

A systematic approach to evaluate in-stope compressed air inefficiencies in deep-level mines

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ABSTRACT

Title: A systematic approach to evaluate in-stope compressed air inefficiencies in deep-level mines

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The current decreasing production trend in South Africa and the role of compressed air inefficiencies in pipe networks are introduced in this study. Compressed air distribution systems that supply mining equipment have low mechanical efficiency. Various factors contribute to this low efficiency such as undersized pipes, poor control valve set-point control, and inactive sections that are not sealed off.

A detailed literature survey revealed the initiative to investigate in-stope compressed air inefficiencies and the effect thereof on drilling pressure. The study provides a verified method for identifying compressed air inefficiencies inside the stoping area and evaluating the viability and efficacy of various approaches to address in-stope compressed air inefficiencies.

A method is developed that systematically evaluates in-stope inefficiencies by establishing the flow and pressure baselines for the supply, demand and reticulation network of a compressed air system. The severities of the inefficiencies of the different compressed air sections are compared and prioritised using a Likert scale.

After the compressed air system has been characterised by means of flow and pressure baselines, the method is used to develop a baseline simulation of a deep-level mine stoping area. The method addresses simulation time, parameters, components and accuracy. The method provides a theoretical approach for verifying the stope simulation model against the pressure and flow baseline, using the mean absolute error method.

Using the verified simulation, the method applies literature studies and theory to highlight how a typical compressed air inefficiency will present itself in a stope network. The method is used to practically verify a compressed air inefficiency inside a stope network using measurement instrumentation. Finally, the method discusses generic simulation strategies that aim to mitigate compressed-air-related inefficiencies.

The method was implemented on a case study mine where it was used to analyse different sections of a compressed air system, aiming to identify in-stope inefficiencies. A Likert scale was used to assess various sections to ensure accurate representation of stope inefficiencies. Through this method, it was determined that the stoping section emerged as the top priority area for improvement in the case study mine.

A baseline simulation of a case study stope was developed using simulation software. The characterisation curves showed the case study stope experienced a total pressure loss of 75 kPa from the travelway to the stope face. The 4" pipe section exhibited a pressure loss of 32 kPa over its length, while a pipe reduction (4" to 2") inside the case study stope resulted in a pressure loss of 43 kPa.

To verify the identified inefficiencies, pressure sensors were installed throughout the stope. The case study stope experienced a total pressure loss of 80 kPa from the cross-cut intake to the face. During the drilling period, the 4" pipe experienced a 37 kPa pressure loss from the cross-cut intake while the 2" section experienced a further 43 kPa pressure loss. These results aligned with the simulated pressure loss.

Six mitigation strategies were developed using a combination of theoretical principles and simulation software. The simulated strategies indicated that the identified inefficiencies can be mitigated by increasing the pipe size of the compressed air network to accommodate the flow demand of the network.

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LIST OF ABBREVIATIONS

KPI	Key Performance Indicator
MAE	Mean Absolute Error
PGM	Platinum Group Metal
PTB	Process Toolbox
ROP	Rate of Penetration

GLOSSARY

“Baseline”	Reference system configuration
“Blasting shift”	Period where ore is released using explosive materials
“Centre gully”	Access route into stopes used for people, materials and ore
“Cleaning shift”	Period where blasted ore is collected and transported to surface
“Compressor ring”	Compressors interconnected with one another
“Drilling shift”	Period during which explosive holes are drilled into rockface
“Stope”	Area where ore is extracted
“Stope face”	Furthest point developed in the stope
“Validation”	The process to establish if the problem statement is addressed with the results obtained
“Verification”	The process of ensuring that the solution strategy is correct

1 INTRODUCTION

The following section introduces the current shift towards platinum group metal (PGM) dominance in the mining sector and discusses the role of compressed air inefficiencies in the pipe networks.

1.1 Platinum production trend

As shown in Figure 1-1, PGM sales in South Africa have risen from 5% in 1980 to 21% in 2018, manganese ore from 10% to 29% while gold mining has declined from 67% to 14% indicating a shift towards PGM dominance [1].

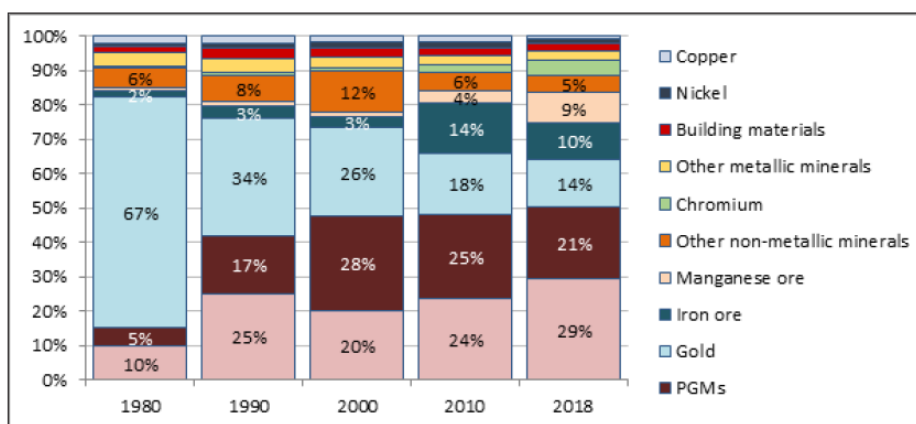


Figure 1-1: South Africa's mining sector distribution by sales [1]

Although PGM sales have increased, South Africa's platinum production has decreased since 2006 [2]. As of 2018, the global platinum supply is shown in Figure 1-2.

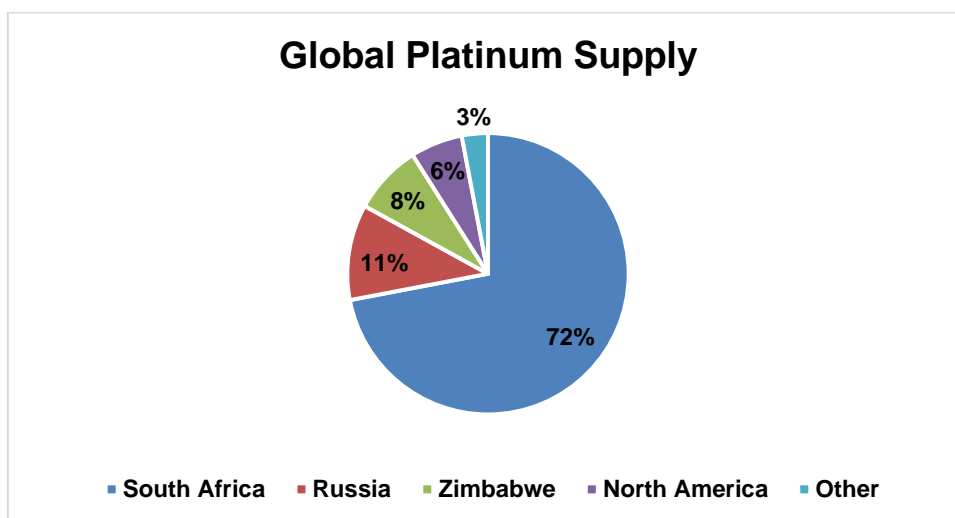


Figure 1-2: Global platinum supply – Adapted from [1]

From Figure 1-2, the decrease in platinum production in South Africa is likely not due to a depletion of reserves but rather to social, infrastructural and equipment limitations [3]. Many mines are hindered by outdated infrastructure and ever-increasing electricity costs, which limit the efficiency of the mining process [3], [4]. Modernisation, including the use of technological advances, aims to offset economic factors [5], [6] but could take time to implement and may not be a viable short-term solution. One potential way of improving overall efficiency in the meantime is optimising inefficient infrastructural mining sub-systems such as compressed air systems. Compressed air systems are known to be some of the most expensive and inefficient systems. Compressed air accounts for up to 20% of a mines energy consumption with a low overall efficiency of about 10 to 30% [7]. Oversizing of compressors, under sizing of pipelines and the low efficiency of pneumatic tools all pose a risk to effective production [7].

1.2 Mining process

Mining can be classified as either open-pit (surface) or underground mining depending on the type of resource and its location [8]. Underground mines require sinking a shaft to access the orebody deep below the surface [8]. Figure 1-3 shows the basic structure of a deep-level mine.

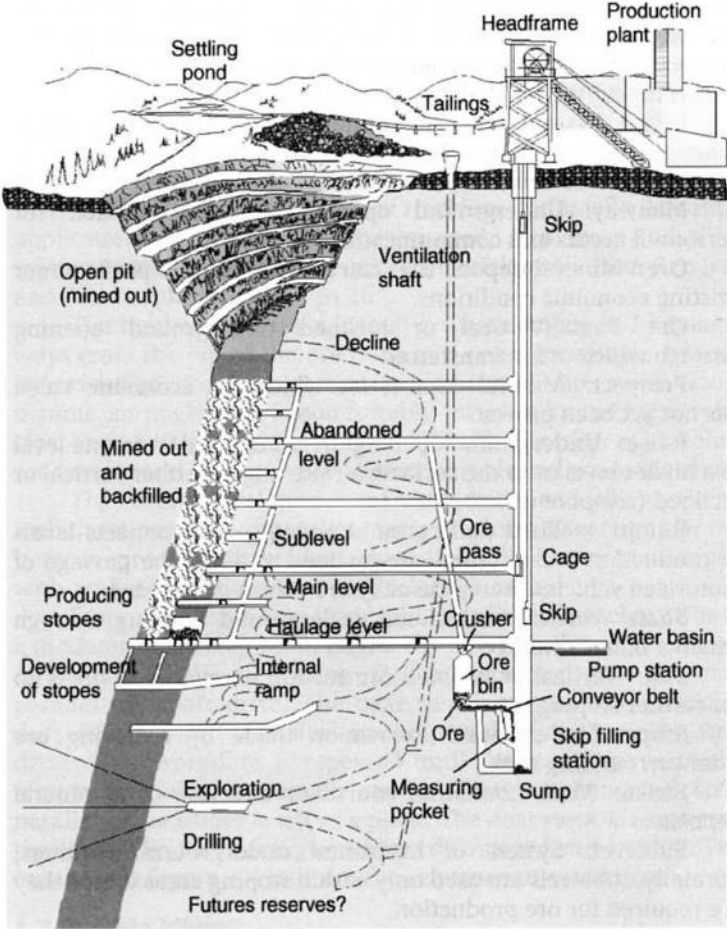


Figure 1-3: Underground mine structure [9]

Shifts

To maximise productivity, a 24-hour mining cycle is typically divided into three shifts: drilling, blasting and cleaning. During the drilling shift (6:00–14:00), all the blasting holes are drilled on the rockface. Mining operations persist throughout the afternoon shift, which typically spans from 14:00 to 18:00. The conclusion of this shift commonly involves a blasting period, during which explosives are loaded into designated blasting holes and subsequently detonated. During the cleaning shift (22:00–06:00), the blasted rock containing the resource is removed from the working areas and transported to the loading sections [10], [11].

Drilling

The stoping operations of South African metalliferous mines are mostly confined to narrow tabular orebodies making mechanised mining difficult [12]. As a result, handheld pneumatically operated rock drills are typically used for drilling applications in mining. These drills are powered by the compressed air network [10], [12], [13]. The drilling pattern on the rockface is chosen based on the type and location of the rock and is designed to break the rock in a specific way when the explosives are detonated [14]. The compressed air usage is the highest during the drilling shift due to the use of rock drills.

Blasting

After the drilling shift, drilled out holes are charged up with explosives and detonated in a timed sequence [10]. In narrow-reef mining, stopes are normally developed at an angle that closely follows the ore grade line [15]. The blasted ore is collected by scraper winches to the centre gullies for collection during the cleaning process. During this shift, there should be little to no compressed air usage [16].

Cleaning and sweeping

After blasting has occurred, the blasted ore is transported to the ore pass located inside the specific stope. This is done by first collecting the blasted ore from the stope face with large scrapers powered by winches [11]. Hereafter, the remaining fines on the stope face are collected through sweeping. Sweeping is normally done using water hoses [11]. This shift uses less compressed air due to equipment such as rock breakers, loaders and loading boxes [16].

Transportation of ore

South African underground mines typically use trains (locomotives and hoppers) as the primary transportation system (a process called tramming) [17]. Hoppers are filled using pneumatically operated loading boxes connected to the ore pass in the stope. The blasted ore is transported through a central ore pass system at the shaft. Each level has its own tipping point that feeds ore

into the shaft ore pass system. The ore pass system uses gravity to feed the broken ore from the level to the bottom of the shaft. Thereafter, the blasted ore is hoisted to the surface using loading skips [17], [18].

The preceding section offered a comprehensive introduction to the mining process, highlighting the prominent role of compressed air as a fundamental aspect in mining operations. The next section provides a brief description of a typical compressed air network used by deep-level mines.

1.3 Compressed air network

Compressed air is considered the normal energy carrier for mining equipment [19]. This is primarily due to its ease of use, scalability, and the safety features associated with this energy carrier [11]. A typical compressed air system includes compressors, air dryers, coolers, filters, pipe networks, valves and controllers [7]. Each component poses the risk of inefficiency in the form of flow or pressure loss [7].

Compressors

Compressors generate air at a specific pressure and volume, which is transferred to underground mining equipment through pipe networks [19]. Centrifugal compressors are commonly used in mining because they are easy to maintain and reliable [20]. Compressed air systems may be composed of a single compressor or include several compressors that work together in a logical manner [20]. Furthermore, they can adjust their guide vanes to maintain the desired set point by either increasing or decreasing its flow [21].

Compressed air ring

Compressors are often interconnected between different shafts to form a compressed air ring. This is done as a preventative measure for tripping compressors [20], [22]. When a single compressor trips at a shaft, the shaft's demand is distributed among the remaining compressors in the ring. Figure 1-4 shows an example of a compressed air ring.

