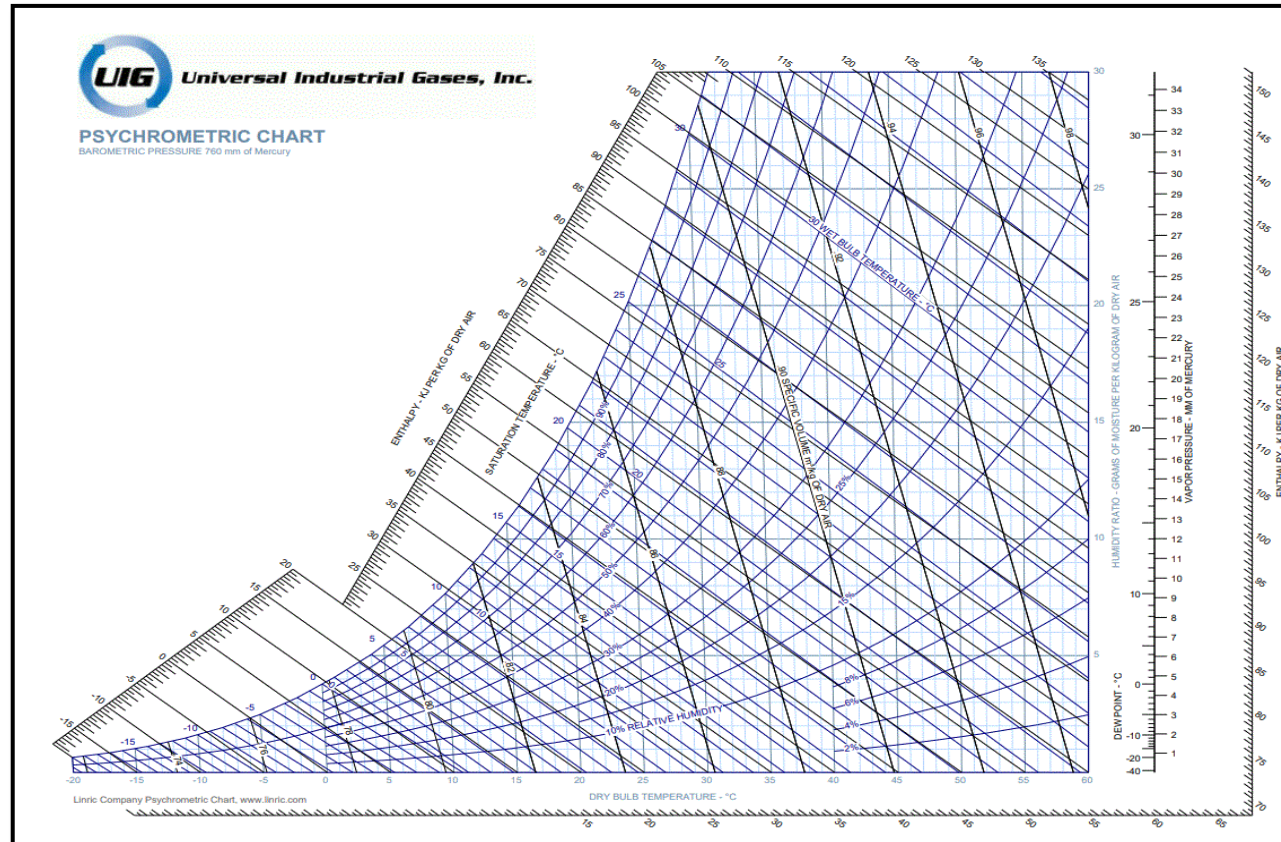


Figure 41: Psychrometric chart

Appendix B: Ventilation audit

Table 24 is an example of the sheet used to record the information obtained in the detailed underground ventilation audit.

Table 24: Ventilation audit sheet

	Volumetric air flow rate [m ³ /s]															Temperature (C°)	
Marker	Velocity [m/s]									Width [m]			Height [m]			Wet Bulb	Dry Bulb
1																	
2																	
3																	
4																	
5																	
6																	
7																	
8																	
9																	
10																	
11																	

Table 25 is an example of the audit sheet used to record the information obtained from the axial surface fan performance analysis.

Table 25: Surface fan audit sheet

	Ambient conditions					Velocity [m/s]		Width [m]			Height [m]		
Audit number	Barometric pressure [kPa]	Temperature – Dry bulb [°C]	Temperature – Wet bulb [°C]	Instantaneous power [kW]	Static pressure [kPa]	Time [s]	Speed [m]	1	2	3	1	2	3

Appendix C: Simulation overview and inputs

A simple simulation has been built to verify the concept of the solution strategy before implementation. Designing a full-scale simulation of the ventilation system may be time consuming, even though a simple solution may prove the concept. The aim of the simulation is to prove that when the resistance of the ventilation network is altered, there will be a variation in the performance of the surface fan. As the systems resistance increases, the performance of the surface fan will increase as a result. An increased performance means supplying more ventilation to active working areas.

Figure 42 illustrates the layout of the simulation used to verify the developed solution strategy (Chap 4). In the figure below, the mine layout used is a simple layout and consists of the main aspects required for a ventilation system. In the system listed below, the simulation consists of air tunnels, ambient condition boundaries, a calibration control and a surface fan.

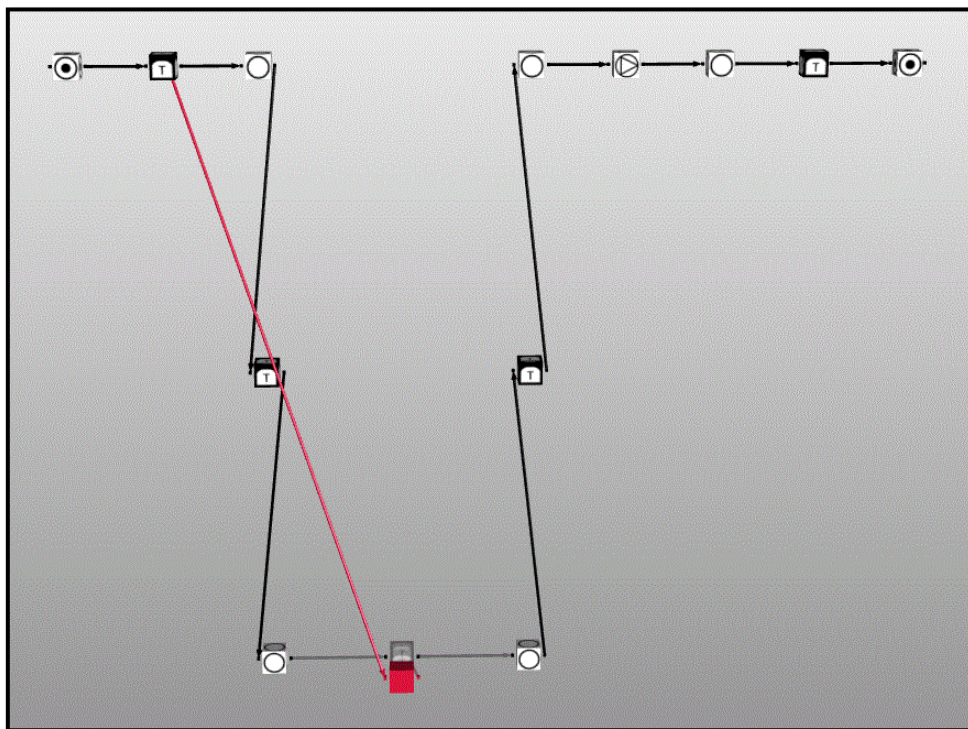


Figure 42: Simulation layout used to verify the solution strategy

Figure 43 is the rendered image of the system illustrated in Figure 42.

