



Improving the ventilation of deep-level gold mines by simulating inactive sections

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Abstract

Title: Improving the ventilation of deep-level gold mines by simulating inactive sections

Keywords: Mine ventilation, deep-level gold mines, inactive sections, decommissioned mines, simulation.

The South African deep-level gold mining industry has experienced several challenges in ensuring profitability. These challenges can be mainly attributed to increasing operational costs as mines continue to reach new depths. Cooling systems comprise a large portion of operational expenses. It is, therefore, essential that the ventilation system, which serves as the primary form of cooling, operates effectively by reducing wastage.

In deep-level mines, the ventilation systems are extensive and, in some cases, incorporate decommissioned areas. These areas are often difficult to access since little maintenance is conducted on structural support. This leads to a unique challenge when attempting to evaluate such systems to ensure key ventilation system performance indicators are achieved. An alternative approach to evaluating such systems is therefore required.

The methodology developed in this study uses thermohydraulic simulation software to accurately model a mine's ventilation network and develop a reconditioning plan. This methodology was applied to a deep-level gold mine in South Africa and led to the development of a comprehensive sealing strategy. The implementation of this strategy resulted in an airflow increase of a measurable 35 m³/s through the mine working areas. The increase in system resistance resulted in an increase in static pressure of the main surface fans. The increase in static pressure is associated with improved air utilisation and makes continuous mining operations possible.

The case study results indicated that the use of simulation software could be used to evaluate and optimise the ventilation of inactive areas accurate to within 10% error. Despite the approach being applied to a deep-level gold mine, it can also be used to address inefficiencies in other mining configurations as well.

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Nomenclature

Symbol	Description	Units
Q	Airflow quantity	m ³ /s
P	Barometric pressure	kPa
F _p	Fan power	kW
R	South African currency	Rands
V	Velocity	m/s
A	Area	m ²
A	Ampere	A

List of Abbreviations

GDP	Gross Domestic Product
DMR	Department of Mineral Resources
LOM	Life of mine
UC	Upcast shaft
DC	Downcast shaft
Pa	Pascal
kW	kilowatt
kPa	kilopascal
km	kilometre
m ³ /s	Cubic meters per second
DB	Dry bulb
WB	Wet bulb
VOD	Ventilation on Demand
VSD	Variable speed drive
FOG	Fall of Ground
DXF	Drawing eXchange Format
3D	Three dimensional
PTB	Process ToolBox
SI-Units	International System of Units
RAW	Return airway
GCS	Geographic coordinate system
L	Level
KPI	Key Performance Indicator
CAD	Computer Aided Design
IGV	Internal Guide Vanes
VRT	Virgin Rock Temperature
GUI	Graphical User Interface

Chapter 1: INTRODUCTION

1.1 Preamble

Chapter 1 highlights the status of the gold mining industry in South Africa and forms the literature study for the dissertation. The focus is directed at the inner workings of deep-level gold mine ventilation networks and the analysis thereof. The use of simulation software and optimisation of ventilation networks are also discussed. The chapter concludes with a problem statement and an overview of the chapter.

1.2 Gold Mining in South Africa

South Africa has the second largest gold reserve in the world when referring to ore deposits that are economically viable to extract [1]. Since the first discovery of gold in June 1884, underground mines have been the primary supply of 95% of gold in South Africa [2]. The gold mining industry forms 6.8% of the total Gross Domestic Product (GDP) of the country and employs around 112 200 people [3]. Figure 1 shows that South Africa is ranked seventh in the top 10 countries for producing the most gold per metric ton [4] [5]. .

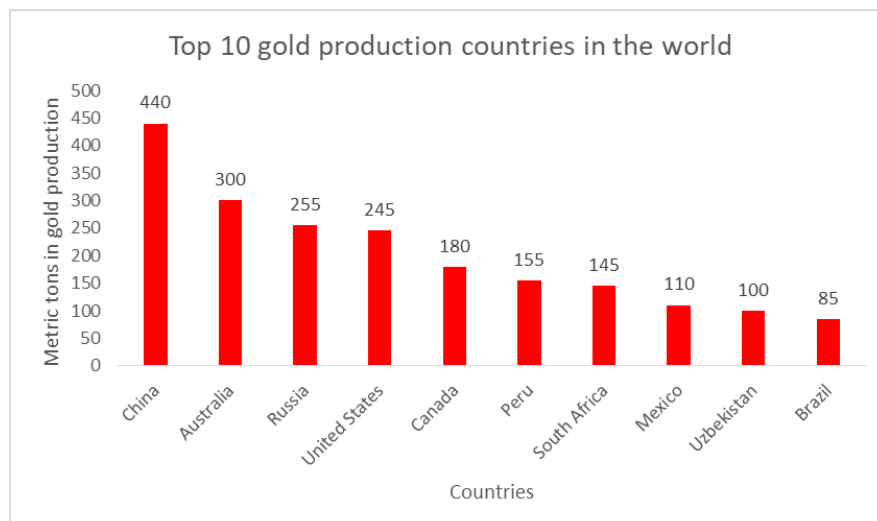


Figure 1 Top 10 gold-producing countries in the world [4]

The global production of gold has increased over the years with continuous mining practice improvements, yet, the South African contribution has been decreasing. Numerous socioeconomic factors contributed to the decline of gold production in South-Africa. As seen in Figure 1, South Africa was in the seventh place for gold production in the year 2018 where once was amongst the top two. South Africa has produced 83% less gold in 2018 than it did in 1980 [6]. This is mainly because of the following [7] [8]:

- The rand-dollar exchange rate,
- high production costs like rises in wages, rises in electricity cost etc.
- frequent employee strikes, and
- depth at which gold is mined from.

The depletion of shallow ore reserves in South Africa has forced the gold mining industry to exploit of reefs at ever-increasing depths [9]. It was already forecasted in the 1960s that by the year 2010, 30% of gold production would come from depths greater than 3000 m [10]. Six of the ten deepest mines in the world reside in a region of South Africa. Table 1 shows the six mines with the deepest mining depths.

Table 1 Six of the top 10 deepest mines in the world [11]

Mine	Deepest mined area
Mponeng mine	4.27 km
Driefontein mine	3.42 km
Kusasalethu mine	3.38 km
Moab Khotsonong mine	3.052 km
South Deep mine	2.998 km
Kopanang mine	2.24 km

Deeper mines are a challenging undertaking due to characteristic problems such as heat, expensive cooling, and delays due to depth, among others. The information provided in Table 1 shows that mines found in South Africa can reach depths of 4 km [12]. For mines to have safe and compliant working conditions at these depths, the mining industry must supply the correct amount of ventilation to working areas of the mine.

The optimisation of ventilation networks of mines can have a large impact on the cost-effectiveness of a mine. Up to 47% of the total electricity usage in the mining industry comes from the gold sector [13]. This illustrates the vast amount of energy that is needed for production and processing in gold mines. As a result, the practice of using simulation software to optimise ventilation networks have increased over the years [14].

1.3 The Cost of Mining

The cost of mining in South-Africa has risen over the past years and optimisation of services has become ever important. Some mines are deemed as unprofitable or marginal due to their declining production numbers [15]. The high operating costs and decreasing production necessitate mines to either reduce operational costs or increase production rates.

A breakdown of electricity consumption of a deep-level gold mine is shown in Figure 2 [13] [16].

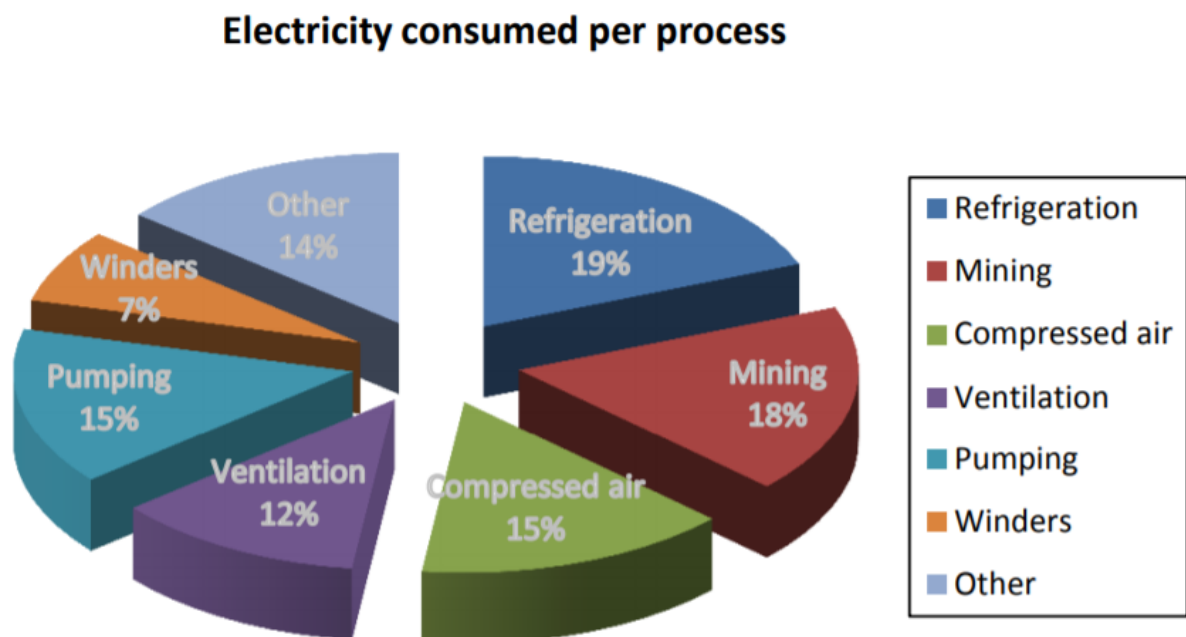


Figure 2 Average electricity consumption per mining process at a deep-level mine [16]

The cost percentage breakdown for each commodity of a mine is shown in Figure 2. Ventilation network devices such as fans are responsible for 12% of electricity consumption on deep-level gold mines. When ventilation networks are not used optimally, the shortages in cooling is typically addressed with the refrigeration section and compressed air systems. Refrigeration

and compressed air make up 34% of electricity consumption. Therefore, the ventilation network can have an expensive impact on the mine's networks.

In South Africa, there has also been a steep increase in electricity tariffs. With Eskom producing 95% of South Africa's electricity and with the rise of electricity costs, as seen in Figure 3. South Africa has a high production costs with regards to energy, compared to other countries in the same industry due to high electricity costs [17].

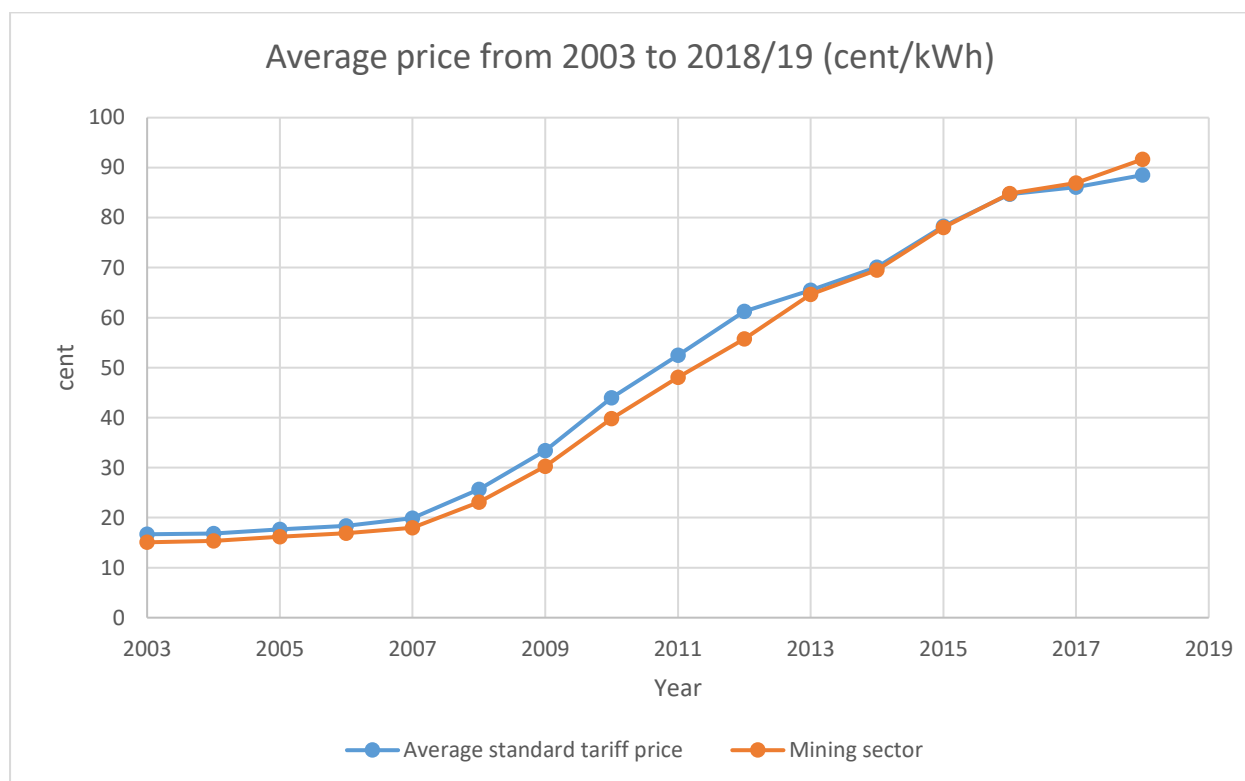


Figure 3 Eskom tariff increase from 2007 [18]

As seen in the figure the cost of electricity has risen by 356% from 2007 to 2018. This increase is more than double the inflation of a 10-year period. The rise in electricity cost has necessitated energy-saving project and cost reduction initiatives lest gold mines in South Africa stand the risk of becoming non-competitive in an ever-competitive market [19].

A ventilation network is the primary form of cooling in a deep-level gold mine. When a ventilation network is not optimally utilised the abuse of other expensive systems, like compressed air and refrigeration, can take place [20]. Thus, a ventilation network can be a large contributor to unwanted operational costs [21].

Although the optimisation of a mine ventilation network has the longest lead time, the impact of the project is the most noticeable in sustaining a competitive and profitable mine [19].

1.4 Literature of Ventilation of Deep-Level Mines in South Africa

1.4.1 Deep-level mine ventilation (network overview)

Ventilation can be described as a system that will deliver airflows in enough quantity and quality [22]. Ventilation has high importance to the occupational health and safety of underground workers. A continuous supply of good quality air is essential to supply fresh air and dilute fumes and toxic gases [23]. Ventilation is also necessary for removing heat in deep-level mines [24] [25]. Designing an effective mine ventilation system is crucial to the safe and efficient operation of underground mines [21] [11].

Gold mines in South Africa commonly practice narrow reef sequential mining [26] [27]. The narrow reef refers to the vein-like ore body that is found underground containing the gold reserves. The sequential mining technique refers to the mining method where multiple areas are mined and developed simultaneously [28]. This method of mining requires ventilation networks to supply fresh air to multiple working areas simultaneously.

Deep-level gold mine ventilation networks consist of multiple airways for travelling, supplying fresh air, and returning hot air. A simplified ventilation network for a deep-level gold mine is shown in Figure 4.

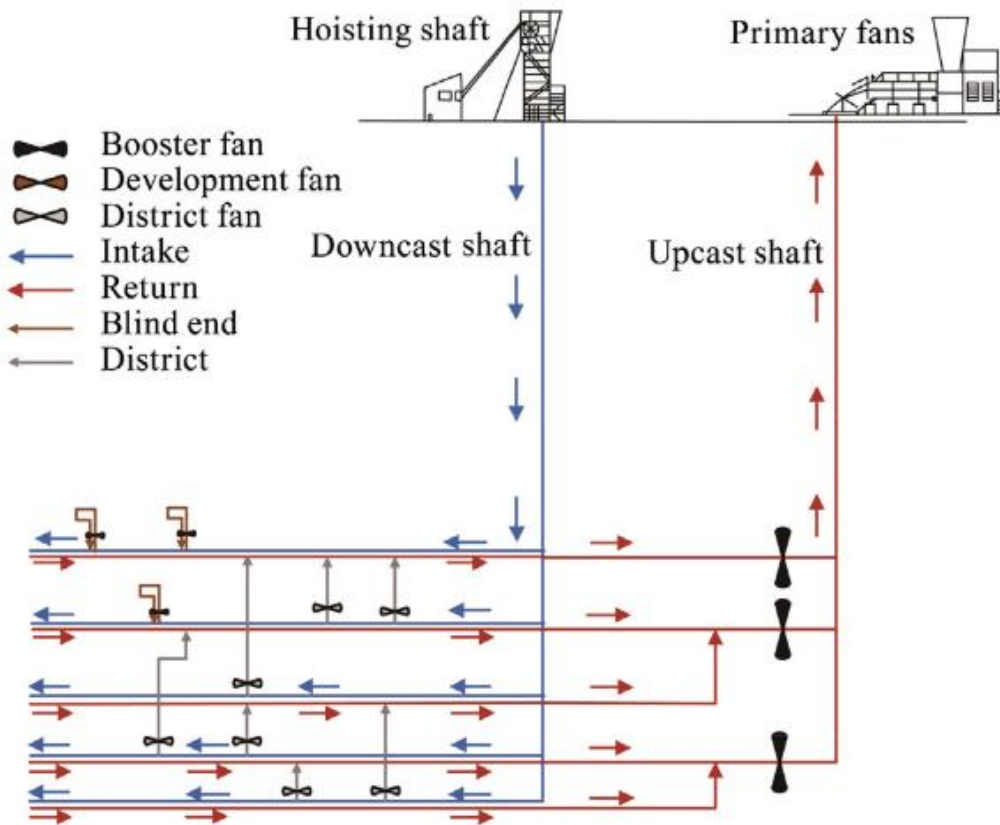


Figure 4 Representation of a mine's ventilation network [29]

The figure shows the fresh air entering the mine from the surface, travelling down the vertical shaft to the entrance of a working level. The air then travels horizontally to various working place, up the stope and makes its way through the rest of the mine until it reaches the surface again. Air is drawn into the mine and through the working areas by a large fan(s) on the surface. Auxiliary fans (development and district fans), as shown in Figure 4, are also placed underground where the redirection of air is required or hot air needs to be extracted.

Ventilation control is one of the disciplines that affect the well-being and profitability of the modern mining industry [30]. Engineers that work on mine ventilation systems currently use personal knowledge and good practice guidelines to identify the best mine ventilation arrangements. Due to the complexity of deep-level gold mines, it takes long to evaluate a small portion of a system manually. Ventilation networks are often made up of hundreds of haulages (travel/roadway) which are ventilated through different types of ventilation control devices.

Examples of control devices [31] [32] include:

1. Regulators
2. Airlocks
3. Brattices
4. Stopping
5. Overcast and undercast systems
6. Ducts
7. Main fans
8. Secondary or booster fans
9. Development or auxiliary fans

A definition for each ventilation control device can be found in Appendix A.

Although ventilation control devices help with the flow of air through the mine, the main supply of ventilation airflow is supplied by the main, or primary, surface fans. Engineers use these to create a controlled flow of fresh air to all the working areas. Each mine should have at least one fan of comparatively large capacity to control main underground air currents. This is very often seen in mines across South Africa where mine networks keep expanding to new depths and distances to reach ore reserves.

With the continual increase of mining depths and expanding mine networks comes an increase in the mine's resistance and system pressure [33] [34]. New working areas can be difficult to properly ventilate due to the increase of the system resistance.

1.4.2 Main surface fans

Main fans draw fresh air into the mine and contaminated air out of the mine. Main fans can be installed on the downcast (intake) airshaft, upcast (return) airshaft, or both [31]. They are found either on the surface or underground and can be axial, centrifugal, or mixed [35]. Explained below;

- Axial fans are high-performance variable and fixed pitch fans.
- Centrifugal fans are high-efficiency aerofoil and backward-curved fans.
- Mixed refers to the use of both an axial and centrifugal fan.

The configuration of main ventilation fans may have a substantial impact on the total performance of the fan [36] [37] [38]. The configuration of the main fan describes the duct sizing, guide vanes, and gearbox ratios. An individual fan can be characterised by its fan curve [39]. A fan performance curve indicates the relationship between all the important characteristic of a fan. Figure 5 shows all these different types of characteristics that can be found on a performance curve.

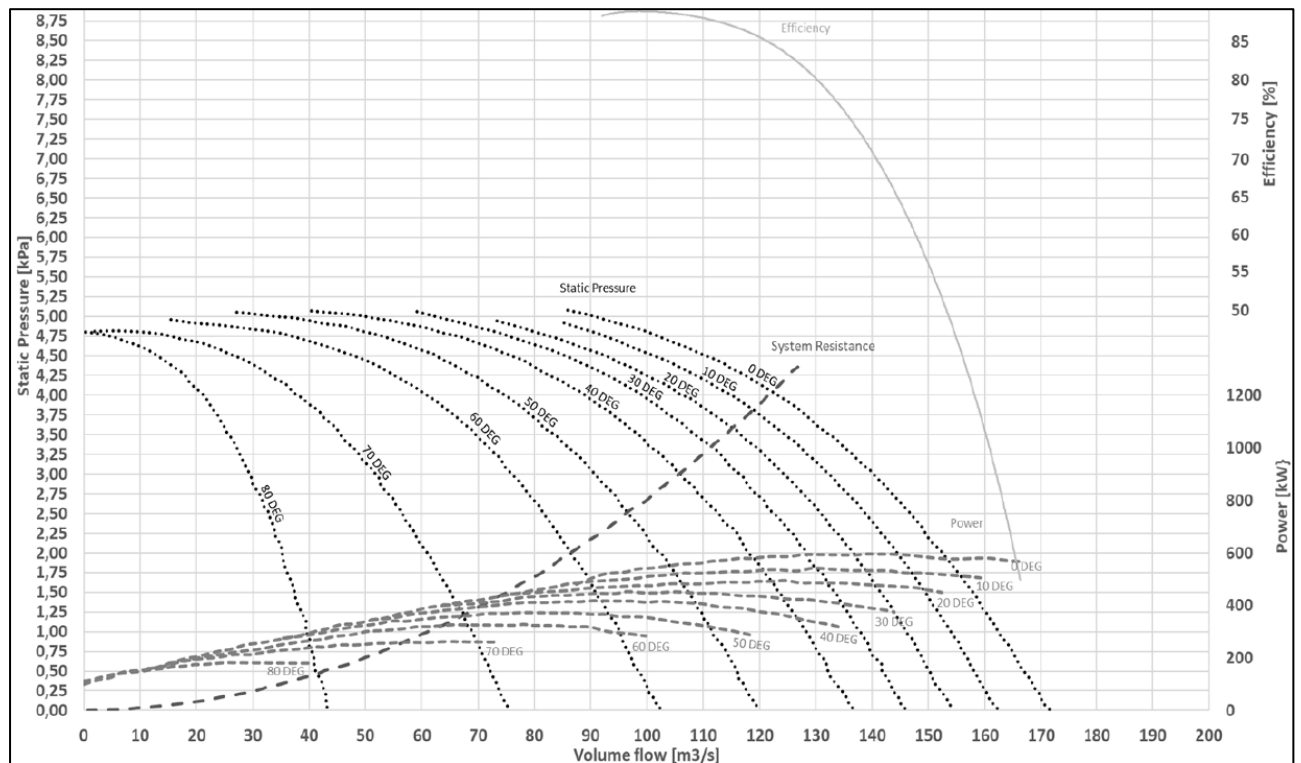


Figure 5 Example of a fan's performance curve and fan curve characteristics [40]

As seen in Figure 5, the characteristic graphs are given as:

- System curve or resistance curve
- Efficiency curve
- Static pressure curve
- Power curve
- Guide vane angles

The fan's total or static pressure curve is used to find the relation between the static or total pressure and the volumetric flow rate when the fan's blades are running at a constant steady speed. The fan efficiency or the power curve can be used to find the power consumption for

the fan at a specific point of airflow. Figure 6 shows the fan power curve plotted against the volumetric flow rate.

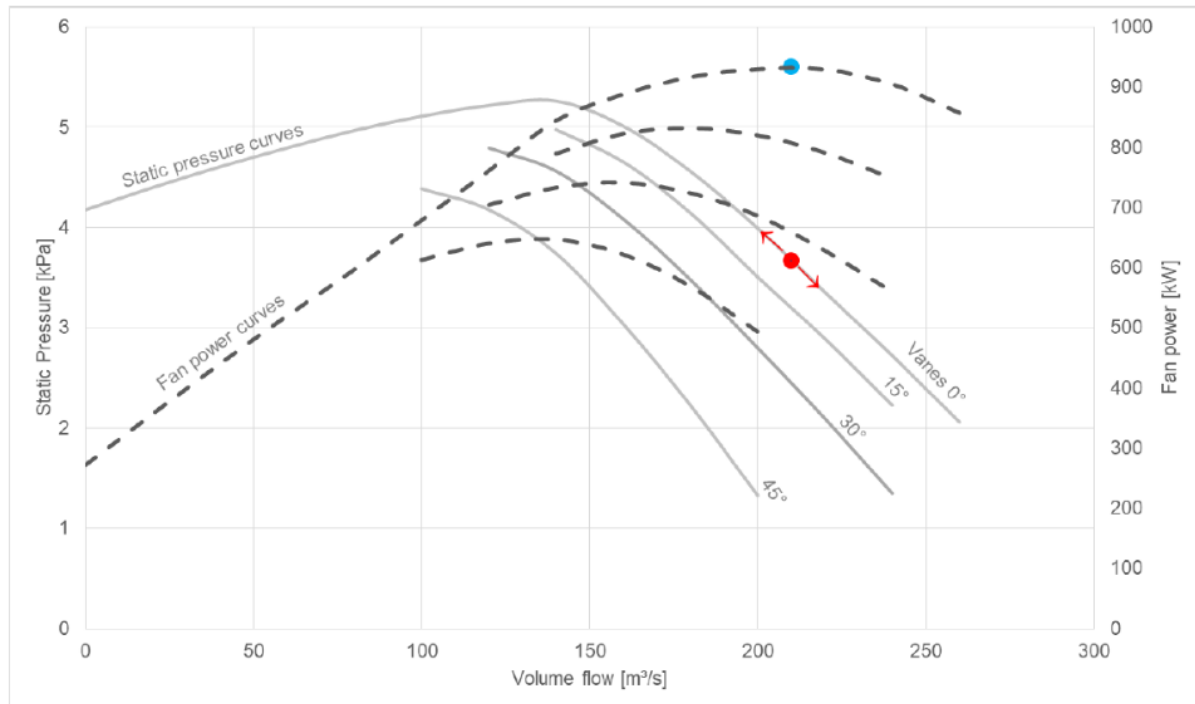


Figure 6 Fan performance curve showing operating point movement

The guide vane's position is also plotted on this curve shown in Figure 6. Guide vanes are usually found at the inlet or outlet of a fan and are stationary [41]. Inlet guide vanes can be used as an energy management system where it can help mines to reduce energy consumption during off-shift periods [42]. The red marker on Figure 6 indicates an example where the guide vane angle is at 0%, and at the specific operating point, the fan providing 210 m³/s at a static pressure of 3.75 kPa. Each guide vane angle has a different static pressure curve on the figure. The blue dot, which indicates the fan power for the corresponding flow rate and guide vane position, at this point it is set at 940 kW.

The combination of all the aerodynamic resistance in a system is represented by the system curve (system resistance curve) [39] [43]. Many factors can play a role in the resistance of a ventilation network and some of these factors are [44]:

- Water accumulation
- Fall of ground (FOG)
- Haulage support structures
- Machinery

- Haulage wall roughness
- Air velocity

The system curve will respond according to the red arrows shown in Figure 6. The friction coefficient of the tunnels is dependent on the rock face conditions. Mines have different ways to line rock faces to decrease the risk of rock face crumbling and fall of ground, like shot-create and cement. There are also possibilities of haulages that can collapse due to age and humid conditions, and this is more likely to happen in decommissioned mines.

For a system with a higher resistance, the operating point will move upwards and to the left on the static pressure curve. An increased system resistance indicates that the air supplied to a mine is reaching the desired areas [45]. When the system resistance is less, the point of operation will move lower and to the right on the static pressure curve; this will result in an increase in airflow and a decrease in static pressure over the fan [46].

The operating point shifts when the fan's speed or guide vanes are adjusted on the fan. When this happens, the operating point will move along the system curve because the system's resistance has not changed. Figure 7 shows the two different operating points on the same system curve.

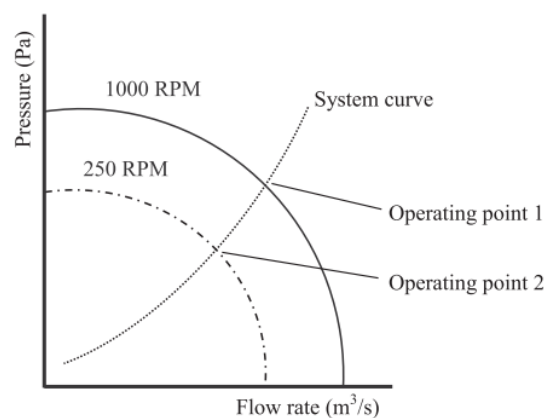


Figure 7 Fan operating points for different speeds [39]

Figure 7 shows an example of two different operating points where the fan speed has changed. The change of flow rate and power of a fan shown in Figure 7 can be characterised by the Fan Laws, known as the Affinity Laws. The speed of the fan (N), the input power of the fan (P), and the pressure developed by the fan (H) are defined by a set of governing equations set by the Fan Laws. These laws are given as [42]:

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2}$$

$$\frac{H_1}{H_2} = \left(\frac{N_1}{N_2}\right)^2$$

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

The subscript 1 is associated with the original conditions and subscript 2 with the resulting variables from change in the fan speed. However, this law will only be valid when the fan is analysed as a separate system. When a fan is analysed as part of a system, the fan laws will result in the incorrect analysis [47]. This is due to the resistance that is applied to the fan when analysed as part of a system. Usually, the reduction in fan speed will result in an overestimation of power savings [48] [47].