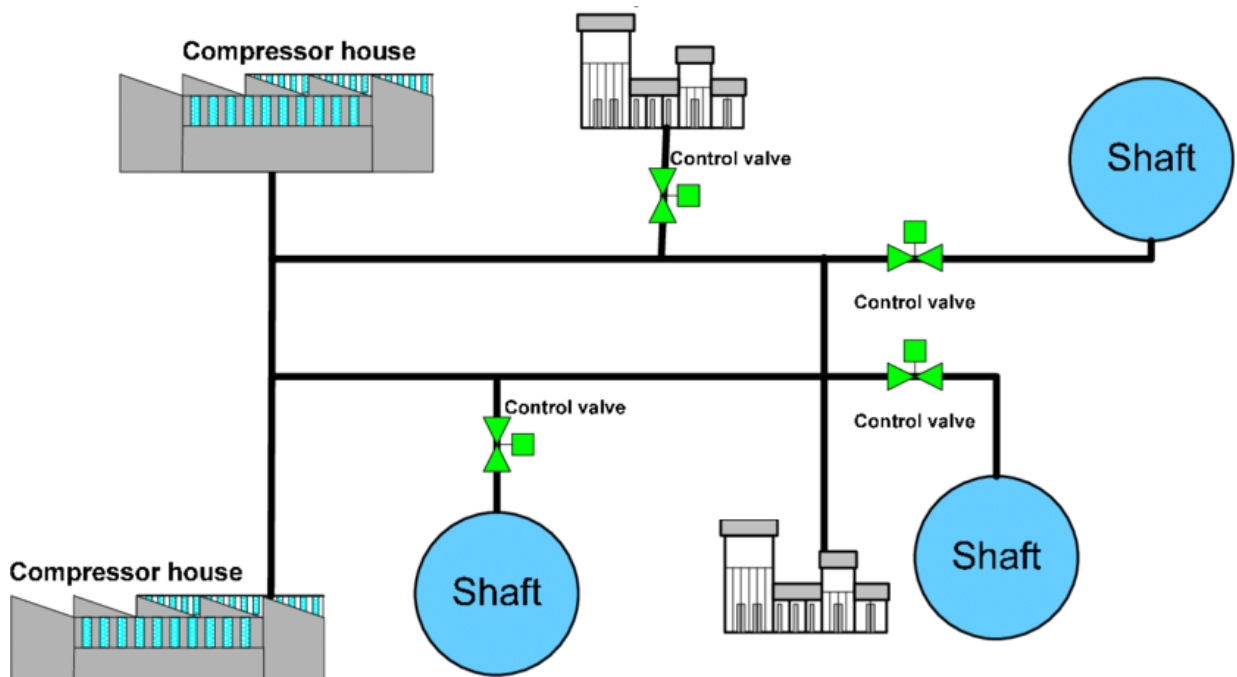


Figure 1-4: Typical layout of a compressed air ring at deep-level mines [23]

Pipe networks

Pipe networks that stretch over several kilometres are used to transfer the generated air from the surface compressors to the underground mining equipment. Figure 1-5 shows a ventilation network in a deep-level mine, with each tunnel typically having a compressed air pipe.

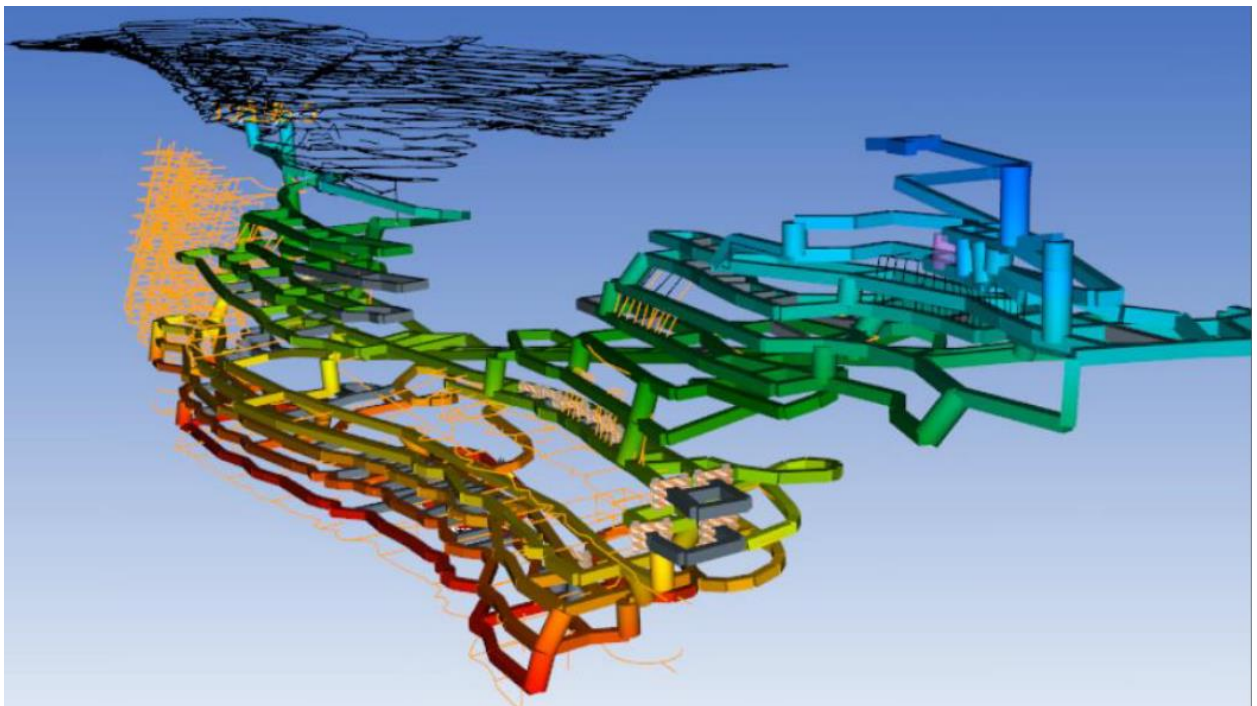


Figure 1-5: Layout of a ventilation network in a deep-level mine [11], [24]

Pneumatic rock drills

Pneumatic rock drills, such as handheld, air-leg-supported compressed air rock drills, are commonly used for drilling blasting holes into the rockface [25]. These drills are easy to use and can be operated by one person. Figure 1-6 illustrates the operation of this type of drill.



Figure 1-6: Typical rock drill operation [16]

The rate of penetration (ROP) is an important specification that refers to the distance in millimetres that the drill bit penetrates the rock each time [13], [25]–[27]. The ROP is used to evaluate the performance of the rock drill in associate with certain rock types and correlates with the fluctuations in production [11]. When blasting targets are not being met, increasing the ROP will result in faster drilling of blasting holes, which leads to increased ore extraction [11].

For compressed air operated rock drills, ROP is subject to the supplied pressure to the rock drill. As the supply pressure increases, the air consumption increases and, subsequently, the ROP increases [13], [27]. Figure 1-7 shows a typical ROP performance graph for various types of rock drill.

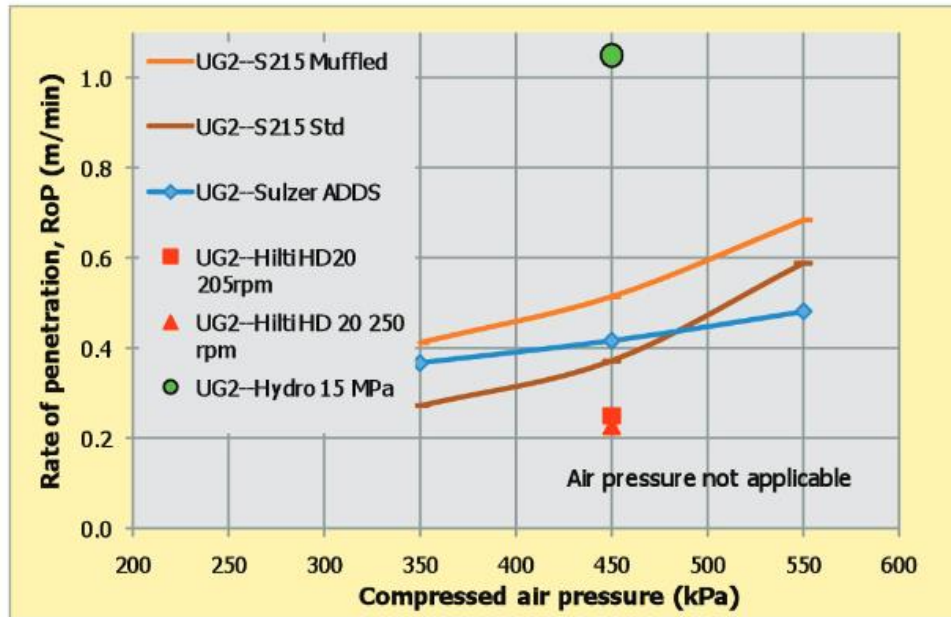


Figure 1-7: ROP graph – Pneumatic drill [13]

Pneumatic loaders

In development ends, after the rockface is blasted, the broken rock is loaded with a pneumatic loader to load hoppers for the transportation of the broken rock to the station waste rock pass system [16].

Loading boxes

Loading boxes use large pneumatic cylinders to open and close control the loading buckets (chutes). The loading boxes fill the hoppers with ore during the tramming process. Compressed air operated cylinders are used to open the loading boxes mechanically [16].

Refuge chambers

A refuge chamber is a life-sustaining chamber designed to keep workers safe in case of an emergency [28]. These chambers are supplied with compressed air that sustains a positive pressure to keep smoke out in case of underground fires [29].

Pneumatic actuators

Pneumatic actuators are used to control the compressed air supply to working areas [16].

Agitators

Agitators are used to agitate water particles such as mud in underground water dams to prevent these particles from accumulating on the bottom of the dam [16].

Table 1-1 summarises the pressure requirements for underground equipment.

Table 1-1: Compressed air users and requirements [10], [16], [28]

User	Pressure requirement [kPa]	Air requirement [Nm ³ /h]
Pneumatic rock drill	400–620	210–1 500
Mechanical loader	450	1000
Loading boxes	350–600	20–500
Refuge bays	200–300	5 per person
Pneumatic rock breaker	450	1 000
Pneumatic cylinder	350–600	1.7–400
Pneumatic actuator	350–600	±0
Agitator	400	1 300

1.4 Evaluating compressed air efficiency

Efficient compressed air systems are important for maintaining high productivity, ensuring good equipment performance, and reducing energy costs [30]. Factors that affect the efficiency of a compressed air system include the demand for air (also known as the shaft demand), the supply of air, and the compressed air distribution network [30]–[33].

Supply and demand

The supply of compressed air consists of centrifugal compressors typically located on surface of the mine. The demand of a compressed air system is determined by the different underground pneumatic equipment that uses compressed air [11]. Properly matching the supply with the demand for air is crucial but can be challenging in large deep-level mining compressed air systems [30]–[33].

Compressed air quality

The quality of compressed air is also important and is determined by the level of contaminants such as water vapour, oil and solid particles [34]. The contamination level of a compressed air network is influenced by the types of compressor, dryer, filter, and other components used [34].

Compressed air distribution network

An efficient compressed air distribution network should meet three outcomes: minimal pressure drop between the compressor and end user, minimal leakage from the pipe network, and sufficient condensate separation [35]. Compressed air systems have low mechanical efficiency (as low as 2% efficiency) compared with alternative energy carriers such as oil electrohydraulic (23%

efficiency), hydro-powered pumps (20% efficiency), hydro-powered gravity (24% efficiency), and electric drills (32% efficiency) [13], [36].

Causes of poor system efficiency include leaks, ineffective water traps, ventilation with compressed air in working areas, and insufficient pipe sizing and connections [37], [38]. Some studies suggest that the distribution network is one of the major contributors to low system efficiency [11], [16], [20], [39]. Poor performing distribution networks force mines to run surface compressors at higher set points, increasing electricity consumption and decreasing profitability [11].

The following section provides information on the theoretical nature of pressure losses inside a compressed air pipe network.

1.5 Theoretical evaluation of compressed air network inefficiencies

Pipe inefficiencies and their effect on pressure can be explained using the mathematics behind the phenomenon of pressure loss. This is classified into major and minor head losses [40]. Major head losses depend on the pipe length, flow regime and fluid viscosity, while minor head losses result from flow disturbances caused by components such as bends and connections in the pipe network [11], [40].

Major head losses

Major head losses are calculated using Equation 1-1 [38], [41], [42]:

Equation 1-1: Major pressure loss formula

$$\Delta P = P_1 - P_2 = \lambda \times \rho \times \frac{V^2}{2} \times \frac{L}{D}$$

With

ΔP = Difference in pressure between two measuring points [Pa]

P_1 = Measuring Point 1 [Pa]

P_2 = Measuring Point 2 [Pa]

λ = Dimensionless friction coefficient [n/a]

ρ = Fluid density [kg/m³]

V = Mean flow velocity of fluid [m/s]

L = Length of pipe [m]

D = Diameter of pipe [m]

The mean flow velocity inside the pipe relates to the mass flow rate inside the pipe. The mass flow rate through a pipe relates to the volume flow rate through a pipe. This is defined using Equation 1-2 [41]:

Equation 1-2: Mass flowrate formula

$$G = \rho \times Q_v = \rho \times \frac{\pi \times D^2}{4} \times V$$

$$G_N = \rho_N \times Q_N = \rho_N \times \frac{\pi \times D^2}{4} \times V$$

With

- G = Mass flow rate in operative conditions [kg/s]
- G_N = Mass flow in standard conditions [kg/s]
- Q_v = Volume flow rate in operative conditions [m³/s]
- Q_N = Volume flow rate in normal conditions [m³/s]
- ρ_N = Fluid density in normal conditions [kg/m³]

The air density in operative conditions relates to the air density in normal conditions using Equation 1-3 [41]:

Equation 1-3: Air density formula

$$\rho = \rho_N \times \frac{P_1}{P_N} \times \frac{T_N}{T}$$

Were

- T_N = Fluid temperature in normal conditions [K]
- P_N = Fluid pressure in normal conditions [Pa]
- P_1 = Fluid pressure in operative conditions [Pa]
- T = Fluid temperature in operative condition [K]

Substituting Equation 1-3 into Equation 1-2 formulates Equation 1-4 as an expression for the mean air velocity at operating conditions and is defined as [6]:

Equation 1-4: Mean air velocity formula

$$V = \frac{4 \times Q_N}{\pi \times D^2} \times \frac{P_N}{P_1} \times \frac{T}{T_N}$$

Therefore, the pressure drop in a pipe at operative conditions can be determined by substituting Equation 1-4 into Equation 1-1 to form Equation 1-5 defined as follows [41]:

Equation 1-5: Pressure drop – Operative condition formula

$$\Delta P = \lambda \times \frac{8 \times L \times \rho_N \times Q_N^2}{\pi^2 \times D^5} \times \frac{P_N}{P_1} \times \frac{T}{T_N}$$

The dimensionless friction coefficient is defined as follows [41]:

Equation 1-6: Dimensionless friction coefficient formula

$$\lambda = \lambda(Re, \frac{\epsilon}{D})$$

With

$Re =$ Reynolds number [n/a]

$\epsilon =$ Pipe wall roughness [m]

$\frac{\epsilon}{D} =$ Relative roughness [n/a]

Table 1-2 provides the pipe roughness values for common materials.