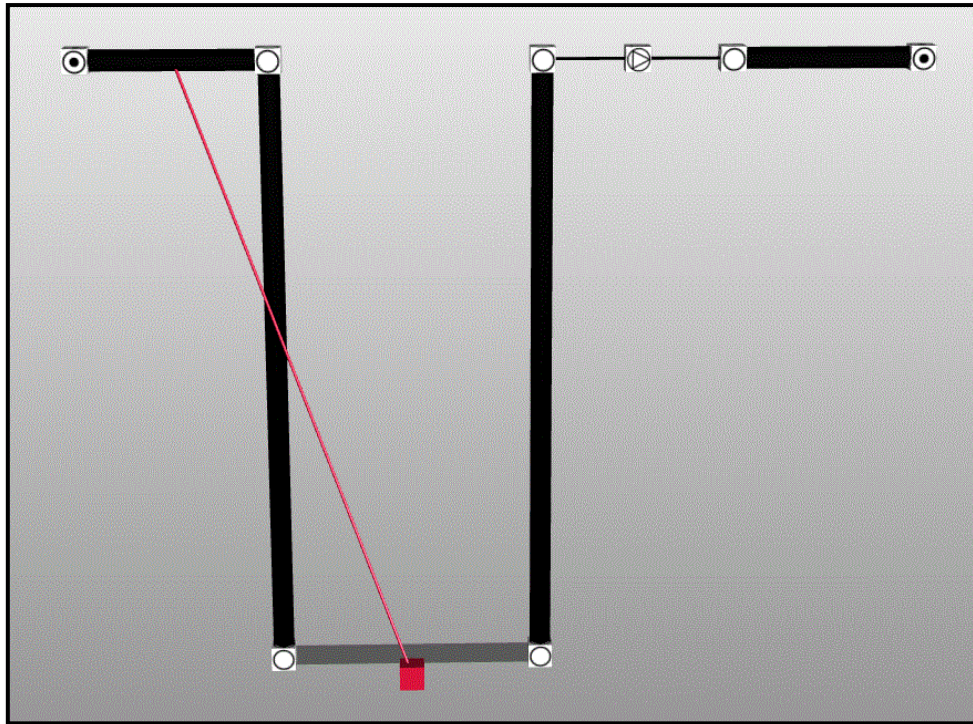


Figure 43: Rendered view of the simulation used to verify the solution strategy

As mentioned in Section 2.2.1 (Literature), changes in the performance of the surface fan, in terms of static pressure and flow, will follow the fan affinity laws and fan curve supplied with the surface fan.

The values contained in Table 26 specifies the inputs required for all the ventilation machinery required to simulate and verify the solution strategy. The inputs of the ventilation machinery and components have been selected to represent similar conditions of Mine A. The simulated results may not mimic the outcomes after the implementation of the solution. I will however provide an indication of the expected results.

Table 26: Simulation inputs before implementation of initiative

Component	Required data	
Air pressure boundary	Ambient pressure	86.5 kPa
	Ambient temperature	20 °C
Surface air tunnel	Flow area	12 m ²
	Door fraction	1

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	Flow perimeter	14 m
	Friction coefficient	0.01.
	Air tunnel length	30 m
Up-cast and down-cast air tunnel	Flow area	12 m ²
	Door fraction	1
	Flow perimeter	14 m
	Friction coefficient	0.01.
	Air tunnel length	100 m
Underground air tunnel	Flow area	12 m ²
	Door fraction	0.8
	Flow perimeter	14 m
	Friction coefficient	0.01.
	Air tunnel length	43 m
Surface air fan	Installed motor capacity	1000 kW
	Pressure 1	5.2 kPa
	Pressure 2	3.8 kPa
	Pressure 3	2 kPa
	Flow 1	135 m ³ /s
	Flow 2	200 m ³ /s
	Flow 3	250 m ³ /s
	Efficiency rating 1	0.6
	Efficiency rating 2	0.6
	Efficiency rating 3	0.6

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	Motor efficiency rating	0.98
	Pressure factor	0.92
Calibration control	Setpoint	250 kg/s

The inputs of the machinery will remain similar to the inputs Table 26, however, the door fraction of the underground haulage will be adjusted to represent the action taken underground. It is expected, as the flow into inactive areas are optimised, the system resistance of the mine increases. Table 27 lists the inputs used for the simulation after implementation of the initiative.

Table 27: Simulation inputs after implementation of initiative

Component	Required data	
Air pressure boundary	Ambient pressure	86.5 kPa
	Ambient temperature	20 °C
Surface air tunnel	Flow area	12 m ²
	Door fraction	1
	Flow perimeter	14 m
	Friction coefficient	0.01.
	Air tunnel length	30 m
Up-cast and down-cast air tunnel	Flow area	12 m ²
	Door fraction	1
	Flow perimeter	14 m
	Friction coefficient	0.01.
	Air tunnel length	100 m
Underground air tunnel	Flow area	12 m ²
	Door fraction	0.5

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	Flow perimeter	14 m
	Friction coefficient	0.01.
	Air tunnel length	43 m
Surface air fan	Installed motor capacity	1000 kW
	Pressure 1	5.2 kPa
	Pressure 2	3.8 kPa
	Pressure 3	2 kPa
	Flow 1	135 m ³ /s
	Flow 2	200 m ³ /s
	Flow 3	250 m ³ /s
	Efficiency rating 1	0.6
	Efficiency rating 2	0.6
	Efficiency rating 3	0.6
	Motor efficiency rating	0.98
	Pressure factor	0.92
Calibration control	Setpoint	240 kg/s

Appendix D: Simulation results & verification

Initial simulation

The results obtained from the first simulation representing prior implementation is listed in Table 28.

Table 28: Surface fan simulated results before initiative implementation

Description	Simulated result
Air pressure	2.05 kPa
Volumetric air flow	249.01 m ³ /s
Fan power	843.6 kW

From the information obtained in Table 28, the fundamental values can be calculated according to the equations listed in Section 2.3.4. Table 29 lists the calculated results from the initial simulation.

Table 29: Calculated simulated results

Description	Simulated result
Airpower	510.45 kW
System resistance	0.033
Fan efficiency	61%

These simulated and calculated results will be used to compare with the results obtained from verification simulation.