The information that can be gathered using fan curves and fan analysis for the primary fans enables mines and engineers to make an accurate prediction of the conditions of a mine. Not only do fans help to predict the underground conditions of a mine but they can also be used in combination with simulation software. This is used as a possible alternative method for analysing ventilation networks of decommissioned mines.

1.4.3 Utilising decommissioned mine ventilation systems

In the 1960s, the Free State province in South Africa experienced a boom in the gold mining industry, and the town Welkom hosted most of the surrounding mines [49]. There were multiple mines in the area and in close proximity. Since then, however, most of the mines have closed and now form part of ventilation networks of active mines.

Inactive mines areas are kept operational at the expense of active mines for future mining needs. Decommissioned mines are kept operational for the sake of planned underground expansion of the mining networks. The advantage of utilising a decommissioned mine in way is that there is already an existing ventilation infrastructure. Sinking a shaft of about 2 km will cost between R6.6 billion and R9.4 billion and may take a minimum of 18 months to complete [50]. On the

other hand, an inactive mine can be used for much less capital expenditure. Thus, using existing mines and older shafts is more feasible in the sense of time and money management [51]. Decommissioned mines that are used by active mines usually serve as an additional escape route or service shaft. The services that can be supplied by inactive mines are as follows:

- Ventilation – Extra fresh air supply or act as return airways (RAWs).
- Dewatering – Pump station utilised for dewatering purposes
- Compressed air – If the infrastructure is still available
- Escape route – May serve as an additional escape route for emergencies

Figure 8 shows the cross-sectional area of a deep-level mine in South Africa. The figure acts as a representation of how different shafts are used in close proximity.

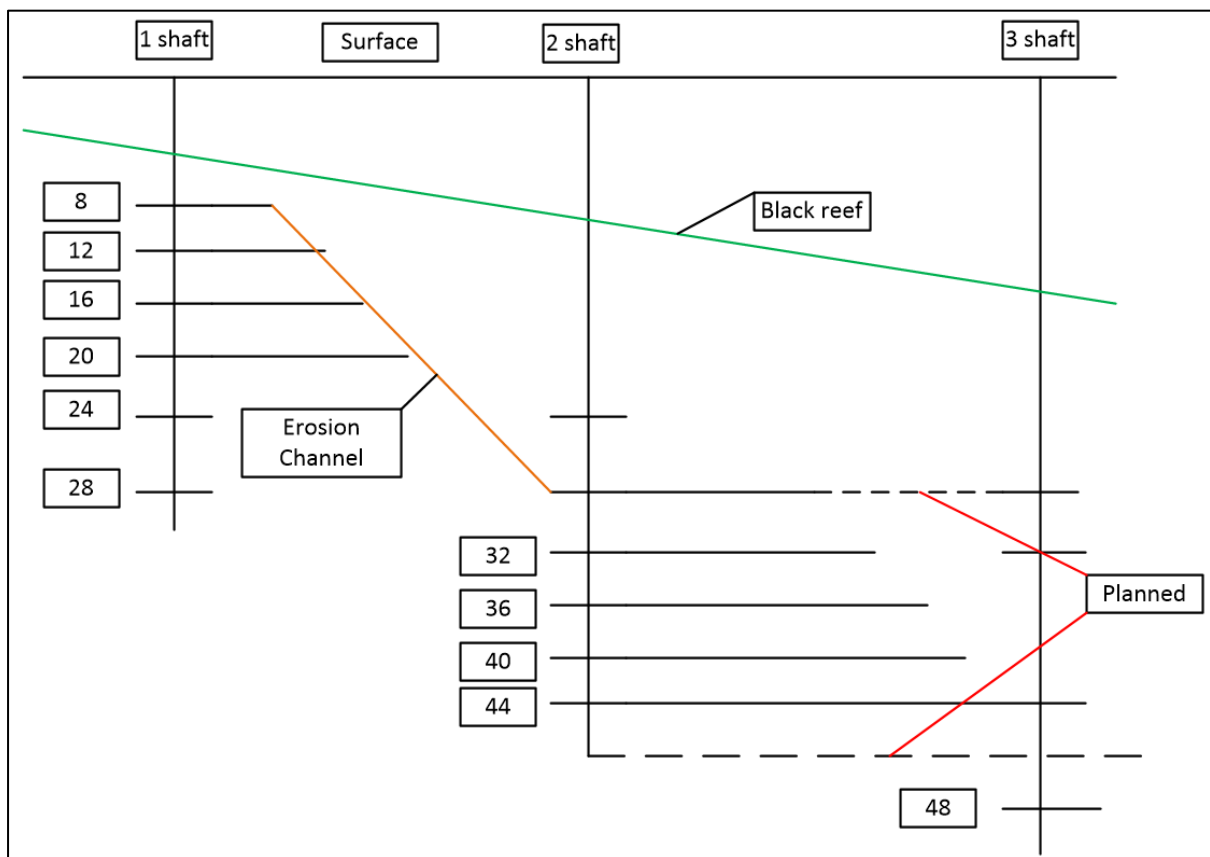


Figure 8 Cross-sectional area of a deep-level mine in South Africa [52]

As a result of the reef dip, the different shafts make it possible to access working areas faster and easier by decreasing travel time. The extra shafts are also used for ventilation to ensure an adequate distribution of fresh air is achieved.

The downfall of using a decommissioned mine's ventilation network is that some of the areas may be inaccessible. Due to the rock deterioration over time, the integrity of the walls and roof of the mine may be compromised in that they could fail and cause a fall of ground [53]. These mines are also subject to high temperatures and a high possibility for dangerous gases like carbon monoxide and methane due to poor ventilation.

The following is a summary of how different researchers investigated the use and reconditioning of decommissioned mines. The headings discussed for each research study are as follows:

- Title.
- Summary of the study and how it focused on decommissioned mines.

1. **Title** [54]: An investigation into the impact of mine closure and its associated cost on life of mine planning and resource recovery.

Summary: The article seeks to quantify the value that may be lost in the event that a mine closure plan is not adequately considered in the life-of-mine plan. To demonstrate this, the paper uses the case study to investigate the effect of closure on many aspects of the mine's design. The results of the study show that mining operation may benefit from an extended life of mine due to the time value of a mine.

The article shows that with adequate mine planning, the life of mine can be extended for deep-level gold mines. The planning can also ensure resource recovery and profitability of mining operations. Extending the life of mine for the use of an active mine will ensure an increase in cost effectiveness planning. This relates to the study of using a decommissioned mine as an additional ventilation shaft for a nearby active deep-level gold mine. However, the study does not include how an inactive mine section can be utilised for extending the life of mine for an active mine.

2. **Title** [55]: The design of push-pull primary and secondary ventilation system and a vertically split intake exhaust ventilation shaft.

Summary: The paper describes an unusual set of circumstances that led to a selection of vertically split ventilation shaft for a major mine expansion. The study looks at a Ventilation-on-Demand (VOD) system as where ventilation is required at new working areas. An unusual push-pull district ventilation system was utilised in the study. Factors that have an impact on the choice of ventilation design and risk management associated with the design are described in the paper.

The unusual case study used in the paper makes it a good literature piece for studying decommissioned mine ventilation networks. The paper correlates with this study due to the ventilation that is needed for a mine that is expanding. The VOD system follows the same path to where ventilation networks change to meet ventilation requirements. The study also raises the value of having a considerable size main surface fans and the impact that the shaft resistance has on the fans. The problems encountered in the case study are also a problem that could be encountered in inactive mining sections.

The studies above show that there are many solutions for optimising ventilation for an expanding mine, for example, fans and ventilation control devices. In some cases, making use of a secondary shaft will help ventilate new areas that are a substantial distance from the primary vent shaft. Due to the inaccessibility of decommissioned mines, studies have omitted ventilation network analysis techniques for inactive or decommissioned areas.

1.4.4 Ventilation network analysis

Ventilation network analysis is focused on the interactive behaviour of airflows within the connected branches of an integrated network [21]. Ventilation network analysis is a generic term for multiple techniques that enables mines to determine and predict airflow [22]. Any operating mine is a dynamic system with continuous workings and development where ventilation analysis should be a routine and continuous process [56]. The ventilation network analysis of a mine is part of ventilation planning [56].

Measuring the ventilation of a mine is an organised process of obtaining the whole mine's airflow, pressure, and air quality (temperature) throughout the walkways, stations, and working areas [56]. Mines that do not have the access to instrumentation underground to give critical information, as listed in Table 2, have to make do with manual surveys.

Table 2 Ventilation survey measuring parameters

Measuring parameters	
Parameter	Units
Barometric pressure	kPa
Airflow velocity	m/s
Airflow quantity	m ³ /s
Cross-sectional area	m ²
WB (Wet-bulb temperature)	°C
DB (Dry-bulb temperature)	°C

The parameters shown in Table 2 are the measurable characteristics that are used to describe the ventilation network at a specific point. Multiple measuring points can be used to characterise a ventilation network. The information can then be used to set a baseline for the network before or after any changes are made to the system.

Manual ventilation surveys are usually done by the occupational hygienist and ventilation department of a mine. Conducting manual measurements is a way of analysing a ventilation network. Methods for conducting manual ventilation surveys are described and shown in Appendix A.

Using manual measurements for analysing a ventilation network is not always possible. Studies have shown that there are multiple ways of analysing a ventilation network. The following is a list of studies that have used different methods in analysing a ventilation network and apply to ventilation networks.

1. **Title** [57]: Reliability calculation of mine ventilation network

Summary: The research paper discusses the reliability of a ventilation network and how it can be calculated using a mathematical model. The study uses the disjoint Boolean algebra method to calculate the reliability of ventilation branches with regards to resistance change, air pressure changes, and random disturbance. The reliability calculations show that the changes made in a ventilation network are predictable.

The reliability of a mine ventilation network is a measurable index and is the probability of a mine ventilation network meeting all requirements. The designing and managing of mine ventilation networks can be a predictable process if the network is analysed correctly.

Relevance: The study showed how a mathematical model could be used to predict the resistance change and air pressure change in a mine ventilation network. This could be applied to a ventilation network when the resistance is unknown.

2. **Title** [58]: Application of depth-first search method in finding recirculation in mine ventilation system.

Summary: The research paper looks at analysing the recirculation of airflow in a ventilation network by using a method called “depth-first”. The recirculation of air can induce a concentration of contaminated air and cause the ventilation network to be less effective. The method is implemented through MATLAB in the form of storing information in a matrix [59].

The method used in the study is a representation of how simulation software can be used for analysing ventilation networks. The method can be used to improve the effectiveness of ventilation networks underground.

Relevance: The study shows how the recirculation of air can reduce the efficiency of a ventilation network. The method of searching for recirculation could be applied to inactive areas to be sealed off and improve the efficiency of the network.

3. **Title** [60]: The analysis of ventilation and cooling requirements for mines.

Summary: The method presented in the article for analysing ventilation and cooling requirements has been developed based on experience gained on several mines in South-Africa. The method dealt with important factors that have a bearing on the ventilation and cooling requirements of gold mines.

The study categorises active mines with the objective to extend the mining operation by using existing facilities for long-term planning as type B mines, for the interest of the study. Type B mines are associated with existing mines where the object is to extend mining operations into new ground and often to greater depth, the aim is to make the best possible use of the existing facilities and to define the additional infrastructure required. The flow diagram in the study shows that analysis of the total airflow through the mine is required for type B mines. The research paper goes into detail on how to create a model and to assess the practicality of the model through airflow.

Relevance: The study gives an adequate guideline on how to analyse a ventilation network and the requirements for a ventilation network. The guideline could be implemented on a ventilation improvement strategy to improve cooling through ventilation control.

4. **Title** [61]: Analysis of mine ventilation systems using operations research methods.

Summary: The study focuses on using a programmed model to analyse and optimise locations for ventilation control devices. The overall cost was minimised through different proposed models. The primary purpose is reducing the cost and the mathematical models were developed to achieve this.

The analysing of the optimal placement of ventilation control devices can explain how airflow can be natural or controlled. The study explains how the resistance of a mine can have an impact on the flow of air. This can also explain how control devices have an impact on the ventilation network.

Relevance: The study uses a programming algorithm for finding the best suitable position for ventilation control devices. The objective is to minimise the power consumption needed to produce the required ventilation airflow. The method of placing ventilation control devices to reduce the power consumption could be applied on decommissioned or inactive mining areas.

5. **Title** [62]: The use of 3D simulation system in mine ventilation management.

Summary: This study, simulation software is used to analyse the effect of operational changes on a complex mine. The simulation software enables users to provide reliable data for decision making. The process of developing and using a 3D mine ventilation simulation can be used to analyse a ventilation network.

Relevance: The study produces good evidence on how simulation software can be used to analyse ventilation networks. The simulation software gives reliable data for decision making and can be used for improving ventilation networks.

6. **Title** [63]: Evaluating complex mine ventilation operational changes through simulation.

Summary: In this study puts forward a methodology for the development of a ventilation simulation. The ventilation simulation is used to evaluate the impact of operational changes on a ventilation system. The method allows for improved ventilation analysis and decision making. This method can be applied to develop a reconditioning plan for a mine's ventilation network.

Relevance: The case study used in the article validates the use of key performance indicators (KPSs) in analysing service delivery. The use of KPIs can be used on ventilation network analysis where minimal data of the network is available. The methodology developed in the study could be applied to inactive or decommissioned mines for developing a simulation model.

Analysing a ventilation network not only consists of measurable data but also the correct tools to make informed discussions. The literature above shows that making use of mathematical models and simulation software can also be a viable solution for analysing ventilation networks. However, sometimes areas are too dangerous to enter and collect information for the purpose of simulation analysis and therefore decommissioned areas need to be analysed with an alternative approach.

1.4.5 Simulation software for ventilation

Technological advances over the past few decades have brought to light new opportunities to the international mining industry. Examples of new technology to assist in the mining industry is simulation software for ventilation networks. It is therefore not surprising that it becomes essential for ventilation engineers to design and plan ventilation networks to a high degree of accuracy [64].

It is a complex task to control a mine's ventilation network. Whether it is to design the ventilation network or restructure its current operations, the use of specialised software is required [65] [66]. There is a huge advantage to making use of simulation software, considering the various number of situations that can occur in a mining operation. From a ventilation network point of view, the advantages can be summarised as the following [67] [68] [69]:

- Computer simulations can aid in making the right decisions.
- Simulations provide modern exploration possibilities based on the three-dimensional (3D), virtual model of the existing mining network.
- Engineers and engineering teams can use the simulation software to explore and evaluate new operating procedures or methods without having to incur the huge capital costs of experimenting with the existing or real system.
- Computer simulations can help in the initial design phase and in preparing the restructuring of the network as well.
- Can help with existing and potential problem diagnostics.

Studies have also shown that simulations that use thermo-hydraulic solvers can be used as a verification technique in operational changes [70] [71] [72] [62]. A thermo-hydraulic solver considers the pressure drops and temperature variation of an airway and includes the effects of water [73]. When using simulation software, the level of the data required should also be taken

into account [63] The following is a discussion on the different types of ventilation simulation software that are available.

Process Toolbox (PTB)

Process Toolbox is a transient thermal-hydraulic system simulation and optimisation tool that enables the user to design, analyse, and optimise system performance [74]. The system's network is constructed through system pressure nodes and pipes specifying the flow path. Process Toolbox uses Drawing eXchange Format (DXF) to build a 3D model of a mine's ventilation network [20]. These models can be built on separate layers and connected on later stages of the building process. PTB also lets the user work with other services in a mine, for example service water and compressed air and cooling systems.

The following is a list of the features and capabilities of the PTB software [75]:

- The simulation platform has a graphical user interface (GUI) to configure systems intuitively on a drag-and-drop interface.
- Pressure drops are calculated in the pipes and the thermal-hydraulic properties in the pressure nodes.
- The gas flow solver is a compressible quasi-steady-state semi-implicit solver.
- The liquid flow solver is an incompressible quasi-steady-state semi-implicit solver.
- The steam flow solver is a two-phase compressible quasi-steady-state semi-implicit solver.
- The system platform has a component library for fast and easy system configuration.
- The optimisation solver minimises the specified objective value for steady-state and transient systems or processes considering the optimisation variables and constraints for any number of time periods and period size.
- The system component inputs, optimisation variables, and optimisation constraints and outputs automatically expand to match the specified number of time periods.

Vuma-3D

Vuma is a network software used by engineers and practitioners, where the simulation program is specifically designed to assist underground ventilation control. The software is also used to design, plan and operate mine ventilation systems. Vuma is an interactive program that allows

the steady state simulation of airflow, thermodynamics of air and dust and gas emissions in underground mines. The 3D model is constructed using DXF files [64].

Ventism

Ventism is a simulation software that is based on an independent platform for mine ventilation implementation software. The 3D model is created by importing data basis from other mine design software or ventilation software into the system. With the help of AutoCAD (computer-aided design) graphic software and DXF's the model can be created [76] [77].

3D-CANVENTS

3D-Canvent presents a new approach to the automation of simulation software. The software uses subroutines and macros to increase efficiency and reduce the level of complexity. Creating the model involves a complex process, which implies a large volume of activity [69] [2].

All the simulation software incorporates thermo-hydraulic solvers, which can solve incompressible flow. Each simulation software has a certain level of accuracy that is measurable. The accuracy of the simulation setup can be measured by using the baseline simulation and verifying the results with the actual collected data from the mine. One of the most effective methods for calculating or measuring the model setup is by using the mean absolute error (MAE), according to Friedenstien, Cilliers, and van Rensburg [78]. The MAE percentage error can be determined by using Equation 1 [79] [20].

$$Error_{\%} = \frac{1}{K} \sum_{k=1}^K \left| \frac{A_k - S_k}{A_k} \right| (100\%) \quad (1)$$

Where:

Error% = Percentage error [%]

K = Total number of data points

k = Specific data point

A_k = Actual data point

S_k = Simulated data point

can therefore be a valuable technique for evaluating ventilation simulation models.

Simulation software is a tool used that is not only capable of analysing ventilation networks but can also be utilised for optimisation projects and planning. The optimisation of a mine's ventilation system can be classified into two categories [24]:

- The optimisation of internal adjustment of ventilation networks to select the optimal parameters to one determined by the ventilation system scheme [80].
- The optimisation of the whole ventilation network [81] [82] [83].

With the large technological advances that have been made with simulation software, the software enables engineers to analyse and optimise mine systems much more efficiently. Inaccessible ventilation networks with minimal data can be analysed using software simulations as an alternative approach.

The software package used further in the dissertation is Process Toolbox (PTB). PTB was selected as the simulation software due to the following reasons:

- The software is available for use.
- Familiarity with software.
- The capability to analyse compressible flow.
- Capability to analyse incompressible flow for deep-level mines.
- The level of data required to use the software.
- The software incorporates a thermo-hydraulic solver.

1.4.6 Optimisation of ventilation networks

The optimisation of a ventilation network of a mine is a combination of complicated optimisation problems, which can be described as a path optimisation problem. For over many years and multiple research papers, there have been many proposed algorithms for optimising a mine's ventilation network [84]. Some of these methods are for example the critical path method, the Hardy Cross method and other more efficient approximation methods [14].

Advanced programming techniques have been used to optimise the modelling techniques for improving computing efficiency [70]. These methods are described as:

The Hardy Cross method

The Hardy Cross method uses Kirchhoff's First Law, which states: "Current flowing into a node must be equal to the current flowing out of it" [85]. In this case, a node is seen as a junction in an airway and the current is seen as the airflow. The ventilation network is built, and all fans, doors, regulators, and other ventilation control devices are noted for size and position. The resistance for each airway is then calculated and the network is divided up into a series of meshes. The minimum number of meshes is calculated using a simple equation:

$$M = B - J + 1 \quad (2)$$

Where

M = minimum number of meshes

B = number of branches

J = number of junction or nodes in the network

A mesh should also not contain more than one high-resistance airway, and such an airway should not appear in more than one mesh. Afterwards, the correct flow direction for each branch should be selected. When all the correct resistance factors and branches have been met, the satisfactory airflow balance will be reached [70].

The method can be applied to a single level due to the size of deep-level gold mines. The method can be used to find the paths with the least and most resistance in the ventilation network.

The Critical Path method

The Critical Path method is also referred to as the Ant Colony Algorithm. This algorithm is used to select the optimal ventilation airways with the lowest ventilation control cost [24]. The ventilation control cost describes the amount of capital needed to achieve the required airflow through an area. The method focuses on improving the airflow in pathways or airways where most activity is recorded [24].

The Critical Path Method is a method that can also be used to simplify a ventilation network and reduce the complexity thereof. A complex level with multiple travel ways and airways can be reduced to only the critical paths used in the level. This is due to the critical path being the largest contributor to airflow supply with the least ventilation control [24].

The mining industry is only made possible through investments of large capital funds. Thus, mines are looking into short- and long-term optimisation strategies due to shifting mining activities and the cost implications [86]. As discussed in the previous section of the study, the use of simulation software is a viable and suitable tool to use for optimising a ventilation network. The following is a summary of how different simulation software has been used to optimise a ventilation network of a mine.

The following headings are discussed for each research study:

- Title
- Summary of the study and how the simulation software was used in optimisation.

1. **Title** [76]: Study of coal mine ventilation system optimisation based on Ventism

Summary: The simulation software Ventism is used to identify airways or tunnels in a coal mine with higher-than-normal resistance. These airways are then reconditioned to produce a lower resistance that is more suitable and will result in higher quality airflow. Thus, using the Ventism optimisation software in ventilation design is practical. The simulation software simulated the impact of reducing the system resistance of the mine network.

Relevance: The study shows that simulation software can help in simulating operational changes of a mine. Simulation software can therefore be used in simulating inactive sections of a mine for an improvement plan.

2. **Title** [87]: Estimating underground mine ventilation friction factors from low-density 3D data acquired by a moving LiDAR.

Summary: The study shows how a LiDAR scanner is used to help in the aid of improving and optimising ventilation models and simulations. The article goes into more detail about the new technique used in estimating underground drift friction factors by using 3D data obtained by a small mobile LIDAR scanner.

The use of new technology can increase the accuracy at which simulation models are created. A more accurate simulation will help to give precise results and help engineers to make more sustainable decision regarding mining operations underground.

Relevance: The use of new technology on analysing and creating ventilation simulation models is used in the article. The study illustrates the implementation of new methods in constructing simulation models, which could apply to mines that are too dangerous for entry.

3. **Title** [70]: Optimization of complex mine ventilation systems with computer network modelling.

Summary: The article discusses the mathematical models and techniques used in ventilation models that are used in the industry. It also discusses the use of ventilation simulation models in making engineering decisions and multi-million-dollar implementations, like adding cooling systems, for a mine ventilation system. The decision making through simulation is a large focal point in the mining industry as the cost of projects are extremely expensive.

Relevance: The study shows that the use of simulation on complex mine ventilation networks can be used for evaluating optimisation projects. Simulation software can be used for improving ventilation on deep-level gold mines due to their high complexity.

4. **Title** [88]: An integrated approach towards the optimization of ventilation, air cooling and pumping requirements for hot mines.

Summary: In this study, an analytical simulation was used to create an optimisation schedule for a mine ventilation network. The study shows that the use of simulation models is vital. The ventilation network was optimised by implementing ventilation of demand (VOD). Variable speed drives (VSDs) were used to vary the amount of air supplied to underground.

Relevance: Air quantities can be optimised by using VSDs on main surface fans. The impact of surface fans on the ventilation network can thereby be monitored. The process for the development of the simulation model can be applied to the simulation model for a decommissioned mine.

5. **Title [89]:** Improving the ventilation system at Rosh Pinah zinc mine.

Summary: In this study, a simulation was used to improve the underground ventilation conditions of a zinc mine. It showed that simulation can be used to optimise the ventilation and improve underground conditions. The desired airflows were achieved by swapping out the fan size. The airflow was also redirected to achieve optimal air usage.

Relevance: The optimisation techniques used can be applied to a decommissioned mine to improve the utilisation of air.

6. **Title [90]:** The integration of mine simulation and ventilation simulation to develop a ‘Life-Cycle’ mine ventilation system.

Summary: The study focuses on the integration of the ventilation optimisation and planning that goes into the overall life cycle of the mine. Simulation software can provide efficient primary ventilation systems. The VOD method was applied to reduce the power consumed by the fans.

Relevance: The study incorporates techniques for optimisation into the design of the ventilation network. The process to incorporate VOD into a ventilation system can be applied to a decommissioned mine that only requires certain areas to be ventilated.

1.4.7 Summary of significant literature

The studies and research papers in Chapter 1 show that the optimisation of mine ventilation networks have a significant opportunity for improving underground conditions. The use of simulation software can help to determine the optimal solution for optimising a ventilation network. Table 3 shows the literature that adds value to the dissertation and had an impact on the methodology developed. The four focus areas highlighted by the literature are also shown in Table 3.

Table 3 Applicable literature matrix

No.	Source	Simulation	Optimisation	Decommissioned mines	Planning and design
1	[54]	✗	✗	✓	✓
2	[55]	✗	✗	✓	✓
3	[57]	✗	✓	✗	✓
4	[58]	✓	✓	✗	✓
5	[60]	✗	✗	✗	✓
6	[61]	✗	✓	✗	✓
7	[62]	✓	✗	✗	✓
8	[63]	✓	✗	✗	✓
9	[76]	✓	✓	✗	✗
10	[87]	✓	✗	✗	✗
11	[70]	✓	✓	✗	✗
12	[88]	✓	✓	✗	✗
13	[89]	✓	✓	✗	✓
14	[90]	✓	✗	✗	✓

Different optimisation techniques for ventilation networks that were used in each study are displayed in Table 3. Table 4 shows in which category for the optimisation of a ventilation

network each study falls. These techniques can be applied to inactive sections of a mine ventilation network.

Table 4 Optimisation techniques used in literature study

Technique of optimisation	Study
Complexity elimination	4, 6, 8, and 10
Ventilation on demand	2, 6, 13, and 14
Evaluating system resistance	2 and 3
Air utilisation improvement	1, 4, 5, 7, and 13
Use of key performance indicators	8

The deficiencies or shortcomings of evaluating and optimising ventilation networks as discussed in the literature are seen in the case of inactive sections or decommissioned mines. The use of a sealing plan to obstruct air from entering or exiting inactive areas are regarded, in literature, as an adequate improvement solution. The sealing plan technique falls under the following categories: elimination of complexity, VOD, an increase of system resistance, and improvement of air utilisation.

The studies that made use of simulation software for improving ventilation networks of mines have done so over the year as simulation software improved. The common development phases for each study using simulation software can be summarised as the following:

1. Obtaining information
2. Simulation model construction
3. Calibrating model
4. Verification of model
5. Optimise system through the assistance of the simulation model

1.5 Need for Study

The increase in mining depth and distance from primary ventilation shafts on deep-level gold mines increases over a mine's active years. The increase of gold mining depth has produced a surge in electricity consumption over the years in meeting ventilation requirements. Improving the ventilation networks of inactive areas can affect the overall efficiency of a gold mine

positively. Thus, there exists a need for optimising inactive areas in a deep-level gold mine to improve ventilation networks.

1.6 Problem Statement and Study Objective

Inactive sections of decommissioned mine ventilation networks can form part of a neighbouring mine's ventilation system. Neighbouring active mines use decommissioned mines as part of their ventilation system in utilising them as additional RAWs. Large portions of decommissioned mines have inactive sections still receiving fresh air. The objective of this study is therefore to simulate the inactive areas to analyse how the airflow through these sections can be improved. Based on this simulation, a sealing plan must subsequently be developed and implemented ultimately to improve the flow through active mining sections.

1.7 Overview of Dissertation

A summary of each section in the dissertation is as follows:

Chapter 1

Chapter 1 provided an overview of the current situation of gold mining in South Africa. The chapter also served as a literature study for the dissertation and highlighted the focus points of the dissertation. The need for improved ventilation systems, which serves as the primary form of cooling, was emphasised in the literature. The chapter concluded with a problem statement and set out the need for the study.

Chapter 2

Chapter 2 introduces a method for evaluating decommissioned or inactive areas of mine ventilation systems. The chapter goes into detail on how simulation software is used and provides a guide for the optimisation process. Different types of data that can be collected from mines are also described, which form part of improving ventilation system of deep-level gold mines through simulation.

Chapter 3

Chapter 3 describes a case study where a decommissioned mine's ventilation system was optimised. The simulation was built, and an optimisation solution was developed. The results for the implemented plan and validation thereof are also discussed.

Chapter 4

Chapter 4 concludes the study and discusses the limitations and further recommendations for the developed method.