Table 1-2: Pipe roughness for different materials [11]

Material type	Roughness [mm]
Concrete	1.2
Fibreglass	0.005
Rubber	0.01
Stainless steel	0.002
Commercial steel	0.045
Cast Iron	0.26
Wrought iron	0.045
Glass	0
Galvanised iron	0.15
Copper	0.001

In the case of smooth pipes, the effect of the parameter $\frac{\epsilon}{D}$ on the dimensionless friction coefficient is neglectable. As stated in the Blasius formulation, for Reynolds numbers above 80 000, the dimensionless friction coefficient is determined as follows [41]:

Equation 1-7: Blasius dimensionless friction coefficient > 80 000 formula

$$\lambda = 0.3164 \times Re^{-1.4}$$

For Reynolds numbers above 80 000 up to 10^8 , Prandtl derived the dimensionless friction coefficient for smooth pipes as [41]:

Equation 1-8: Prandtl dimensionless friction coefficient for smooth pipes formula

$$\lambda = \frac{1}{(2 \times \log(Re \times \sqrt{\lambda}) - 0.8)^2}$$

Combining the Blasius and Prandtl formulations, Reynolds numbers for smooth pipes up to 10^8 can be approximated. The formulation is defined as [41]:

Equation 1-9: Dimensionless friction coefficient for smooth pipes formula

$$\lambda = \frac{1}{\left(2 \times \log(0.5625 \times Re^{\frac{7}{8}}) - 0.8\right)^2}$$

For a cylindrical pipe, the Reynolds number is calculated using:

Equation 1-10: Reynolds number for cylindrical pipe formula

$$Re = \frac{4 \times \rho_N \times Q_N}{\pi \times D \times \mu}$$

With

$$\mu = \text{Fluid viscosity [kg/m}\cdot\text{s]}$$

The fluid viscosity is determined as [41]:

Equation 1-11: Fluid viscosity formula

$$\mu = \left(1.84 - \left(\frac{300 - T}{300}\right)\right) \times 10^{-5}$$

By substituting Equation 1-9 into Equation 1-5, the pressure loss between two points inside a pipe can be calculated theoretically. Finally, for pipes that are not smooth, a correction factor (c) can be applied to Equation 1-9 as follows [41]:

Equation 1-12: Dimensionless friction coefficient for non-smooth pipes formula

$$\lambda = \frac{1}{\left(2 \times \log(0.5625 \times Re^{\frac{7}{8}}) - 0.8 - c \times Re\right)^2}$$

A study that focused on testing the accuracy of the Prandtl and Blasius formulations for major head losses through pipes concluded that these formulations provide exceptional accuracy when compared with experimental tests [41]. Figure 1-8 provides proof hereof with the markers representing experimental tests and the lines representing theoretical calculations.

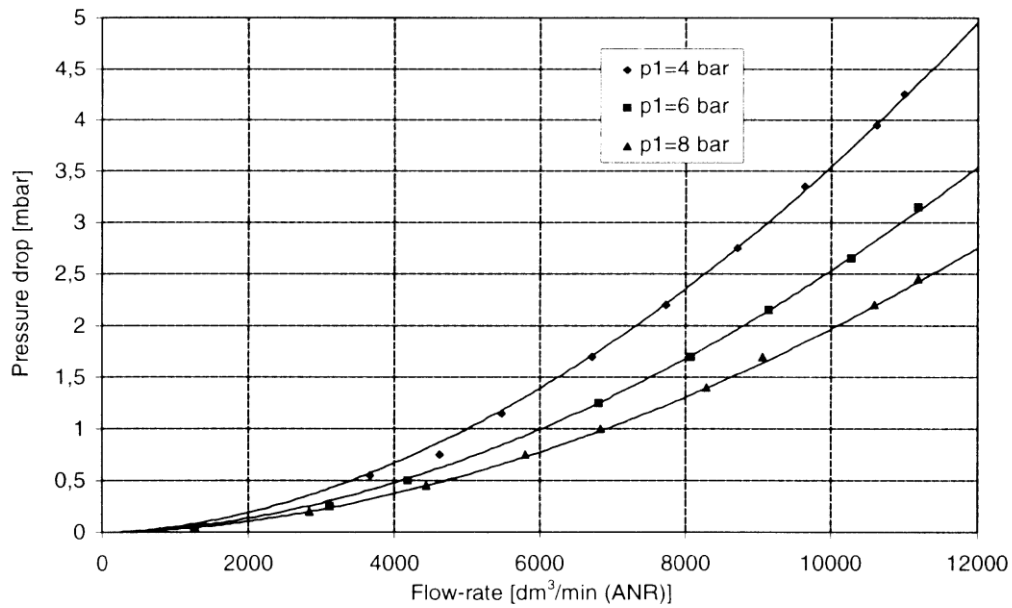


Figure 1-8: Blasius and Prandtl theoretical formulation vs experimental tests [41]

As mentioned, while Prandtl and Blasius’s formulations seem to provide exceptional accuracy for straight pipes, deep-level mines consist out of numerous bends and connections. Therefore, minor head losses need to be accounted for.

Minor head losses

Minor head losses are defined using Equation 1-13 and Equation 1-14 [11], [40], [44]:

Equation 1-13: Minor head loss formula

$$h_m = K_m \times \frac{V^2}{2 \times g}$$

Equation 1-14: Bernoulli equation

$$\frac{v_1}{2 \times g} + \frac{p_1}{\rho \times g} + z_1 = \frac{v_2}{2 \times g} + \frac{p_2}{\rho \times g} + z_2 + h_m$$

With

h_m = Minor head loss in pipe network [m]

K_m = Minor head loss coefficient related to network components [n/a]

V = Flow velocity [m/s]

g = Gravitational constant [9.81 m/s²]

ρ = Density of fluid [kg/m³]

p_1 = Initial fluid pressure [Pa]

p_2 = Final fluid pressure [Pa]

- $v_1 =$ Initial fluid velocity [m/s]
- $v_2 =$ Final fluid velocity [m/s]
- $z_1 =$ Initial fluid elevation [m]
- $z_2 =$ Final fluid elevation [m]

Using Equation 1-14, the minor head loss in the network is translated into a pressure drop that is summed with the major pressure losses to obtain the total system losses. This can only be done when the following assumptions hold true [11]:

- Fluid travels at a constant velocity
- Fluid density remains constant
- There is no friction present
- Points 1 and 2 lie on a streamline

The effect of autocompression

When working with compressed air systems that operate under great depths, such as deep-level mine compressed air systems, it is crucial to account for the autocompression of air. Auto-compression refers to the increase in pressure due to the weight of the air [10]. The pressure increase due to autocompression is calculated using Equation 1-15 [10]:

Equation 1-15: Autocompression equation

$$p_2 = p_1 \left[1 - \frac{g(Z_1 - Z_2)}{T_1 C_p} \right]^{\frac{1}{k}}$$

Where:

- $p_2 =$ Final pressure [Pa]
- $p_1 =$ Initial pressure [Pa]
- $g =$ Gravitational constant [9.81 m/s²]
- $Z_1 =$ Initial elevation [m]
- $Z_2 =$ Final elevation [m]
- $T_1 =$ Temperature of compressed air [K]
- $C_p =$ Specific heat capacity of compressed air [kJ/kg.K]
- $k =$ Specific heat capacity ratio of compressed air [1.4 kJ/kg.K]

The next section uses the theoretical formulations presented to interpret pipe network inefficiencies mathematically.

1.6 Interpreting compressed air network inefficiencies

Compressed air network inefficiencies can be interpreted using the theoretical equations discussed in the previous section.

Air leaks and venting

Air leaks or venting using compressed air increases the flow and velocity of air in the pipe network, resulting in higher pressure losses [30], [38], [45]. This is due to the quadratic effect of velocity on head losses (as seen in Equation 1-1 and Equation 1-13) [41]. This is relevant to consider when setting a specific supply-side pressure set point since compressors will ramp up to maintain the desired set point [21]. This, in turn, will increase the electric power consumption of the compressor [46].

Pipe network design

A well-designed compressed air system will have minimal pressure loss from the compressors to the end user as the pipe network is sized properly for the desired flow rate [45], [46]. Excessive flow velocities in undersized pipe networks will increase unwanted frictional pressure losses [38], [45]. Once again, this can be related to the quadratic effect of velocity on head losses (as seen in Equation 1-1 and Equation 1-13) [41].

1.7 Simulation as an evaluation tool

Modern day computers have grown significantly in terms of processing power [47]. As a result, the use of simulation software today is evident in numerous industries. These include but is not limited to the manufacturing, defence and healthcare industries [48]. In the past, the mining industry have not lent well to simulation software due to the difficulty of obtaining data [49]. However, recent development in simulations and data availability allow better modelling of deep-level mines [50]. Recent studies show that with these advances in the mining and simulation industries, the ventilation, compressed air and refrigeration systems on deep-level mines can be simulated accurately [51].

By using simulation software to model complex compressed air systems, accurate results can be obtained without the need for physical testing [11], [16]. The software can also be used to generate characteristic curves that show system behaviour under different conditions, which can identify inefficiencies for optimisation [52]. Some simulation packages for simulating systems in the mining industry are evaluated below [16].

SolidWorks [53]

SolidWorks uses the Navier–Stokes equation to compute flow characteristics for a specific flow scenario. A detailed part should be modelled before a flow simulation is executed since the flow simulation is an add-on package. This makes it time-consuming since it entails modelling thousands of parts first before a flow simulation can be conducted in a deep-level mine.

KYPipe [54]

KYPipe solves steady-state flows and pressure for pipe network systems. The software is subject to liquid flow and can only solve for gases with a constant density. Van Tonder stated that some of the drawbacks are that data must be entered manually for every scenario and that there is no interface for real-time system data to be accessed. This results in a time-consuming simulation experience that requires skill to be used [55].

Flownex [56]

Flownex can solve both compressible gases and incompressible liquids. However, the demo version has limited functionality. This software can be used for mining applications but comes at a premium. As with KYPipe, data must be entered manually for every scenario and there is no interface for real-time system data to be accessed. Although Flownex can batch-process data, it is a time-consuming feature [57].

Process Toolbox [11]

Process Toolbox (PTB) is specifically designed for mining applications and allows all components in a compressed air system to be modelled [57]. PTB simulates transient and steady-state conditions and has built in functionalities for thermal hydraulic systems such as compressed air systems. PTB can also be used to evaluate various scenarios and system changes [16].

In the next section of this study, an overview of previous research relevant to the scope of this study is provided. The scope of this research includes the investigation of compressed air inefficiencies related to supply and demand and the evaluation of pipe network inefficiencies using simulation. The research also aims to understand the correlation between pipe inefficiencies and drilling pressure.

1.8 Literature review

To gain a comprehensive understanding of compressed air networks, pressure losses in pipe networks and the effect of pressure losses on equipment, existing research should be evaluated. This section of the document provides an overview of previous literature relevant to this scope. The following studies have the most relevance to compressed air inefficiencies in deep-level mines.

Study 1 [11]

Title: Optimising production through improving the efficiency of mine compressed air networks with limited infrastructure

Type M.Eng

Authors: D. Nell

Overview: The study by Nell developed a method to address compressed air usage inefficiencies with the goal of improving drilling time. The method used root cause analysis and provided guidelines for effective boundary selection procedures to identify and evaluate compressed air network inefficiencies. Nell used flow and pressure baselines to evaluate possible concerning areas within the compressed air system. Nell considered a decrease in supply pressure during high demand periods as a supply shortfall and pressure loss between two measuring points in a closed pipe as a possible pipe network inefficiency. For the pressure baselines, the author measured at the outlet of the compressor, common manifolds, and various measuring points on the compressed air network. At a case study mine, a specific compressed air inefficiency was found to result in a pressure drop of 87 kPa during the peak drilling shift when measured from the station to the start of the working area. Using the developed method, the root cause analysis identified that some pipes were undersized. Using the PTB simulation software, Nell simulated that replacing certain pipes would increase the pressure at the start of the stope by 45 kPa during daily operation. The proposed pipelines were replaced, and the simulation was verified. The improved pressure at the start of the stope was used to determine the improvement in rock drill penetration rate, with a mathematical model indicating a 20% increase in drilling rate due to the improved pressure.

Shortfalls: Nell's study only considered pipelines up to the start of a stope and did not account for inefficiencies inside the stope. It was assumed that the improvement observed

at the start of the cross-cut would also be seen at the rock drills, but this may not necessarily be the case. Previous research (such as the study by Bester [37]) had indicated that many inefficiencies in compressed air systems exist inside the stope; therefore, it is important to consider inefficiencies in any analysis or improvement efforts. This is a limitation of the study by Nell because it means that the full extent of the compressed air inefficiencies in the mine may not have been identified or addressed.

Study 2 [13]

Title:	The energy and water required to drill a hole
Type	Conference paper
Authors:	P. Fraser
Overview:	Fraser calculated the energy required to drill a hole using three different drilling methods. These include compressed air, hydro and electric drills. The aim was to determine a best to worst rating for the three types of drilling method in terms of overall efficiency. The efficiency of a drill was defined as the energy from the source to the hole being drilled. The efficiency of hydro and compressed air sources was assessed by the author through an examination of the pressure versus penetration rate relationship. Fraser found that compressed air systems have low mechanical efficiency (as low as 2% efficiency) compared with alternative energy carriers such as oil electrohydraulic (23% efficiency), hydro-powered pumps (20% efficiency), hydro-powered gravity (24% efficiency), and electric drills (32% efficiency).
Shortfalls:	The study by Fraser successfully determined which drilling method is the best in terms of overall efficiency. However, no mitigation strategies to improve the overall efficiency of compressed air was investigated.

Study 3 [16]

Title: Using simulation to prioritise implementation of platinum mine compressed air efficiency solutions

Type M.Eng

Authors: M.M. de Jager

Overview: De Jager looked at a new method to determine the implementation priority of various energy efficiency solutions. The method uses a simulation model that assesses compressor power, compressed air pressure, and compressed air flow. The method evaluates and prioritises various energy efficiency solutions. The criteria for prioritisation include factors such as payback period, energy savings, level of automation, and implementation time, collectively referred to as implementation factors by the author. These implementation factors were compared using a pairwise comparison matrix, which assigns relative importance levels to different factors. The matrix serves as a tool to quantify the significance of each factor in relation to others.

To further refine the prioritisation process, de Jager utilised a five-point Likert scale based on the calculated weights. This scale allowed for a nuanced rating of the implementation factors, ranging from the most favourable to the least favourable. The study by de Jager reviewed four energy efficiency solutions, namely valve control, installation of smaller compressors, guide vane control and network reconfiguration. The combination of the pairwise comparison matrix and Likert scales proved to be an effective methodology for systematically prioritising the diverse influencing factors in a project related to compressed air within a deep-level mine.

Shortfalls: The four different energy efficiency solutions were from a supply-side management point of view. None of the simulated solutions focused on the demand side of the mines where most compressed air efficiency is typically lost [13].

Study 4 [19]

Title: Evaluating compressed air operational improvements on a deep-level mine through simulations

Type Conference paper

Authors: P. Maré, J.I.G. Bredenkamp, and J.H. Marais

Overview: This study by Maré, et al developed a new approach for investigating operational efficiency and service delivery solutions using simulation. The solutions considered in this case study included increasing set points on compressors, interconnecting compressed air pipelines to form a ring, and installing an additional compressed air supply pipeline. Maré, et al evaluated diverse simulated pressure and flow baselines to showcase shortfalls within the compressed air system. Simulated flow baselines represented the shaft demand, while simulated pressure baselines indicated the discharge pressure or pressure at a specified measurement point on the compressed air network. From these baselines clear pressure inefficiencies were noted and mitigation strategies were formulated. The study found that interconnecting compressed air pipelines and installing an additional compressed air supply pipeline was most feasible options. These options increased the peak drilling pressure by 51 kPa without increasing electricity costs. Increasing the set points, on the other hand, would have increased electricity costs due to the increased output power required to maintain a higher set point.