The calculated results are then plotted on the surface fan pressure and efficiency curve to analyse the performance and state of the simulation. The results are plotted on Figure 44 and Figure 45.

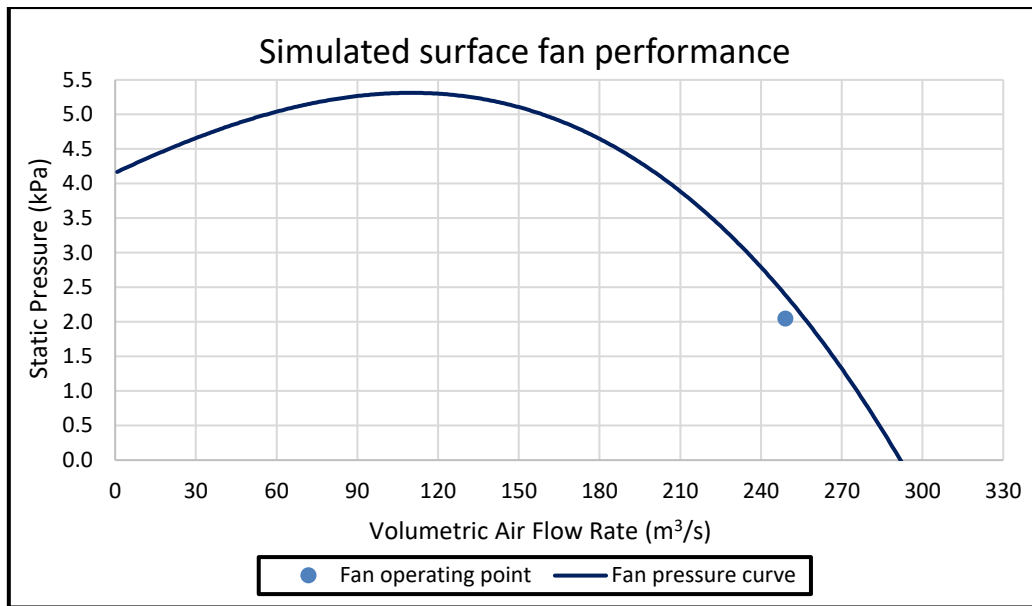


Figure 44: Surface fan performance - Initial simulation

Figure 44 displays the operating point of the surface fan against the set surface fan curve. It can be seen from the graph that the operational point is just below the pressure curve. This means that in the initial simulation, the surface fan is operating near the design specification.

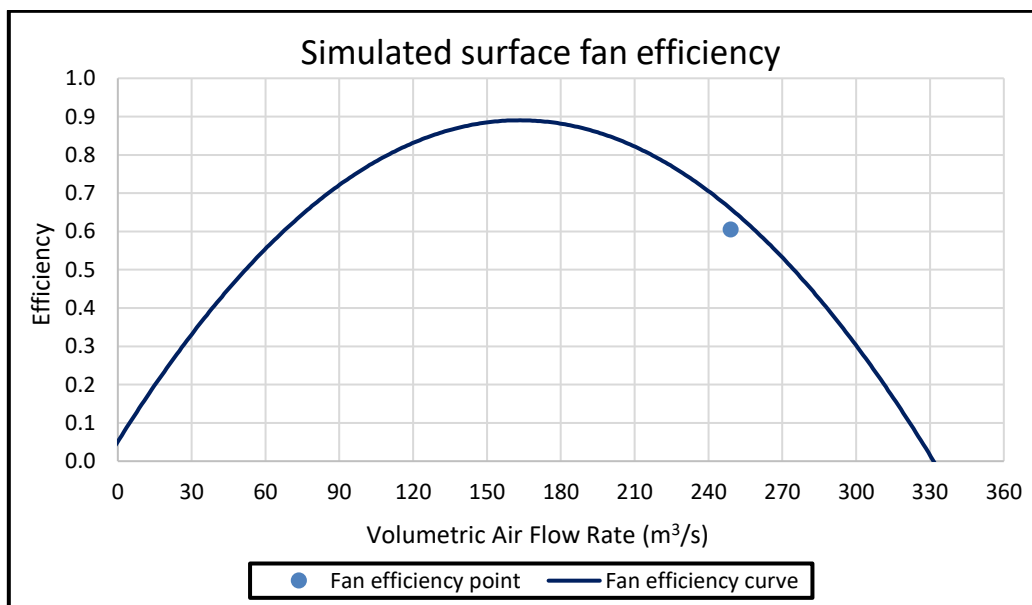


Figure 45: Surface fan efficiency - Initial simulation

Figure 45 displays the surface fan efficiency. The surface fan efficiency is also near the design specification efficiency.

Verification simulation

The verification simulation entails increasing the system pressure. The simulation replicates the implementing the solution, sealing off areas etc., therefor re-channelling ventilation to the working areas and increasing the system pressure.

Table 31 lists the results of the surface fan obtained from the simulation.

Table 30: Surface fan simulated results after initiative implementation

Description	Simulated result
Air pressure	2.39 kPa
Volumetric air flow	238.66 m ³ /s
Fan power	902 kW

The results obtained in Table 30, can be used to calculate the critical values required to determine the performance and efficiency of the surface fan. these values are then used to verify the simulation and solution strategy. The fundamental values can be calculated according to the equations listed in Section 2.3.4.

Table 31 lists the calculated results of the surface fan and ventilation system.

Table 31: Calculated simulated results

Description	Simulated result
Airpower	570.41 kW
System resistance	0.042
Fan efficiency	63%

The calculated results are then plotted on the surface fan pressure and efficiency curve to analyse the performance and state of the simulation. The results are plotted on Figure 45 and Figure 46.