Chapter 2: A NEW APPROACH TO EVALUATING DECOMMISSIONED MINE VENTILATION SYSTEMS

2.1 Overview

Chapter 2 elaborates on a solution methodology for improving the ventilation on a deep-level gold mine that has been decommissioned. The decommissioned mine is still in use and forms part of an active mine's ventilation network.

The methodology created in the dissertation for optimising a ventilation network of a decommissioned deep-level mine by using simulation software is shown in Figure 9.

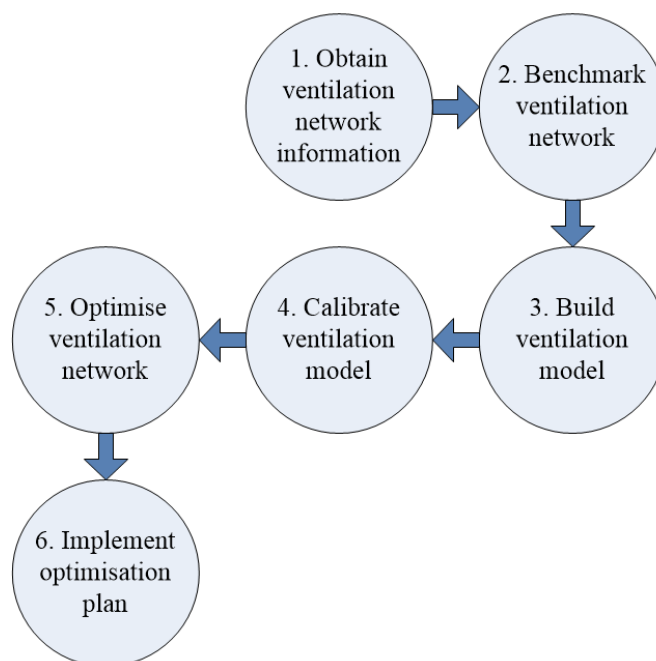


Figure 9 Methodology for optimising a ventilation network using simulation software

The methodology shown in Figure 9 was refined into six steps by comparing different simulation software and using different optimisation strategies from literature shown in Chapter 1.4.7.

2.2 A Method for Mine Ventilation Analysis Using Simulation

Analysis of a mine's ventilation network comprises characterising the mine's network as a whole system. When characterising a ventilation network, the gathering of reliable data is essential for high-accuracy results. Having access to this information will improve the accuracy of the analysis of the ventilation network. Therefore, using methodical steps to analyse a ventilation network is advantageous.

In a study done by A. Nel, J. Vosloo, and M. Mathews [63], a method was developed for evaluating operational changes in deep-level mine ventilation. The study was used as a guideline for creating the methodology used in this dissertation. The study produced a flow diagram for describing the means of analysing mine ventilation networks. The flow diagram is shown in Appendix C as Figure 44.

The first section of the flow diagram is where the operational changes and benchmarking of the service delivery system takes place. This consists of collecting measurable data and understanding the internal workings of the mine. Steps **A** to **B5** in the flow diagram were used to develop the first two steps of the dissertation's methodology.

The first two steps developed from the flow diagram in Figure 9 is to obtain system information and benchmark the service delivery system. Step **B5** is shown as the network data collection step and forms part of obtaining ventilation network information. The analysis of ventilation networks is described in detail in Chapter 1 and what other researchers have done in the field.

The second section of the flow diagram is where the focus moves towards using the data collected in the first part to construct and calibrate a simulation model of the mine. Steps **C** to **I** in the second part of the flow diagram were used to develop the third and fourth step in the study's methodology. Although the flow diagram develops a simulation model and evaluates the operational changes and their impact on the mine, it does not include how to optimise a ventilation network.

The six steps for the methodology shown in Figure 9 are described in detail below.

2.2.1. Obtain ventilation network information

Obtaining system information is the first step of the methodology. Collecting useful and available data will help in creating an accurate simulation model. The geometrical location of the mine is an important part of how the mine temperatures fluctuate underground depending on how deep the mine is. The Virgin Rock Temperature (VRT) of mines vary around the world; therefore, the location of the mine is also important when using thermal-hydraulic simulation solvers.

Having access to the mine's DXF files will help in step 3 when constructing the simulation model and is part of the system information. Most mines draw and build their mining plans on a geographic coordinate system (GCS). The drawings help to accurately create simulation models as a result of to the GCS system having not only longitudinal and latitudinal dimensions but also depth. Figure 10 shows a simplified DXF layout of a single level at a mine. The figure only shows the boundaries in which the haulages and crosscuts are found.

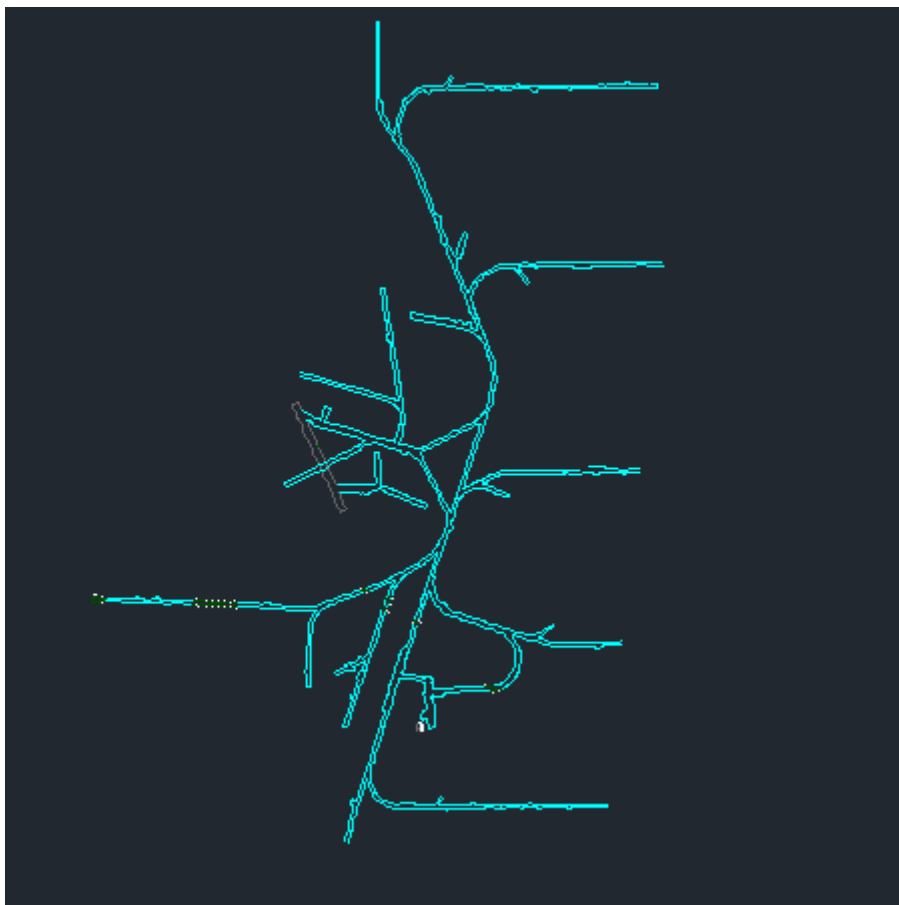


Figure 10 Two-dimensional DXF layout of a single level of a mine

DXF's can also show more than just the travelling ways. Figure 11 shows the same mine level as in Figure 10 but is rotated for a three-dimensional view.

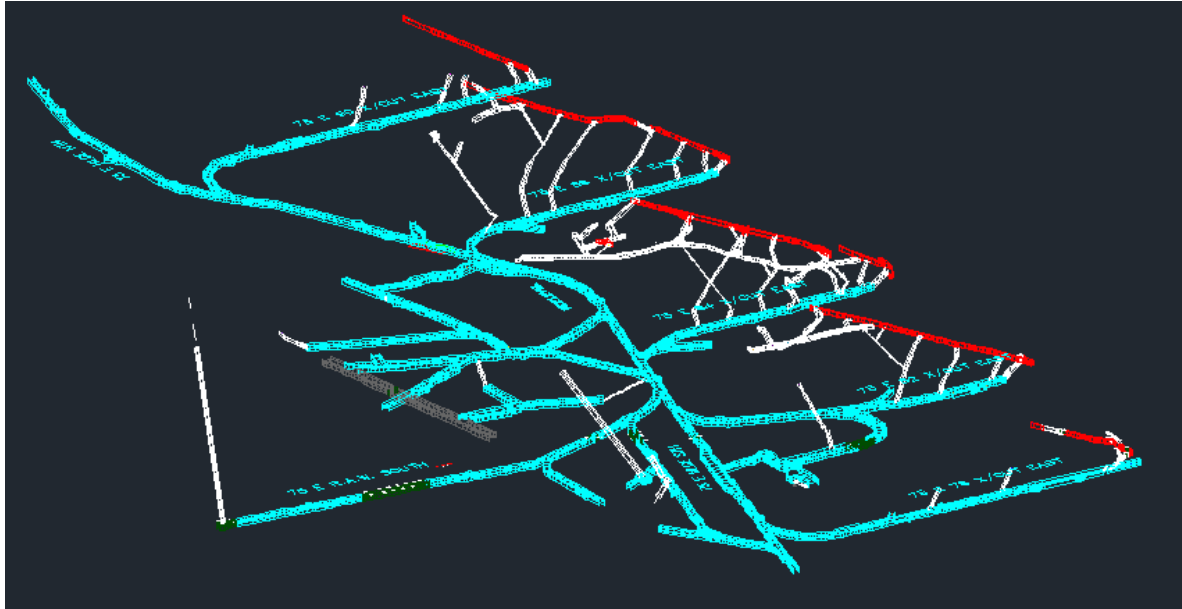


Figure 11 Three-dimensional DXF layout of a single level

The isometric view of the DXF shown in Figure 11 shows more detail such as:

- Red lines – Raise lines
- White line –Boreholes used for ventilation or box holes used for transporting ore out of raise lines.

Collecting the DXF layouts will also help in finding the position of the ventilation control devices and cooling systems of the mine. The occupational health and ventilation department mark layouts where all the ventilation control devices can be found. The ventilation departments conduct detailed audits to update layouts quarterly. These layouts are of great value when done according to mining laws and regulations. Mining laws and regulation describing mine ventilation layouts can be found under the MVSSA (Mining Ventilation Society of South Africa) [91]. The key parameters that can be found on a ventilation department's layouts are:

- Ventilation control devices,
- airflow direction,
- temperatures,

- air mass flow,
- fresh air intakes,
- return air ways and
- barometric pressure.

The key parameters found in the ventilation department will be required to enable benchmarking. Using the layouts with the information provided by them is an adequate way to obtain system information, especially when underground visits are not possible.

Simulation model accuracy is dependent on the type of data and information collected. Different levels of data are found at a mine, ranging from low-level to high-level data. Mines have network systems available called SCADA systems. Due to decommissioned mines having limited information and literature available the obtaining of information or data can be difficult. The following is a list and description of the level of data that can be acquired from a mine [20].

SCADA data: The Supervisory Control and Data Acquisition (SCADA) system of a mine uses a network to collect data and data communication for supervision. Controlling and managing complex systems is the main goal of the SCADA network. The data collected by the system is stored and can be accessed to view operating conditions and mining trends. SCADA data can produce accurate simulation due to the large amount of data that the system can recall and produce.

Low-level data: Low-level data can produce the most accurate simulation models. This is the most detailed data available from the mine. The data includes airflow quantities, temperature, and barometric pressure, which forms the key measuring characteristic of ventilation. Low-level data can be found on a mine's SCADA system if the mine is equipped with instrumentation to supply the level of data.

Intermediate-level data: Intermediate data can be described as a data level that gives the status of a subsection. An example of this in a mining environment would be to only have data for the intake and return conditions of a mine's levels. This data will help in constructing a mass balance of the mine.

High-level data: Using high-level data does not produce the highest accuracy when used. This type of data only characterises KPIs of a mine ventilation network. A KPI is a quantifiable measure that is used to gauge or compare performance in terms of meeting strategic and operational goals [92]. Therefore, KPIs must be aligned with the objectives.

The KPIs of mines vary since ventilation networks of mines are not all the same. Examples of KPIs of a mine ventilation network are total airflow into the mine, surface fan airflow quantities, average haulage airflow, average face velocity, average stope airflow, auxiliary fans, and main surface fans.

Manual measured data: Manual measurements are also only possible where it is safe to enter, and this can be a constraint for decommissioned mines or areas. When or where SCADA data is unavailable, the data needed can be collected through manual measurements. Conducting manual measurements can yield a high accuracy simulation in ideal conditions. Data from SCADA can be wrong due to uncalibrated equipment or instrumentation, but it can be verified with manual measurements. It is always good engineering practice to do sanity checks on collected data for increased accuracy on simulations.

Since mines are highly active and changing, the use of manual measurements cannot give a full profile of underground changes since they are instantaneous measurements [20]. However, this method of data collecting is an adequate method for benchmarking the service delivery system. The techniques and methods used in manual measurements are described in detail in Section 1.2 under ventilation network analysis.

2.2.2. Benchmark ventilation network

Benchmarking the service delivery and ventilation network is an iterative process. A mine's network data is required when creating and calibrating a simulation model. Benchmarking the service delivery, in this case the ventilation system of a mine, can be done in different ways. The benchmarking is dependent on the type of data that is available to the user. Table 2 in Chapter 1 shows the different parameters that can be used for benchmarking a ventilation network and creating a baseline simulation model.

A suitable method for benchmarking the ventilation network is conducting a volume survey of the mine's ventilation network. The volume survey uses manually measured data to describe the distribution of airflow over the mining levels. Figure 12 is a simplification of the measuring points for a volume survey on a mine where point **A** to point **D** is the survey points.

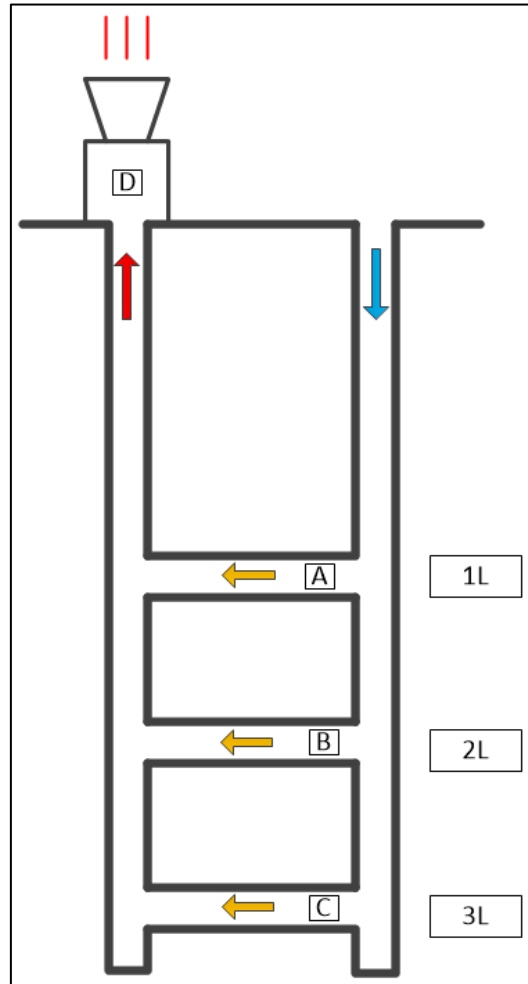


Figure 12 Representation of a ventilation volume survey

A volume survey measures the sum of the amount of air mass flow entering each level of a mine and the air mass flow exiting the mine. As shown in Figure 12, the sum of the air mass flow measured at points A, B, and C should equal the amount of air mass flow measured at point D. Points A, B, and C are usually measured at the entrance of the level at the station area. Point D is the amount of air that is expelled out of the mine by the main surface fan(s).

The surface fan(s) air mass flow is measured by a pitot tube and a manometer. The pitot tube is inserted into the fan ducts to measure the dynamic pressure, which is read from the

manometer and can be converted to velocity. With the duct area and air density, the air mass flow through the fan can be calculated.

High-level accuracy benchmark information would require a full volume audit of each level on a mine. An audit for each level will result in a better understanding of air distribution deeper into the mine. A simulation model can be calibrated more accurately with the full understanding of how a mine's ventilation network flows.

In the case where it is not possible to obtain any underground data, the ventilation network can be characterised through KPIs. Using KPIs for benchmarking the service delivery system is an adequate way of creating accurate simulation models [92]. KPIs can also be characterised as ventilation control devices that have a substantial impact on the ventilation network.

The main surface fans are set up such that it can be used for characterising a whole ventilation network to reduce the complexity of system analysis. The following list are parameters that can be calculated by using the fan performance curve when certain fan measurables are used.

- Static pressure

The static pressure can be measured with a u-tube manometer. The one end of the manometer is placed inside the fan's ducting and the other end is left open to ambient conditions. The static pressure is shown on the vertical manometer by subtracting the two pressure readings from each other as shown in Figure 13.

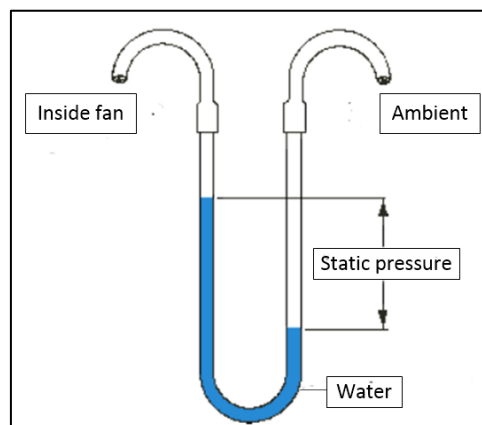


Figure 13 Representation of static pressure with a U-tube manometer

- System resistance

System resistance can be calculated by using the fan performance curve. This process is described in more detail in Chapter 1.4.2.

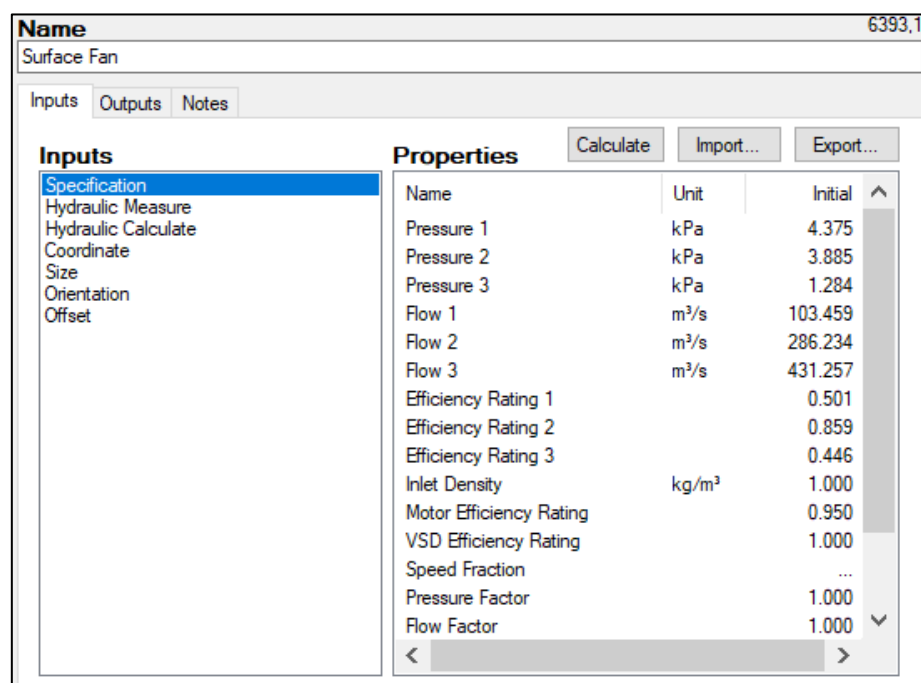
- Power

If an ammeter is installed on the fan the measured amps can be converted to power. The conversion from amps to power can be done by multiplying the measured amps by the input voltage.

- Volume flow rate

The volume flow rate can be measured manually as described in Chapter 1.4.4. If manual measurements are not possible the volume flow rate can be read off by using the power value and static pressure.

The fan characteristic that should stay constant to be able to obtain the values is the guide vane angle if there are any. The fan resistance curve will be the most valuable for benchmarking the system, as this curve describes the total resistance of the ventilation network. In the software PTB, the set-up for the surface fans required three points from the fan performance curve. The three points that can be selected are shown in Figure 14.



Name	Unit	Initial
Pressure 1	kPa	4.375
Pressure 2	kPa	3.885
Pressure 3	kPa	1.284
Flow 1	m³/s	103.459
Flow 2	m³/s	286.234
Flow 3	m³/s	431.257
Efficiency Rating 1		0.501
Efficiency Rating 2		0.859
Efficiency Rating 3		0.446
Inlet Density	kg/m³	1.000
Motor Efficiency Rating		0.950
VSD Efficiency Rating		1.000
Speed Fraction		...
Pressure Factor		1.000
Flow Factor		1.000

Figure 14 Fan characteristics for simulation software

The three points that are selected each reads the static pressure, flow for the specific pressure and efficiency rating at the specific flow. The points that are selected should contain the baseline operating point for the surface fan.

2.2.3. Build ventilation model

Step 3 will result in a theoretical model of the mine's ventilation network. The model will only be a representation of how the ventilation network of the mine should function in an ideal world. However, this is not the case since multiple variables play a role in the mine. The model therefore requires to be calibrated so that it can be used for optimisation projects.

Building the simulation can begin once the required data has been obtained and is found to be satisfactory. When selecting a simulation software package to use, the level of the solution should be considered. High accuracy results can be achieved by using a 3D software package that incorporates a thermal-hydraulic solver and solves mass balances. The simulation software package that was selected to use for the dissertation was PTB. The reasons that PTB was selected are explained in Chapter 1.

The mining network can be assembled in the simulation software by using the DXF files and data collected in the previous steps. In the unusual case where DXF files are not available, perhaps due to a mine's age, the GCS system can be used. Figure 15 shows how the coordinates are entered into the PTB simulation software.

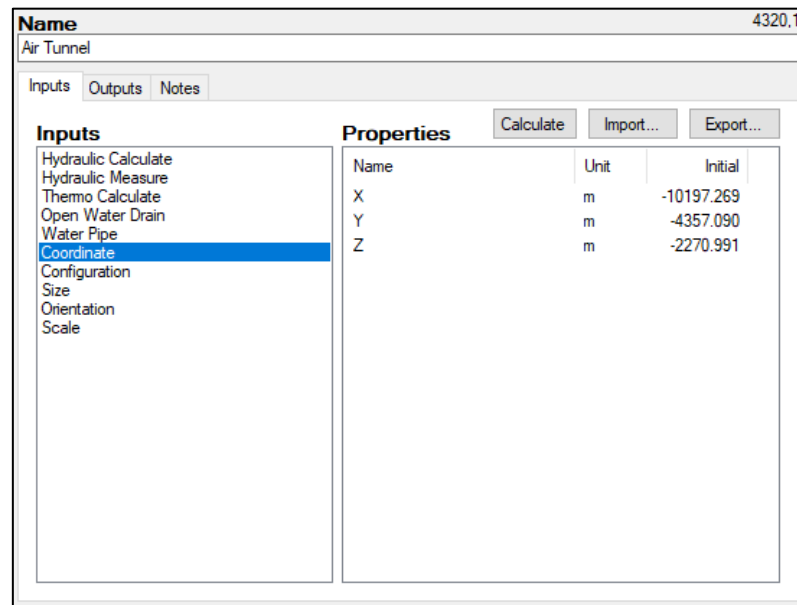


Figure 15 Coordinate input into PTB

Each component in the simulation has its coordinate location and can be set by changing the X, Y, and Z location. The X parameter is the **longitudinal** distance, and the Y parameter is the **latitudinal** distance. The Z location is the depth parameter from the international datum line. These parameters can be used to construct a detailed ventilation model of a mine when digital layouts are not available.

After the model of the ventilation network has been constructed, more detail can be added. The following is a list of all the variables that have to be built into a ventilation network model:

- Haulage size – The size of haulage varies in a mine depending on its purpose and the mining technique. The size of haulages can have a large impact on the overall resistance of the mine's ventilation network. The narrow reef mining method in South Africa usually sees an average haulage size of 9 m² to 12 m². The size used in the simulation will depend on the type of mining method used.
- Ventilation control devices – Ventilation control devices such as fans, doors, walls, and restrictions should also be built into the simulation. The position of these controlling devices has an impact on the airflow through the network.
- Surface fans – The correct size fan and fan ducting are important for future calibration processes.

The mining model created in the simulation software can be described as the mine skeleton. The mine skeleton is a representation of the mine's ventilation system and is an uncalibrated model.

2.2.4. Calibrate ventilation model

The next step is selecting boundary points in the simulation for calibrating the simulation model. The boundary points serve as individual constraints for each parameter that is simulated. Simulation boundaries are determined through the selected KPIs of the ventilation system.

The calibration process is an iterative process that uses the collected data from previous steps. An average operating point can be programmed into the model for the first iteration. The calibration process consists of multiple iterations. The different parameters to consider for calibration are air mass flow, barometric pressures, temperature and humidity. The following details how the parameters can be calibrated in a simulation model:

Air mass flow and barometric pressure

There is a direct correlation between air mass flow and barometric pressure and as such need to be calibrated simultaneously. Both the air mass flow and barometric pressure are affected by depth. The resistance of a mine plays a substantial role in the airflow through the mine. Resistance can be adjusted for obtaining the correct flow through tunnels, ducting, and shafts. The correlation between resistance and airflow is as follows:

Higher system resistance = Lower airflow = Higher pressure difference

Lower system resistance = Higher airflow = Lower pressure difference

The PTB simulation software uses a friction coefficient and tunnel fraction to meet the required resistance. A more accurate way to achieve the correct resistance is by increasing or decreasing the friction coefficient of the tunnels, but only when the area of the haulages in the mine are accurately built into the simulation software.

Changing the resistance of a mine's area that cannot be entered is extremely challenging. In this event, selecting a KPI to indicate the calibration level of the area is useful. Fans and main

fans play the largest role in the air mass flow and barometric pressure of the mine, as stated in Chapter 1. A fan's operating point can be adjusted to produce the needed pressure and airflow. Given the characteristics of primary fans and their impact on a ventilation system, they can be a useful KPI of the whole ventilation system.

Temperature and humidity

The temperature calibration can follow a step-by-step process. The process for calibrating the temperature is as follows:

1. Calculate the VRT [93] – The VRT is a constant for any fixed location. The constant takes into account the area of the mine, depth of the level, and age of the haulage. This will produce the heat added to the mine from the rock faces.
2. Add additional heat contributors – Mechanised equipment, lights, and personnel are a part of heat generators in a mine [94]. Each component contributes to the heat pickup and can therefore be added to the simulation model. Heat loads done on a mine can produce the total heat added to the system by different components [95].

The humidity can be calibrated by adjusting the amount of moisture that is added by components to the air of the system. Humidity is a ratio that can be calculated on a psychrometric chart between the dry-bulb and wet-bulb temperature at a certain pressure. Therefore, the humidity is already produced once the wet-bulb temperature, dry-bulb temperature, and barometric pressure have been calibrated.

In the PTB simulation software, the heat added to the system is adjusted through the tunnels that make up the simulation model. The following is a list of the parameters that can be set and changed for calibration:

- Virgin rock temperature – ($^{\circ}\text{C}/\text{m}$)
- Rock specific heat – ($\text{kJ}/\text{kg}/^{\circ}\text{C}$)
- Wet area fraction
- Heat – Used to add heat to the system from additional heat contributors.

The simulation accuracy of the calibrated model must be verified by comparing the simulated data with the actual data. To verify the model's calibration accuracy, the MAE method is used, as shown in Equation 2. The points measured should correspond to the points in the simulation

within a 10% error margin for the simulation to be deemed adequate and have accurate results for optimisation [96] [97].

2.2.5. Optimise ventilation network

The focus of the dissertation is on improving a deep-level gold mine's ventilation network by simulating inactive sections. Previous literature shows that using simulation software is a suitable method for optimising a ventilation network. Comparing the current ventilation system with its ideal conditions will help to identify inefficiencies. An efficient system provides the required amount of air at the defined working areas and travelling ways without using excessive electrical power.

The impact of the optimisation plan can be evaluated by implementing an optimisation plan in the simulation model. The simulation software makes it easy to evaluate possible optimisation solutions.

The following subsection discusses how a ventilation network can be optimised.

Complexity elimination

The extensive size of ventilation networks makes it an ideal area to reduce or eliminate complexity. Complexity elimination can be done in various ways, from reducing the ventilation control devices to reducing the number of airways used. A sealing plan is such a method used for reducing complexity when areas are inactive or have been mined out. Figure 16 shows an example of how a sealing plan can reduce complexity in a mine.