Shortfalls: This study by Maré, et al has a limitation in that the improvement in level pressure was not verified at the rock drills inside the stope. As a result, it is not certain whether the improvement in level pressure resulted in an improvement in the achieved pressure at the rock drills. This could potentially affect the feasibility and credibility of the solutions proposed.

Study 5 [20]

Title: Improving mine compressed air network efficiency through demand and supply control

Type Conference paper

Authors: B. Pascoe, H.J. Groenewald, and M. Kleingeld

Overview: Pascoe, et al investigated inefficiencies in compressed air networks with a focus on compressors, the compressed air pipeline and compressed air consumers. They developed a strategy to ensure that the compressed air consumers received sufficient supply pressure and flow. They found that the case study mine had been using an ineffective compressor selection during blasting periods. Simulation was used to develop a calibrated shaft flow and pressure baseline that was used to prove the proposed effectivity improvement method would not affect drilling pressure. By switching to a smaller compressor, the mine was able to save R15.7 million annually.

Shortfalls: It appears that the improvement achieved from fixing the leaking pipeline is not reported in their study, and the benefits of the compressor selection change are only demonstrated during the blasting shifts, not during the drilling shifts. Additionally, their study does not provide any evidence that the compressed air users received adequate pressure and flow, but rather compares the total shaft consumption and supply pressure before and after the changes were made. It would be useful to have more information on how these changes affected the pressure and flow received by the compressed air users.

Study 6 [23]

Title: Energy efficiency opportunities resulting from splitting a compressed air ring

Type Journal article

Authors: H.P.R. Joubert, J.F. van Rensburg, and R. Pelzer

Overview: The aim of the study by Joubert, et al was to implement an energy efficiency strategy which involved dividing a single compressed air system into two compressed air systems. The reasoning was to supply both high- and low-pressure end users with the correct respective pressures during their respective working periods. They examined a supply pressure and flow baseline, measured at the outlet of the surface compressors of a specific mine, and identified the potential for reducing pressure and air flow during specific times of the day. Energy savings were achieved from the lower pressure system because of reduced pipe friction losses and fewer leaks.

Shortfalls: Their study did not consider energy efficiency during high-pressure demand, during which greater frictional losses occur because of the elevated pressure. Although the study implemented pressure regulating valves to lower the supply

pressure during periods of low demand, this approach does not address the underlying issues that still exist during times of high-pressure demand. Installing valves to reduce pressure only when low-pressure users are active does not solve the underlying problem that forces compressors to run at higher operating costs.

Study 7 [29]

Title: Reducing deep-level mine refuge bay compressed air consumption

Authors: P. de Villiers

Type M.Eng

Overview: The study by de Villiers focused on optimising the use of compressed air in South African deep-level gold mines, with the aim of reducing operating costs. The valves controlling the flow to the refuge bays were identified as an area where compressed air is wasted. The theoretical benefit was calculated using simulation. The solution was implemented by replacing the valves in a deep-level gold mine, leading to significant power and cost savings.

Shortfalls: De Villiers aimed to decrease the electrical costs associated with compressed air usage in the mining industry and successfully achieved its objective. However, it would have been more comprehensive if the study by de Villiers had evaluated the impact of reducing flow through compressed air lines to improve pressure and compared it to the effects of production improvements versus cutting back on the compressors. By doing so, the study could have provided a more holistic approach to achieving a more profitable mining industry.

Study 8 [31]

Title: Energy efficiency opportunities in mine compressed air systems

Type M.Eng

Author: F.W. Schroeder

Overview: This study by Schroeder investigated the effectiveness of various energy efficiency methods on compressed air systems and found that optimised set-point control and compressor selection were effective strategies for improving the efficiency of these systems.

Shortfalls: Schroeder only considered the potential for energy savings through set-point control but did not consider other factors such as improved service delivery conditions or the potential for increased production. In addition, it is important to consider that the pressure achieved at the rock drills may differ from the pressure measured at the set point due to pressure losses in the pipe network. Therefore, the set-point control on compressors should be verified by measuring the pressure at the rock drills to avoid potential production losses.

Study 9 [33]

Title: Optimization of the compressed air-usage in South African mines

Type Journal article

Authors: A. Hassan, K. Ouahada, T. Marwala, and B. Twala

Overview: The study by Hassan, et al investigated two different methods that have the potential to improve and optimise compressed air usage with the goal to reduce electricity consumption. Hassan, et al looked at compressor set-point control and the utilisation of control valves to achieve energy savings. Their study used air pressure baselines measured at the outlet of the compressor and power baselines to evaluate the effectivity of the two proposed methods.

Shortfalls: Although Hassan, et al successfully achieved their objective with both methods, these methods were case study specific and did not provide a generic method for evaluating the energy efficiency of a compressed air system. The study by Hassan, et al did not include the effect on drilling pressure because of control valve control on inactive levels.

Study 10 [37]

Title: The effect of compressed air pressure on mining production and energy demand

Type Conference paper

Authors: S. Bester

Overview: Bester investigated the possible reasons for a decrease in productivity over the last few years and found that the volume of air required to produce one ton had increased 2.6 times from 2002 to 2013, and the compressed air energy used per ton had increased 4.6 times over the same period. During underground audits,

Bester observed stope pressures between 290 kPa and 350 kPa during drilling shifts, which is reflected in the penetration rate shown in Figure 1-9. Bester also reported that according to historical data, the supply pressure (measured at the outlet of surface compressors) was above 500 kPa in 2002. These findings suggest that there may be inefficiencies in the compressed air system that are contributing to the decrease in productivity.

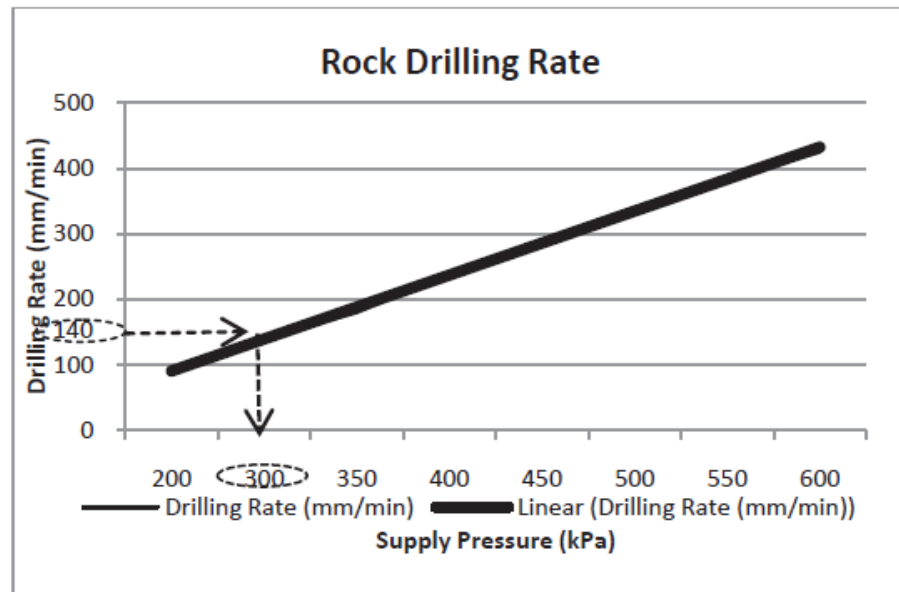


Figure 1-9: Rock drill penetration rate vs supply pressure [37]

Based on the findings described above, Bester concluded that the main cause of the slow drilling rate was the lower supply pressure. Upon comparing historical surface pressures with the pressures at the time of the study, Bester found that there was no significant change in supply pressure between 2002 and 2013. As a result, the underground network was evaluated using simulation. The simulation used the required flow rate per level and the measured station pressure on the level as inputs. The simulation calculated an average pressure loss of 250 kPa on levels where drilling problems were experienced and 100 kPa on levels with lower production. This result suggested to the author the possibility of undersized pipes in the network.

Shortfalls: Bester used simulation to identify that the compressed air pipes may be undersized and unable to meet the demand of the stope levels. However, the simulation results were not verified with actual measurements, and there was no concrete evidence to show that the undersized pipes were the cause of the reduced drill pressure. This is a limitation of the study by Bester because it means that the

conclusion about the cause of the reduced drill pressure is based on an unverified simulation, rather than direct observations or measurements.

Study 11 [39]

Title: Improving efficiency of a mine compressed air system

Type M.Eng

Authors: S.J. Fouché

Overview: The study by Fouché found that fixing leaks was one of the best ways to improve the energy efficiency of a compressed air system. Fouché formulated a new approach to leak auditing. The method was implemented on a case study mine where a large leak was identified. Fouché investigated numerous energy savings initiatives and outlined typical strategies that can be implemented. The study by Fouché used pressure, flow and power as key performance indicators to the effectivity of energy savings initiatives.

Shortfalls: While considering energy savings initiatives, Fouché calculated the effect of underground pressures using only autocompression theory. The author states in the future recommendations section that frictional losses were neglected. Frictional losses are an important factor when different energy initiatives are considered as they affect drilling pressures. Therefore, Fouché did not consider the end user in any of its approaches to save energy.

Study 12 [46]

Title: An approach to optimising compressed air systems in production operations

Type Journal article

Authors: F. Doyle and J. Cosgrove

Overview: The study by Doyle, et al describes a method for quantifying the energy lost due to leaks in a compressed air system. The study considered five case studies and determined that 30–60% of leaks can be saved. Doyle, et al state that management rarely knew about energy-saving measures and the effect of leaks on the compressed air system. Their study states that often due to leaks, pressure losses are combatted with higher set points on compressors leading to increased operational cost. Doyle, et al proved that by raising awareness, significant improvements in energy efficiency can be achieved.

Shortfalls: Doyle, et al study objective was to optimise a compressed air system. However, only leaks were considered. Their study stated that because of leaks, pressure losses are often combatted with higher set points on compressors leading to increased operational cost. The study by Doyle, et al did not consider pressure losses due to frictional losses in compressed air pipelines.

Study 13 [58]

Title: Local benchmarking in mines to locate inefficient compressed air usage

Type Journal article

Authors: D. du Plooy, P. Maré, J. Marais, and M.J. Mathews

Overview: The study by du Plooy, et al developed a local benchmarking method that used the correlation between compressed air usage and production as a key performance indicator (KPI) to identify inefficiencies in compressed air usage. The method was applied to underground working levels to identify levels with significant compressed air inefficiencies. The local benchmarking method was able to accurately identify the levels with the most potential for improvement. Du Plooy, et al conducted an underground audit to determine the appropriate initiatives to implement. The audit revealed that most of the compressed air wastage was caused by inactive sections that were not sealed off and control valves with poor control. To address this issue, the inactive sections were sealed off and proper set-point control was implemented on the control valves. The KPI for the identified levels improved between 37% and 61%.

Shortfalls: The underground audit conducted by the engineers was limited to main haulages, so the compressed air inefficiencies inside the stope where production took place were not accounted for or addressed. Additionally, du Plooy, et al used the correlation between production and compressed air usage as a KPI but did not address how more efficient compressed air usage could potentially increase production. Their study also did not explain why there were little to no production improvements after addressing compressed air wastages. It would be useful to have more information on these issues to fully understand the impact of the proposed solutions on production.

1.9 Literature summary



Several studies have investigated compressed air inefficiencies in mining operations and have proposed various strategies for improving efficiency. These strategies include optimising set-point control and compressor selection, interconnecting compressed air pipelines to form a ring, installing an additional compressed air supply pipeline, sealing off inactive sections, limiting refuge bay air consumption, implementing set-point control on control valves, and replacing undersized pipes.

Some studies have used simulation and root cause analysis to identify inefficiencies and evaluate potential solutions, while others have used numerical methods, local benchmarking methods or underground audits.

From the thirteen core literature studies presented, only one addressed inefficiencies inside the stope and the majority of the studies did not consider improving underground working pressures because of improved efficiency. Instead, the studies focused on saving energy by reducing compressor load because of improved efficiency. The research focus is shown by Table 1-3.

Table 1-3: Literature study summary matrix

Compressed air inefficiencies								
Source	Energy saving	Service delivery	Supply	Demand	Reticulation network			Method
					Supply to level	Level to cross-cut	Cross-cut to face	Simulation
[11]	Not considered	Considered	Considered	Considered	Considered	Considered	Not considered	Considered
[13]	Considered	Considered	Not considered	Not considered	Not considered	Not considered	Not considered	Not considered
[16]	Considered	Not considered	Considered	Not considered	Not considered	Not considered	Not considered	Considered
[19]	Considered	Considered	Considered	Considered	Considered	Considered	Not considered	Considered
[20]	Considered	Not considered	Considered	Considered	Considered	Considered	Not considered	Considered
[23]	Considered	Not considered	Considered	Considered	Not considered	Not considered	Not considered	Not considered
[29]	Considered	Not considered	Not considered	Considered	Not considered	Not considered	Not considered	Considered
[31]	Considered	Not considered	Considered	Considered	Not considered	Not considered	Not considered	Considered
[33]	Considered	Not considered	Considered	Considered	Considered	Not considered	Not considered	Not considered
[37]	Not considered	Considered	Considered	Not considered	Considered	Considered	Considered	Considered
[39]	Considered	Considered	Considered	Considered	Not considered	Not considered	Not considered	Not considered
[46]	Considered	Considered	Not considered	Considered	Not considered	Not considered	Not considered	Not considered
[58]	Considered	Not considered	Not considered	Considered	Not considered	Considered	Not considered	Not considered

 Considered
 Not considered

1.10 Problem, need and objectives

Compressed air distribution systems used to supply mining equipment have low mechanical efficiency that leads to reduced drilling pressures [11], [16], [20], [39]. Various factors contribute to this low efficiency such as undersized pipes, poor control valve set-point control, and inactive sections that are not sealed off [37]. A detailed literature survey revealed the initiative to investigate in-stope compressed air inefficiencies and the effect thereof on drilling pressure.

Need for the study

There is a need for a method that identifies and evaluates in-stope compressed air inefficiencies for improved drilling pressures.

Study objectives

1. Identify the compressed air inefficiencies inside the stoping area using a systematic system evaluation approach.
2. Verify the identified inefficiencies with actual measurements.
3. Assess the efficacy of various approaches to address in-stope compressed air inefficiencies through simulation-based evaluation.

1.11 Dissertation overview

In Chapter 1, the dissertation was introduced by evaluating the mining process, current decreasing production trend in South Africa, and the role of compressed air inefficiencies in the pipe networks. A detailed literature survey revealed the initiative to investigate in-stope compressed air inefficiencies and the effect thereof on drilling pressure. There is therefore a need for a method that identifies and evaluates in-stope compressed air inefficiencies that lead to reduced drilling pressures.

Chapter 2 addresses the problem statement formulated in Chapter 1. The chapter describes how a method was developed that identifies and evaluates in-stope compressed air inefficiencies using simulation and characterisation. The chapter elaborates on how the method uses prioritisation techniques for different compressed-air-related inefficiencies.

Chapter 3 presents the results of a case study mine where the method developed in Chapter 2 was implemented. The results are discussed, prioritised, and verified against the study objectives listed in Chapter 1.