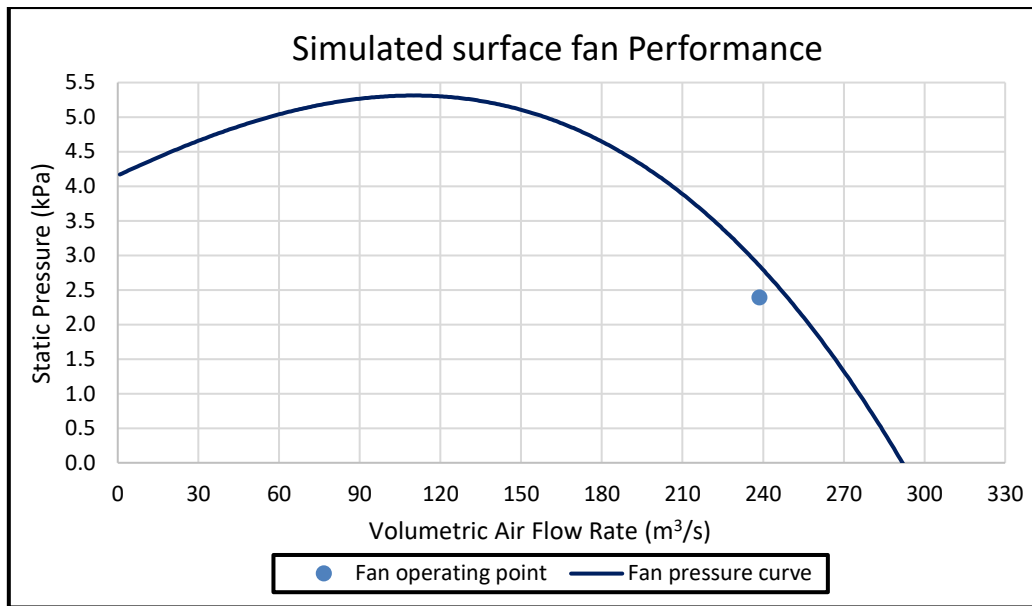


Figure 46: Surface fan performance – Verification simulation

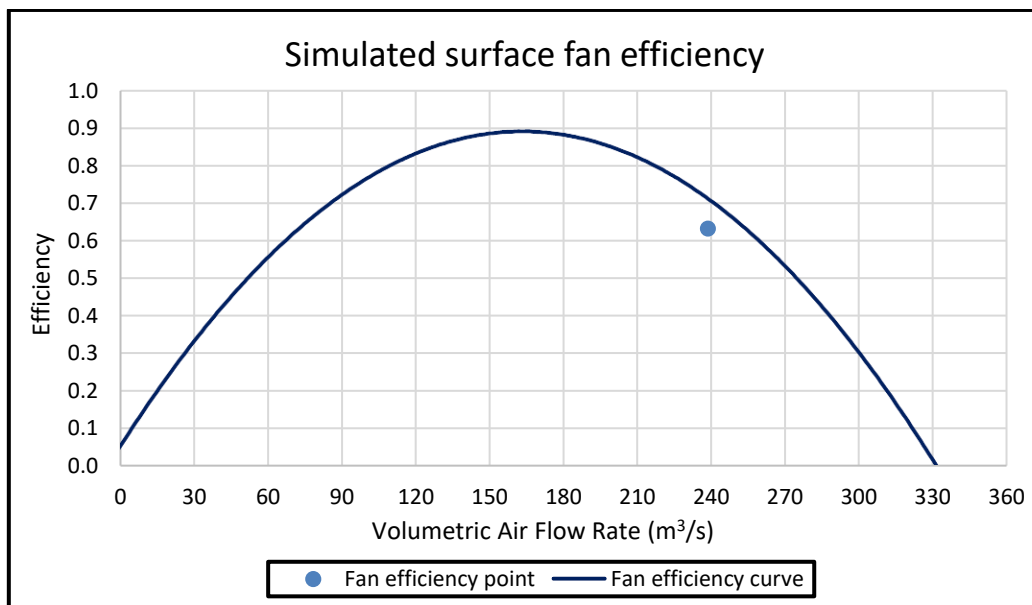


Figure 47: Surface fan efficiency - Verification simulation

The pressure and efficiency curve are relatable to each other. The result obtained in the pressure curve will have an impact on the efficiency curve as the values are directly proportional.

Appendix E: Case study A ventilation details & results

Prior to the solution implementation, initial audits were performed on the main mining levels, mainly 117L, 121L and 129L. Figure 48, Figure 49 and Figure 50 illustrate the detailed representations of the mining levels prior solution implementation.

Figure 48 is a detailed representation of 117L.

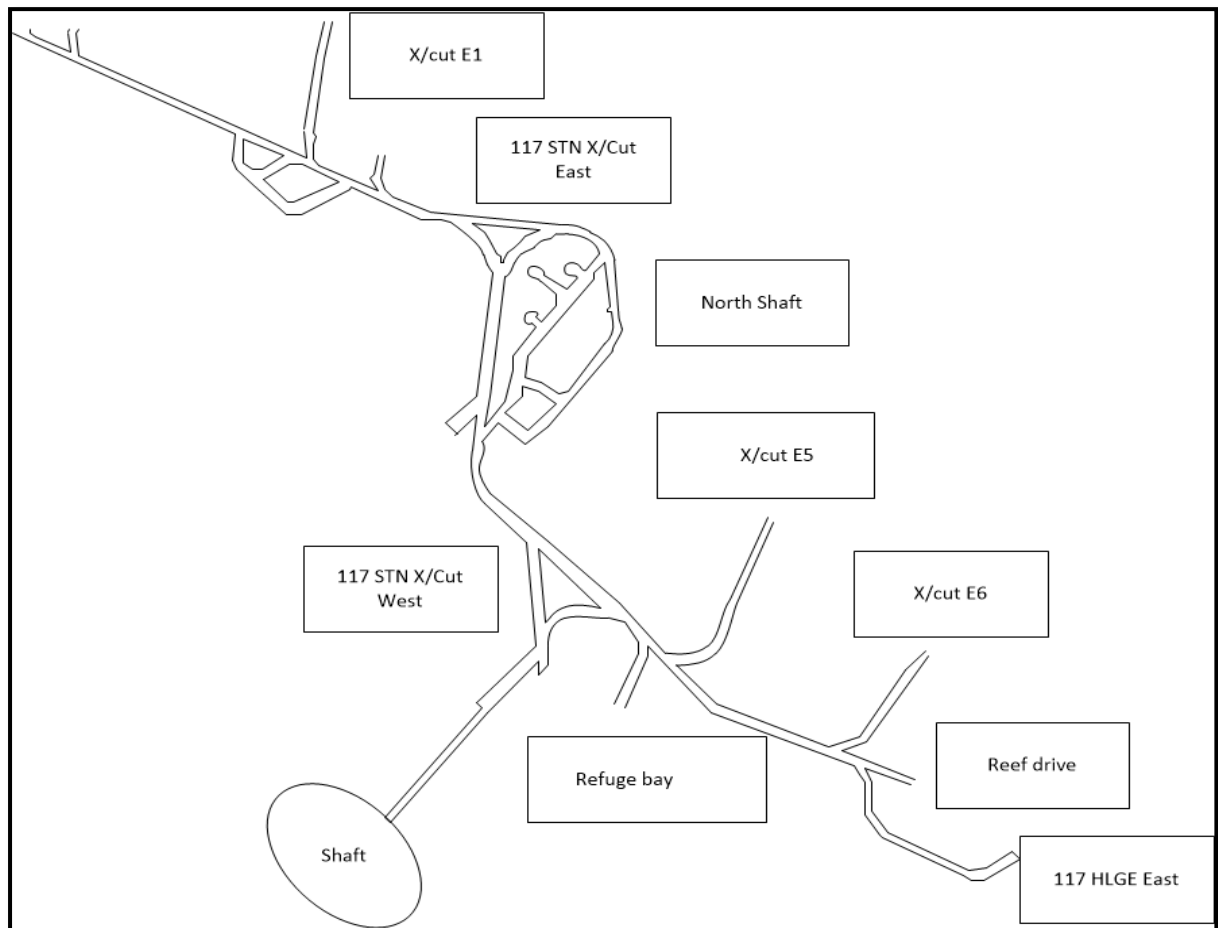


Figure 48: 117L detailed layout – Initial audit

From the detailed layout of 117L obtained from the initial audit, it can be seen the ventilation system for the level is outdated. The system requires updates and control devices to improve and enhance the airflow, pressure and temperature.