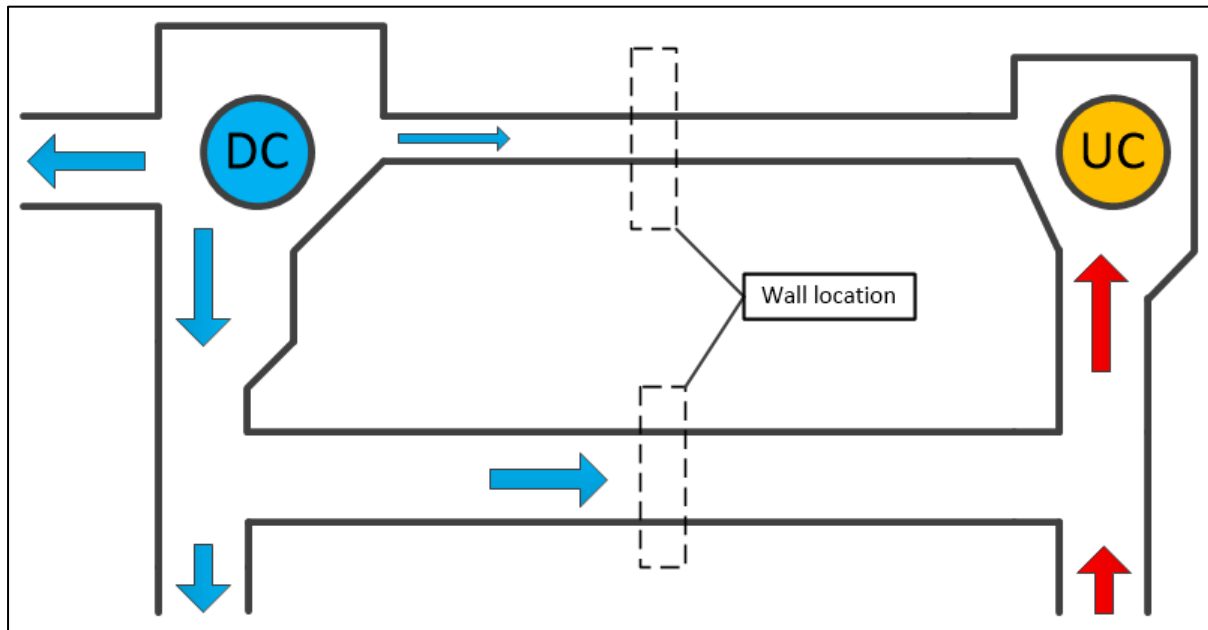


Figure 16 Example of a sealing plan reducing complexity on a station level

The downcast (DC), in Figure 16, delivers fresh air to the mining level, from which air moves to the working areas and some air short-circuits to the upcast shaft. Building walls or seals to reduce air short-circuiting to the upcast shaft reduces complexity and improves air utilisation. The sealing plan blocks air from entering areas where there is no need for ventilation and is usually done by building a wall.

This method also incorporates itself with the critical path method. Short-circuiting air can be sealed off and will improve the utilisation of air through the mine. Over a long period, the ventilation control devices may lose their effectiveness due to high temperatures and humid conditions. Reducing the number of ventilation structures reduces the chances of leaks occurring in the ventilation network and can also reduce the complexity of the ventilation network.

Improved air utilisation

Depending on the size of the mine, the air velocity can reduce as the ventilation network expands. To reach areas that are far from the upcast and downcast shaft, the fans will have to perform at a high pressure and power, which results in higher electricity consumption. Using a methodical sealing plan can help in utilising the airways correctly to lead to a more efficient system. Figure 17 shows an example of how a sealing plan can improve air utilisation in a mine.

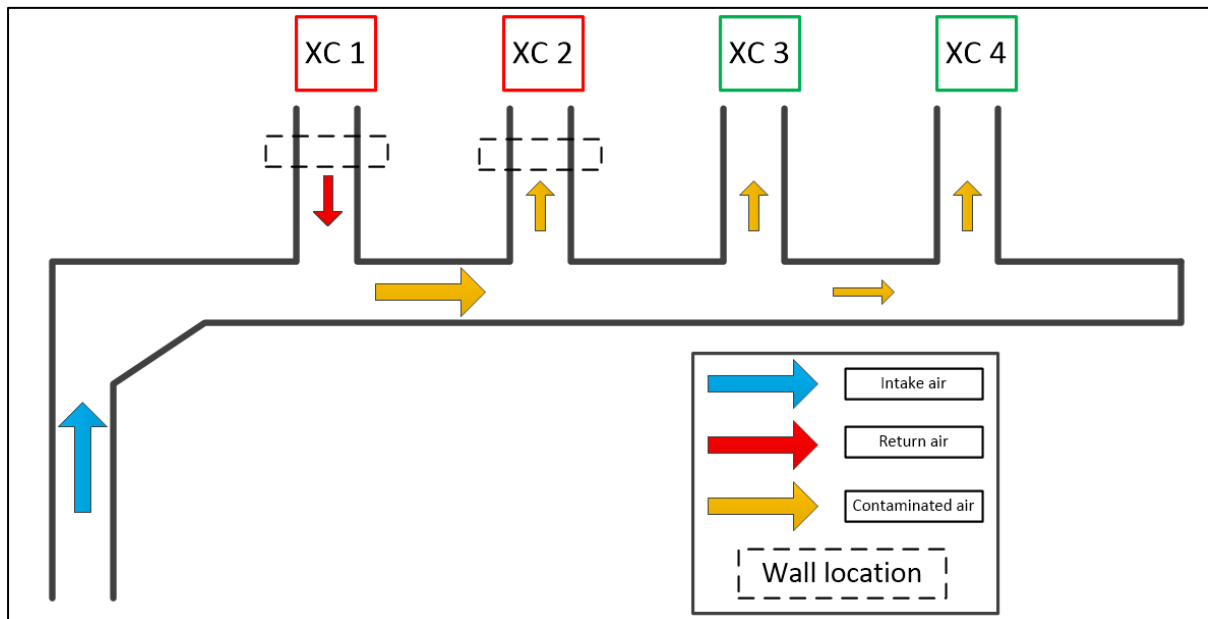


Figure 17 Example of how a sealing plan can improve air utilisation

In Figure 17, XC 1 and 2 are inactive areas and XC 3 and 4 are active areas. The air intake in Figure 17 is contaminated by hot air returning from XC 1 which also moves into XC 2 where fresh air is not needed. With XC 1 and 2 open, the air that reaches XC 3 and 4 is less and warmer than it would be had the XC's been sealed. Sealing off the two non-active XCs will improve air utilisation for that section of a mine.

Fan optimisation

Replacement of primary fans with a more efficient primary fan will reduce the power used to ventilate the same area. Fans used underground have the possibility of working against each other. The improved air utilisation can avoid the use of fans underground and in so doing eliminate the problem.

Optimising will result in operational changes, which will have a direct result on KPIs. For each operational change that is made, the resulting conditions will have to satisfy the service delivery and operational needs. The optimisation plan selection will depend on the objective of the optimisation. Factors that may also influence the selection, regardless of the KPIs, are listed as:

- Cost of implementation
- Safety concerns

- Ease of implementation

2.2.6. Implement optimisation plan

The optimisation plan that is developed for optimising a deep-level gold mine's ventilation network will be implemented and evaluated. After implementation, the plan must be validated to see if it was successful. The plan can be revisited and changed if necessary to achieve the set goals of the strategy.

2.3 Expectation from implementation of methodology

The objective of this dissertation is to improve a deep-level gold mine's ventilation network. The expected results section is a prediction of the outcomes for a possible case study that involves a decommissioned or inactive area in a mine. The expected results are derived from the literature study in Chapter 1.

The challenge with inactive sections of mines is that there is little to no information available to benchmark the ventilation network. Conducting manual measurement audits underground can also be challenging or not feasible due to health and safety concerns. Using the main surface fans as a KPI to benchmark the ventilation network is a suggested option for benchmarking the system and evaluating the impact of the proposed reconditioning plan. The expected results will be shown by the simulation software together with whether the reconditioning plan for the mine's network is feasible.

The implementation of a reconditioning plan for the ventilation network is expected to improve air utilisation. Figure 18 shows the expected outcome of the fan performance curve from the reconditioning plan.

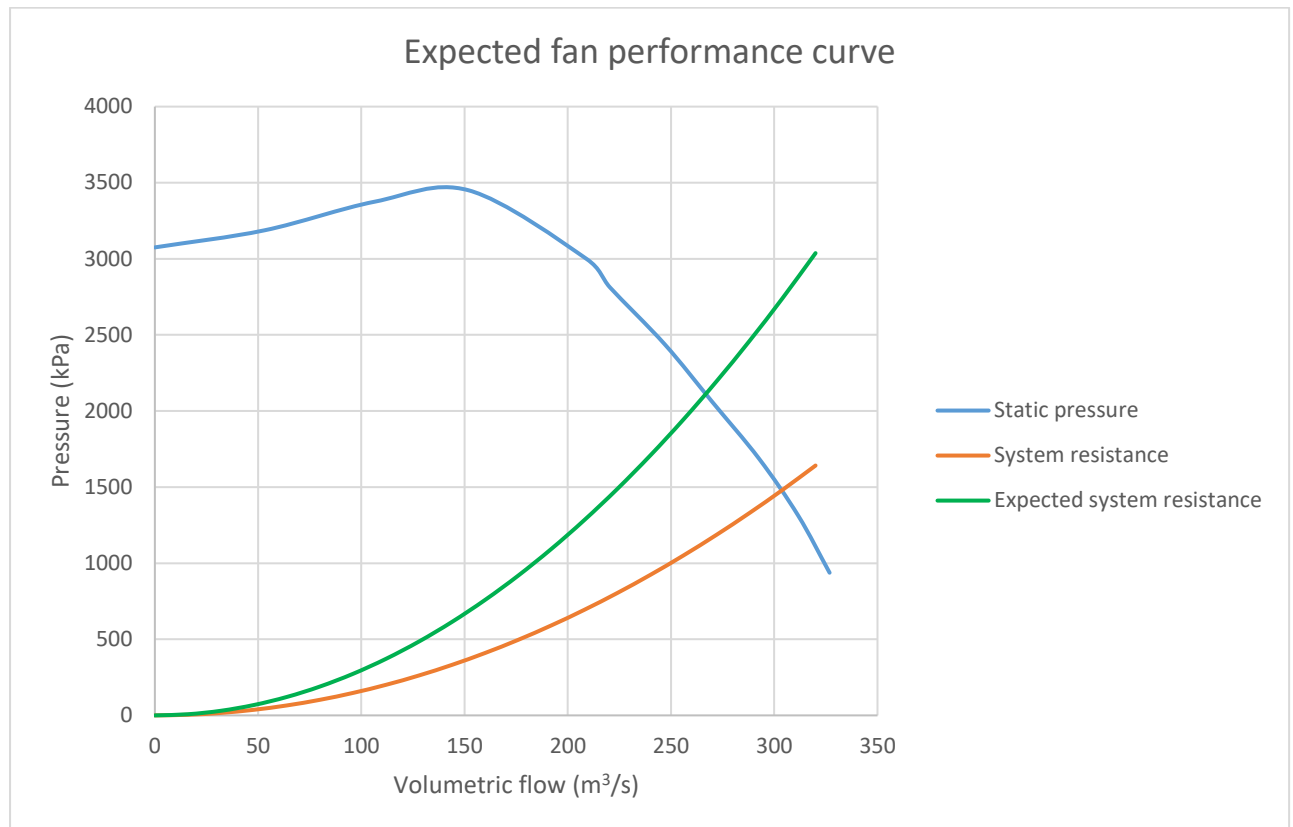


Figure 18 Expected fan performance results

The expected results from the reconditioning plan are that it will increase the system resistance of the decommissioned mine. Figure 18 shows the baseline system resistance curve and the expected system resistance curve. With an increase in system resistance, the operation point of the fan will be higher. The operating point of the fan is the point where the static pressure curve intersects with the system resistance curve. A higher operating point on the main fans is expected to result in improved air utilisation in the ventilation network.

2.4 Conclusion

This chapter presented an approach for evaluating decommissioned or inactive mine ventilation networks. Implementing the method on a mine ventilation network will improve the airflow utilisation and efficiency.

Section 2.2 of this chapter looked at how simulation software can be used to analyse a mine ventilation network. A methodology for optimising a ventilation network of a deep-level mine by using simulation software was also described.

Section 2.3 indicated the expected results from the use of main surface fans as the KPI.

Chapter 3: RESULTS

3.1 Introduction

Chapter 3 applies the method discussed in Chapter 2 to a deep-level gold mine's ventilation network. Simulation software is used to construct a model of the mine and evaluate the optimisation plan set out for optimising the ventilation network. The mine that was selected as the case study is a decommissioned deep-level gold mine in South Africa. The optimisation plan for reconditioning the mine's ventilation network was implemented on the case study mine and then evaluated.

3.2 Case Study Results

The section of Chapter 2 discusses the case study used for the dissertation and the results that were obtained. The results that were obtained was used to evaluate the use of simulation software to optimise the ventilation network. Included in the results are the volumes that were achieved and not the cost impact of the optimisation. The cost impact or reduction was not evaluated in the dissertation.

3.2.1 Reconditioning of mines A's ventilation network

A decommissioned deep-level gold mine's ventilation network in South Africa was selected as a case study. A simplified representation of the cross section view of the case study mine is shown in Figure 19.

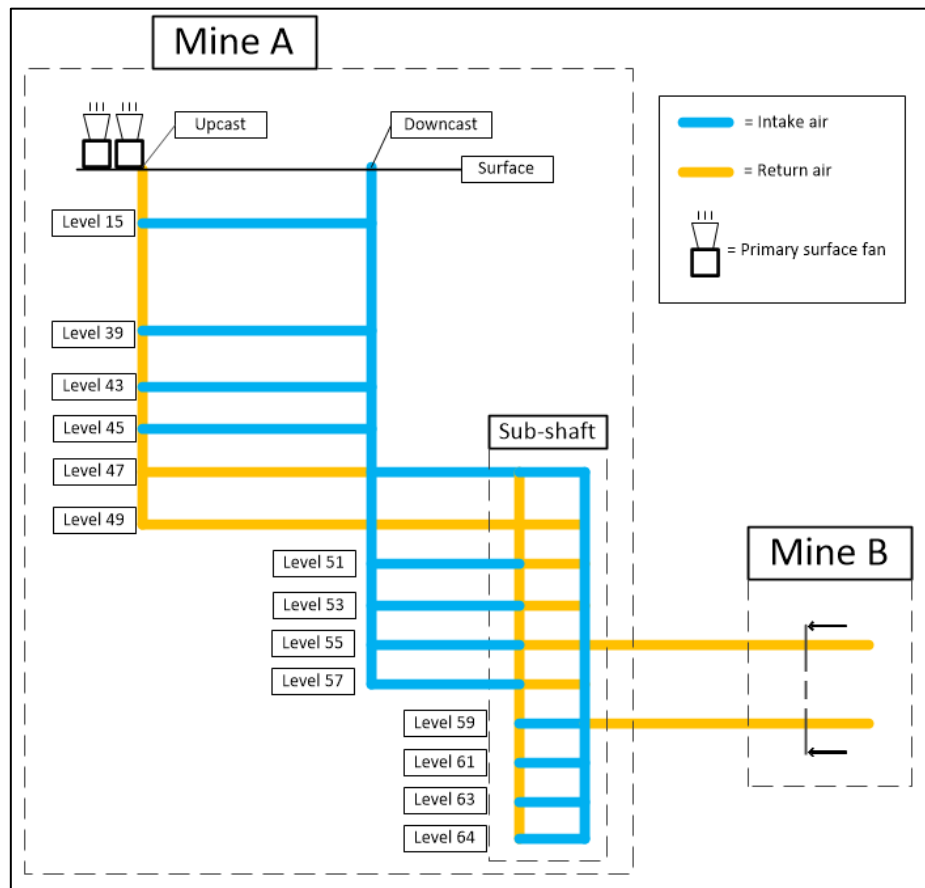


Figure 19 Simplified cross section view representation of the case study mine

For the purpose of this study, the mine will be referred to as Mine A. Mine A was an active mine several years ago but has since been decommissioned from mining activities. Mine A serves as a secondary ventilation shaft for a nearby deep-level gold mine that is actively mining. The nearby mine will be referred to as Mine B for the study. The representation of the case study mine only shows the shafts, connections between the stations for each level, and the connection between Mine A and Mine B.

Mine A has a layout of 14 levels of which six, (Level 15, 39, 43, 45, 47 and 49), form part of the upper-level mining block. The other remaining eight levels (51, 53, 55, 57, 59, 61, 63 and 64) are connected to the sub-shaft and form part of the lower-level mining block. The main upcast shaft and sub-shafts are connected on levels 47 and 49. These two connections between the main upcast shaft and sub-shafts serve as the main RAW for air from the sub-shaft.

Mine B is a deep-level gold mine that has made Mine A apart of its mining plan and ventilation network strategy. In addition, the mining plan of Mine B has included Mine A for future mining

ventilation needs. Mine B's plan is to extend mining activities towards the decommissioned mine in the near future. These advances have made it all the more feasible to use Mine A as a ventilation shaft. The two mines are connected by two levels, and these levels are level 55 and level 59. However, old mining areas that are inactive are still open on other levels with connecting raises.

Mine B also has two auxiliary fans on 55L that is positioned inside the RAW. The two fans are used to return air from Mine B to Mine A. Optimising Mine A's ventilation network will contribute to the effectiveness of using it as a ventilation shaft for Mine B. The ventilation network of Mine A is analysed and evaluated in the following section to optimise the system.

3.2.2 Application of method

The method shown in Figure 9 was applied to the ventilation network of Mine A. A simulation model was constructed and used to evaluate a proposal to optimise the ventilation network. The following section provides a step-by-step discussion of how the method was applied to the case study mine.

1. Obtain ventilation network information

Mine A is an old mine that has been active since the 1920s. The mine's layout has never been captured onto computer software and is only available on paper because of the lifespan of the mine. Building the layouts for each level made it difficult due to there not being DXF files. The paper layouts do have a latitudinal and longitudinal line that were used to obtain key points for each level. These key points made it possible to construct an accurate model in PTB.

Mine A has also fallen victim to an issue that many gold mines in South-Africa face. Illegal miners migrate and occupy old working areas in gold mines. The occupying of the mine by illegal miners have made it a security risk for going underground and consequently conducting manual measurements is difficult. Due to the illegal miners, a deteriorating mine, and unsafe conditions, collecting of ventilation information about the mine was a challenge.

The information that could be obtained of the mine was collected from the occupational hygienist of the mine. The information obtained from the mine is as follows:

- Paper layouts of all the levels
- Active levels and used haulages
- Main RAW locations
- Ventilation control device locations
- Main fan curve
- Volume survey of upper levels

The mine has multiple mining levels that are not in use anymore but still receives fresh air from the downcast shaft and then returns the air to the upcast shaft. Figure 20 shows the active levels from which the information is collected for which levels are still being used and are critical to the ventilation network of Mine A. The levels that are still active are level 15, 47, 49, 57, 61, and 64 shown in Figure 20.

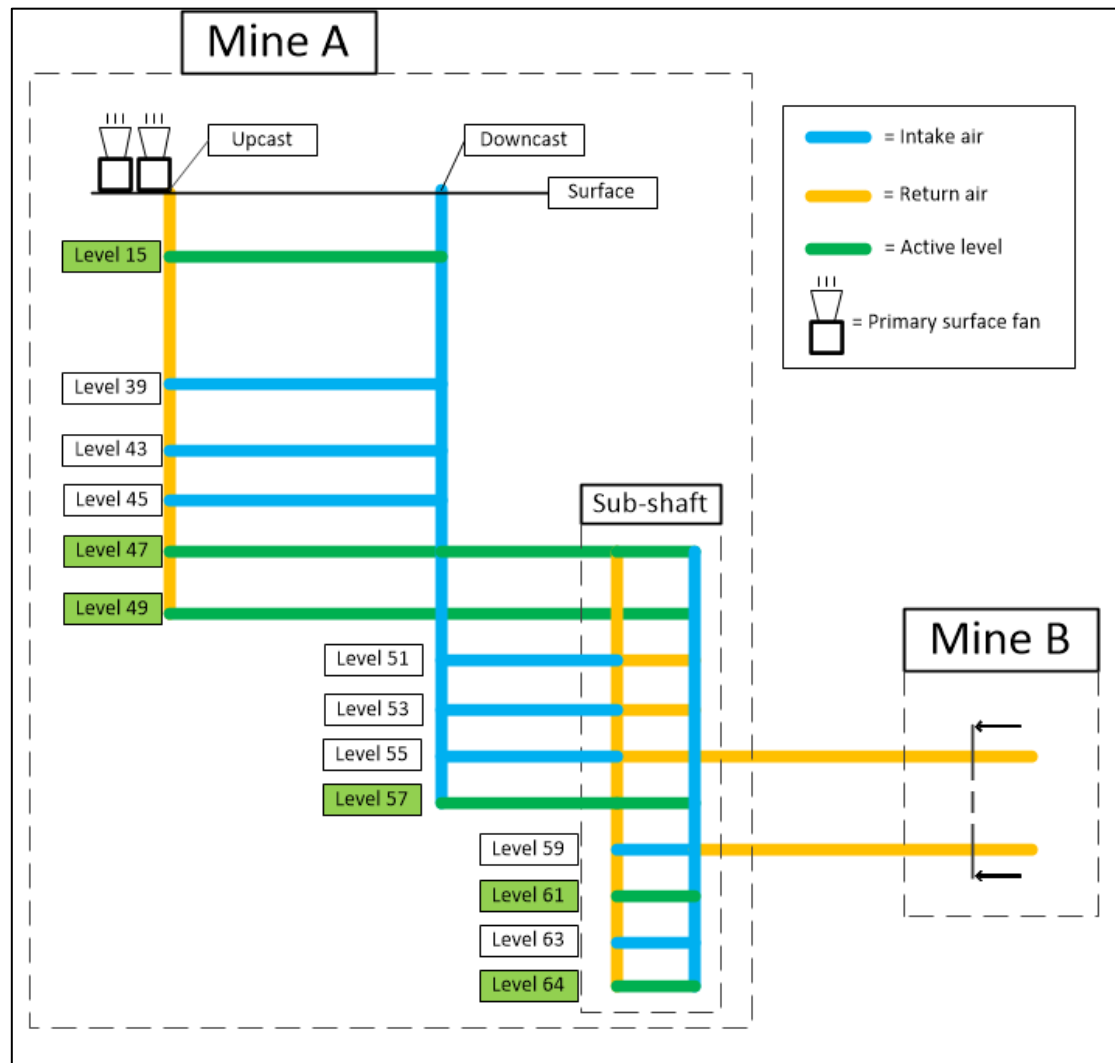


Figure 20 Active levels for case study mine

Level 15 is used as a pump station and requires minimal airflow. The level is only a connection between the upcast shaft and downcast shaft with a wall and a 22-kW fan in the wall. Level 47 and 49 are the levels used to travel between the main shaft and sub-shaft. These two levels are also used for the main return air from the sub-shaft and Mine B. Level 57, 61, and 64 are service levels each with a pump station for dewatering of the lower mine. Fissure water accumulates in the mine and needs to be removed using these pump stations.

Due to the inaccessibility of the mine's levels, the importance of the main surface fans has increased to characterise the ventilation network. The surface fan curve has been provided and is shown in Figure 21.

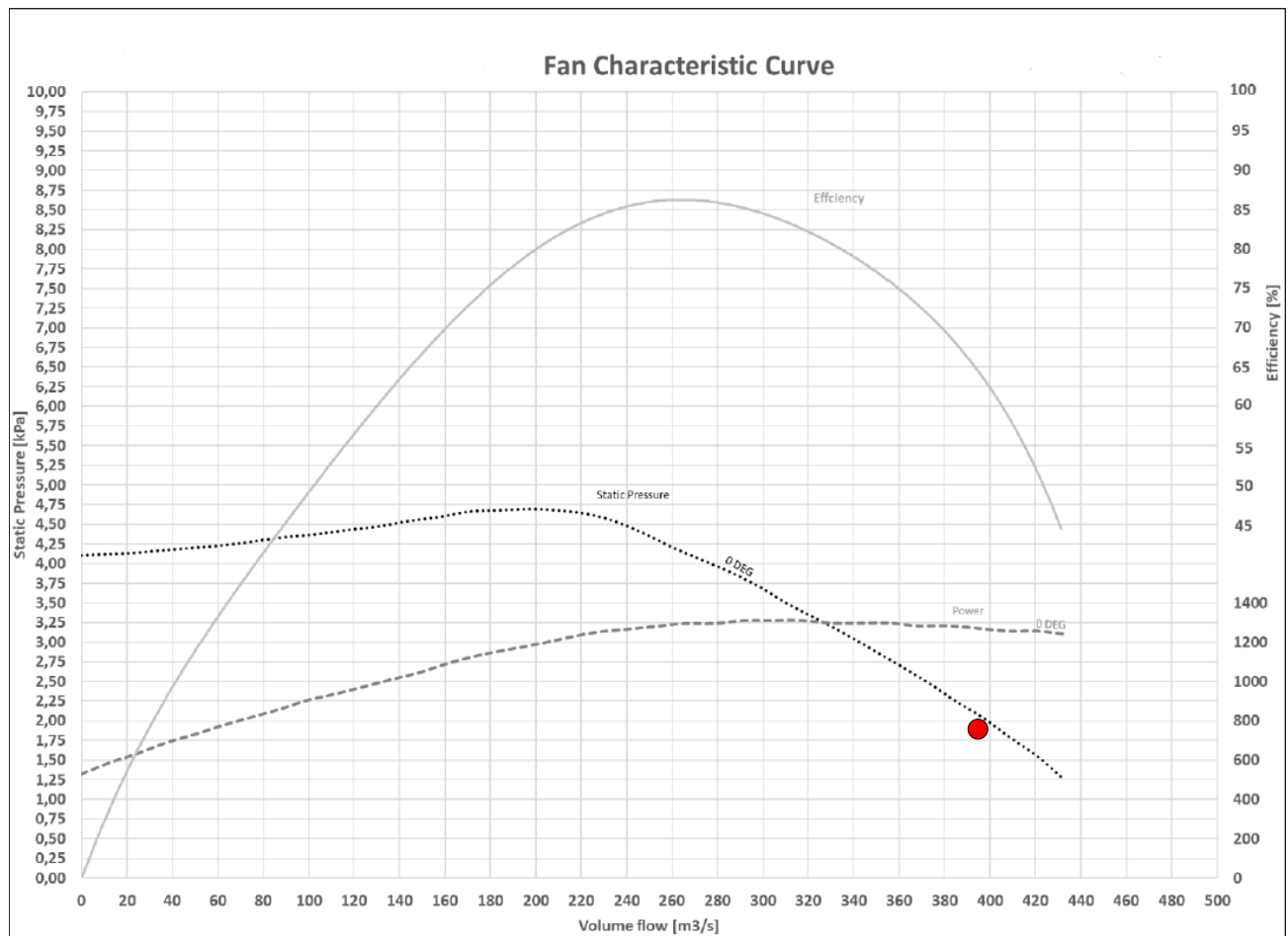


Figure 21 Mine A surface fan characteristic curve

The fan characteristic curve shown in Figure 21 was created at certain conditions for the fan impeller and motor. The operating point of the main fan is shown Figure 21 with a red marker. The conditions where the fan's curve was characterised are shown in Table 5. The fan's characteristics curve is in relation to the conditions where the fan is tested and benchmarked. Fans operate at different pressures and volume flow due to the location that they are installed in for use. Air temperature and air density changes with elevation loss or gain.

Table 5 Fan characterisation conditions

Air temperature	25°C
Air density	0.96 kg/m ³
Fan speed	448 rpm

From the fan characteristics curve, the fan specifics were calculated and are shown in Table 6. The fan specification shown in the table was measured as the baseline conditions of the fan. The information is used to calibrate the model in later steps of the methodology.

Table 6 Mine A main fan specification

Parameter	Unit	Value
Design operating flow	m ³ /s	390
Design operating pressure	kPa	1.9
Design operating shaft power	kW	1360
Design fan efficiency	%	55
Design operating RPM	rpm	454
Design operating density	Kg/m ³	0.92
Rated motor power	HP	2000
Rated motor power	kW	1491.4
Maximum motor amps	A	151
Design motor RPM	rpm	744

A volume survey was done on the upper mining level of Mine A. The volume survey could only be done on 39L to 49L due to safety concerns and ease of access. Table 7 shows all the information that was collected on the volume survey. The location of all the measurements is shown on simulation layouts in Figure 45 to Figure 49 under Appendix .

Table 7 Volume survey data for Mine A

Level	Pressure (kPa)	Area (m ²)	WB (°C)	DB (°C)	RH	Density (kg/m ³)	Velocity (m/s)	Volume flow (m ³ /s)
39L	100.37	9.67	14	25	0.2795	1.688	4.26	41.2
43L	102	9.92	15	26	0.2916	1.183	1.89	18.79
45L	102.2	11.89	15	27	0.256	1.182	3.97	47.25
47L point 1	102.5	8.64	15	28	0.2234	1.182	4.56	39.47
47L point 2	102.56	8.4	15	28	0.2232	1.182	2.09	17.59
47L point 3	102.56	13.05	16	29.5	0.224	1.176	0.458	5.98
49L point 1	103.28	3.18	18	28	0.221	1.191	4.905	15.6
49L point 2	103.28	7.66	15	28	0.221	1.191	2.85	21.83

Mine A and Mine B are connected at two levels, and 55L contains two fans. The auxiliary fans on 55L of Mine B are two booster fans, which are the same. Figure 22 shows the fan performance curve for one auxiliary fan.