Chapter 4 summarises the dissertation. The completion of study objectives is discussed and the problem statement addressed. This chapter also outlines the shortcomings of this dissertation and recommends study objectives for future related studies.

2 METHOD TO IDENTIFY IN-STOPE INEFFICIENCIES

Drawing on the literature examined in Section 1.8, the literature survey revealed the initiative to investigate in-stope compressed air inefficiencies and the effect thereof on drilling pressure. A need for a method that identifies and evaluates in-stope compressed air inefficiencies that lead to reduced drilling pressures was identified.

The time and expenses spent on the research process can be minimised using a research methodology [59]. This study takes a quantitative research approach by developing a literature-based method to identify in-stope inefficiencies that lead to reduced drilling pressures. The method will be validated using practical measurements [60].

From the literature study presented, valuable insights were realised that are incorporated in the development of the research method in this dissertation. A basic outline of the method is summarised as follows:

1. Baseline development
2. Baseline evaluation
3. Creating a baseline simulation model
4. Identification of compressed air inefficiencies
5. Using simulation to develop improvement strategies
6. Validation

2.1 Baseline development

Compressed air system baselines take the form of pressure and flow baselines and can be used to identify any inefficiencies or shortcomings in the system [41], [61]. Flow baselines should be measured as nominal cubic metres per hour, which refers to the flow at standard operating conditions (0°C and 101.325 kPa). By using nominal cubic metres per hour, flow can be compared at different pressures [16]. By comparing the generated baselines to the expected performance of the system, areas for improvement can be identified and targeted for further analysis and solution development [16], [58].

Data acquisition

The aim of data acquisition is to gather pertinent data related to the study data boundaries. The study's data boundary establishes the confines that specify which data is considered or omitted. In Table 1-3, the research matrix illustrates that most authors assessed the compressed air network from the supply boundary to the start of the stope. The summary table highlights the

absence of in-stope evaluation in most of these studies. Consequently, for this study, the data boundary extends from the supply of compressed air to the end of the stope.

Data is gathered using instrumentation and underground audits. Typical sensors include compressed air flow and pressure sensors. The collected data is used to develop section baselines. The data-collection process is crucial in determining the status of the compressed air system and will act as a standard for assessing the efficacy of the proposed solution [11], [60]. Figure 2-1 provides a visual representation of the various steps involved in the data-acquisition process [11], [62].

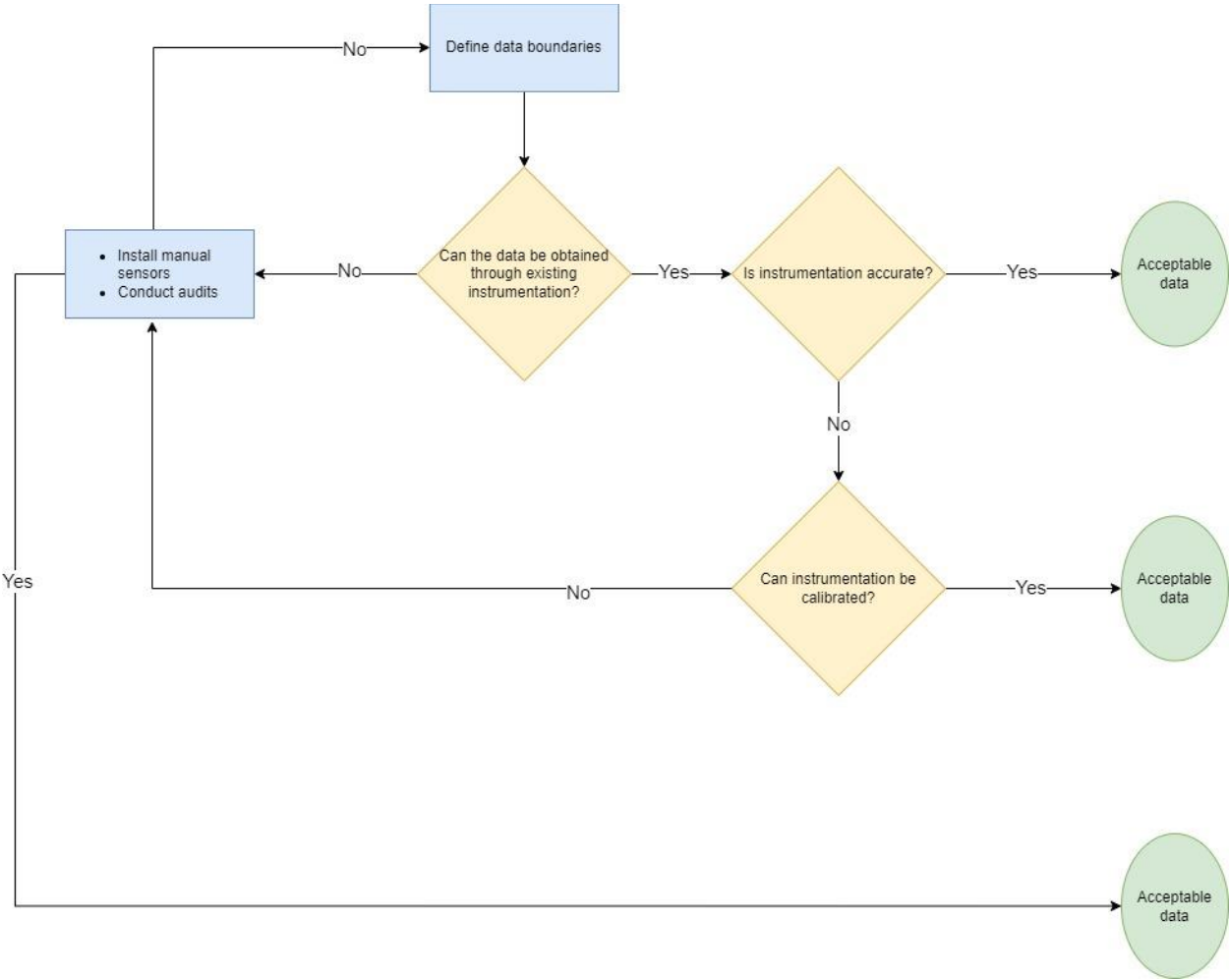


Figure 2-1: Data-acquisition process – Adapted from [11]

Baseline measurement locations

From the research matrix presented in Table 1-3, most authors evaluated the compressed air network from the supply boundary to the start of the stope [19], [20], [37], [39], [52], [63]. Therefore, the method in this study includes the evaluation of these sections. By doing so, inefficiencies outside of the stope are considered. The sections are evaluated by establishing precise baselines for the supply, demand and reticulation sections [11], [31]–[33], [37].

The supply pressure baseline is measured at the compressor’s outlet. This allows understanding of the pressure supplied to the reticulation network before any losses occur [33], [61], [64]. The demand-side baseline is determined by measuring the total flow consumption of the system at a given time [adapted from 36]. In deep-level mine compressed air systems, multiple baselines for different sections of the pipe network are necessary [11], [64]. Baseline measurements of pressure and flow should be taken between the surface and level station, level station and level split, level split and cross-cut intake, and cross-cut intake and stope face [11]. Figure 2-2 shows an example for typical reticulation network sections to be measured.

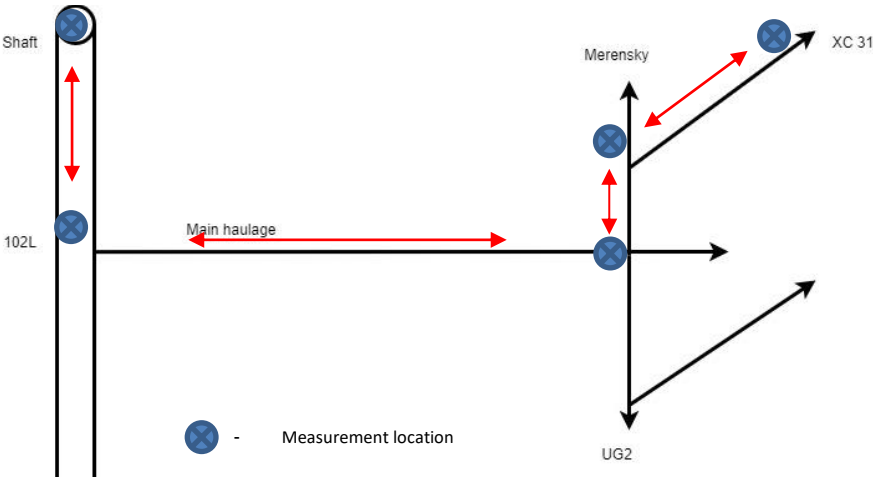


Figure 2-2: Reticulation network measurement points

This study focuses on identifying and evaluating in-stope compressed air inefficiencies that lead to reduced drilling pressures. Therefore, the time frame for the baseline is a drilling shift time frame (06:00–14:00).

2.2 Baseline evaluation

The measured baselines can be evaluated for inefficiencies as follows:

Supply side

The baseline for the supply-side boundary is evaluated by gathering information on the number of active compressors, their type and performance, historical pressure and flow data, pressure set-point schedules, and the control capabilities of the compressors [11]. This information is used to determine whether the compressors are able to supply the required flow at the required pressure set point for a given network. If a compressor is below specification, it may show a pressure drop when the flow demand exceeds its ability [11]. This can be illustrated through a baseline, such as in Figure 2-3, which shows an example of a compressor that is unable to maintain the pressure set point due to an increase in flow demand.

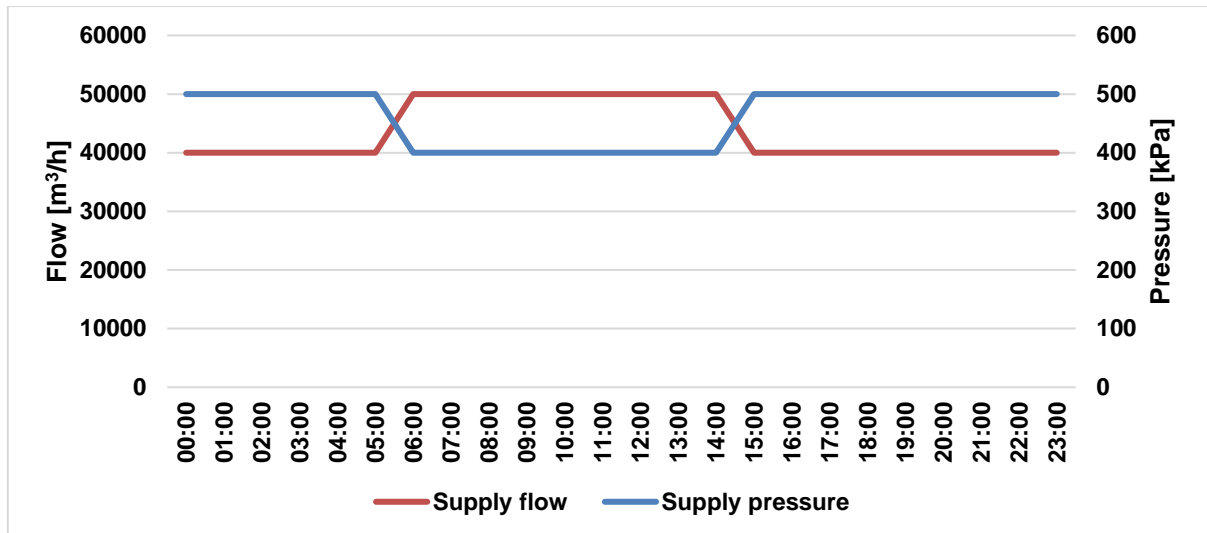


Figure 2-3: Example of a compressor supply limitation – Adapted from [1]

Compressors connected to a ring-feed system should be accessed together with the demand side. The ring-feed system is designed to sustain shafts during high-demand periods but is known to be inefficient due to leaks in the system. These leaks can result in the ring supplying air to the leaks rather than the end users [20].

Demand side

The demand-side boundary of a compressed air system is evaluated using various factors such as compressed air user requirements (pressure and flow), distance of users from supply compressors, and the nature of their operations (shift or constant) [11]. Excess demand in the system is identified through means of a baseload test. A baseload test is performed to identify and pinpoint significant leaks in the system [16], [46]. To conduct a successful baseload, the following steps are required:

1. Schedule the test during a period of low compressed air demand.
2. Coordinate with all mine personnel and departments, including ventilation and production teams, to ensure that all compressed air users are turned off.
3. Record the pressure and flow rate of the air at each compressor unit and at different locations throughout the mine.
4. Identify and note the location of any leaks, their size and severity.

Reticulation network

The reticulation network of a compressed air system is evaluated by assessing various factors such as the network's piping and instrumentation diagram layout [35], the effect of auto-compression (applicable to large underground systems) [65], system design specifications, pipe material, the overall condition of the network, and the availability and locations of measurement instrumentation [11].

A well-designed reticulation network should have minimal pressure loss from the supply boundary to the demand boundary [41], [43], [45], [64]. Inefficiencies in the network are identified by comparing the pressure and flow at different locations throughout the system as discussed in Section 0. For example, severe inefficiencies are seen in the pressure drop between the two measuring locations shown in Figure 2-4. It is important to note that these inefficiencies will be more pronounced during peak demand periods.

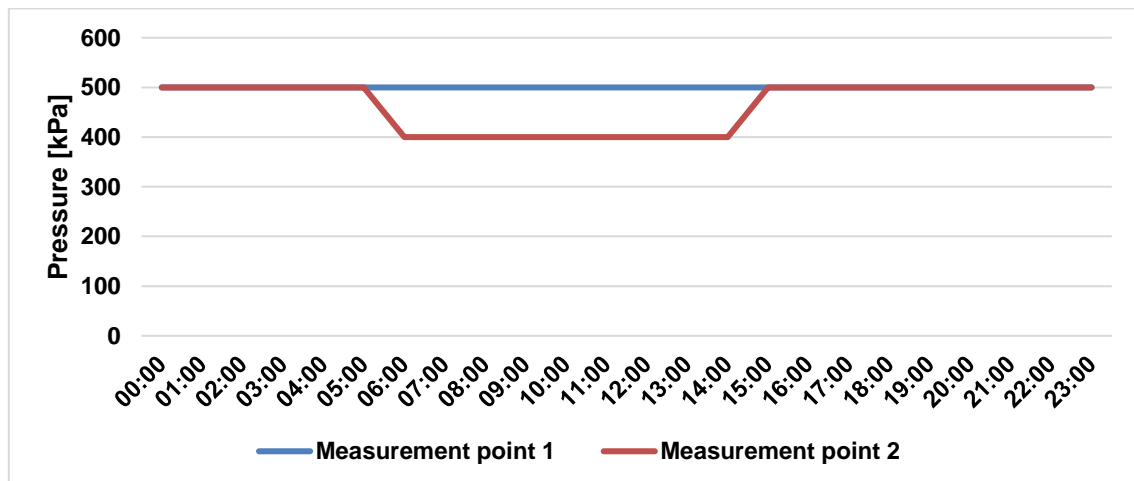


Figure 2-4: Example of an incorrectly specified reticulation network

Comparing baseline efficiencies

As stated in the study objectives, this dissertation focuses on a method that identifies inefficiencies inside the stoping areas. However, most authors that had related study outcomes evaluated the compressed air network from the supply boundary to the start of the stope [19], [20], [37], [39], [52], [63]. To interpret stope-related compressed air inefficiencies effectively, the supply and demand sections should also be considered. By doing so, inefficiencies that stem from outside the stope region into the stoping section are also highlighted.