Figure 49 is a detailed representation of 121L.

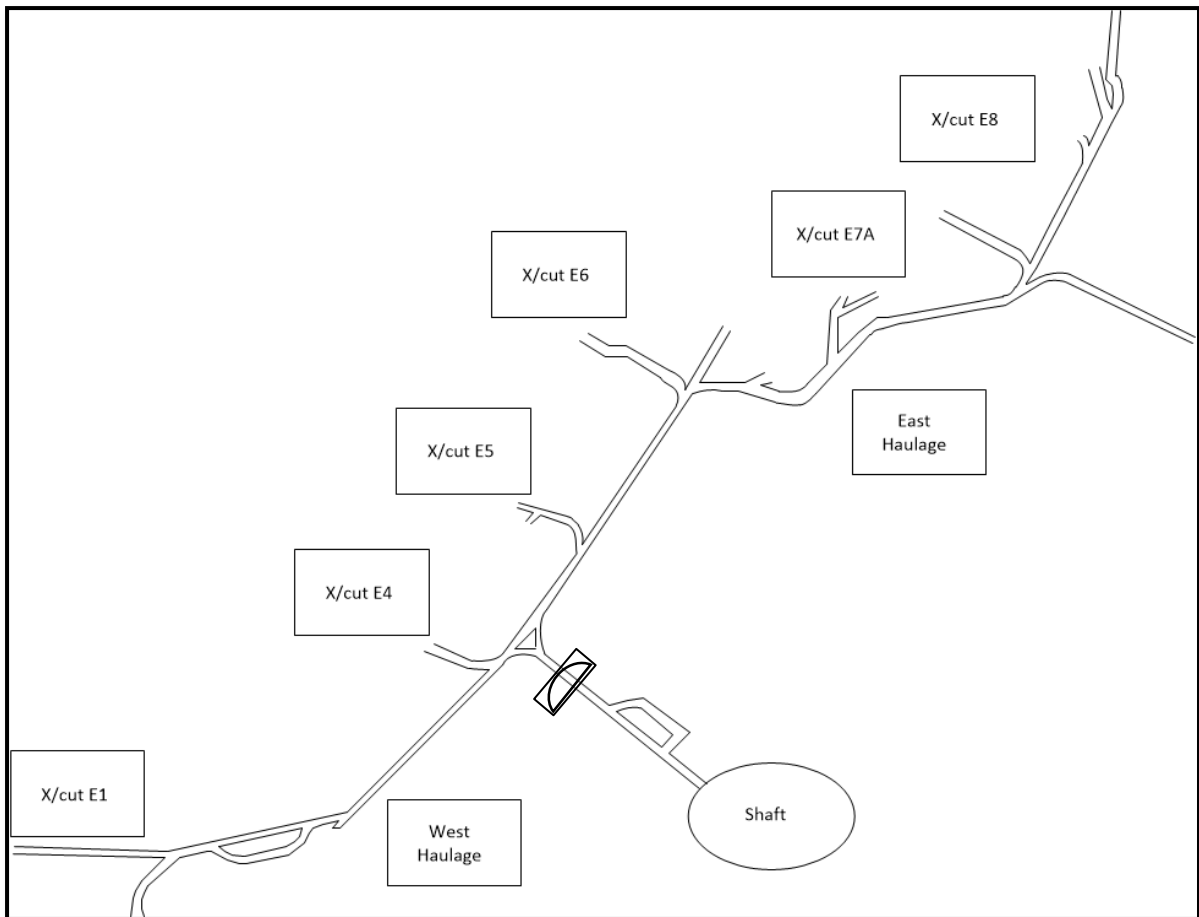


Figure 49: 121L detailed layout – Initial audit

The above illustrated layout shows the outdated ventilation system of 121L. The system requires improvements.

Figure 50 is a detailed representation of 129L.