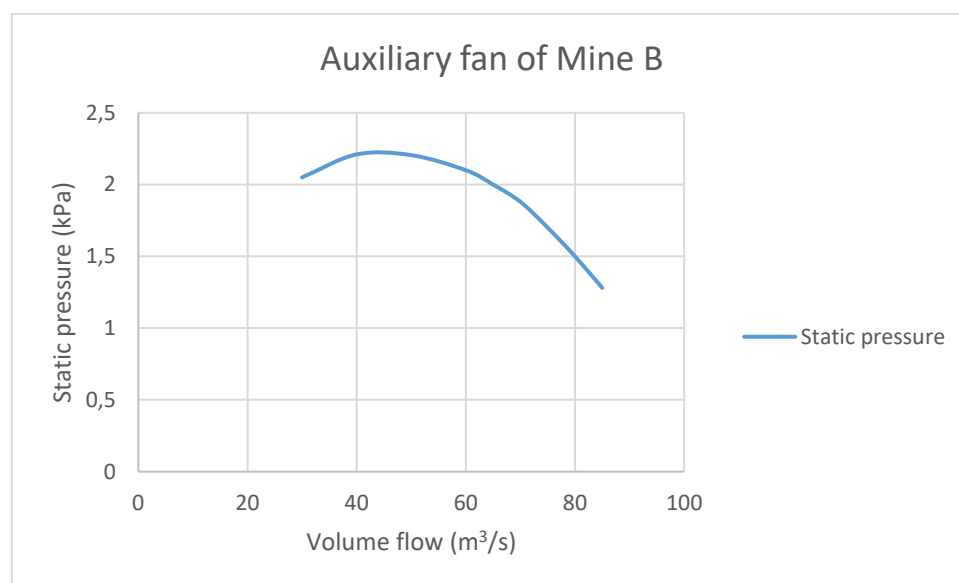


Figure 22 55L auxiliary fan curve

The auxiliary fan performance curve shown in Figure 22 only shows the static pressure curve. The design operating conditions for the fan are as follows:

- Power – 190 kW
- Operating pressure – 1.8 kPa
- Operating flow – 70 m³/s

The two auxiliary fans have a static pressure sensor that could be used to track the fan's static pressure over the SCADA of the mine.

Obtaining system information is a vital part of producing an accurate simulation, but due to the unique challenges faced by the mine, the information available is minimal. The information that has been collected will be used further in the methodology to build the simulation and calibrate the simulation model. The next step in the methodology is to benchmark service delivery and system.

2. Benchmark ventilation network

Mine A has no SCADA system available to produce low- or intermediate-level data. This can make it challenging in benchmarking the ventilation network. Therefore, finding a baseline condition will have to be done with high-level data. The mine's network is a simple network, meaning the ventilation network does not make use of multiple ventilation control devices. The ventilation control devices of the mine are:

- Two main surface fans
- 22 kW fan on level 15
- Multiple walls built before the study

Using high-level data means that KPIs of the system will have to be used to obtain a baseline for Mine A. The KPIs for the case study used is the two main surface fans and the 55L auxiliary fans. Figure 23 shows one of the main surface fans used as a KPI.



Figure 23 Main surface fan for Mine A

Figure 23 shows one of the two surface fans. The access hatch next to the fan ducting was used to take manual measurements with a pitot tube. In Appendix B it is shown how to use a pitot tube. A pitot tube with manometer is used to measure the dynamic pressure and static pressure of the fan. The pressures, however, could not be measured due to the conditions inside the fan's ducting. The air that is returned from underground is saturated and causes blockages inside the pitot tube.

The cause for the humid air in the surface fan ducting is due to high temperature and water accumulation underground. The only measurement that could be taken is the static pressure of the surface fans. The static pressures of the two surface fans were measured as 1.88 kPa and 1.89 kPa. Due to the unique circumstances of the mine, the mine's ventilation network will be characterised with the use of the main surface fans. The static pressure taken from the main surface fans will serve as the baseline state of the mine. Figure 24 shows the baseline conditions for the main surface fans.

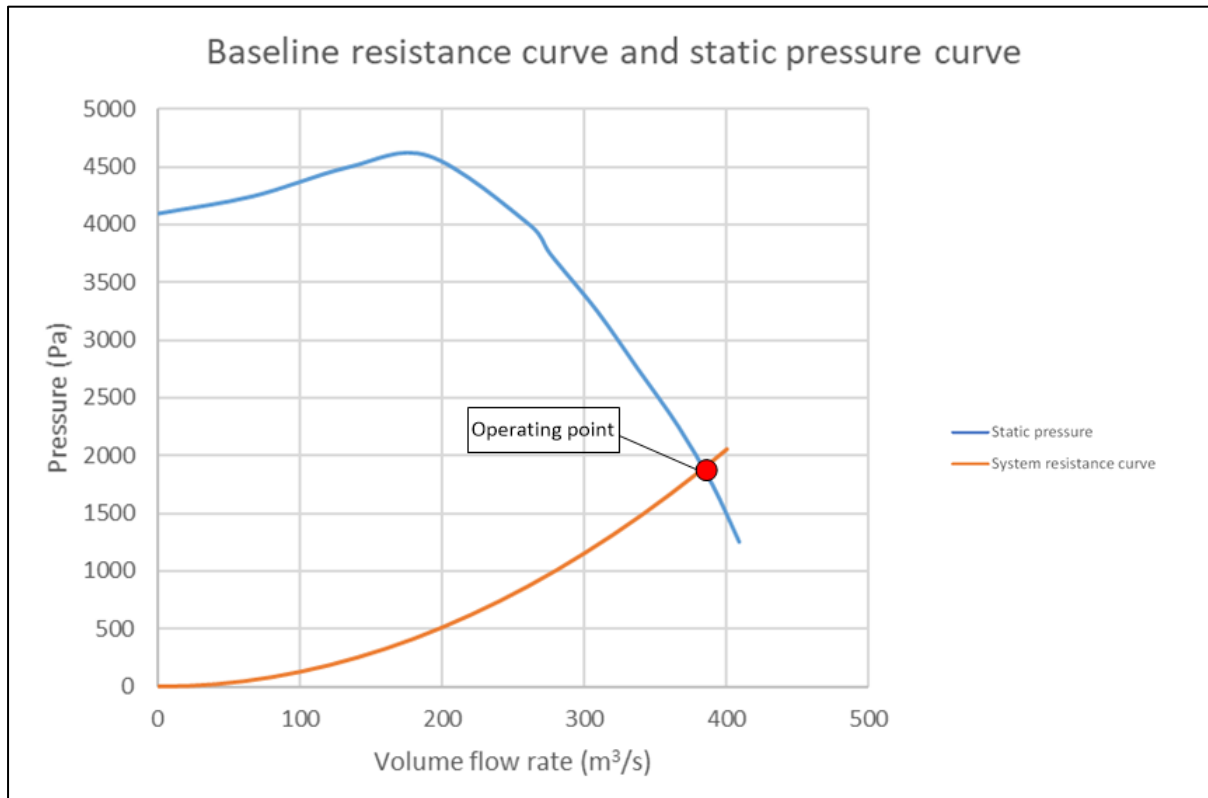


Figure 24 Baseline conditions on the main fan's curve

The blue curve in Figure 24 shows the static pressure curve of the fan and the orange curve shows the system baseline conditions. The system resistance curve is used as the baseline condition for the fan. The point where the two curves intersect each is the measured operating point of the fan. In this case, the operating point of the fan is at 1.88 kPa.

The 55L auxiliary fans were benchmarked at 2.1 kPa of static pressure. Figure 25 shows the operating point for the auxiliary fans on 55L.

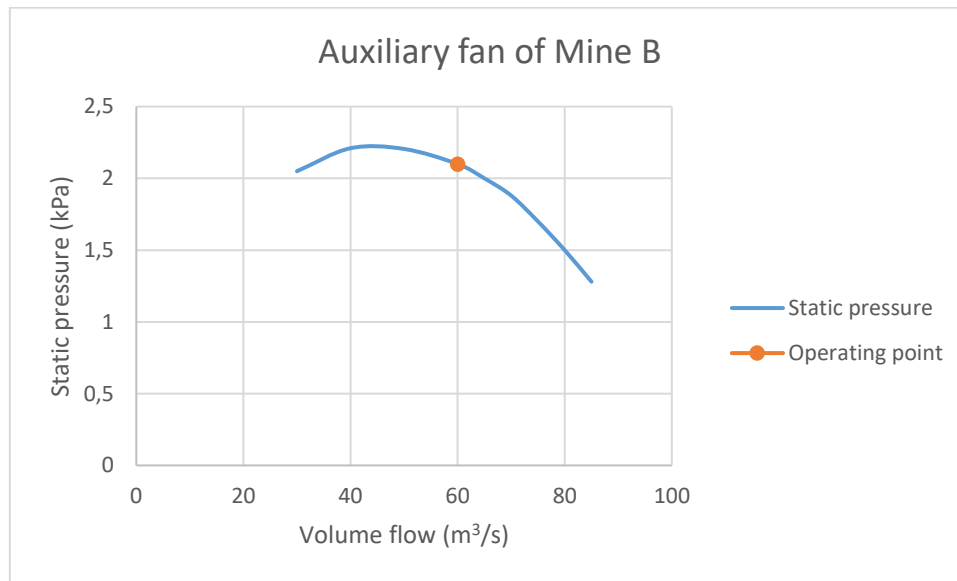


Figure 25 55L auxiliary fan operating point

The operating point shown in Figure 25 was used as the benchmark condition for the fans. Benchmarking the ventilation network was done by using the fan performance curve and measured static pressure of the main surface fans only. In previous literature from Chapter 1, the use of a fan curve is explained and how it can be used to describe a mine's ventilation network and its condition. The information that was gathered of the mine sets the benchmark conditions and the simulation model can be constructed with the information.

3. Build ventilation model

The section will focus on the construction of the ventilation network simulation of Mine A and steps in from Chapter 2 to construct the model. As previously stated, the simulation software that is used is Process Toolbox. The simulation software is a 3D mine ventilation simulation software that solves mass balances.

The simulation model was constructed by using paper layouts from the mine. The paper layouts were used with the coordinate system to place nodes on specific identified points to construct the model. Figure 26 shows a paper layout from Mine A of one level.

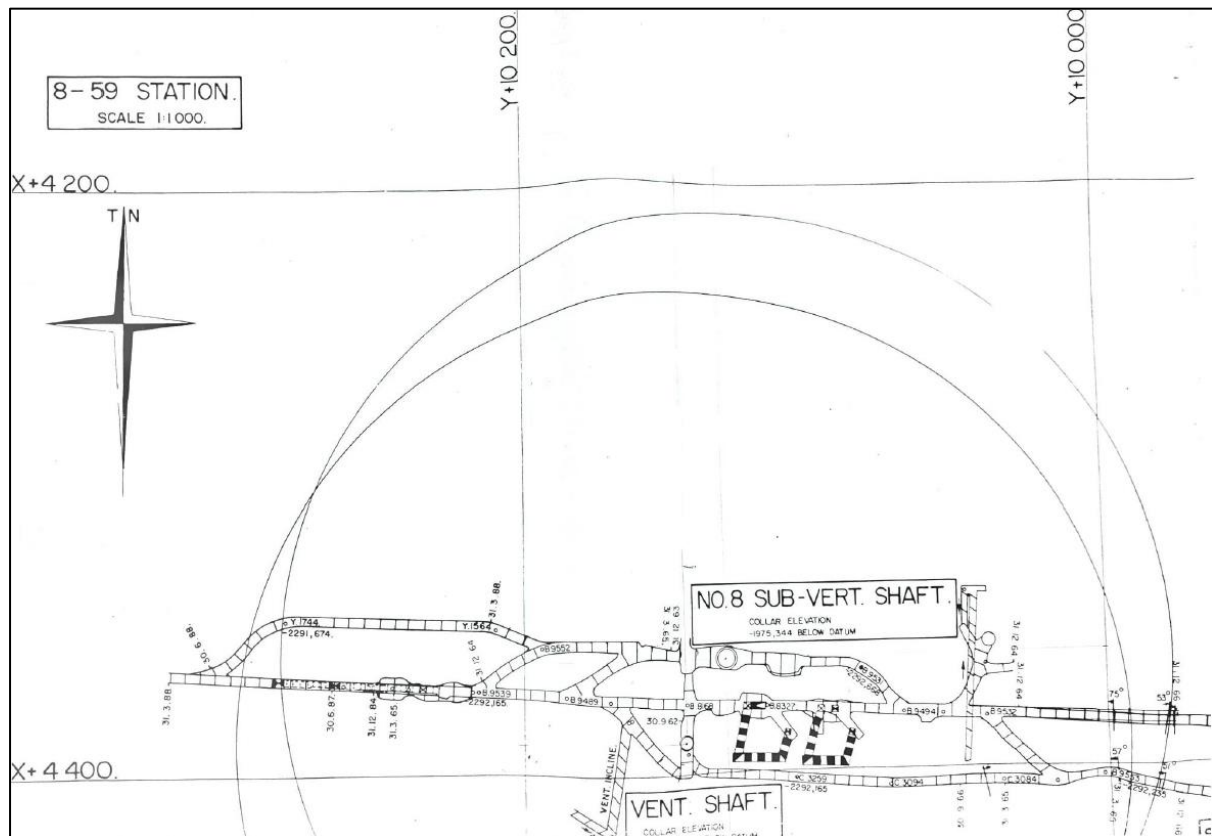


Figure 26 Paper layout of a level in Mine A

The figure shows the longitudinal and latitudinal line that was used to pinpoint the specific location for the mine. The specific points were identified as the following:

- Shafts
- Intersecting points of haulages
- Crossovers of haulages

Each of the levels for Mine A has a specific depth and can be calculated by using the level number. The international datum line is at 475 m below the shaft collar for Mine A. Multiplying the level number with a factor of 100 will give the depth below the datum line in feet. The multiplied number is then converted to meters and 475m added to obtain the depth below the shaft collar in meters.

The PTB simulation model of Mine A was constructed with the information gathered from step 1 of the methodology. The simulation model is a skeleton of the ventilation network and the components used were set to the default settings of the PTB software that is shown in Appendix E. The ventilation control devices were added to the skeleton and placed according to the

information gathered. Figure 27 shows the simulation model constructed in PTB as an isometric view.

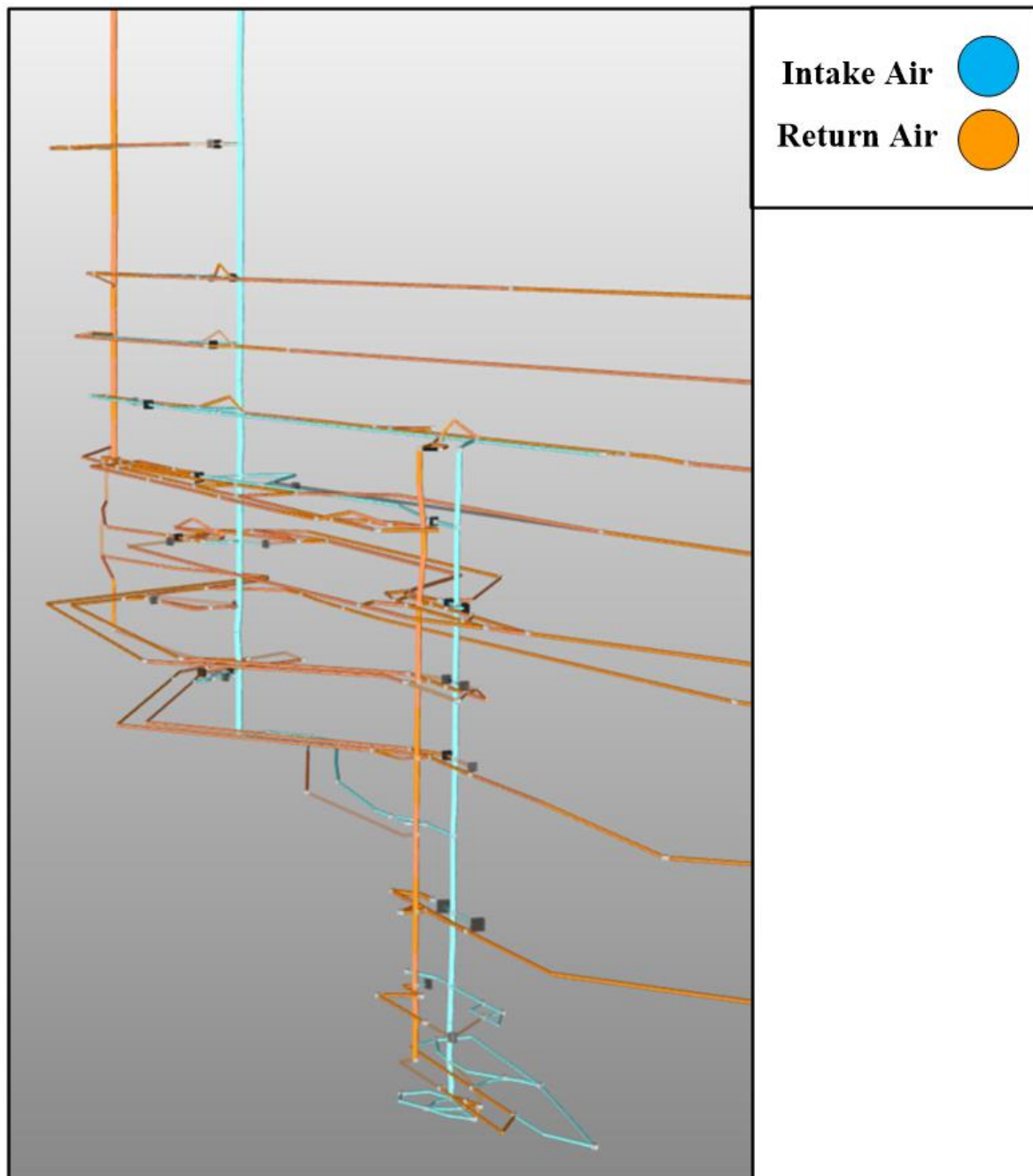


Figure 27 Isometric view of the simulation model

The simulation model in Figure 27 shows the levels and all the connections between the levels. The model consists of 1 755 components and 1 853 connections. The connections between the station and working areas were also constructed for possible airflow through old working areas and stopes. Each level of the simulation model for Mine A is shown individually in Appendix

D. The levels are coloured according to intake air (blue) and return air (orange). The finished simulation model is only a representation of Mine A. The simulation model must be calibrated using the identified KPIs so that it can be used for identifying solutions.

4. Calibrate ventilation model

Step 4 focuses on calibrating the simulation model of Mine A. Calibration was done by using the identified KPIs and information obtained from the mine. The only KPI that was identified is the two main surface fans of the mine. The occupational hygienist of Mine A specified the locations of all the ventilation control devices, airflow directions, and working areas needing airflow.

All the hydraulic calculations for the tunnels were set to the same values. The values that were changed were the following:

- Flow area (m²)
- Flow perimeter (m)
- Friction coefficient

Mine A used tracked mining for moving materials and transporting heavy equipment to working areas. Therefore, the flow area and flow perimeter values were selected as an average size for haulages in deep-level gold mines that use tracks to mine. The friction coefficient that was selected for the starting value is for a haulage area that has been lined with shotcrete or cement. The values for the PTB simulation are shown in Appendix in Figure 63.

The main surface fans that were selected as the KPI for the system also had to be set up in PTB before the calibration could be done. Table 8 shows the values that were used in the PTB main surface fan components of Mine A. The range of values contains the baseline operating point for the two main surface fans.

Table 8 Values for PTB simulation main surface fans

	Pressure (kPa)	Flowrate (m ³ /s)	Efficiency rating
1	4.375	103.459	0.501
2	3.885	286.234	0.859
3	1.284	431.257	0.446

All the data was programmed into the baseline simulation model, and an iterative approach was followed to calibrate the model for Mine A. The simulation model started with a low resistance and the main surface fans having a high-volume flow rate and low static pressure. The resistance of the mine had to be increased to meet the required baseline conditions.

An iterative process was followed to increase the mine's resistance. Increasing the resistance of the mine was done by gradually increasing the overall friction coefficient of the mine and decreasing haulage sizes. Due to the haulage conditions that are unknown and thus could not be entered for inspection, the sizes had to be adjusted to smaller values. This iterative adjustment simulated fall-of-ground conditions where haulages had blocked by FOG and were minimal to no airflow was achieved.

The baseline simulation was achieved and verified by comparing the simulation outputs to the actual measured data. The MAE method, shown in Equation 1, was used to calculate the baseline accuracy of the simulation. The surface fan baseline simulation had an error margin of less than 5%. The error made was within the recommended accuracy limits according to the literature. Table 9 shows the results for the baseline simulation and the actual measured data. The data in the table was used to calculate the MAE.

Table 9 Baseline simulation results for surface fans static pressure

Fan 1		Fan 2	
Simulation	Actual	Simulation	Actual
1 880 Pa	1 900 Pa	1 880 Pa	1 885 Pa

The reason for the difference between the fan's actual and simulation pressure can be due to system resistance that was absent. In the same step of calibrating the surface fans, the volume survey data was used to calibrate the volume airflow for each point on the upper mine levels. Table 10 shows the measured volume flow and the simulated baseline with the calculated accuracy for each point. The table shows that the upper mine levels were adequate to be used further in the study.

Table 10 Baseline simulation results for upper mine levels

Calibration Point	Measured baseline volume flow (m ³ /s)	Simulation baseline volume flow (m ³ /s)	Calibration accuracy (%)
39L point	41.2	43.31	99.95
43L point	18.79	19.56	99.96
45L point	47.25	48.32	99.97
47L point 1	39.47	37.11	99.94
47L point 2	17.59	18.56	99.94
47L point 3	5.98	2.98	99
49L point 1	15.6	17.82	99.87
49L point 2	21.83	24.62	99.88

The lower levels of the mine were not calibrated according to manually measured data. The average flow area, flow perimeter, and friction coefficient that were used in calibrating the upper levels were implemented on the lower levels. The parameters are as follows:

- Flow area = 9.4 m²
- Flow perimeter = 12.27 m
- Friction coefficient = 0.011

The auxiliary fans on 55L were also calibrated to meet the benchmark operating point of 2.1 kPa. The two fans gave an airflow of 120 m³/s with each one supplying 60 m³/s.

In the unique case of the case study, where there is little to no data available for the mine, the simulation model is deemed accurate even though it was difficult to obtain sufficient data. The simulation model could therefore be used to create optimisation proposals for the mine's ventilation network. The following step describes how the simulation model was used to optimise the ventilation network of Mine A.

5. Optimise ventilation network

Step 5 focuses on optimising the ventilation network of Mine A. The goal is to increase the efficiency of the ventilation network of Mine A to increase airflow from Mine B to Mine A. Improving the airflow through the mine entails that air is channelled through the least resistant

path and closing off areas that do not require airflow. Simulation software is used to evaluate the impact of the ventilation control devices that are used.

Optimising the ventilation network for Mine A has a few unique challenges. The challenges faced in optimising the network of a decommissioned mine is that some areas are too dangerous to enter due to high temperature, illegal miners, and toxic gasses. Travelling deep into a level is not feasible and optimisation will have to take place close to the shaft areas. The proposed locations that were selected are as follows:

- Level 39, 43, 45, 47, and level 49.
- Station areas that are close to the main upcast and downcast shafts.

The upper mining levels were a good starting point since air had been short-circuiting from the main downcast to the main upcast shafts. Each of these levels of the mine was analysed by using the calibrated baseline simulation model. The critical path for airflow was identified and optimisation followed from there. The following is a layout of each level from Mine A and a description of how the level was optimised.

The layouts shown are coloured according to fresh intake and return air. The fresh intake haulages are light blue and the RAWs are orange. Ventilation control devices are also shown in the layout with D-shaped figures being ventilation doors and double white lines being walls that are used as ventilation seals.

39 Level:

Figure 28 shows the level 39 layout of the baseline simulation.

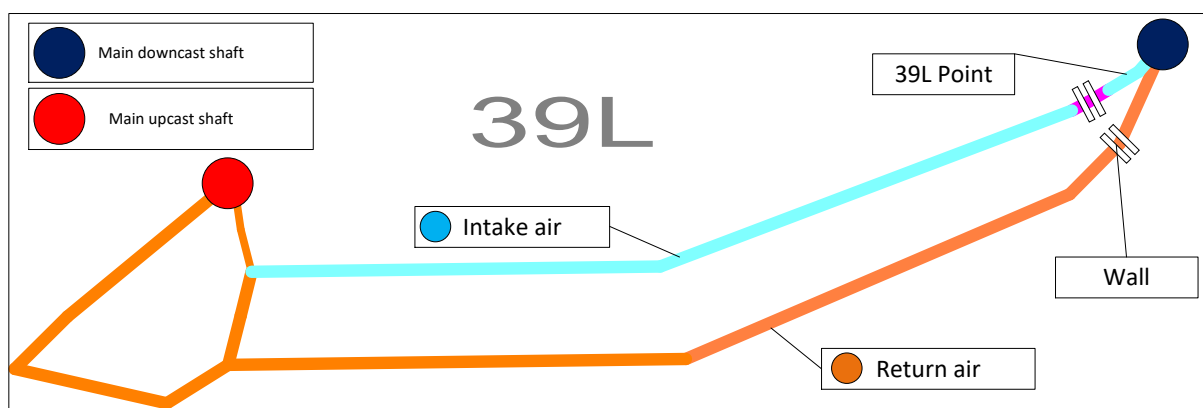


Figure 28 39L layout

The red dashed line shows the critical path that air is short-circuiting to the upcast shaft. The baseline simulation showed that $64.57 \text{ m}^3/\text{s}$ of airflow is moving through the area. The level is no longer in use and does not need fresh intake air. A wall was placed in the simulation model and marked as seal 1. This should restrict air from entering the level completely.

43 Level:

Figure 29 shows the level 43 layout of the baseline simulation.

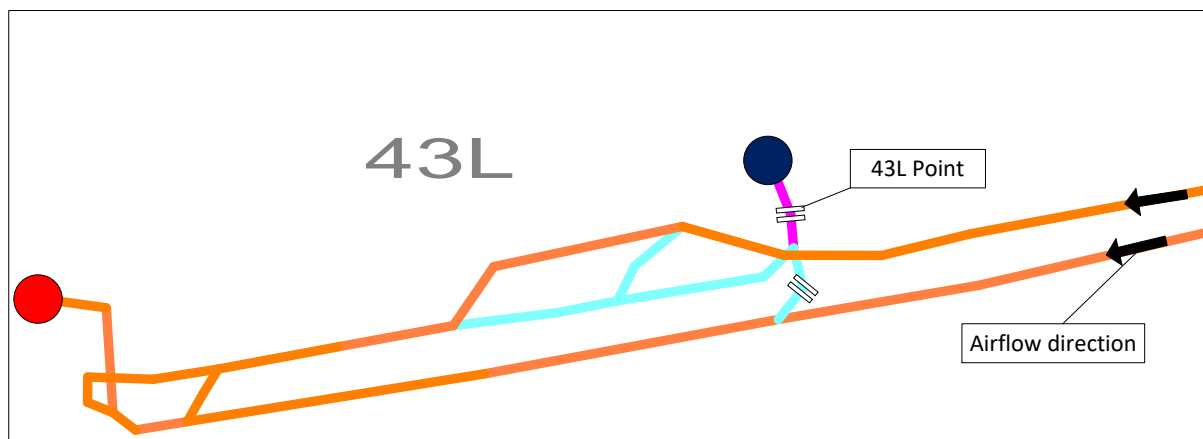


Figure 29 43L layout

The two black arrows in Figure 29 show the return air from old working areas in the level. Level 43 is not used for mining activities anymore but still receives $95.73 \text{ m}^3/\text{s}$ of fresh air. The red dashed line shows the fresh airflow path and joins into the return air. Seal 2 is proposed as a wall to be built at the station area sealing of the level from the fresh air intake.

45 Level:

Figure 30 shows the level 45 layout of the baseline simulation.

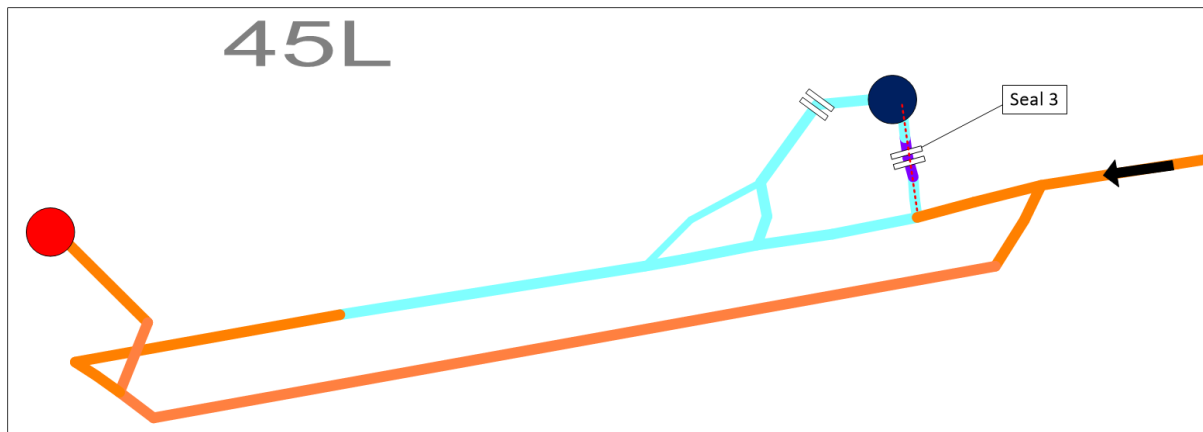


Figure 30 45L layout

The black arrow in Figure 30 shows the return air from old working areas in the level. The air returning from these areas can also be return air from Mine B. Level 45 is no longer in use and can be sealed off to increase the ventilation efficiency and mine ventilation network resistance. There is already a wall built at the station, but an extra wall is proposed. The extra wall is shown as “Seal 3” in the figure. The amount of air entering the level in the baseline simulation is $74.28 \text{ m}^3/\text{s}$. Seal 3 will stop fresh air from entering the level.