To determine the significance of the different section inefficiencies, the section baselines are compared across three main factors. These include pressure loss, volatility, and cost to mitigate (hereafter referred to as priority factors). The three priority factors are considered KPIs when considering the overall effectiveness of a compressed air system [37]. The cost of a project is

commonly evaluated in terms of its payback period, which refers to the duration required for the project's benefits to offset its implementation costs [16]. However, predicting the production improvement resulting from a specific mine's pressure increase proves challenging. As a result, only the initial and ongoing costs are considered.

The priority factors are defined as follows (adapted from [5]):

- Pressure loss: Refers to the pressure lost in that section of the compressed air system.
- Volatility: Assesses the likelihood of sudden changes or rapid fluctuations in behaviour in the section. By examining the level of interaction with the section by mine employees, maintenance schedules and environmental conditions, the volatility of different sections can be compared.
- Cost: Assesses the cost of implementing a solution in a section of the compressed air system.

To determine the weights of each factor, the Likert scale shown in Table 2-1 is used to assign scores [66], [67]. Appendix A and Appendix B elaborate on how the weights and scores are calculated. In short, each factor is assigned a score between 1 and n with 1 being the worst score and n being the best score.

Table 2-1: Likert scale for determining priority score

Priority factor	Weight	Score		
		1	2	... n
Pressure loss	45.5			
Volatility	9.0			
Cost	45.5			

The score range is determined based on the number of compared sections, as all priority factors can be compared numerically to establish the best and worst scenarios. This means that the worst score is 1 and the maximum score is the number of sections being compared. For example, if the supply, demand and compressed air pipe network sections are compared, the maximum score that can be achieved is 3. Conversely, a score of 1 is considered the worst score possible among all the sections being compared.

To identify the section that should be given the highest priority, it is necessary to utilise the ranges to compute a priority score for each section. The scores are multiplied by the corresponding factor weights, as presented in the following equation [66], [67]:

Equation 2-1: Priority scoring formula

$$S_p = S_{pl} \times \text{Weight} + S_v \times \text{Weight} + S_c \times \text{Weight}$$

With

S_p = Score of section indicating priority

S_{pl} = Score of pressure loss in section

S_v = Score of volatility

S_c = Score of cost

The prioritisation method presented above indicate the most severe compressed air sections. However, this study focuses on the stopping section where Bester [37] suggested most inefficiencies are located.

2.3 Creating a baseline simulation

The use of simulation software, such as PTB, can be an effective tool for analysing complex compressed air networks. It allows for a detailed examination of the compressed air system and can provide valuable insights into potential solutions [16], [19]. PTB simulation software is specifically designed for the mining environment and is, therefore, well-suited to the scope of this study [11], [19].

The simulation software is used to create a virtual model of the compressed air system, considering the various elements of the system, such as compressors, pipes and compressed air users. Thereafter, the software is used to simulate different scenarios and test potential solutions to the identified shortfalls, such as changes to the system layout or the addition of new equipment [19]. The following section discusses the development of such a model.

A baseline simulation model that accurately represents the measured baseline can be developed by taking the following considerations into account [16]:

Simulation focus

Various parameters are present when considering compressed air systems, including pressure, flow rate, humidity, temperature and enthalpy [16]. The key parameters for this study are pressure and flow. Each parameter is discussed below.

Pressure

The equipment used in the stoping sections relies on a specific pressure to function correctly. Therefore, the simulated pressure along various points in the stope network should be representative of the measured pressure in the pressure baseline [16].

Flow

As with pressure, stoping equipment requires a certain flow to function correctly. The flow in the network also relates to the pressure losses inside the network. Therefore, the simulated flow along various points in the network should be representative of the measured flow in the flow baseline [16].

Simulation parameters

The following simulation parameters are considered when working with PTB:

Simulation period

The simulation time should match the baseline measurement time frame. For this study, the key is to identify pressure losses that affect the drilling pressure [16]. Therefore, the time frame used is the drilling shift for one day (06:00–14:00).

Step size

PTB allows the user to determine the time between subsequent simulation data points. Larger step sizes simulate faster but with less accuracy. Smaller step sizes are more accurate but take longer to simulate [16]. For this study, 3,600 seconds is used as the step size. This is small enough to facilitate accuracy, yet large enough to achieve a fast simulation time. Therefore, the simulation consists of nine steps of 3,600 seconds.

Simulation boundaries

After the simulation focus areas have been identified, the next step is to determine the boundaries of the simulation model. The boundaries should be defined in such a manner that simulation accuracy does not suffer [11], [16]. For this study, it is the start of the stoping section up to the end of the stoping section. By selecting the boundaries in this manner, all inefficiencies that stem from the stoping section are accounted for.

Model components

The following model components are considered when working with PTB:

Air pressure boundary

An air pressure boundary is a component that represents air conditions [16], [57]. These components are used to represent a specific pressure, temperature and humidity at the beginning or end of a compressed air network [16]. They can be placed at the beginning of a stope network to simulate the measured pressure at the start of the stope. Another pressure boundary can be used at the end of the stope to simulate the measured ambient conditions at the outlet of the rock drills [16]. Air pressure boundaries allow an unlimited supply of air at a specified pressure, temperature and humidity.

Nodes

Nodes are used in PTB to connect different components to one another. They also represent the calculation points of the simulation model [16].

Pipes

Pipe components represent the physical pipe and its properties. Pipe components can be modified to mimic pipe material, surface roughness, diameter, and length of the measured pipe network [16].

Compressed air rock drill/demand component

Rock drill components are used to simulate real-world rock drills. The component allows a pressure and flow curve to be specified. Meaning that at a specific pressure, the component consumes a specific flow. This makes it easy to adjust the component to fit the specific rock drill used [16].

With the baseline simulation model in place, various solution strategies can be simulated, and the outcome can be evaluated easily. By simulating these different scenarios, it is possible to identify the most effective and efficient solution [16].

Simulation verification

Once the baseline simulation model has been developed, the next step is to verify the accuracy of the model using the measured baselines collected in Section 2.1.2. By comparing the measured baseline to the baseline produced by the simulation model, it is possible to determine the accuracy of the model to ensure that the results are reliable [16].

Numerous methods exist for comparing the similarity of two data sets [68]. The mean absolute error (MAE) method is used in this study. This method calculates the error of each data point throughout the data set by subtracting the simulated data point from the measured data point. The difference of all the data points is summated. This value as a percentage is shown in Equation 2-2.

Equation 2-2: MAE method

$$\text{Error \%} = \frac{1}{N} \sum_{n=0}^N \left| \frac{M_n - S_n}{M_n} \right| \times 100$$

With

Error % =	Absolute error percentage	[%]
N =	Total number of data points	[-]
n =	Data point	[-]
M =	Measured actual data point	[-]
S =	Simulated data point	[-]

For this study, an error percentage of below 5% is considered accurate. This percentage is also considered accurate by De Jager [16]. The simulation results should be compared with the real measurements of the system. If the deviation is more than 5%, the model should be investigated for deviations from the real-world system. The accuracy of the simulation model can be affected by several factors such as measurement errors, model assumptions and uncertainty, the representation of the system in the model, and the precision of the simulation software. The mentioned simulation parameters should, therefore, be built as accurately as possible to eliminate timely calibration efforts.

2.4 Identification of compressed air inefficiencies

The verified simulation model is used to generate characterisation curves for the simulated system. These curves provide a graphical representation of the performance of the system, which is used to identify areas of inefficiency and to evaluate the effectiveness of different solutions and strategies. Typical characteristic curves for compressed air systems include pressure and flow distribution characterisation curves [38], [41], [44]. These curves show the pressure and flow at various points in the system and are used to identify areas of high-pressure loss or poor flow distribution. For example, a pressure distribution characteristic curve is used to plot the pressure at different points in the system and highlight areas where the pressure is lower than expected, indicating a leak or other issue. A flow distribution characteristic curve is used to plot the flow rate

at different points in the system and highlight areas where the flow rate is lower or higher than expected, indicating an issue with the distribution of compressed air.

By using theoretical formulations, it is possible to narrow down the possible causes of pressure loss. By narrowing down the causes, relevant simulations can be simulated. For example, the inefficiencies could be related to insufficient pipe sizing, unnecessary fittings or excessive flow. Insufficient pipe sizing will result in a higher pressure drop as the compressed air has to travel through a smaller pipe, therefore increasing the frictional losses in the pipeline [41]. Unnecessary fittings, such as elbows and tees, can cause an additional pressure loss as they create additional resistance to the compressed air flow. Excessive flow could be caused by leakages that once again increase the flow velocity, therefore increasing the frictional losses through the pipeline. Examples of these types of inefficiencies are shown in Figure 2-5.

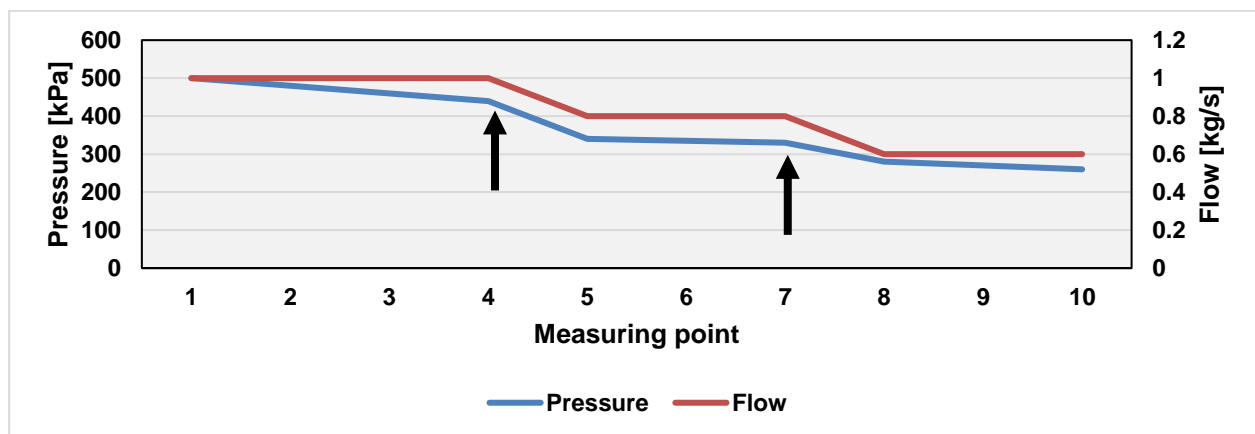


Figure 2-5: Figure indicating an example of a pressure and flow characterisation curve measured at various points

2.5 Simulating improvement strategies

Using the verified simulation model, the identified inefficiencies in the compressed air system are analysed by simulating various improvement strategies in a timely manner. Understanding the theory discussed in Section 1.5 is paramount when simulating improvement strategies since simulation strategies will differ from case study to case study. The following generic strategies can be considered regarding compressed air inefficiencies [38], [45]:

1. Increase pipe size to minimise the energy lost through distribution network.
2. Reduce system air waste such as air leaks.
3. Optimise the compressed air demand by ensuring that only the required equipment is utilised.
4. Reduce system complexity by eliminating unnecessary bends in the network.

By comparing the characteristic outcomes of the simulated improvement strategies with the baseline characteristic curves, it is possible to evaluate the potential impact of the different solutions. The effectiveness of the different simulated strategies can be evaluated by comparing their pressure improvement with the baseline [19].

2.6 Validation

The method will be validated using the study objectives:

Objective 1

The method addresses this objective by establishing the flow and pressure baselines for the supply, demand and reticulation network of a compressed air system. The different baselines represent the different sections of the compressed air system.

To successfully interpret inefficiencies inside the stoping section of the reticulation network, the supply, demand and reticulation network are considered. This ensures that a systematic approach is followed and inefficiencies stemming from the supply to the stoping section are accounted for. This is done by evaluating the different baselines for inefficiencies by means of theoretical principles derived from literature. For reference, the severity of the inefficiencies for the different compressed air sections is compared and prioritised using a Likert scale.

The method shines light on where the highest area of improvement is. However, as the literature study revealed, authors tend to stop compressed air investigation before they reach the stoping section. Therefore, the method focuses on the stoping section of the reticulation network despite what the priority Likert table suggests.

After the compressed air system is characterised by means of flow and pressure baselines, the method shows how to develop a baseline simulation of a deep-level mine stoping area. The method addresses simulation time, parameters, components and accuracy. The method provides a theoretical approach to verify the stope simulation model against the pressure and flow baseline using the MAE method.

Using the verified simulation, the method uses literature studies and theory to highlight how a typical compressed air inefficiency will present itself in a stope network.

Objective 2

To determine whether the method correctly identifies inefficiencies, practical measurements need to be taken as close to the identified inefficiency as possible. To measure the pressure difference across an inefficiency, pressure sensors should be installed at the stope intake (reference point), and before and after the simulated inefficiency. To ensure accurate results, sensors should

measure for at least the entire drilling shift (06:00–14:00). Furthermore, the measurements should be taken under similar compressed air demand from the equipment inside the stoping section.

Objective 3

The method uses literature studies and theory to provide generic simulation strategies that can potentially be implemented to mitigate the identified inefficiencies. The effectiveness of the strategies is evaluated according to the simulated pressure improvement achieved compared with the baseline.

2.7 Conclusion

In this chapter, the development of a systematic method that identifies, evaluates and verifies stope inefficiencies was discussed. The method incorporates the entire compressed air system instead of isolating the stoping section. This approach is concurrent with previous studies and ensures correct interpretation of in-stope inefficiencies.

The method establishes flow and pressure baselines for the supply, demand and reticulation network of a compressed air system. It further evaluates these sections for inefficiencies and prioritises them using a Likert scale.

The method indicates where the highest area of improvement is. However, as the literature study revealed, the gap in literature was inside the stoping section. Therefore, the method focuses on the stoping section of the reticulation network despite what the priority Likert table suggests.

The chapter discussed a method for simulating a compressed air stoping section using PTB and elaborated on the MAE verification method. Literature studies and theory were used to highlight how a typical compressed air inefficiency would present itself in a simulated stope network. Generic simulation strategies that can mitigate the identified inefficiencies were also discussed.

Finally, the chapter concluded by stating the study objectives and how the developed method aims to verify and validate the study objectives.

3 RESULTS

This chapter demonstrates the application of the developed method to a case study mine. The aim of this chapter is proving that the developed method can successfully accomplish the following criteria:

1. Identify the compressed air inefficiencies inside the stoping area using a systematic evaluation approach.
2. Verify the identified inefficiencies with actual measurements.
3. Assess the efficacy of various approaches to address in-stope compressed air inefficiencies through simulation-based evaluation.