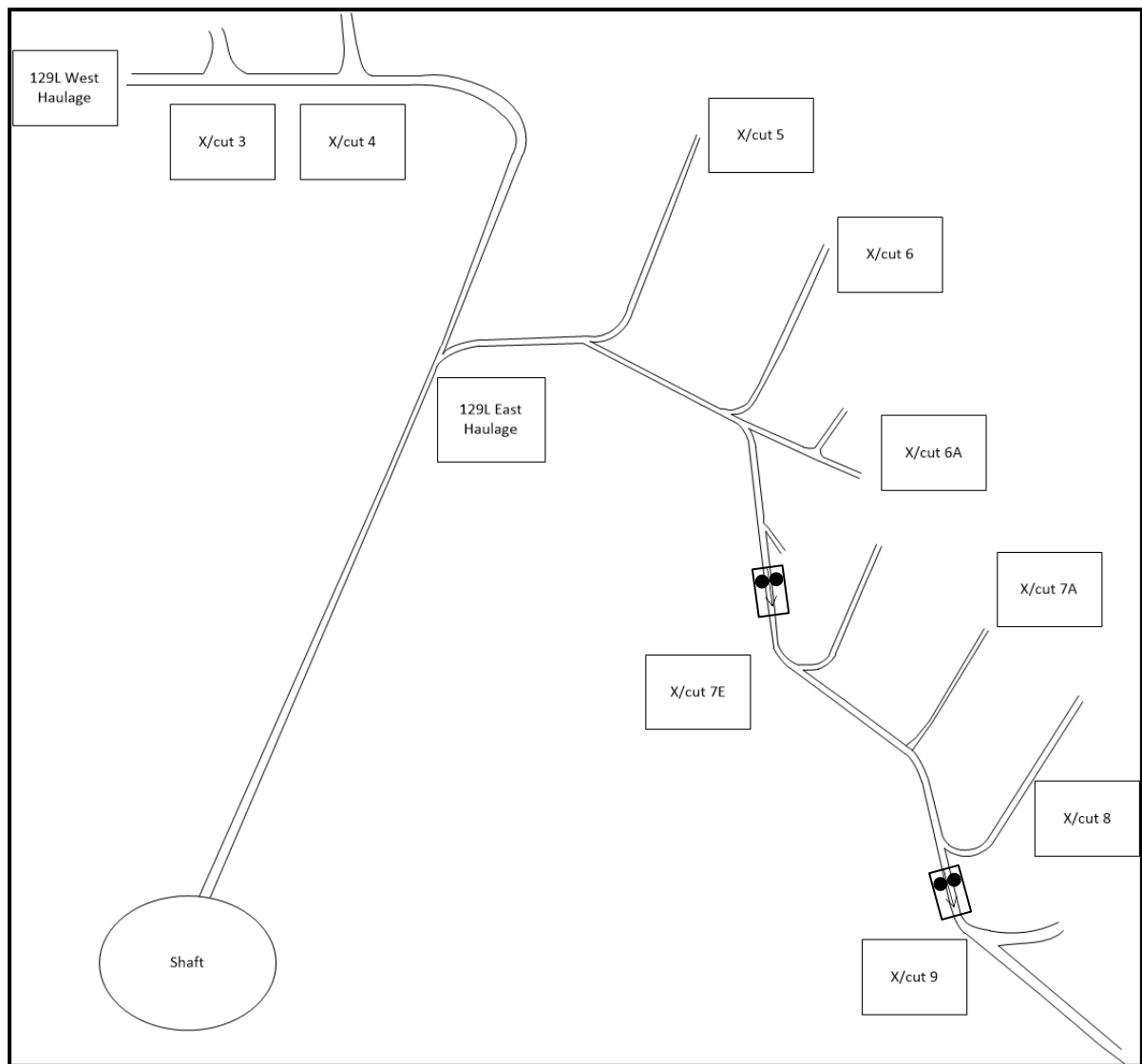


Figure 50: 129L detailed layout – Initial audit

129L is illustrated in the above-mentioned figure. Attempts have been made to resolve inefficiencies and update the ventilation system, however requires extensive analysis and updates as this is a primary level.

After the generic solution strategy process was applied and implemented, the levels layout and status changed dramatically especially 129L which can be seen in the figures that follow. Figure 51, Figure 52 and Figure 53 illustrate the detailed representations of the mining levels post solution implementation.

Figure 51 is a detailed representation of 117L post solution implementation.

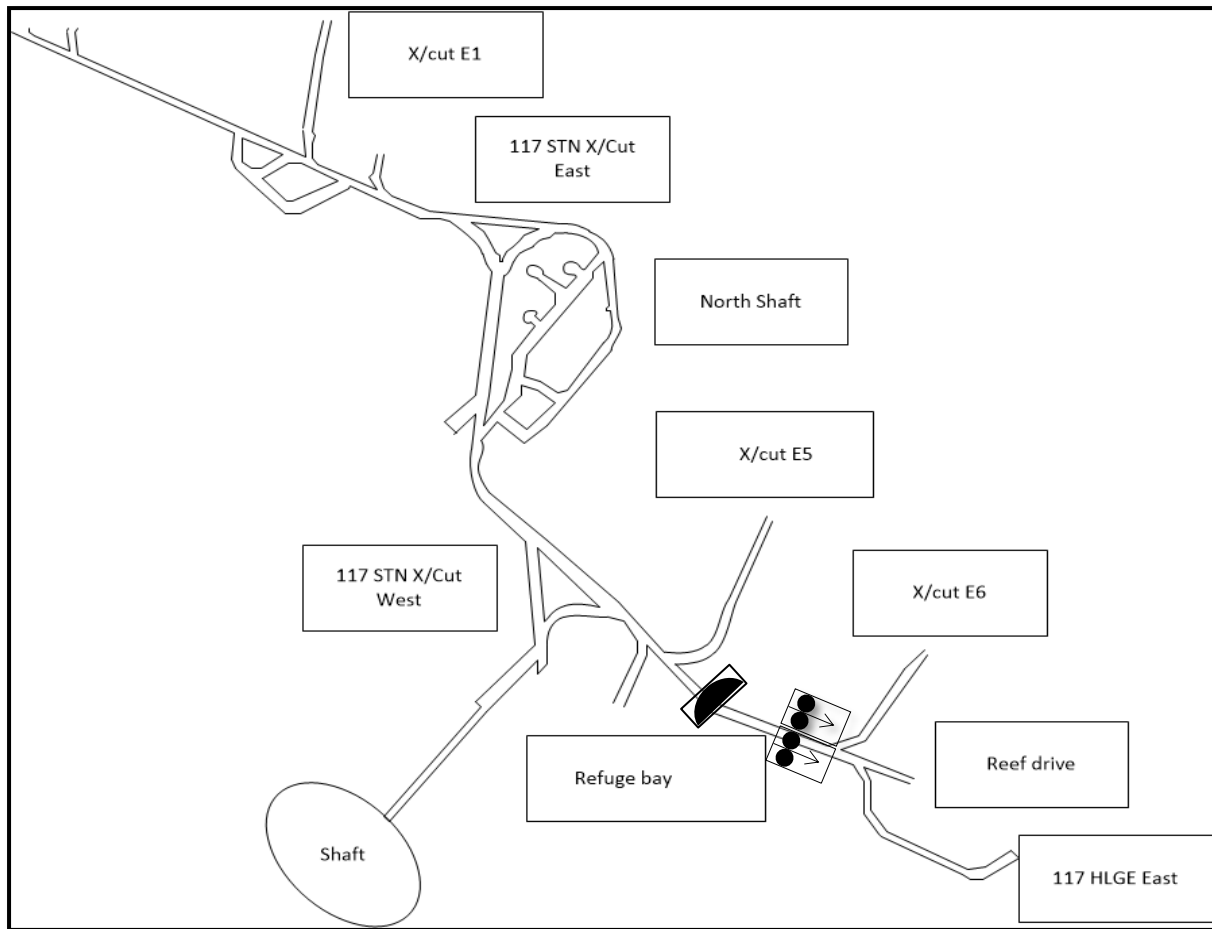


Figure 51: 117L Detailed layout – Validation audit

Figure 52 is a detailed representation of 121L post solution implementation.