47 Level:

Figure 31 shows the level 47 layout of the baseline simulation.

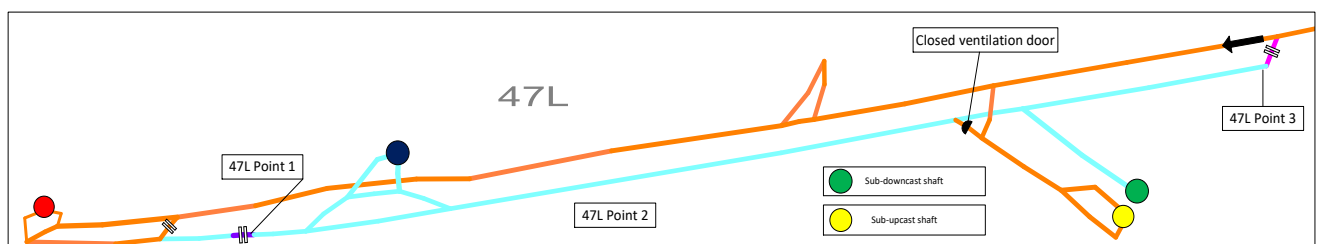


Figure 31 47L layout

Level 47 is used for travelling to the sub-shaft to gain access to the lower levels of the mine where the pump stations are situated. The red dashed line shows the path miners use to travel to the sub-shaft. This path is a critical path and requires airflow for health and safety regulations.

Seal 4 is placed in the haulage to restrict fresh air from moving directly to the main upcast shaft. The amount of air that was short-circuiting at the seal 4 location according to the

simulation was $37.11 \text{ m}^3/\text{s}$. Seal 5 is placed near the sub-shaft so that hot air does not contaminate the fresh air that is supplied to the sub-shaft. The amount of return air entering at seal 5 location in the baseline simulation is $2.98 \text{ m}^3/\text{s}$.

49 Level:

Figure 32 shows the level 49 layout of the baseline simulation.

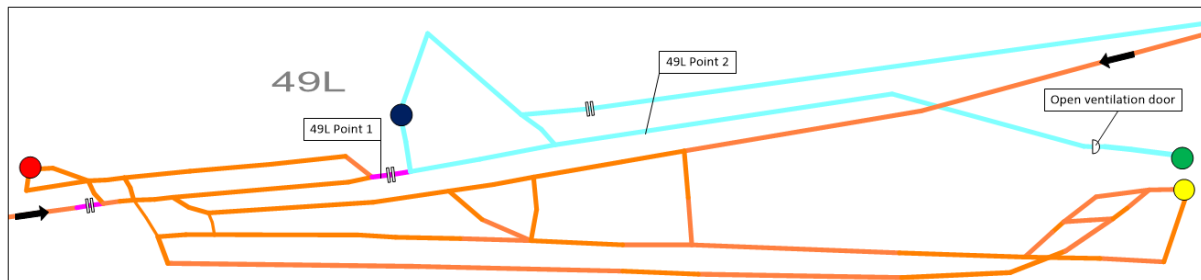


Figure 32 49L layout

Level 49 is also used for travelling from the main shaft to the sub-shaft and serves as the main RAW for the return air from the sub-shaft. A ventilation door was placed near the sub-shaft downcast to restrict air. The seal proposed on the level is seal 6 which serves to restrict air from short-circuiting to the main upcast shaft. The amount of air flowing through the area according to the baseline simulation is $17.82 \text{ m}^3/\text{s}$.

The proposals for each level optimisation was implemented on the baseline simulation. The seals were built into the simulation according to their numbers. With each seal built in, the pressures of the main fans were noted. The prediction with each seal built is that the static pressure of the fans will increase. This increase in static pressure is the result of the ventilation network resistance increasing.

The results of the optimisation on the baseline simulation model is shown in Table 11 for the two surface fans.

Table 11 Simulation optimisation results of the surface fans

Seal number	Surface fan 1 (Pa)	Surface fan 2 (Pa)
Baseline	1880	1900
Seal 1	1930	1950
Seal 2	1950	1980
Seal 3	1970	1990
Seal 4	2040	2050
Seal 5	2070	2090
Seal 6	2300	2300

The prediction of increased static pressures on the surface fans has been confirmed with the results shown in Table 11 above. An enlarged graph where the resistance curves and static pressure curve intersect is shown in Appendix F.

Figure 33 shows the system resistance curve after each seal is built. It shows how the resistance curve moves up on the static pressure line. This upwards movement of the resistance curve changes the operating point of the fans, thus giving the fans a higher operating static pressure.

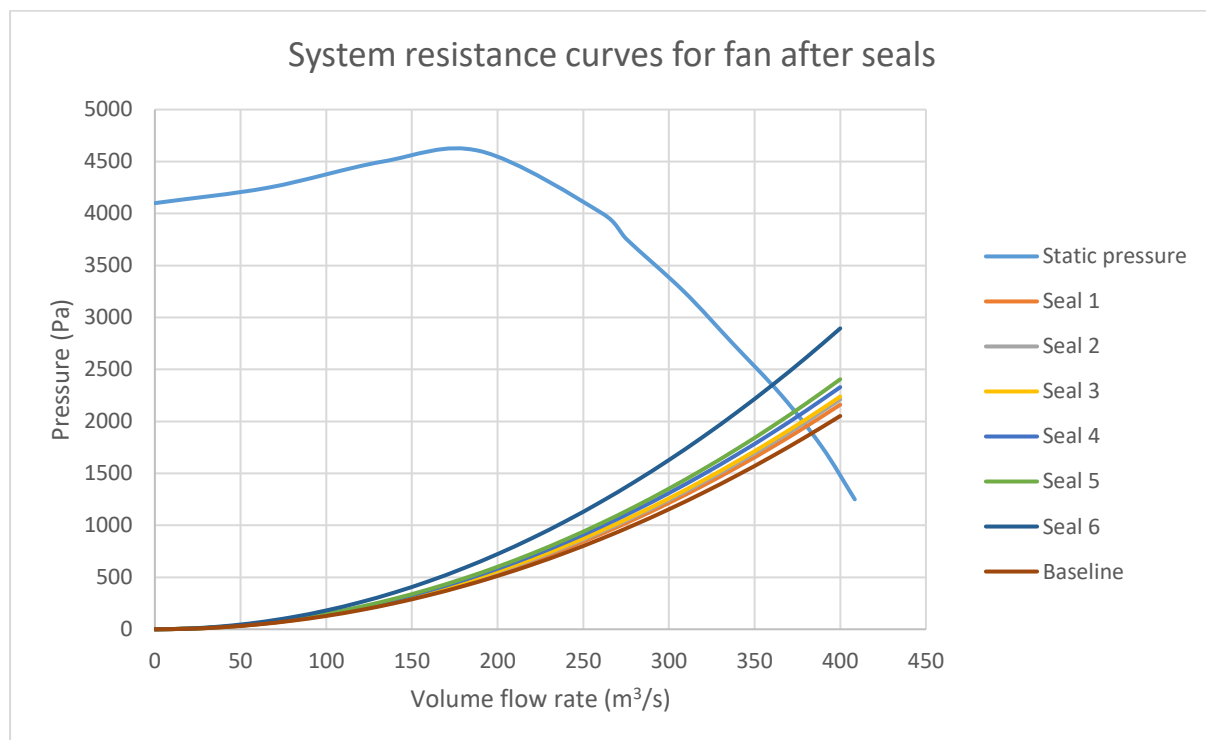


Figure 33 System resistance curves for each seal

Different points were selected in the simulation model to monitor the impact of the seals on the airflow quantity. For each seal in the simulation model, the airflow was recorded at the points shown in Table 12. A more detailed position is shown in Appendix D on each layout with numbers corresponding to those in Table 12. The following are the reasons for the points selected and a description of the impact of the seals:

- 55L and 59L are connected to Mine B.

The increase of system resistance increased the airflow on 55L and 59L returning from Mine B. This increase in airflow is additional air pulled from Mine B towards Mine A.

- 47L and 49L serve as main RAW from the sub-shaft.

47L and 49L showed an overall increase in airflow towards the main upcast. This shows that air is moving faster in areas with less resistance due to direct connections between the main shafts and sub-shafts. The air from the sub-shaft from Mine B is returning through these two levels.

- 45L to show airflow from old working areas.

The airflow on the 45L RAW increased and shows that air is moving up and through other levels. This can be the cause of additional airflow moving through raise lines and open inactive areas.

- 57L, 61L and 64L active service levels.

An overall increase of airflow was recorded on these levels. Due to the system resistance increase, the main fans can pull air from deeper levels and thus creating more flow.

Table 12 Simulated airflow points

Seal number	Airflow (m ³ /s)	Baseline	Seal 1	Seal 2	Seal 3	Seal 4	Seal 5	Seal 6
1	55L from Mine B	22.12	24.79	30.11	50	74.12	75.4	77.33
2	59L from Mine B	10.85	11.58	26,59	37,24	57,80	67,37	87.22
3	47L to Main UC shaft	79,40	86,39	82,00	90,22	145,78	145,36	155,87
4	49L to Main UC shaft	87,02	94,64	92,00	87,83	100.52	107,31	109,40
5	45L from RAW	19,83	21,25	21,23	22,84	27,16	26,86	29,99
6	57L	16,03	18,74	19,20	18,16	24,69	23,43	33,04
7	61L	17,30	19,02	19,14	27,45	40,70	42,46	56,11
8	64L	0,22	1,35	1,89	2,17	4,01	4,20	5,66

The auxiliary fans on 55L of Mine B showed a drop in static pressure over the course of the sealing plan implementation in the simulation. Table 13 shows the static pressure and total volume flow rate of the two auxiliary fans on 55L of Mine B.

Table 13 55L auxiliary fan simulation results

	Static pressure (kPa)	Volume flow rate (m ³ /s)
Baseline	2.1	120
Seal 1	2.09	122
Seal 2	2.07	123
Seal 3	2.03	128
Seal 4	1.90	136
Seal 5	1.85	142
Seal 6	1.81	146

The results from the simulation model showed an overall increase in system resistance for the ventilation network. The simulation results also showed an increase of airflow from Mine B of approximately 140 m³/s to 160 m³/s. With the confirmed prediction from the simulation model, the optimising proposal was presented to the mining personal and could be implemented on the case study mine.

6. Implement optimisation plan

In this step, the optimised proposal was presented to mining personnel and implemented on the mine. The results are evaluated and the simulation validated. The sealing plan was given to the mining construction teams and the plan was implemented. The mine's construction team did not follow the sealing plan according to the seal numbers. A risk assessment had to be done by the mine's occupational hygienist for each level before the construction of each seal could continue. This meant that the seals were built according to ease of entrance and safety. Table 14 shows the order in which the seals were built.

Table 14 Order of seals built

Order of seals built	Seal number
1	Seal 5
2	Seal 4
3	Seal 6
4	Seal 1
5	Seal 2
6	Seal 3

The order in which the seals are built will have an impact on the actual measured results when compared to the simulation results. This is due to the amount of resistance that is added by each seal that is built. Not every seal will have the same impact on the ventilation network after it is built. Unfortunately, due to time constraints of the project, not all the seals were built. The last seal, seal 3 on level 45, could not be built.

The simulation sequence of seals built were re-evaluated to match the order in which the mine construction team built the walls. Table 15 shows the order in which the mine built the seals and the static pressure results for each fan after every seal.

Table 15 Simulation results for changed optimisation plan

Seal number	Surface fan 1 (Pa)	Surface fan 2 (Pa)
5	1 900	1 890
4	1 960	1 940
6	2 000	1 990
1	2 090	2 070
2	2 250	2 240

After each seal that was built, the static pressure of the surface fans was measured for evaluating the simulation. Table 16 shows the measured static pressure values after each seal that was built. These values are used for evaluating the accuracy of the simulation model that was used.

Table 16 Measured fan static pressure for each seal

Number of seals built	Measured static pressure (Pa)
1	1 900
2	1 930
3	1 960
4	2 000
5	2 050

The static pressure of the two auxiliary fans on 55L of Mine B was monitored as the sealing plan was implemented on Mine A. Table 17 shows the results for the implemented sealing plan versus the simulated results. The average accuracy for the simulated versus the actual results is close to 99.98% as a result of the small difference in static pressure seen on the fans.

Table 17 Implemented results for the static pressure of the 55L auxiliary fans

Number of seals built	Measured static pressure (kPa)	Simulated static pressure (kPa)
1	2.05	2.09
2	2.03	2.07
3	2.01	2.03
4	1.85	1.9
5	1.81	1.85

After five seals had been built, the total volume flow that the fans supplied were measured. The measurement of the total volume flow for the two auxiliary fans was 155 m³/s. This was 35m³/s more than the initial volume flow of 120 m³/s. The pressure drop saw the fan operating closer to its design pressure and reduced the electricity consumption and the time the fan went into a stall pressure.

3.2.2 Interpretation of results

Several differences were noted while measuring the fans' static pressure as the sealing plan was implemented. This section discusses the discrepancies, results, and the consequences thereof. The previous section stated that the optimisation proposal was implemented out of the initial sequence that was intended. The sequence of the simulated proposal was changed and could be compared to the implemented project.

Problems that were encountered involved the illegal mining activities in the mine. The walls that were used as seals in the project needed a means of passing through without influencing the ventilation system. Large pipes were built into the wall with a large rubber seal that could be opened and closed. Some of the seals had been left open or broken with air leaking through while other walls had been damaged.

Results were still collected regardless of the problems that were faced. To validate the simulation results, the actual measured data of the proposed optimisation plan can be compared

to the simulation results. The MAE method was used to determine the accuracy of the model. Table 18 shows the simulation results and the measured results with the accuracy of each seal that was built. The average error that was made was 3.12%.

Table 18 Results accuracy

Number of seals	Sim Fan 1 (Pa)	Sim Fan 2 (Pa)	Fan 1 and 2 Measured (Pa)	Accuracy (%)
Baseline	1 880	1 900	1 885	99.2
Seal 1	1 900	1 890	1 900	99.47
Seal 2	1 960	1 940	1 930	99.48
Seal 3	2 000	1 990	1 960	98.47
Seal 4	2 090	2 070	2 000	96.5
Seal 5	2 250	2 240	2 050	90.73

Although the average error that was made is less than 5%, the error for each seal that was built increased. The last seal that was built had an error of 9.27%. The large error made on seal number 5 indicates that the seal did not affect the ventilation network as initially simulated. The error made with the simulation model may have an exponential error with each change made to the simulation software. However, the average error of the simulation could be a result of the potential for error when following the methodology or by the potential for error of the data gathering.

The 55L auxiliary fans showed an increased flow of 35 m³/s where the original total return airflow was simulated as 150 m³/s through 55L and 59L. In the absence of information on the level conditions between the two mines, the airflow could be distributed over all the levels returning to Mine A. Due to the percentage error of the simulation results, the return airflow amount from Mine B can also result in a 10% error. This will amount to 15 m³/s less airflow than originally simulated.

The rise in static pressure has a direct influence on the power usage of the surface fans. Due to the higher static pressure that was observed from the results, in Table 18, the electricity usage will also increase. However, the aim of the study was not to decrease the electricity costs or

usage but rather to improve ventilation network efficiency. The improvement in ventilation network of Mine A can potentially increase productivity and the LOM for Mine B.

Considering the minimal data that was available and the amount of data that could be collected with manual measurements, the resulting error that was made can be deemed as acceptable. This validates using the methodology on a decommissioned deep-level gold mine's ventilation network where this level of accuracy is required.

3.3 Validation

The case study that was selected for the dissertation had unique challenges where very limited information was available. The limited access to underground measurements made the process in constructing a simulation model difficult. Benchmarking a ventilation network usually requires a large quantity of information. Entering the mine to take manual measurements was limited due to health and safety risks. Thus, alternative methods were used to evaluate the ventilation network of the mine.

In the dissertation, the case study mine's ventilation network was constructed into a simulation model. A large portion of the mine's network is inactive and inaccessible for obtaining the necessary data. The ventilation model was constructed using averaged data from a volume survey that was done on the upper levels of the mine. The simulation model was calibrated according to the main surface fans, which served as the key performance indicators, and a few underground measured points.

After calibration, the simulation model was validated, and the airflow evaluated through the inactive sections. A sealing plan was developed to reduce fresh airflow into inactive sections. The sealing plan increased the ventilation network resistance, which impacted the main surface fans. The main surface fans had an increase in static pressure due to the increase in system resistance.

The sealing plan was implemented on the case study mine, where the simulation results could be verified with measured data from the KPIs. This dissertation shows that by using simulation

software, a mine's ventilation network can be evaluated and improved. With this software, unknown or inaccessible areas in mines can be characterised by using KPIs.

The mining industry in South-Africa has made use of multiple energy-saving projects to reduce electricity costs and operational expenses. Improving the ventilation networks of mines by simulating inactive sections can improve the productivity and extend the life of mine. The dissertation focused on the improvement of ventilation for decommissioned deep-level gold mines. The alternative methodology is not only limited to the deep-level gold mining industry but can be applied to shallow mines. The methodology developed in the dissertation can be applied to any underground mine that uses fans as the main source of ventilation supply.

3.4 Conclusion

This section concludes Chapter 3 of the study and provides a summary of the results of applying the methodology created to a case study mine.

In section 3.2.1, the case study mine was explained and a figure shows the cross-sectional view of the case study mine.

In section 3.2.2, the methodology for reconditioning a decommissioned mine's ventilation network was applied to the case study mine. The ventilation network was benchmarked by using the surface fans as the KPIs and the baseline simulation was constructed. The simulation software was used to create a proposal for optimising the ventilation network of the mine. The proposal was implemented, and the results verified and evaluated according to the simulation results.

In section 3.3, the validation of simulation software to improve ventilation networks was discussed.

Chapter 4: CONCLUSION

4.1 Summary

This dissertation explored the different methods for optimising deep-level gold mine ventilation networks. It found that simulation software is an accurate method for modelling a mine's ventilation network and evaluating optimisation projects. However, there little literature was available on decommissioned mines and no literature on the reconditioning of the ventilation networks of decommissioned mines.

As mines move further away from primary ventilation shafts, the use of decommissioned mines has been made part of the South-African mining industry to decrease operational and capital costs. Active mines have incorporated neighbouring decommissioned mines as part of their ventilation networks towards an increase of their life of mine. However, due to the deteriorating ventilation networks of decommissioned mines, the efficiency of the ventilation network is very low.

The solution for improving the ventilation networks of decommissioned mines was identified and the design for a method that could be implemented on any current ventilation network was discussed and formulated. The method makes use of simulation software to construct the mine's ventilation network. A sealing plan was produced as the optimisation plan for the case study mine. The simulation software was used to evaluate the optimisation plan before implementing it on the mine.

The method was tested on a decommissioned deep-level gold mine in South Africa (Mine A) through implementation. The results obtained showed an increase in the main fan pressures of **165 Pa**, which was the result of increased ventilation network resistance. The increased resistance indicates that air is only reaching the desired areas. The measurable results showed an increase of **35 m³/s** and a **0.29 kPa** drop in booster fan pressure. This was associated with an improvement in ventilation network efficiency.

The dissertation shows, that there is value added to the deep-level gold mining industry through using simulation software to evaluate inactive sections. The mining industry can benefit largely

from improving inactive sections of ventilation networks through sealing plans and ventilation control devices.

It is concluded that implementing this study's designed method by using the main fans as a KPI to characterise a ventilation network is achievable. Hence, the main objective of this study, which is to improve the ventilation network of a deep-level gold mine by simulating inactive sections, was achieved.

4.2 Limitations and Recommendations

Throughout this dissertation, various limiting factors regarding the method were identified. Given that the method is designed for a large amount of data access, the case study had limiting factors. These limiting factors were the following:

- Mine paper layouts and incomplete mine layouts
- Limited underground access
- Limited underground measurements
- Illegal miners

The unavailability of underground measurements made it difficult to measure the impact of the sealing plan that was developed. The sealing plan was also implemented in a different sequence than initially set out due to the safety risk involved in the case study mine.

Given that the goal of the study was to improve the ventilation network and increase airflow from an active mine, an additional optimisation method may be developed to increase the amount of airflow. Underground auxiliary fans can be used to increase the airflow to a desirable amount. The use of airflow restriction may be helpful to decrease an abundance of airflow. Thus, further development of this study's method towards a generic model for all mining ventilation networks may yield pleasing results.

References

- [1] D. Nell, “Optimising production through improving the efficiency of mine compressed air networks with limited infrastructure,” Masters dissertation, North West University, 2017.
- [2] D. Cioclea, “Diminishing the explosion risk at Jiu Valley’s coal underground mines by computerized management of ventilation networks,” *Journal of the University of Petrosani Mining Engineering ER*, vol. 6, no. 2, pp. 12-18, 2011.
- [3] Africa Mineral Council of South, “Integrated annual review 2017,” Chamber of mines of South Africa, Johannesburg, 2017.
- [4] J. Burton, “World Atlas,” 05 June 2019. [Online]. Available: <https://www.worldatlas.com/articles/top-14-gold-producers-in-the-world.html>. [Accessed 12 January 2020].
- [5] N. Nattrass, “The Crisis in South African Gold Mining,” *World development*, vol. 23, no. 5, pp. 857-868, 1995.
- [6] Statistics of South Africa, “Stats SA,” 15 February 2019. [Online]. Available: <http://www.statssa.gov.za/?p=11921>. [Accessed 12 January 2020].
- [7] R. v. d. Berg, “South African History Online,” 19 October 2011. [Online]. Available: <https://www.sahistory.org.za/article/discovery-gold-1884>. [Accessed 03 January 2020].
- [8] Mineral Council of South Africa, “SA gold mining,” Mineral council of South Africa, [Online]. Available: <https://www.mineralscouncil.org.za/sa-mining/gold>. [Accessed 12 January 2020].
- [9] D.F. Malan, F.R.P. Basson, “Ultra-deep mining: The increased potential of squeezing conditions,” *The Journal of The South African Institute of Mining and Metallurgy*, pp. 353-364, 1998.
- [10] R. Johnson; J.K. Schweitzer,, “Mining at ultra-depth : evaluation of alternatives,” in *NARMS'96 : North American rocks mechanics symposium. A regional conference of ISRM*, Quebec, 1996.
- [11] Verdict media limited, “Mining technology,” 11 June 2019. [Online]. Available: <https://www.mining-technology.com/features/feature-top-ten-deepest-mines-world-south->

- africa/#:~:text=Mponeng%20gold%20mine%20in%20South,a%20depth%20of%203.4 km.. [Accessed 12 August 2020].
- [12] T. Tholana, P.N. Neigo, “Trends in productivity in the South African gold mining industry,” *The Journal of The Southern African Institute of Mining and Metallurgy*, vol. 116, no. 3, pp. 238-290, 2016.
- [13] N. Minnaar, “Living lifestyle,” 26 September 2016. [Online]. Available: <http://www.living-lifestyle.co.za/how-is-gold-found-and-extracted/>. [Accessed 11 August 2020].
- [14] E. D. Souza, “Application of ventilation management programs for improved mine,” *International Journal of Mining Science and Technology*, vol. 27, no. 4, pp. 647-650, 2017.
- [15] J. H. Marais, “An integrated approach to optimise energy consumption of mine compressed air systems,” Ph.D. thesis, North-West University, 2012.
- [16] A. Botha, “Optimising the demand of a mine water reticulation system to reduce electricity consumption,” M.Eng. thesis, Dept. Mech. Eng., North-West University, 2010.
- [17] L. F. v. d. Zee, “Modelling of electricity cost risks and opportunities in the gold mining industry,” Ph.D. thesis, North-West University, 2014.
- [18] S. Moolman, “Power Optimal,” 29 September 2019. [Online]. Available: <https://www.poweroptimal.com/350-increase-decade-expensive-electricity-south-africa-compared-countries/>. [Accessed 31 July 2020].
- [19] E. Ernst and B. Young, “Productivity in mining,” BMC, United Kingdom, 2017.
- [20] R. Fair, “Optimisation of mine secondary fan systems,” M.Eng Dissertation, North West University, 2019.
- [21] E. Acuna, I. Lowndes, “A review of primary mine ventilation system optimization,” *Interfaces*, vol. 44, no. 2, pp. 163-175, 2014.
- [22] K. Wallace, B. Prosser, J. Stinnette, “The practice of mine ventilation engineering,” *International Journal of Mining Science and Technology*, vol. 25, no. 2, pp. 165-169, 2015.

- [23] D. Michaud, “Underground mine ventilation,” 25 October 2016. [Online]. Available: <https://www.911metallurgist.com/blog/underground-mine-ventilation>. [Accessed 16 August 2020].
- [24] G. Wei, “Optimization of mine ventilation system based on bionics algorithm,” *Procedia Engineering*, vol. 26, no. 1, pp. 1614-1619, 2011.
- [25] J. Cheng,, “Assement of mine ventilation system reliability using random simulation method,” *Enviromental Engineering and Management Journal*, vol. 15, no. 4, pp. 841-850, 2016.
- [26] S. Bluhm and M. Biffi, “Variations in ultra-deep, narrow reef stopping configuration and the effects on cooling and ventilation,” *The Journal of The South African Institute of Mining and Metallurgy*, vol. 101, no. 3, pp. 127-134, May/June 2001.
- [27] F. Fourie; P. Valicek; G. Krafft; J. Sevenoaks, “Narrow-reef mechanized mining layout at Anglo American Platinum,” *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 117, no. 3, pp. 263-274, 2017.
- [28] M.F. Handley, J.A.J. de Lange, F. Essrich, and J.A. Banning, “A reveiw of the sequential grid mining method employed at Elandsrand Gold MIne,” *The Journal of The South African Institute of MIning and Metallurgy*, vol. 100, no. 3, pp. 157-168, 2000.
- [29] D. J. de Villiers, M. J. Mathews, P. Maré, M. Kleingeld, and D. Arndt, ““Evaluating the impact of auxiliary fan practices on localised subsurface ventilation,” *Int. J. Min. Sci. Technol*, vol. 3, no. 29, pp. 2-10, 2019.
- [30] A.M. Donoghue, M.J. Sinclair, G.P. Bates, “Heat exhaustion in a deep underground,” *occupational & Enviromental Medicine Journal*, vol. 57, no. 3, pp. 165-174, 2000.
- [31] J. C. Tien,, “Practical mine ventilation engineering,” *Interec publishing company*, vol. 1, no. 3, pp. 20-32, 1999.
- [32] D.J Brake, C.A Nixon, “Design and operational aspects in the use of booster, circuit and auxiliary fan systems,” *Proceedings of the 11th U.S./North American Mine Ventilation Symposium - 11th U.S./North American Mine Ventilation Symposium*, pp. 543-553, 2006.
- [33] J.M. Wempen, F. Calizaya, R.D. Peterson, M.G. Nelson, “Evaluating the use of booster fans in two underground coal mines,” *Mining Engineering*, vol. 63, no. 6, pp. 115-119, 2011.