3.1 Case study problem statement

A stope in a deep-level platinum mine, referred to as Mine A, was chosen as the site for implementing the method. The decision was prompted by multiple complaints of low pressure during the drilling shift at 23 Level cross-cut 89 (23L XC 89) at Mine A.

3.2 Baseline development

Data acquisition

On 4 December 2020, a compressed air audit was conducted at 23L XC 89 of Mine A to investigate low-pressure complaints. Mine A has two VK50 machines on surface running at a 600 kPa set point during the drilling shift and that are connected to a ring-feed system. Each compressor can supply about 50 000 m³/h. Compressed air is fed down the shaft through a 700 mm line, and a 300 mm line feeds compressed air from the shaft barrel through the level's station. The pipeline typically reduces to a 200 mm line when it splits into the four half levels, and cross-cuts leading to the stoping areas typically reduce to 100 mm pipes. The drilling manifold has four 32 mm pipe outlets for drills and one 25 mm outlet pipe for a chainsaw. The working equipment for 23L XC 89 is summarised in Table 3-1 and the pipe configuration is shown in Figure 3-1. The red sections of the layout indicate pipeline that is below Mine A's stoping pipe size standard.

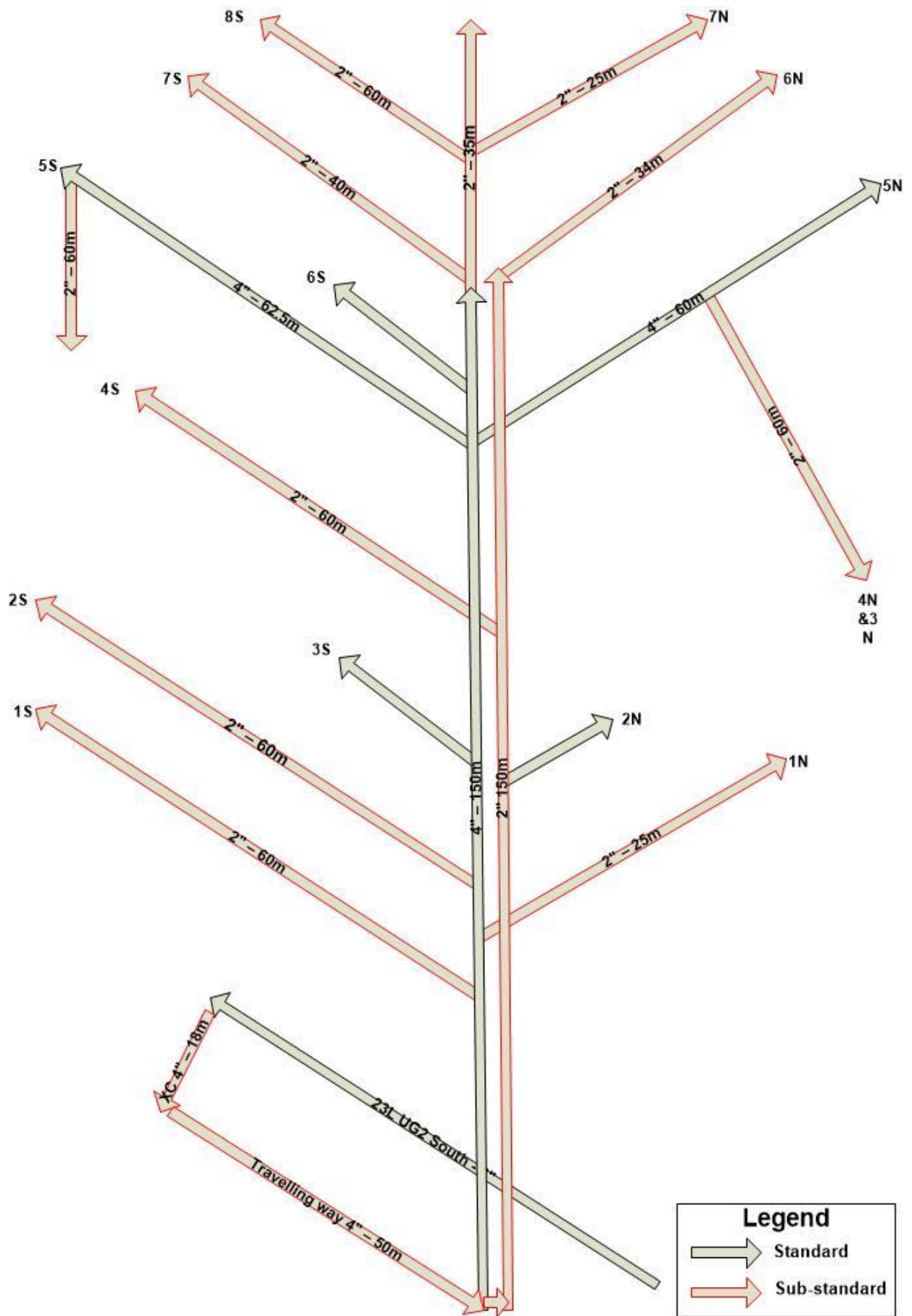


Figure 3-1: Mine A – 23L XC 89 CA pipe layout

Table 3-1: Mine A – Stopping flow demand [11], [16]

Equipment	Air consumption [kg/s]	Quantity	Total [kg/s]
Rock drill (S215)	0.064	12	0.768
Roof bolter	0.064	3	0.192
Air leg	0.025	15	0.375
Water pump	0.016	3	0.048
Total consumption		–	1.383

The collected data was used to develop baselines for each system boundary. Pressure and flow baselines were created for the supply, demand and reticulation network. Flow measurements were measured as nominal cubic metres per hour. These reference the flow at standard operating conditions (0°C and 101.325 kPa). By using nominal cubic metres per hour, flow could be compared at different pressures [16]. Sensors were installed to record pressure for a full week, with all baselines measured at the same time interval to minimise changes in system parameters.

Baseline measurement locations

The baselines for the case study mine compressed air system were measured at the positions discussed in Section 0. In summary, these are:

- The supply pressure and flow baselines were measured at the outlet of the surface compressor of Mine A.
- The demand-side baseline was measured as the total flow consumed by Mine A. The baseline was measured from the flow consumption that the compressor supplied to the network.
- The first reticulation baseline was measured between the outlet of the compressor and the level.
- The second reticulation baseline was measured between the level and the cross-cut intake.
- The third reticulation baseline was measured between the cross-cut intake and the stope face (furthest working point in the cross-cut).

3.3 Baseline evaluation

Supply-side pressure baseline

The supply pressure and flow baselines were measured at the outlet of the surface compressor of Mine A. The baselines are shown in Figure 3-2. The orange line represents the supply pressure,

measured at the outlet, from the surface compressors of Mine A. The blue line shows the total supplied flow, measured at the outlet, from the surface compressors of Mine A.

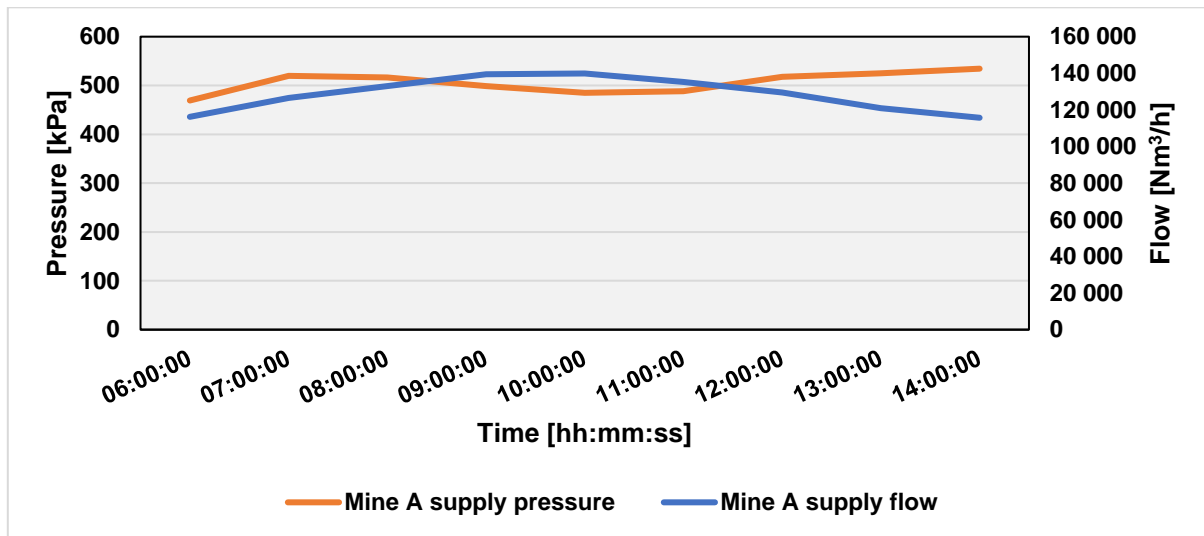


Figure 3-2: Mine A – Supply baseline

The VK50 machines have a maximum capacity of 50 000 m³/h at a 600 kPa pressure rating. The supply-side boundary baseline indicates that Mine A's surface compressors were running at maximum capacity as they could not meet the 600 kPa set point during drilling shifts. The baseline in Figure 3-2 shows that Mine A had a total peak shaft consumption of 140 000 m³/h, suggesting that an additional 40 000 m³/h were drawn from the ring-feed system to meet the demand.

It is worth noting that the ring-feed system is designed to support high-demand periods, such as those experienced by Mine A. However, there was a possibility that the ring was supplying leaks instead of end users. To confirm whether there was a capacity concern on the supply-side boundary, the demand-side boundary had to be evaluated simultaneously.

Demand-side flow baseline

The demand-side baseline was measured as the total flow consumed by Mine A. The baseline was measured from the flow consumption that the compressor supplied to the network. The baseline is shown in Figure 3-3.

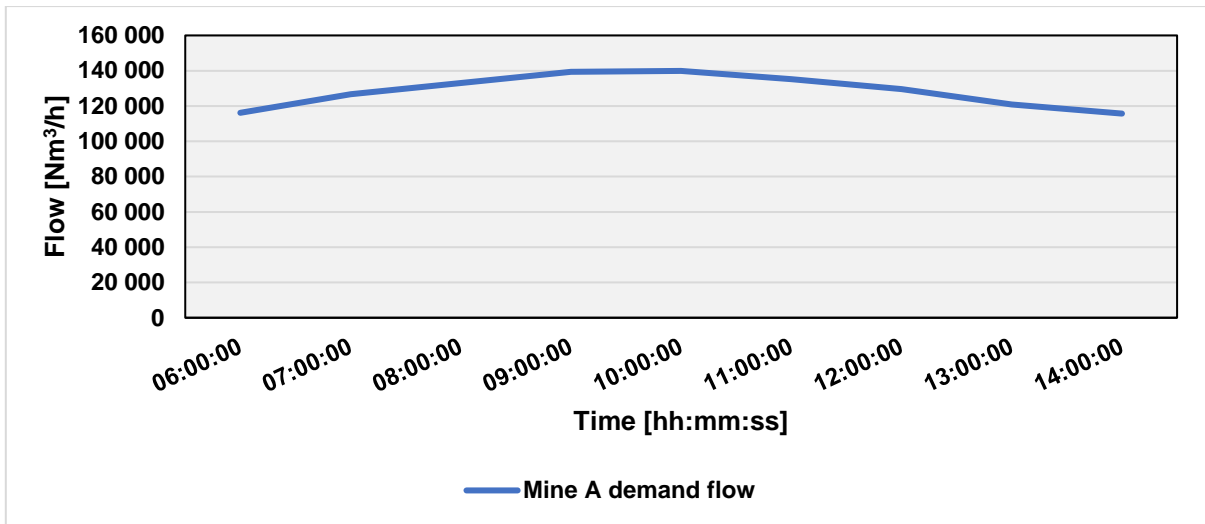


Figure 3-3: Mine A – Demand baseline

The demand-side boundary baseline shows that Mine A consumed a maximum of about 140 000 m³/h during the peak drilling shift. To determine whether leaks were contributing to the high demand for Mine A, a baseload test was done on all the levels during Mine A's cleaning shift. The results are presented in Figure 3-4.

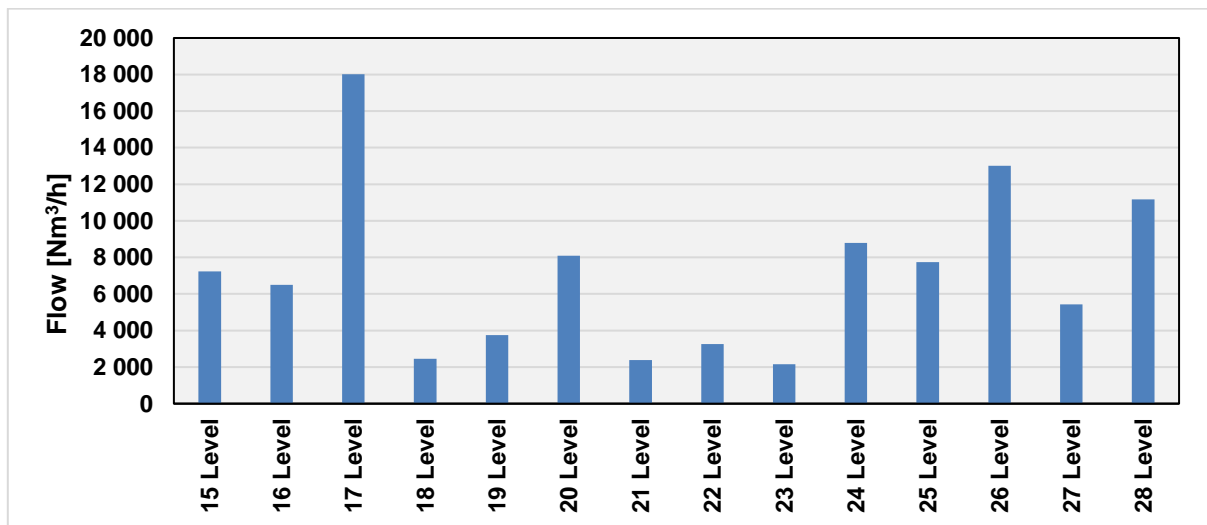


Figure 3-4: Mine A – Baseload test

Based on the supply and demand boundaries analysis, addressing leaks in the compressed air network could improve supply pressure from the surface compressors and reduce wastage. However, it is notable that only 23 level experienced pressure-related issues despite other levels having significantly more wastage. Additionally, the baseload for 23 level was relatively small compared with other areas of the mine. This suggests that the pressure loss may have been related to issues in the reticulation network.

Reticulation network pressure baseline

As determined in the method, baselines for the reticulation network are measured at relevant sections between the supply and end user locations. The baselines are shown below.

Section 1 – Surface to level station

The first reticulation baseline was measured between the outlet of the compressor and the level. The supply pressure from the compressor is indicated by the blue line while the pressure measured at the level intake is indicated by the orange line in Figure 3-5.