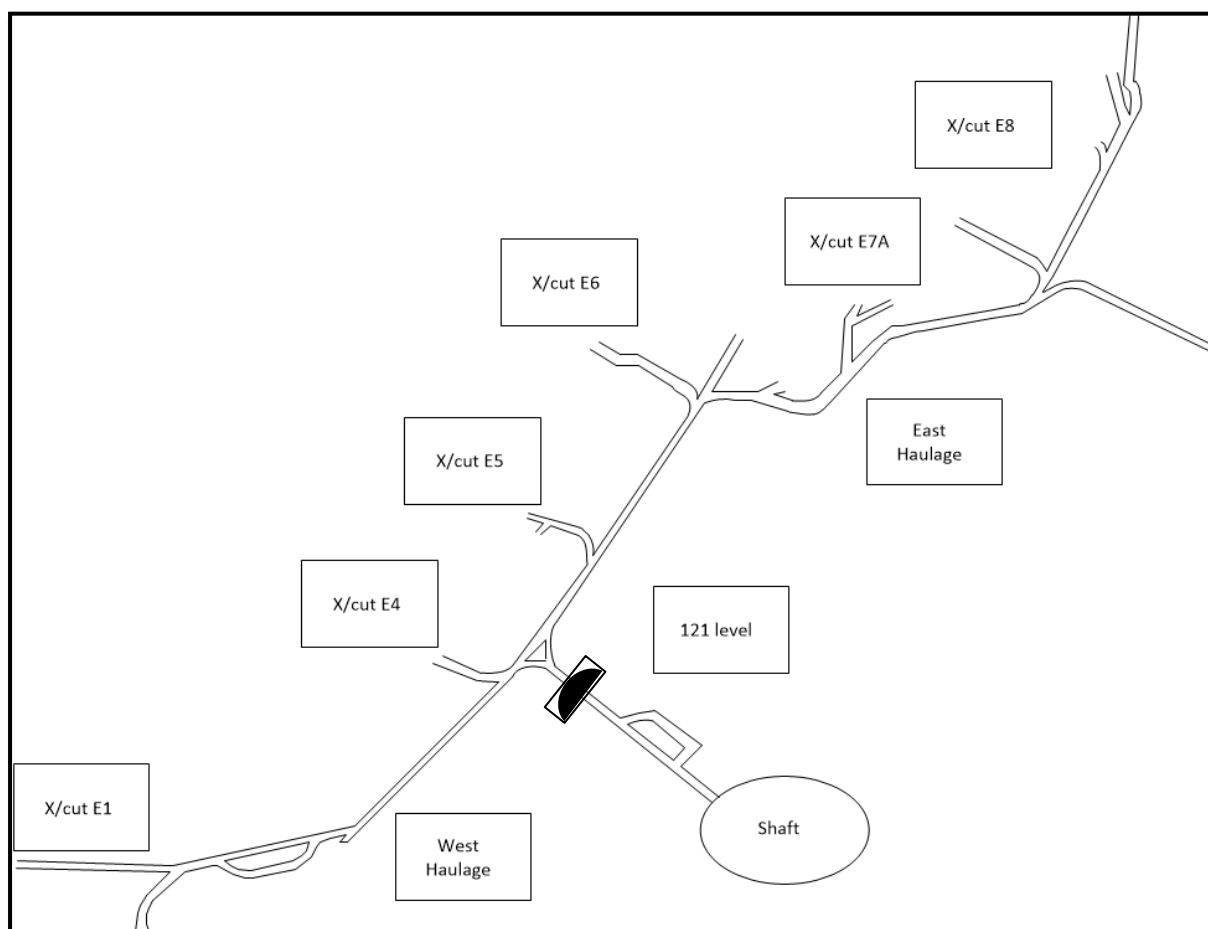


Figure 52: 121L Detailed layout – Validation audit

Figure 53 is a detailed representation of 129L post solution implementation.

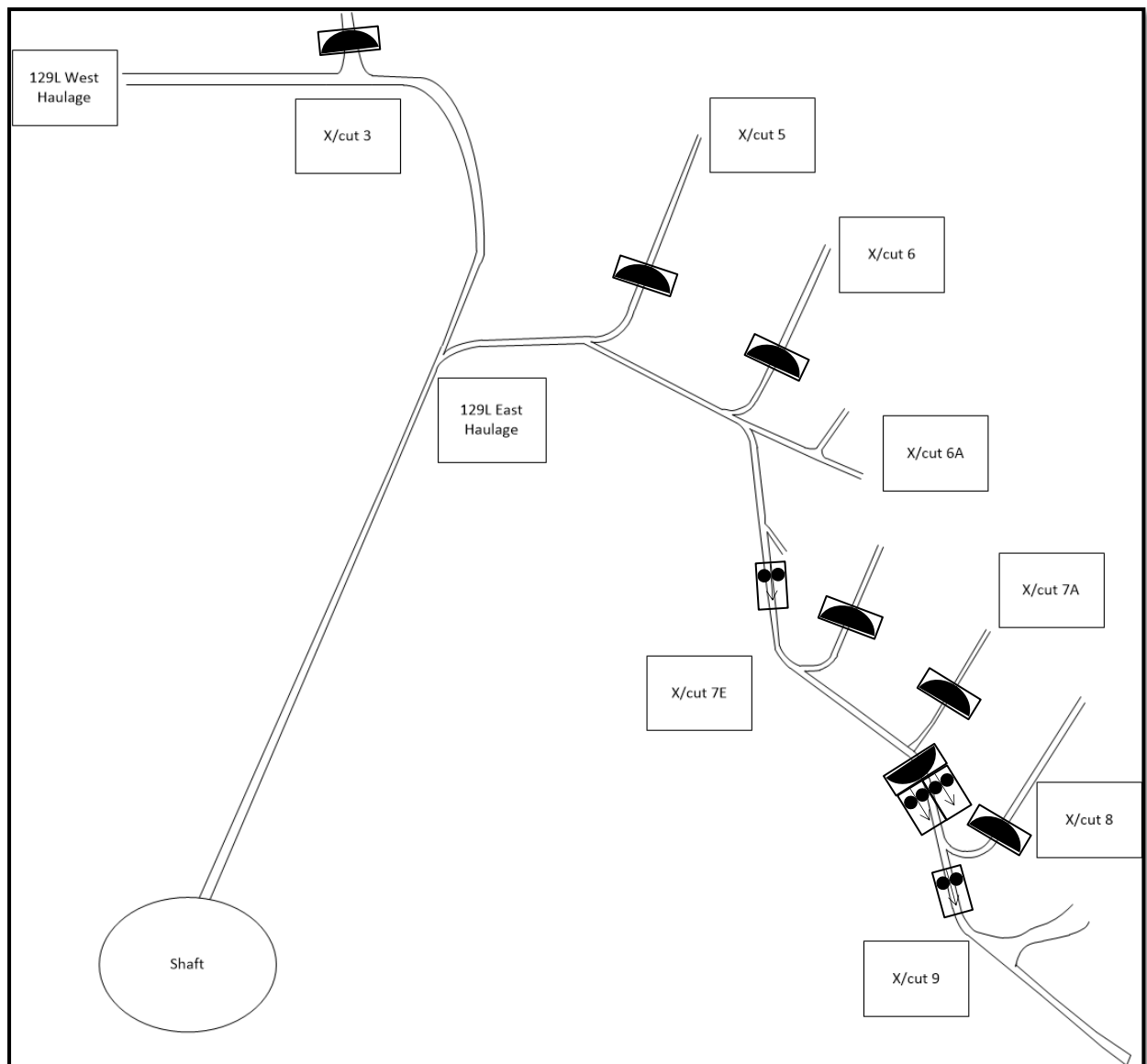


Figure 53: 129L Detailed layout – Validation audit

The difference between the initial and validation audits can be seen and compared with the detailed layouts. A dramatic update has been implemented which has proven to be effective.

Appendices

Table 32: Case study A - Audit details

Ventilation Audit										
					Audit completed			Audit Date		
	Location	Status	Description	Date Closed	129L	121L	117L	129L	121L	117L
0	-	-	-	-	Y	Y	-	14-Aug-17	15-Aug-17	-
1	129L E6	Completed	Construct a wall	24-Aug-17	Y	Y	Y	05-Sep-17	07-Sep-17	05-Sep-17
2	117L	Completed	Install Ventilation door and booster fan	13-Sep-17	-	-	Y	-	-	14-Sep-17
3	129L E6A & 129L E6	Completed	Install a regulator & seal off the x/cut E6	14-Sep-17	Y	Y	Y	20-Sep-17	20-Sep-17	20-Sep-17
4	129 E7A, W6A, E7E, E8, E3	Completed	Install ventilation doors & construct a wall at X/cut E3	28-Oct-17	Y	Y	Y	30-Nov-17	30-Nov-17	30-Nov-17

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5	60L, 90L, 95L, 110L	Completed	Construct a wall, install a regulator, install a regulator, install two ventilation doors	31-Mar-18	Y	Y	Y	18-Apr-18	09-May-18	16-May-18
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Table 32 shows the actions completed at the certain levels, the date of completion, the audits completed on the focussed levels and the dates of the audits completed.