- [34] J. Tien, “Mine ventilation systems,” in *Practical Mine Ventilation Engineering*, Missouri, Intertec Publishing Co., 1999, pp. 162-183.
- [35] “AirEng Industrial fans and Blowers,” 2016. [Online]. Available: [https://www.aireng.com.au/products/mining-fans/primary-fans/#:~:text=Primary%20\(also%20called%20Main\)%20Fans,on%20the%20surface%20or%20underground..](https://www.aireng.com.au/products/mining-fans/primary-fans/#:~:text=Primary%20(also%20called%20Main)%20Fans,on%20the%20surface%20or%20underground..) [Accessed 17 August 2020].
- [36] E. De Souza, “Improving the energy efficiency of mine fan assemblages,” *Applied Thermal Engineering*, vol. 90, pp. 1092-1097, 2015.
- [37] C. J. P. Venter, The effect of controlling main ventilation fan inlet guide vanes for a deep level platinum mine to reduce electrical costs, North West University: M.Eng. Dissertation, 2017.
- [38] X. Chen, W. Chu, H. Zhang, X. Li, “Numerical study on inlet angle of guide vane in recess vaned casing treatment,” *Aerospace Science and Technology*, vol. 93, 2019.
- [39] A. Chatterjee, L. Zhang, X. Xia, “Optimization of mine ventilation fan speeds according to ventilation on demand and time of use tariff,” *Applied Energy*, vol. 146, pp. 65-73, 2015.
- [40] “Axair Fans UK Limited,” Finding The Duty Point & Operating Point, 2019. [Online]. Available: <https://www.axair-fans.co.uk/all-technical-information/duty-point-operating-point/>. [Accessed 4 April 2020].
- [41] C. S.L.DixonB, “Chapter 7 Centrifugal pumps, Fans, and Compressors,” in *Fluid Mechanics and Thermodynamics of Turbomachinery*, Cambridge, Elsevier, 2010, pp. 217-263.
- [42] R. Papar, A. Szady, V. Martin, and A. Mckane, “Increasing energy efficiency of mine ventilation systems,” *Lawrence Berkeley-National*, pp. 611-617, 1999.
- [43] J. Sui, L. Yang, Z. Zhu, H. Fang, H. Zhen, “Mine ventilation optimization analysis and airflow control based on harmony annealing search,” *Journal of Computers*, vol. 6, no. 6, pp. 1270-1277, 2011.
- [44] D.H. Diering, “Tunnels under pressure in an ultra-deep,” *The Journal of The South African Institute of Mining and Metallurgy*, pp. 319-324, 2000.
- [45] J. McLoone, “Flidflow,” Fluid flow, 9 August 2019. [Online]. Available: <https://fluidflowinfo.com/fan-performance-and-fan->

- laws/#:~:text=The%20system%20resistance%20curve%20can,identify%20the%20actual%20duty%2Dpoint.. [Accessed 12 September 2020].
- [46] M. Singh; M. Jradi and H.R Shaker, “Monitoring and evaluation of building ventilation system fans operation using performance curves,” *Energy and Built Environment*, vol. 1, no. 3, pp. 307-318, 2020.
- [47] S.Sjöström, E.Klintenäs, P.Johansson, J.Nyqvist, “Optimized model-based control of main mine ventilation air flows with minimized energy consumption,” *International Journal of Mining Science and Technology*, vol. 30, no. 4, pp. 533-539, 2020.
- [48] R. Carlson, “The correct method of calculating energy savings to justify adjustable frequency drives on pumps,” in *Industry applications society 46th annual petroleum and chemical industry conference*, San Diego, CA, 1999.
- [49] I. Vegter, “IRR,” *The Star*, 26 March 2019. [Online]. Available: <https://irr.org.za/media/welkom-to-a-world-where-mining-dies-the-star>. [Accessed 16 August 2020].
- [50] J. d. Lange, “City Press,” *News24*, 22 February 2016. [Online]. Available: <https://citypress.news24.com/Business/deep-ore-mining-goes-cutting-edge-20160219>. [Accessed 28 April 2020].
- [51] F. Yagodkin, M. Pleshko, A. Prokopov, “Perspective scheme equipment ultra-deep shafts,” *Procedia Engineering*, vol. 206, pp. 293-298, 2017.
- [52] S. Smith, “Gold Flieds,” *South African operations - Driefontein Gold Mine*, 2008. [Online]. Available: https://www.goldfields.com/reports/rr_2008/sa_driefontein.php. [Accessed 28 April 2020].
- [53] J. Burghardt, “Abandoned and inactive mine safety training – Underground mine hazards,” *National Park Service Geologic Resources Division*, 2003.
- [54] M. Nehring; X. Cheng, “An investigation into the impact of mine closure and its associated,” *Journal of Cleaner Production*, vol. 127, pp. 228-239, 2016.
- [55] D. Brake, “The design of push-pull primary and secondary ventilation systems and a vertically-split intake-exhaust ventilation shaft,” in *North American Mine Ventilation Symposium*, United States, 2010.
- [56] M. J. McPherson, “Ventilation Surveys,” in *Subsurface Ventilation Engineering*, Berkley, 1993, pp. Chapter 6 1-33.

- [57] L. Wenguia, X. Xianpinga, X. Houzaob, C. Chaoa, Y. Xiaoyua, S. Meiweia, W. Tinjuna, L. Jiangonga, T. Xingyua, “Reliability calculation of mine ventilation network,” *International Symposium on Safety Science and Technology*, vol. 84, pp. 752-757, 2014.
- [58] H. An, J. Shi, X. Wang and L. Lyu, “Application of depth-first search method in finding recirculation in mine ventilation system,” *The civil engineering journal*, vol. 3, no. 24, pp. 286-295, 2017.
- [59] J. Pearl, *Intelligent search strategies for computer problem solving* addison, Michigan: AddisonWesley Publishing Company, 1984.
- [60] J. van der Walt; E.M. de Kock and L.K. Smith, “The analysis of ventilation and cooling requirements for mines,” *The Southern African Institute of Mining and Metallurgy*, vol. 83, no. 2, pp. 25-34, 1983.
- [61] X.S. Wu and E. Topuz, “Analysis of Mine Ventilation Systems Using Operations Research Methods,” *Pergamon*, vol. 5, no. 4, 1998.
- [62] F. Wei, F. Zhu, and H. Lv, “The use of 3D simulation system in mine ventilation management,” *Procedia Engineering*, vol. 26, pp. 1370-1379, 2011.
- [63] A. J. H. Nel, J. C. Vosloo, and M. J. Mathews, “Supplementary file for : Evaluating complex mine ventilation operational changes through simulation.,” *J. Energy South. Africa*, vol. 29, no. 3, pp. 22-32, 2018.
- [64] S J Bluhm, W M Marx, F H von Glehn, M Biffi, “Vuma mine ventilation software,” *Journal of the Mine Ventilation Society of South Africa*, vol. 54, no. 3, pp. 65-72, 2001.
- [65] C.O. Karacan, “Modeling and prediction of ventilation methane emissions of U.S. longwall mines using supervised artificial neural networks,” *International Journal of Coal Geology*, vol. 73, pp. 371-387, 2008.
- [66] Şuvar M., Cioclea D., Gherghe I., Păsculescu V., “Advanced software for mine ventilation networks solving,” *Environmental Engineering and Management Journal*, vol. 11, pp. 1235-1239, 2012.
- [67] O.S Asfour ., M.B. Gadi , “A comparison between CFD and Network models for predicting wind-driven ventilation in buildings,” *Building and Environment*, vol. 42, pp. 4079-4085, 2007.
- [68] C.K. Kocsis, R. Hall, S.G. Hardcastle , “South African Institute of Mining and Metallurgy,” *Application of Computers and Operations Research in the Minerals*

- Industries, 2003. [Online]. Available: <http://www.saimm.co.za/Conferences/Apcom2003/22 3-Kocsis.pdf>. [Accessed 06 April 2020].
- [69] M. Şuvar, C. Lupu, V. Arad, D. Cioclea, V. Păsculescu, N. Mija, “Computerized simulation of mine ventilation network for sustainable decision making process,” *Environmental Engineering and Management Journal*, vol. 13, no. 6, pp. 1445-1451, 2014.
- [70] E De Souza, “Optimization of complex mine ventilation systems with computer network modelling,” *IFAC Proceedings Volumes*, pp. 323-329, 2007.
- [71] P. Maré, Novel simulations for energy management of mine cooling systems, North West University: PhD Thesis, 2017.
- [72] A. Nikolaev, N. Alymenko, A. Kamenskikh, S. Fet, and V. Nikolaev, “Results of modelling of mine ventilation with air curtain installed into downcast and upcast shafts,” *Perm J. Pet. Min. Eng.*, vol. 26, pp. 1370-1379, 2011.
- [73] E. S. Menon, *Transmission Pipeline Calculations and Simulations Manual*, Oxford: Elsevier Inc., 2014.
- [74] D. Nell, “Practical determination of heat loads for existing deep level gold mines,” P.hD Thesis, North-West University, 2020.
- [75] D. Arndt, “Process toolbox Thermal hydraulic simulation tool,” Enermanage, Pretoria, 2016.
- [76] J. ZHANG , C. SUO, “Study of coal mine ventilation system optimization based on ventsim,” in *MATEC Web of Conferences 44*, Beijing, 2016.
- [77] M. Morar, A. Matei, and R. Dragoescu, “Efficiency of complex ventilation networks,” *Annals of the University of Pitrosani, Mining Engineering.*, vol. 9, pp. 183-192, 2018.
- [78] B. Friedenstien, C. Cilliers, J. Van Rensburg, “Simulating operational improvements on mine compressed air systems,” *S. Afr. J. Ind. Eng.*, vol. 29, no. 3, pp. 69-81, 2018.
- [79] J. Watkins, “Trade-off between simulation accuracy and complexity for mine compressed air systems,” M. Eng Dissertation, North West University, 2018.
- [80] X. Xianping, Z. Zicheng, “Research development of ventilation system optimization design for mining,” *Xinjiang Nonferrous Metal*, vol. 4, pp. 14-19, 1995.

- [81] Y. Zhongming, W. Yuguang, “Application of analyzing hierarchy procedures to optimization of mining ventilation system,” *J. of Guizhou University of Technology*, vol. 26, pp. 62-69, 1997.
- [82] W. Weidong, J. Guoxun, W. Jianping, “The application of grey relevancy analyzing method in ventilation system scheme,” *Journal of China Coal Mining Society*, vol. 26, no. 6, pp. 290-293, 2001.
- [83] X. Xianping, F. Changgen and Z. Zicheng, “Research on fuzzy optimization for mining ventilation systems,” *Journal of China Coal Mining Society*, vol. 24, pp. 397-382, 1999.
- [84] X. Wenxun, X. Jinxing, “Modern optimization computation method,” in *Tsinghua University Press*, Beijing, 1999.
- [85] K. Charles, A. Sadiku and M.N.O. Sadiku, “Basic Laws,” in *Fundamentals of Electric Circuits*, New York, McGraw Hill, 2013.
- [86] L. Campeau, M. Gamache, “Short-term planning optimization model for underground mines,” *Computers and Operations Research*, vol. 2, no. 2, pp. 50-65, 2019.
- [87] C. Watson, J. Marshall, “Estimating underground mine ventilation friction factors from low density 3D data acquired by a moving LiDAR,” *International Journal of Mining Science and Technology*, vol. 28, no. 4, pp. 657-662, 2018.
- [88] R. Weber-Youngman, “An intergrated approach towards the optimization of ventilation, air cooling and pumping requirements for hot mines,” PhD Thesis, North West University, 2005.
- [89] E. Develo, M. Pillalamarry and E. Garab, “Improving the ventilation system at Rosh Pinah zinc mine,” *Journal of South African Institute of Mining and Metallurgy*, vol. 116, no. 4, pp. 301-305, 2016.
- [90] C.K Koscis, R. Hall, and S.G. Hardcastle, “The integration of mine simulation and ventilation simulation to develop a 'Life-Cycle' mine ventilation system,” *South African Institute of Mining and Metallurgy*, vol. 13, no. 6, pp. 223-229, 2003.
- [91] Mining Ventilation Society of South Africa, “MVSSA,” 2021. [Online]. Available: <https://mvssa.co.za/>. [Accessed 15 02 2021].
- [92] M. Jahangirian, S.J.E. Taylor, T. Young and S. Robinson, “Key performance indicators for successful simulation projects,” *Journal of the Operational Research Society*, vol. 68, pp. 747-765, 2017.

- [93] M.Q.W. Jones, “Virgin rock temperatures and geothermal gradients in the Bushveld Complex,” *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 118, no. 7, pp. 671-680, 2018.
- [94] T. Maurya, K. Karena, H. Vardhan, M. Aruna, “Potential Sources of Heat in Underground Mines,” *Procedia Earth and Planetary Science*, vol. 11, pp. 463-468, 2015.
- [95] R. Anderson, E. DeSouza, “Heat stress management in underground mines,” *International Journal of Mining Science and Technology*, vol. 27, no. 4, pp. 651-655, 2017.
- [96] A. de Myttenaere, B. Golden, B. Le Grand, F. Rossi, “Mean Absolute Percentage Error for regression models,” *Neurocomputing*, vol. 192, pp. 38-48, 2016.
- [97] J. Glimm; S. Hou; Y. Lee; D.H. Sharp; and K. Ye, “Sources of uncertainty and error in the simulation of flow in porous media,” *Computational & Applied Mathematics*, vol. 23, pp. 2-3, 2004.
- [98] G. Warne, “AMS Haden,” BN AMS Haden Technology Solutions, 2019. [Online]. Available: <https://www.amshaden.co.za/observer-kit/>. [Accessed 8 April 2020].
- [99] Unknown, “Measurements of Airflow and Mine-wide Monitoring,” 11 February 2002. [Online]. Available: <http://web.mst.edu/~tien/218/Lab3-measure.pdf>. [Accessed 8 April 2020].
- [10] H. Bengton, “Bright hub engineering,” [Online]. Available: <https://www.brighthubengineering.com/hydraulics-civil-engineering/58382-how-to-measure-fluid-velocity-with-a-pitot-tube/>. [Accessed 8 April 2020].
- [10] B. Mayur, “Mayur Instruments,” The application of a manometer, 2012. [Online]. Available: <http://www.mayurlevelindicators.com/manometer.html>. [Accessed 8 April 2020].

Appendix A: LIST OF VENTILATION CONTROL DEVICES AND DEFINITIONS

1. Regulators

Regulators are used to restricting the airflow through an airway and limit the quantity of air.

2. Airlocks

Airlocks are two ventilation doors placed in sequence/series and used to give workers and vehicles a way through to travel without air short-circuiting. Airlocks are usually placed in travel ways where there is a large pressure difference.

3. Brattices

Brattices are temporary sheets that are fixed to the roof, walls and floor to provide a seal and guide air.

4. Stopping

Stoppings are temporary or permanent seals that are used to guide air. In most cases brick or cement walls.

5. Over-cast/under-cast

Over-casts/under-casts are air bridges that allow two airstreams to pass each other without mixing.

6. Ducts

Ducts are a temporary air pipe system that is used to direct air to specific locations with or without the aid of fans.

7. Main fans

The main fans are fans that have a significant impact on the airflow in a mine, such as the surface fans.

8. Secondary/Booster fans

Secondary fans, or booster fans, are installed in series to the primary fans and are used to overcome flow resistance.

9. Development/Auxiliary fans

Development fans are used to ventilate areas where there is no through-flow of air. Their aim is to take air from through flow and direct it to a face or development.

Appendix B: EQUIPMENT USED IN A MANUAL VENTILATION SURVEY

The equipment used by ventilation departments in South Africa are listed in Table 19.

Table 19 Equipment used in a ventilation survey

Ventilation survey equipment		
Equipment	Short description	Diagram
Rotating vane anemometer	Using the <i>traverse method</i> in conjunction with a stopwatch the number of “meters of air” is measured that have passed through the vane at the recorded time.	 Figure 34 Vane anemometer [98]
Stopwatch	Used in conjunction with a vane anemometer to time how long it takes to traverse the cross-sectional area at the measuring point.	
Whirling	Measures WB and DB	 Figure 35 Whirling hygrometer [98]

Laser distance meter	Measures the cross-sectional area of the measuring point.	 <i>Figure 36 Laser distance meter [98]</i>
Powder	Used for the <i>Puff-Puff</i> method where the airflow is too low for a vane's capabilities.	
Barometer	Measure the static pressure.	 <i>Figure 37 Barometer [98]</i>

The methods listed in Table 19 are described as:

Traverse method

Measuring with a vane anemometer, parallel to laminar air-flow, the vane should start in one corner of the airway and move up and down to the opposite corner as shown in Figure 38. The whole traverse should at least take 50 seconds for accuracy purposes.

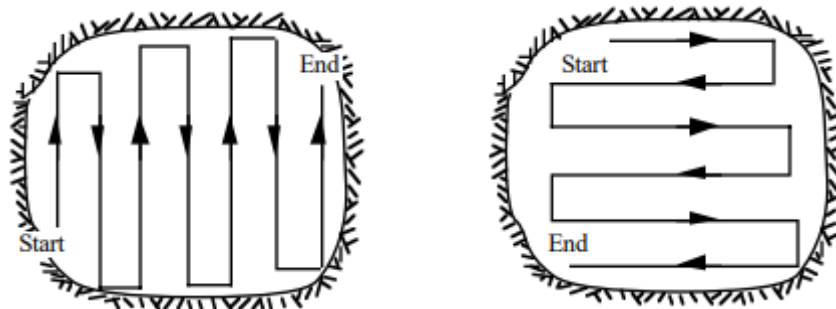


Figure 38 Traverse method in mine airways [99]

Puff-Puff method

Air velocities that are lower than 0.5 m/s are too slow for a vane's capabilities. Using a stopwatch, the powder can be puffed into the air and timed to see how long it takes to reach a

certain point at a known distance away. Two people are required for this method to be accurate. The method is shown in Figure 39.

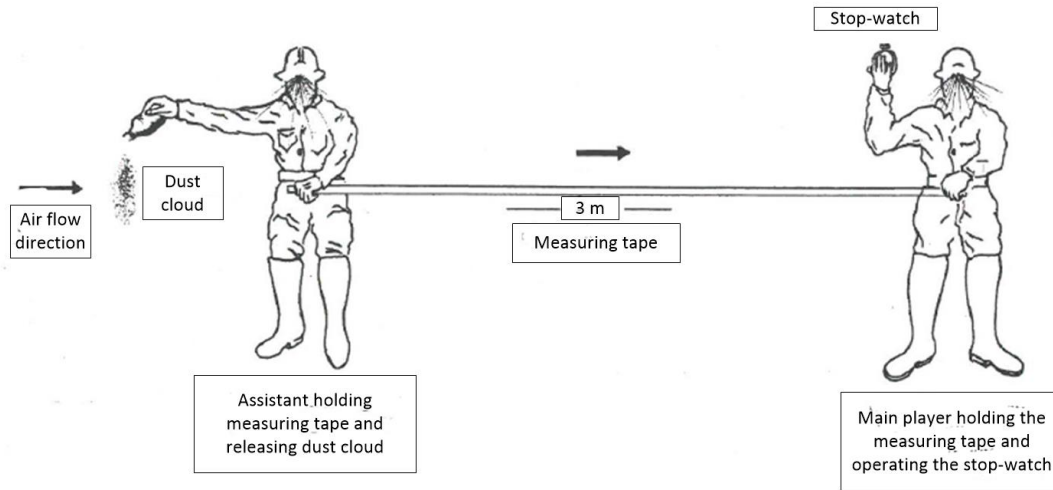


Figure 39 Puff-Puff method

Pitot tubes are used in many applications to measure the velocity of a fluid [100]. Using a pitot tube is a convenient method to measure the velocity of airflow in the main surface fan, these surface fans can have extremely high velocities and thus making it dangerous to enter. Therefore, the pitot tube is the best possible method to measure the velocity by inserting it into the fan's ducting. Figure 40 shows the layout or the workings of a pitot tube. With the help of a vertical U-tube manometer shown in Figure 41 the static, stagnation and dynamic pressures can be obtained. When connecting the U-tube to the pitot tube at the static pressure (horizontal tube point) and the stagnation pressure (vertical tube point) the dynamic pressure can be read off. The velocity in SI-units can then be calculated using Equation 2.

$$\Delta P = \frac{1}{2} \rho V^2 \quad (2)$$

Where:

ΔP = Dynamic pressure (kPa)

ρ = Fluid density (kg/m³)

V = Velocity (m/s)

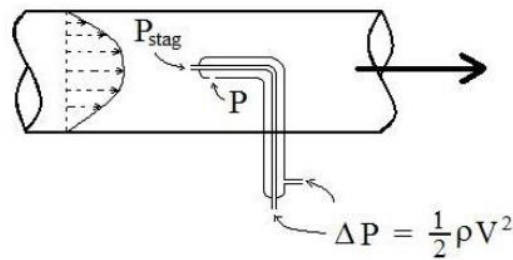


Figure 40 Pitot tube schematic [100]



Figure 41 Vertical U-tube manometer [101]

Calculating the quantity of air that is extracted from the mine by the surface fan the velocity obtained from Equation 2 can be multiplied by the area (m²) of the ducting where the pitot tube was placed. Pitot tubes are extremely sensitive and should only be used when the air being measured is dry air because humid air may cause blockage in the tube and give false readings.

Method for using a pitot tube:

Using a pitot tube requires two instruments, a pitot tube and a manometer. Average velocity pressure is taken at multiple distances as prescribed by the MVSSA. The distances are shown in Table 20. Measuring with the pitot tube can be done either horizontally or vertically as shown in Figure 42 and Figure 43.

Table 20 Pitot tube measuring points [20]

Point number	General case
1	0.026 d
2	0.082 d
3	0.146 d
4	0.226 d
5	0.342 d
6	0.658 d
7	0.774 d
8	0.854 d
9	0.918 d
10	0.974 d

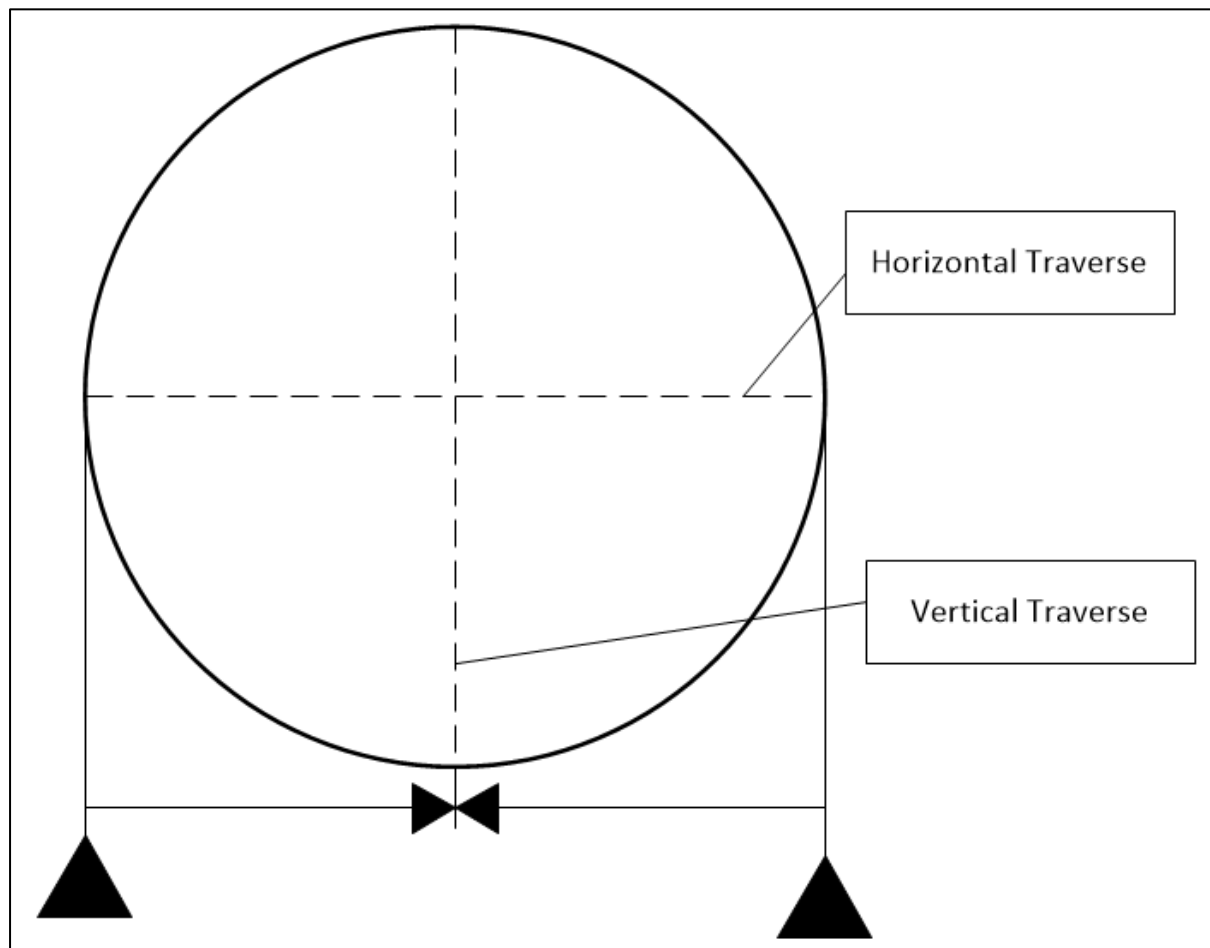


Figure 42 Pitot tube traverse method [20]

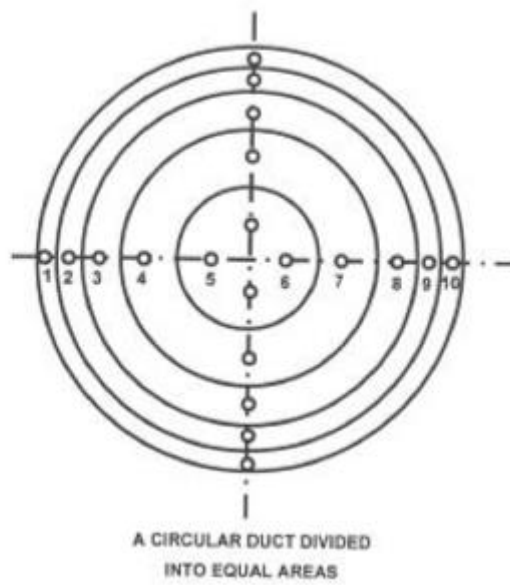


Figure 43 Pitot tube measuring points in round ducting [20]