Table 33 lists the audit details and schedule of actions completed on the levels as well as the whether the individual active mining levels were audited.

Table 33: Audit details and schedule

					Audit completed		
	Location	Description	Status	Date Closed	129L	121L	117L
0	Surface fan						
	Levels	-		-	Yes	Yes	-
1	129L E5	Install ventilation door	Completed	24-Aug-17	Yes	Yes	Yes

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2	117L Main haulage	Install ventilation door Install two booster fans (45kW)	Completed	13-Sep-17	-	-	Yes
3	129L E6	Install a ventilation door	Completed	14-Sep-17	Yes	Yes	Yes
4	129 E7A	Install ventilation door	Completed	28-Oct-17	Yes	Yes	Yes
	129 W6A	Install ventilation door					
	129 E7E	Install ventilation door					
	129 E8	Install ventilation door					
	129 E3	Install ventilation door					
5	60L Station	Install ventilation door	Completed	31-Mar-18	Yes	Yes	Yes
	90L Station	Install ventilation door					
	110L Main haulage	Install two ventilation doors					
6	Surface fan		Completed	8-May -18			

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Table 34: Case study A - Audit results

Table 34 shows the results obtained from the various ventilation audits performed on the different locations.

Ventilation Audit										
		Fan 1			Fan 2			Fan 3		
	Date of action	Pressure [kPa]	Air velocity [m/s]	Volumetric airflow [m³/s]	Pressure [kPa]	Air velocity [m/s]	Volumetric airflow [m³/s]	Pressure [kPa]	Air velocity [m/s]	Volumetric airflow [m³/s]
0	Initial audit	2.089	11	205	2.055	11.25	210	2.0	12.5	234
1	24-Aug-17	2.095	11	205	2.055	11.25	210	2.015	11.5	215
2	13-Sep-17	2.1	11.5	215	-	-	-	2.03	11	205
3	14-Sep-17	2.15	11.5	215	-	-	-	2.05	11	205
4	28-Oct-17	2.16	12	224	2.125	12.6	235	-	-	-

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5	31-Mar-18	-	-	-	2.2	11.8	221	2.15	12.2	229
6	8 May-18	0.17	0.7	13	2.25	12.48	234	2.3	13.45	252

Figure 54 illustrates the static pressure fan curve for the main fan at Mine X.

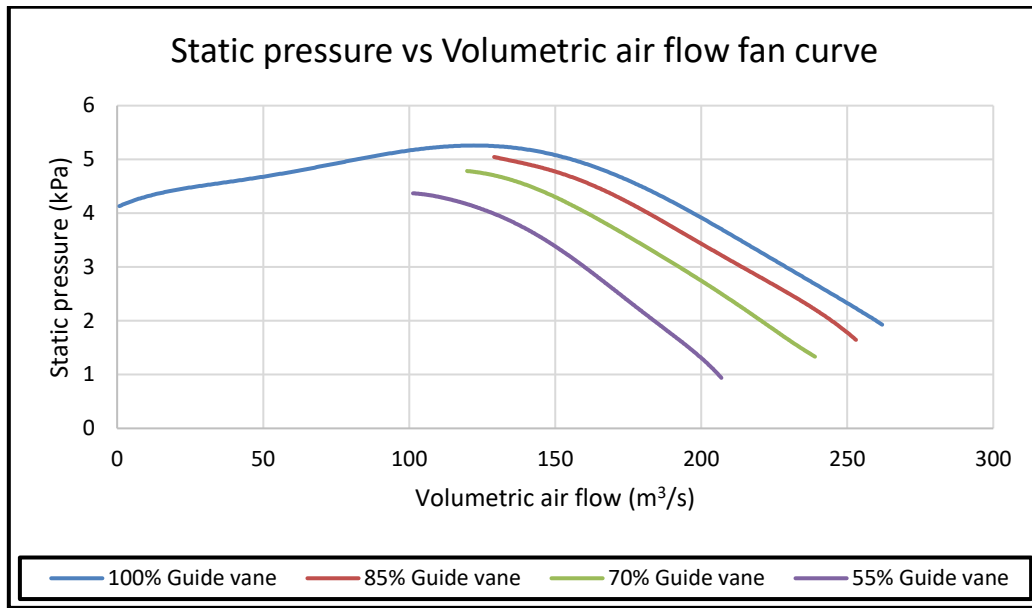


Figure 54: Mine X static pressure fan curve

Figure 55 illustrates the power fan curve for the main fan at Mine X.

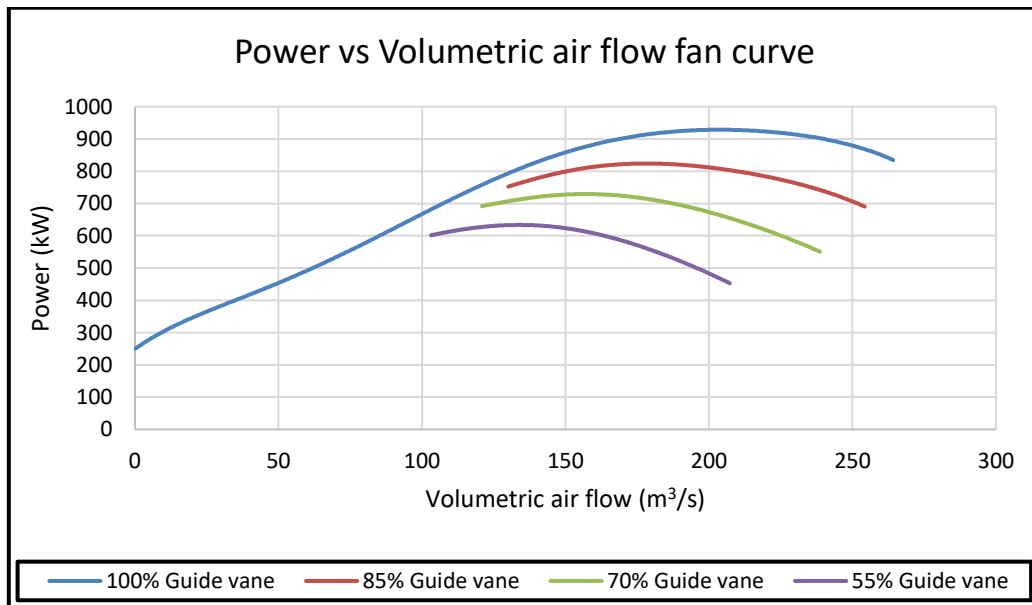


Figure 55: Mine X power fan curve