Appendix C: SCALABLE METHOD FOR VENTILATION NETWORKS

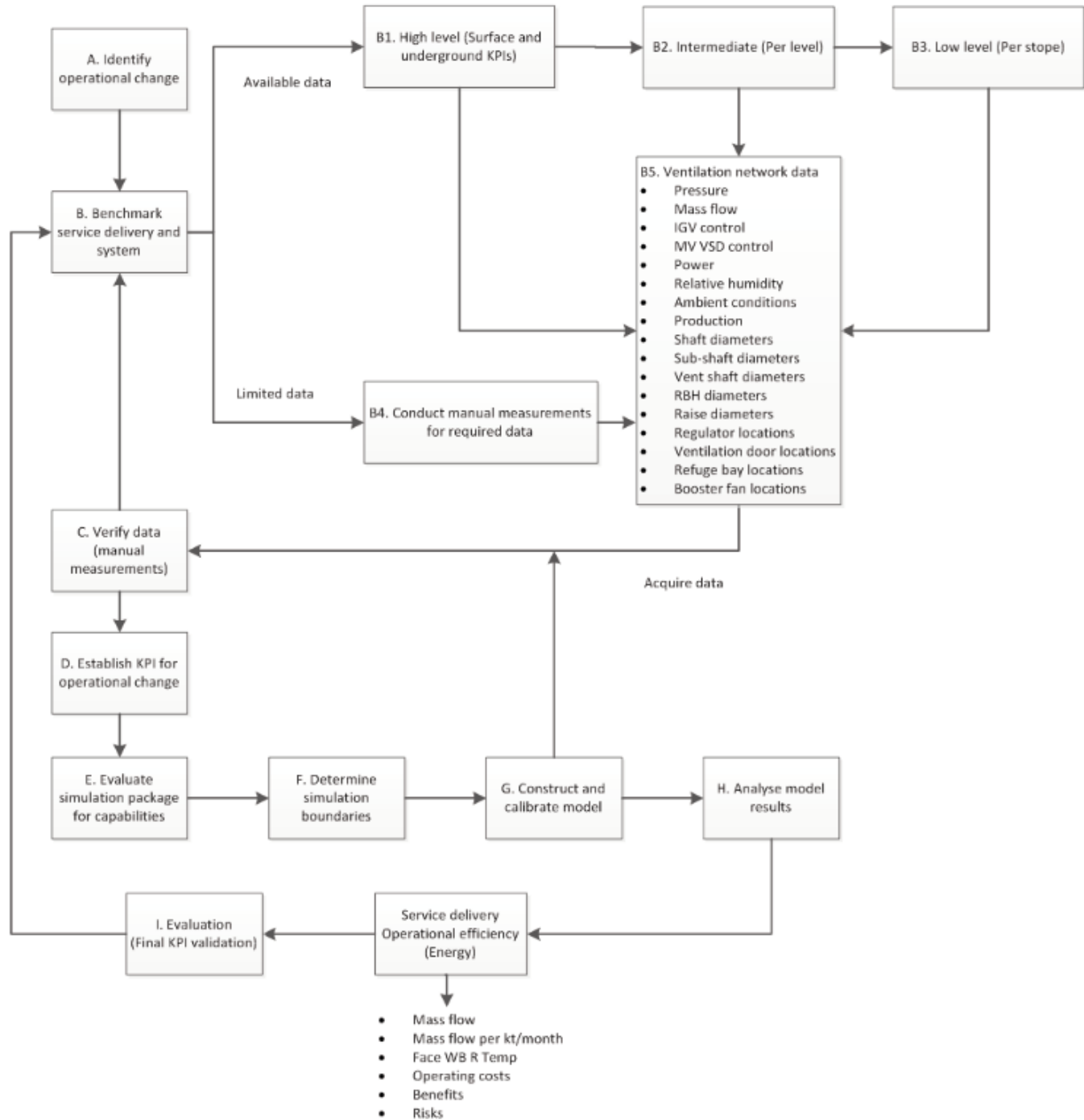


Figure 44 Scalable method for mine ventilation networks

Appendix D: PTB SIMULATION LEVEL LAYOUTS

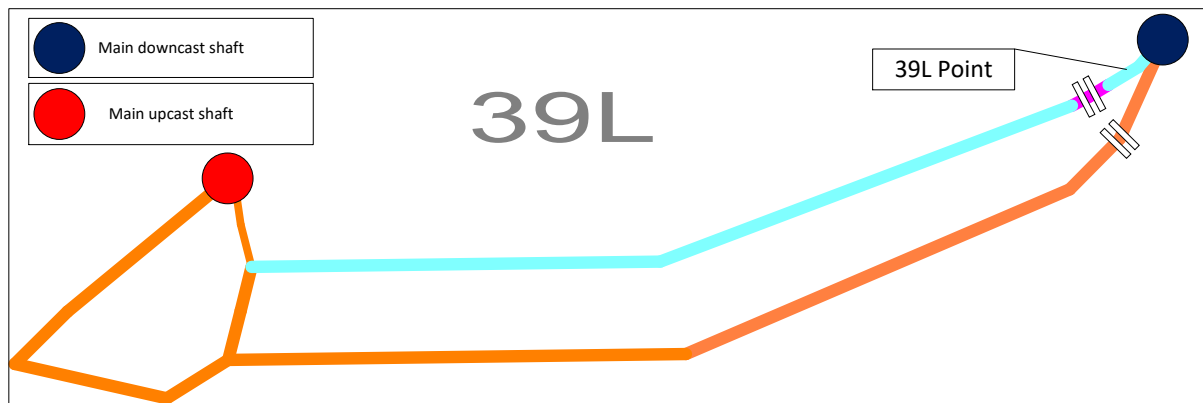


Figure 45 39L volume survey point

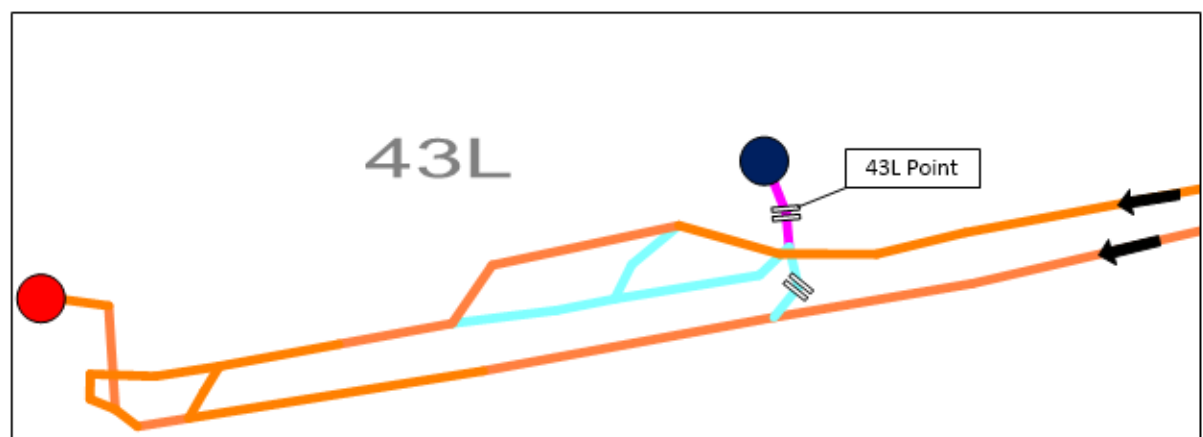


Figure 46 43L volume survey point

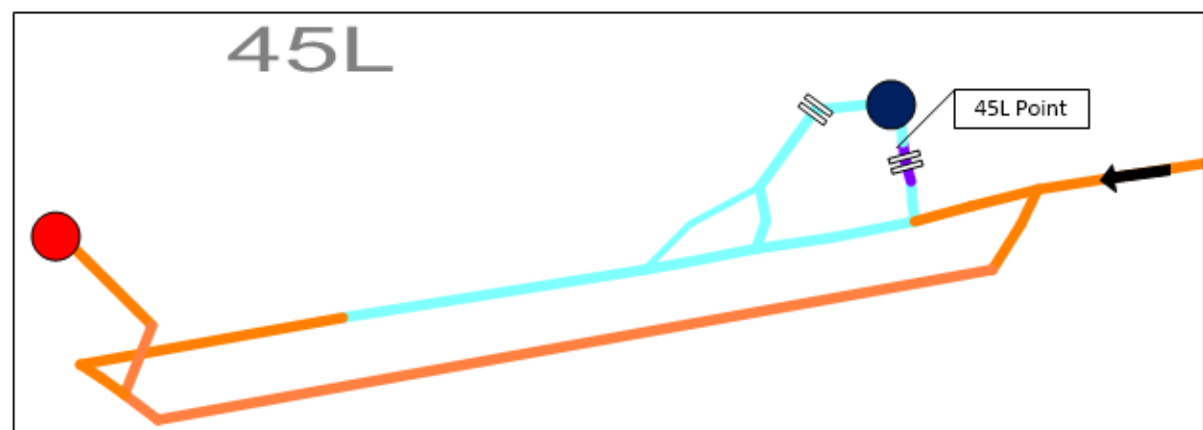


Figure 47 45L volume survey point

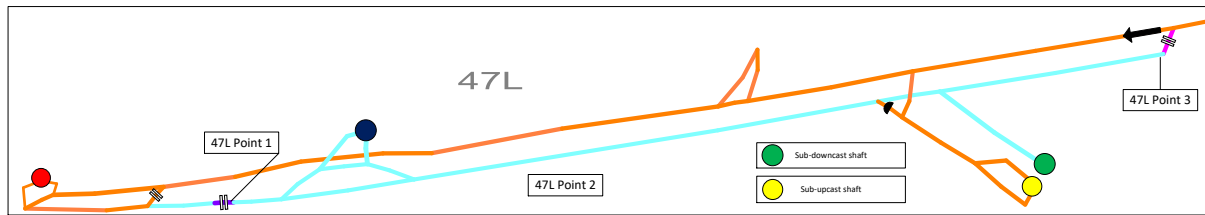


Figure 48 47L volume survey points

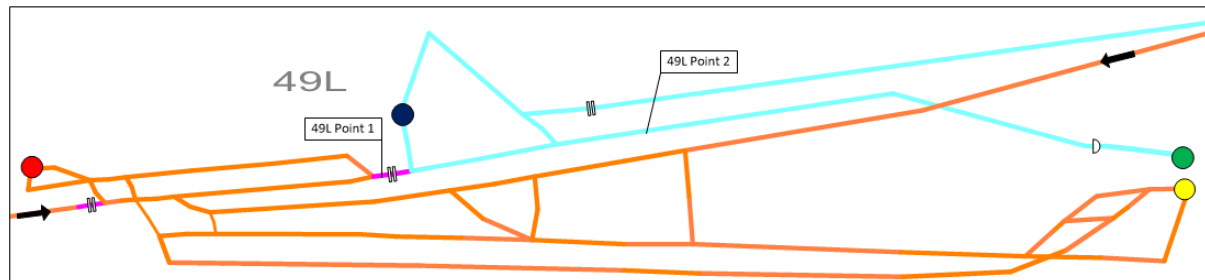


Figure 49 49L volume survey points

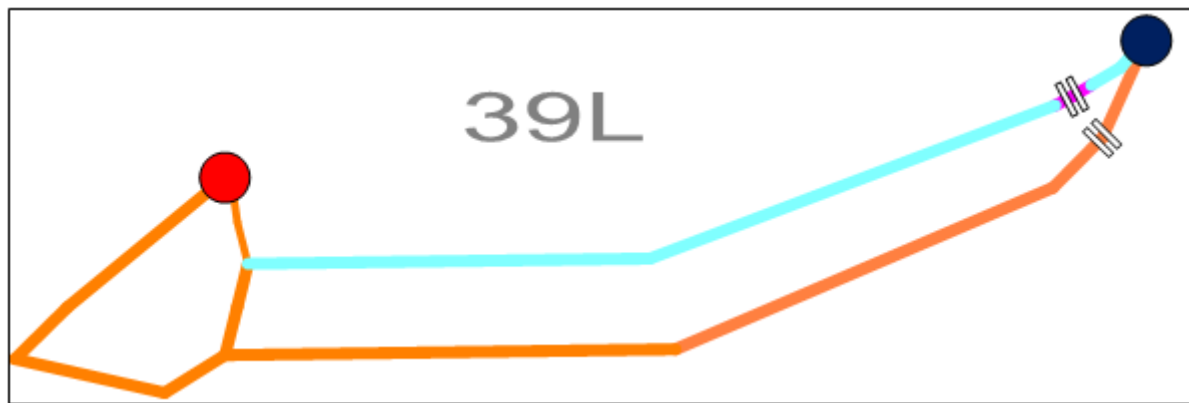


Figure 50 39L layout of simulation

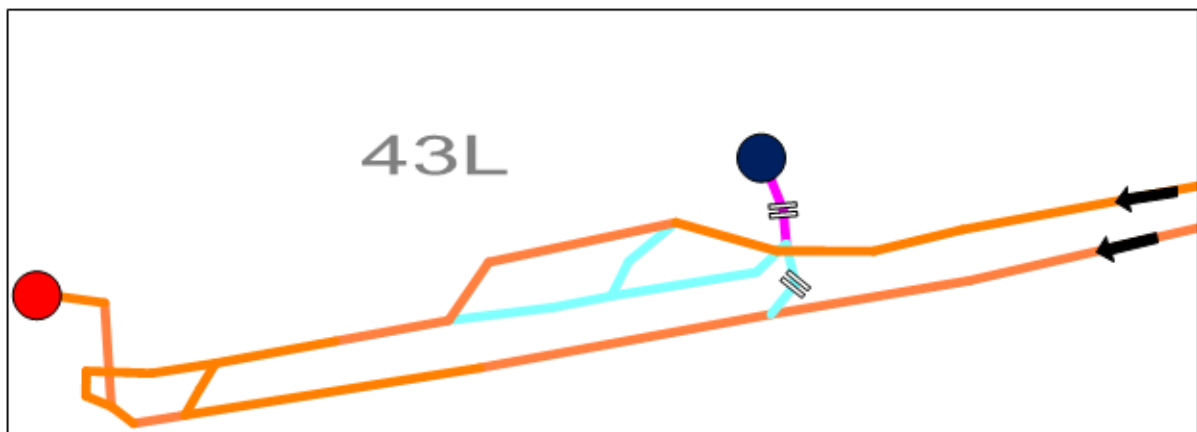


Figure 51 43L layout of simulation

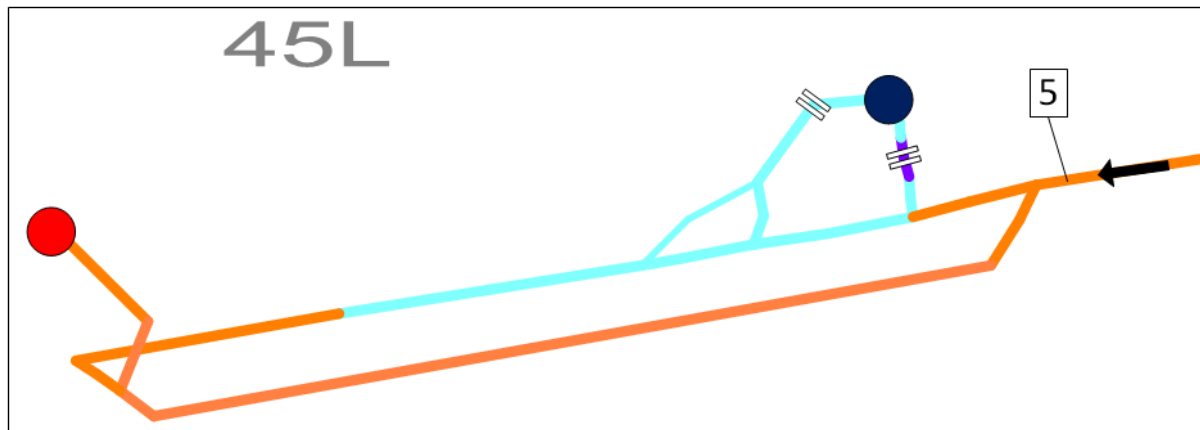


Figure 52 45L layout of simulation

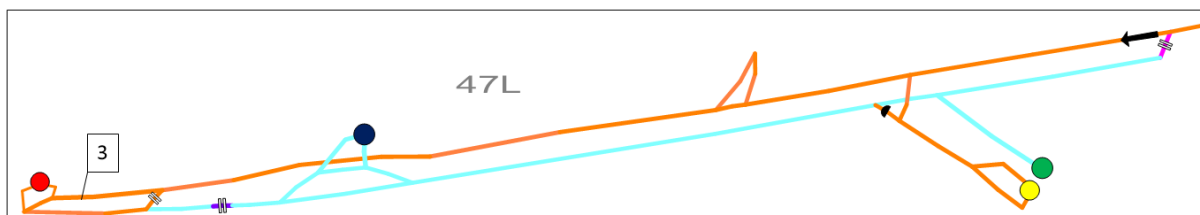


Figure 53 47L layout of simulation

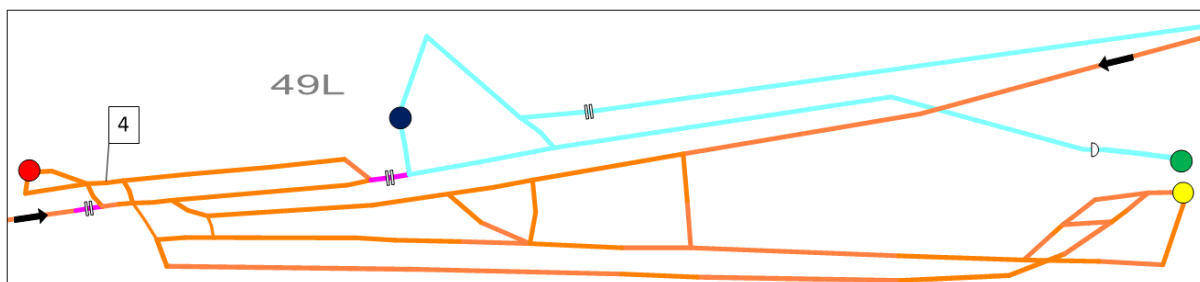


Figure 54 49L layout of simulation

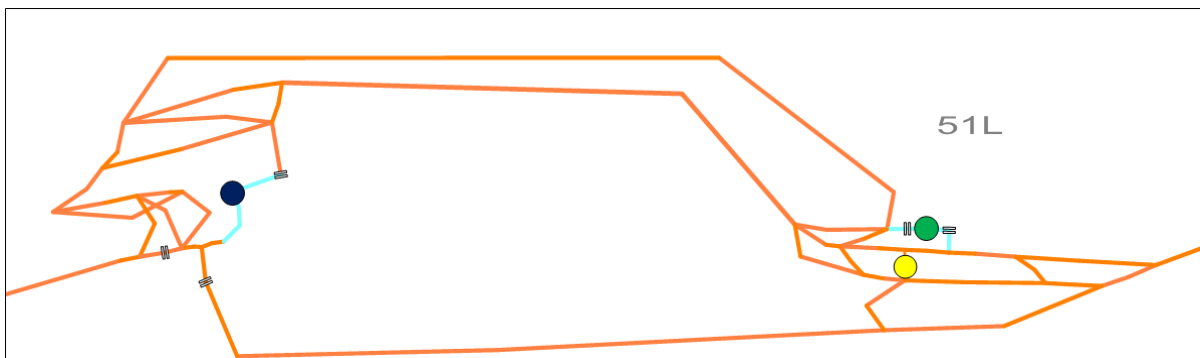


Figure 55 51L layout of simulation

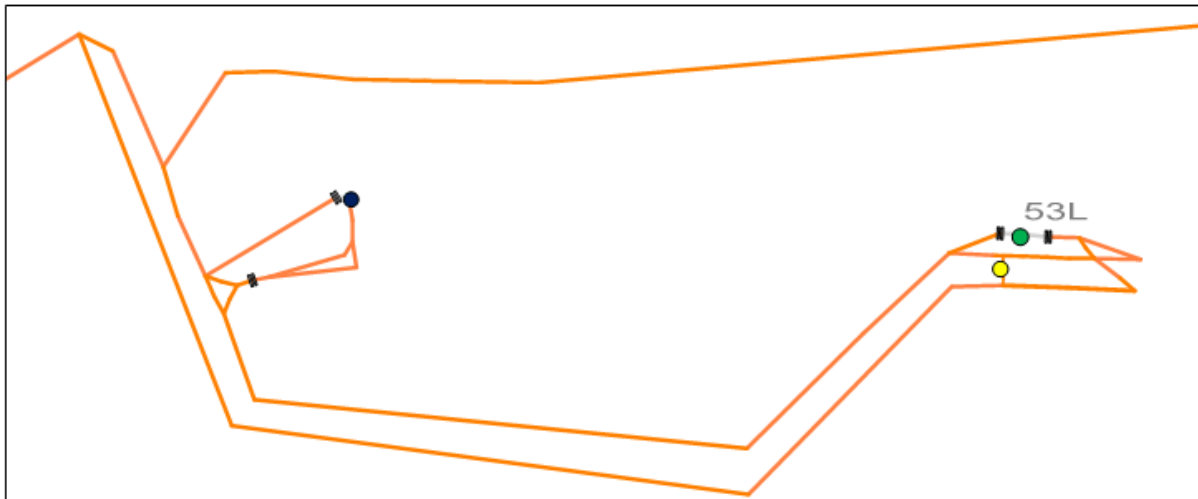


Figure 56 53L layout of simulation

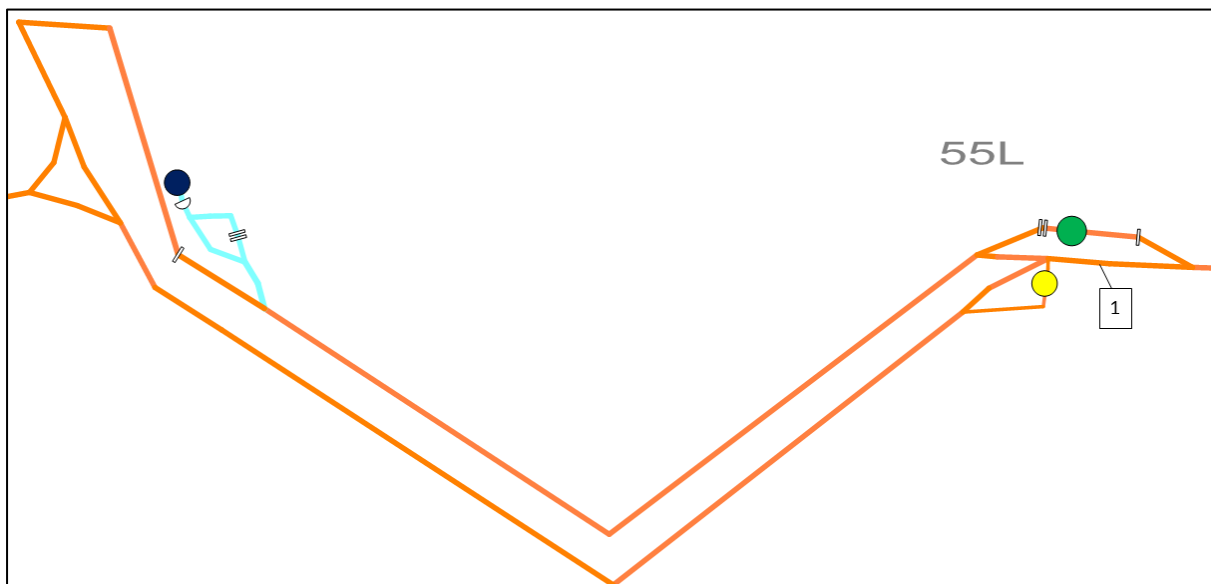


Figure 57 55L layout of simulation

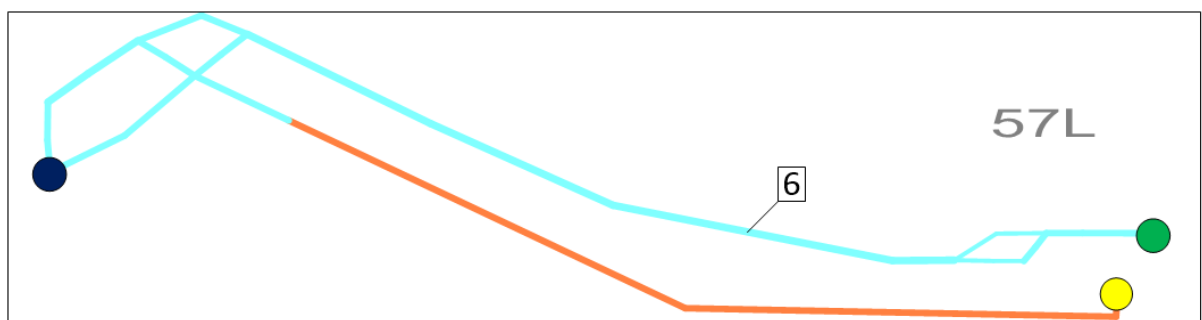


Figure 58 57L layout of simulation

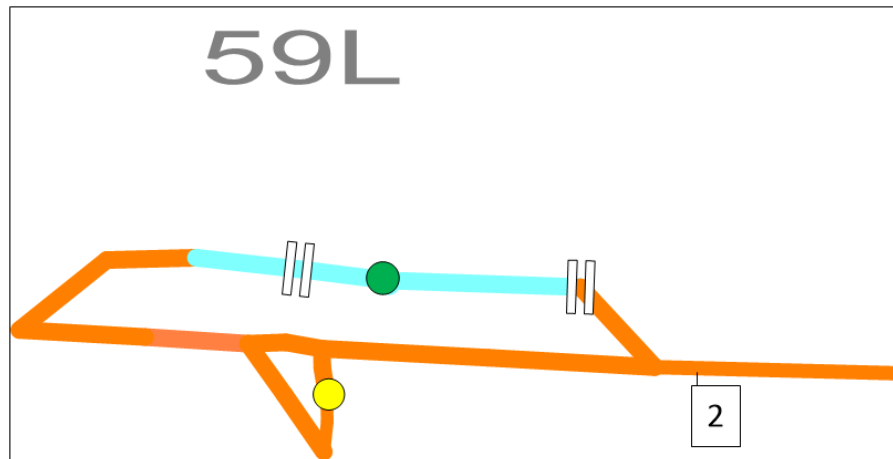


Figure 59 59L layout of simulation

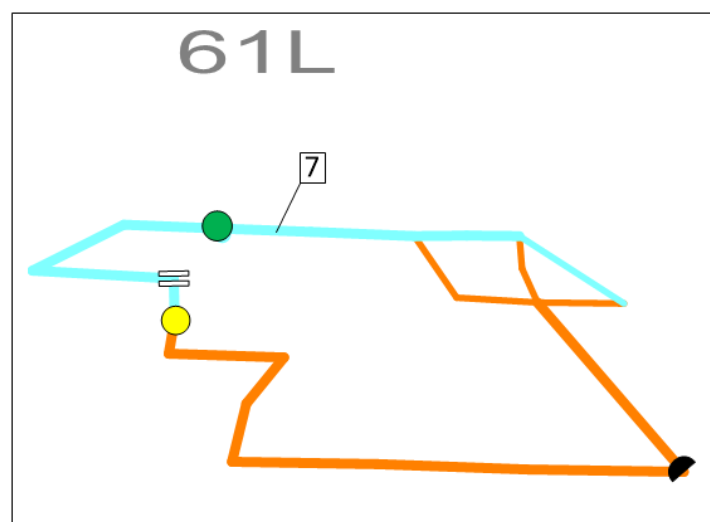


Figure 60 61L layout of simulation

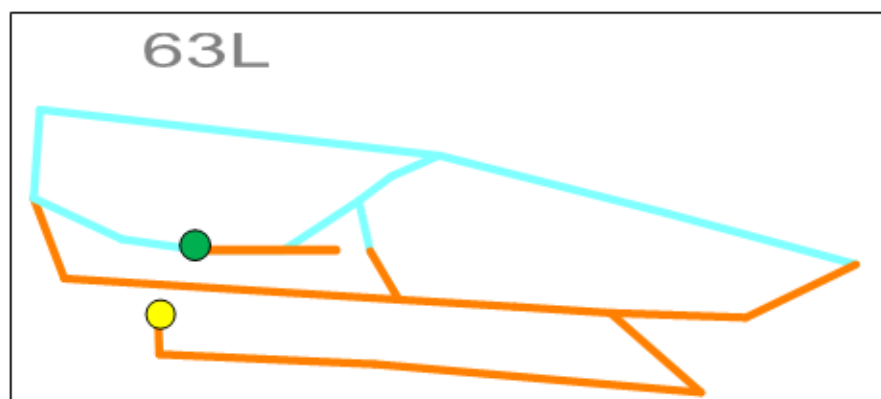


Figure 61 63L layout of simulation

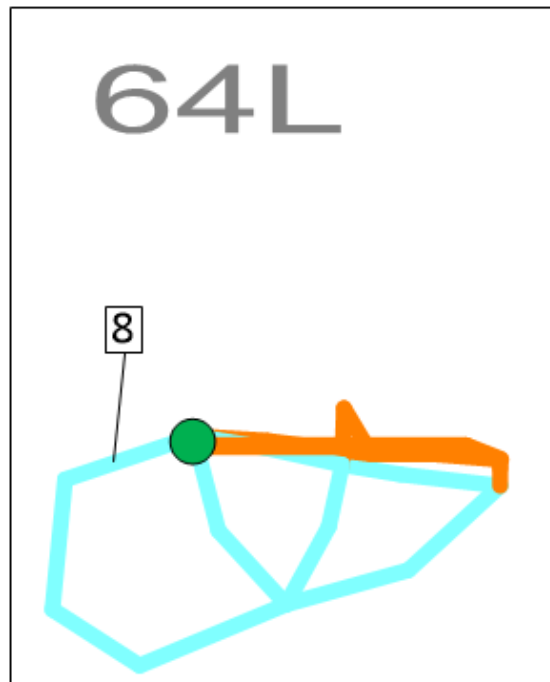


Figure 62 64L layout of simulation

Appendix E: PTB TUNNEL NODE INPUTS

Name
3754.1

Air Tunnel

Inputs
Outputs
Notes

Inputs

- Hydraulic Calculate
- Hydraulic Measure
- Thermo Calculate
- Open Water Drain
- Water Pipe
- Coordinate
- Configuration
- Size
- Orientation
- Scale

Properties

Calculate
Import...
Export...

Name	Unit	Initial
Flow Area	m ²	10.000
Flow Perimeter	m	12.600
Tunnel Length	m	221.416
Friction Coefficient		0.011
Door Fraction		...

Figure 63 Hydraulic calculate in PTB

Appendix F: SYSTEM RESISTANCE CURVE OF SEALING PLAN

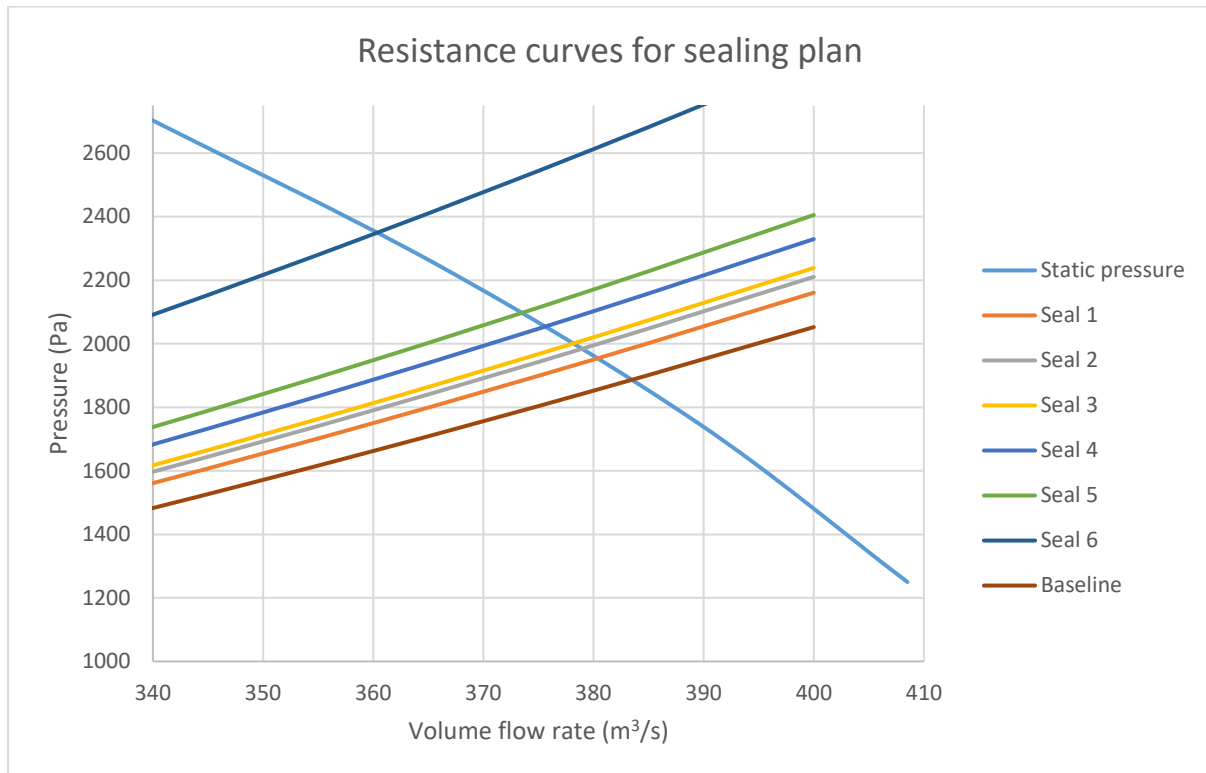


Figure 64 Enlarged graph of resistance curve of sealing plan