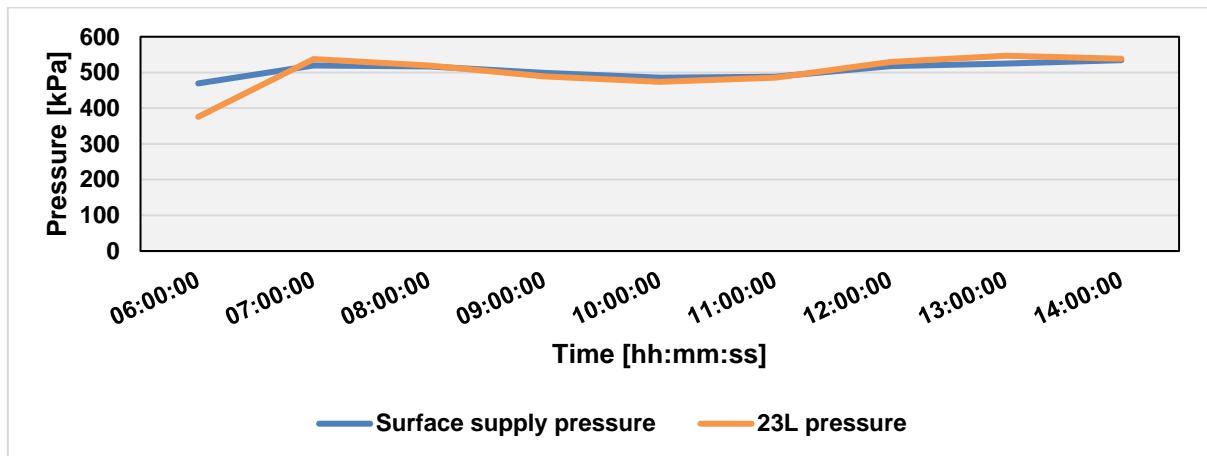


Figure 3-5: Mine A – Reticulation network, Section 1 baseline

Section 2 – Level station to cross-cut intake

The second reticulation baseline was measured between the level and the cross-cut intake. The level pressure is indicated by the blue line while the pressure measured at the cross-cut intake is indicated by the orange line in Figure 3-6.

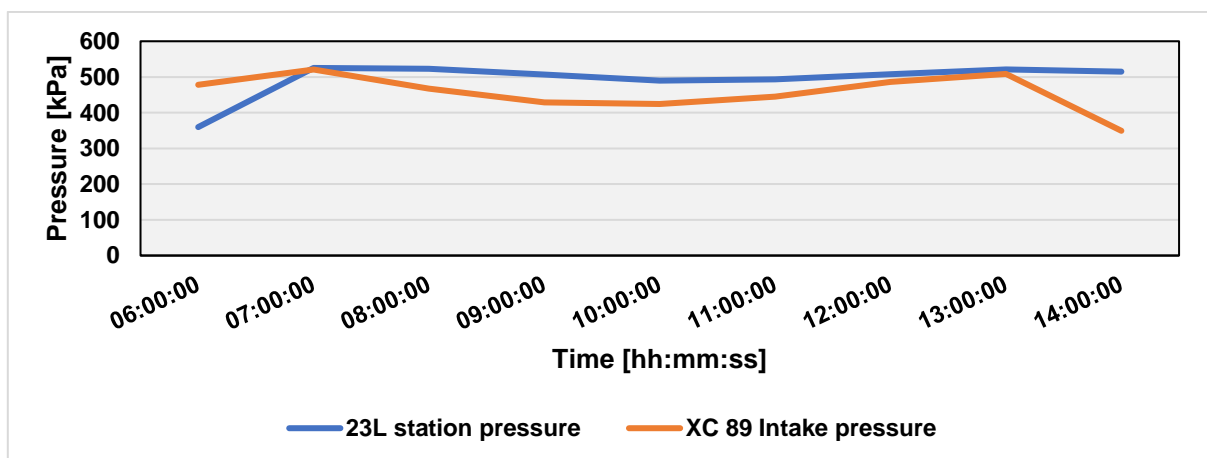


Figure 3-6: Mine A – Reticulation network, Section 2 baseline

Section 3 – Cross-cut intake to stope face

The third reticulation baseline was measured between the cross-cut intake pressure and the stope face, which is the furthest working point in the cross-cut. The cross-cut intake pressure is indicated by the blue line while the pressure measured at the face is indicated by the orange line in Figure 3-7.

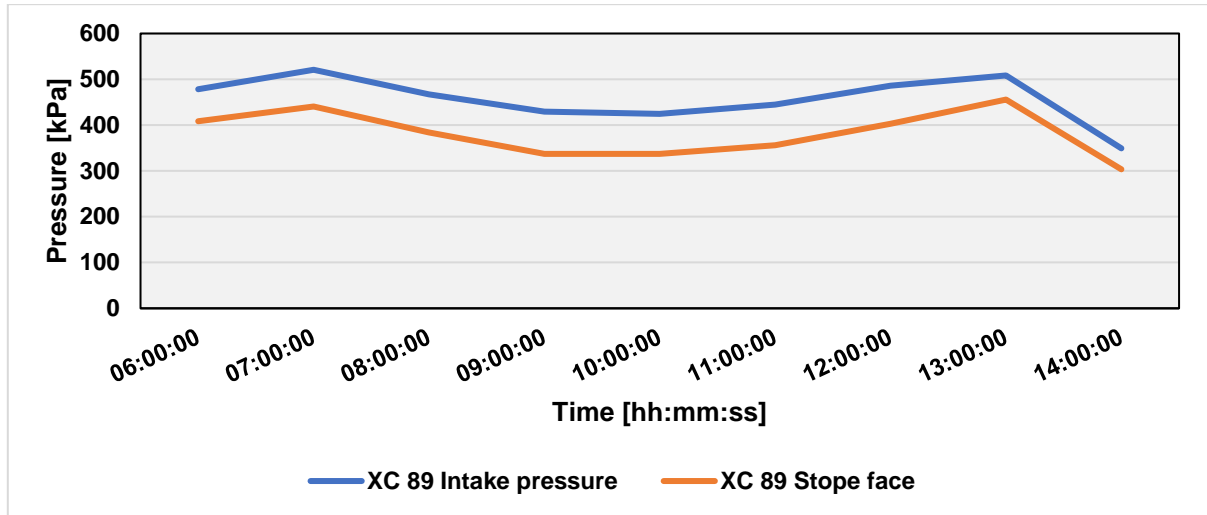


Figure 3-7: Mine A – Reticulation network, Section 3 baseline

Evaluating the reticulation network baselines showed significant pressure losses of 65 kPa and 87 kPa from the level station to the cross-cut intake and from the cross-cut intake to the face of the stope, respectively. As seen from the literature presented in this study, significant pressure losses occur in pipes that are insufficient in size.

Comparing compressed air baseline efficiencies

The different constructed baselines were evaluated using a Likert scale table and Equation 2-1 as discussed in the method Section 0. Table 3-2 shows the different baselines and their respective category and priority scores.

Table 3-2: Mine A – Boundary shortfall priority matrix

Baseline	Pressure loss (45.5%)	Volatility (9%)	Cost (45.5%)	Priority score
Supply baseline	5	5	1	3.180
Demand baseline	5	1	2	3.275
Pipe Section 1	1	4	3	2.180
Pipe Section 2	2	3	4	3.000
Pipe Section 3	3	2	5	3.820

Based on Table 3-2 presented above, it is evident that Pipe Section 3 had to be the primary focus. These results align with findings from Bester [37] who suggested that most inefficiencies are located inside the stoping area.

The following section discusses the development of a simulation model that accurately represents the measured baseline for the compressed air pipe section inside the stope (Pipe Section 3).

3.4 Creating a baseline simulation

The data gathered from Sections 3.2 and 3.3 was used to develop a baseline simulation model. This model represented the current configuration of the case study stope during its drilling shift. As determined from literature studies, PTB was used.

Simulation focus

The simulation focus parameters for the case study stope model were selected as pressure and flow. The simulated pressure along various points in the stope network represented the measured pressure in the pressure baseline. The simulated flow along various points in the stope network represented the measured flow in the flow baseline.

Simulation parameters

The following simulation parameters are considered when working with PTB. The specified parameters is shown in Figure 3-8.

Simulation period

The simulation represented a nine-hour drilling shift for 23L XC 89, which was divided into nine time periods.

Step size

The total number of time steps was 200 to ensure simulation stability.

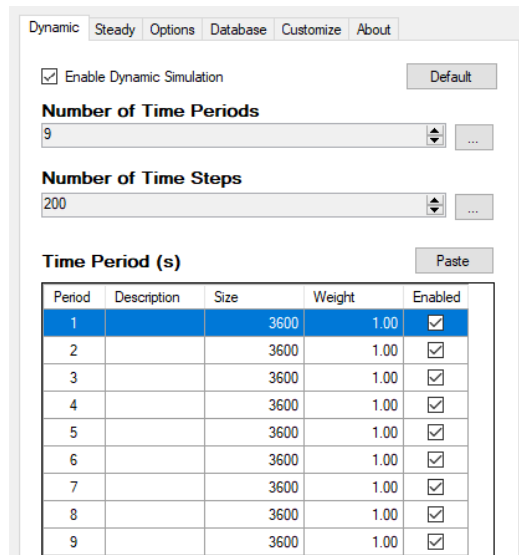


Figure 3-8: Mine A – Simulation properties

Simulation boundaries

At Mine A, compressed air is produced by centrifugal compressors located on the surface and transported to the underground working levels. The compressed air is subsequently distributed to the active cross-cuts, with specific emphasis placed on 23L XC 89 in the simulation model. The boundary conditions for the model started at the beginning of 23L XC 89 and extended up to the farthest working point inside the stope.

Model components

The following model components are considered when working with PTB:

Air pressure boundary

Table 3-3 shows the case study stope’s inlet ambient boundary conditions. The measurements were obtained using underground specific measuring equipment.

Table 3-3: Mine A – Inlet boundary conditions

Hour	Gauge pressure [kPa]	Temperature [°C]	Relative humidity [%]
1	478	20	50
2	521	20	50
3	467	20	50
4	429	20	50
5	424	20	50
6	445	20	50
7	486	20	50
8	509	20	50
9	349	20	50

The boundary component in PTB acted as a compressor that would increase its flow to maintain the boundary pressure. In other words, when a boundary component is coupled to a demand, the flow from the boundary component will increase if the demand increases. Table 3-4 shows the case study stope's outlet ambient boundary conditions.

Table 3-4: Mine A – Outlet boundary conditions

Hour	Gauge pressure [kPa]	Temperature [°C]	Relative humidity [%]
1	100	20	50
2	100	20	50
3	100	20	50
4	100	20	50
5	100	20	50
6	100	20	50
7	100	20	50
8	100	20	50
9	100	20	50

Nodes and pipes

The pipe and node components' representation are displayed in Table 3-5.

Table 3-5: Case study – Simulation model pipe and node representation

Component	Description	Component	Description
Pipe 1	Pressure loss from cross-cut intake to end of cross-cut travelway	Node 2	Volume of Pipe 1
Pipe 2	Pressure loss from start of centre gully to manifold	Node 3	Volume of Pipe 2
Pipe 3	Pressure loss from start of centre gully to manifold	Node 4	Volume of Pipe 3
Pipe 4	Pressure loss from manifold to rock drill manifold	Node 5	Volume of Pipe 4
Pipe 5	Pressure loss from manifold to rock drill manifold	Node 6	Volume of Pipe 5
Pipe 6	Pressure loss from manifold to manifold	Node 7	Volume of Pipe 6
Pipe 7	Pressure loss from manifold to rock drill manifold	Node 8	Volume of Pipe 7
Pipe 8	Pressure loss from manifold to rock drill manifold	Node 9	Volume of Pipe 8
Pipe 9	Pressure loss from manifold to manifold	Node 10	Volume of Pipe 9
Pipe 10	Pressure loss from manifold to manifold	Node 11	Volume of Pipe 10

Simulation verification

To verify the baseline simulation, the measured baseline presented in Figure 3-7 was compared with the simulated data from the developed model. The simulated data intervals were compared with the same measured data intervals for effective verification of the simulated model. Figure 3-10 shows the simulated pressure at the stope face in blue vs the measured pressure at the stope face in yellow. The orange line shows the measured cross-cut inlet pressure.

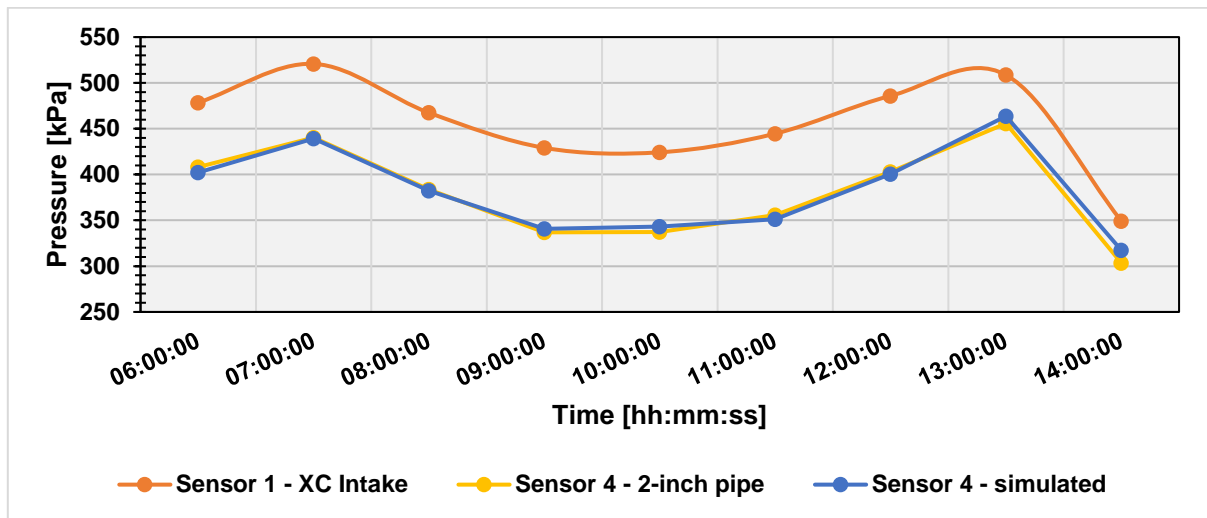


Figure 3-10: Mine A – Simulation verification

The MAE method was used to determine the error percentage between the two data sets. This is shown in Table 3-6.

Table 3-6: Mine A – MAE simulation verification data

Time	XC 89 intake pressure [kPa]	Measured stope face drilling pressure [kPa]	Simulated stope face drilling pressure [kPa]	MAE [%]
06:00:00	478.47	408.17	402.39	1.41
07:00:00	520.79	440.44	439.38	0.24
08:00:00	467.41	383.82	382.46	0.35
09:00:00	429.13	337.06	340.56	1.04
10:00:00	424.26	337.23	343.21	1.77
11:00:00	444.60	355.73	351.33	1.24
12:00:00	485.86	403.09	400.46	0.65
13:00:00	508.66	455.77	463.73	1.74
14:00:00	349.28	303.49	317.33	4.56
			Total error %	1.45

The model has a total error percentage of 1.45% compared with the baseline measurement and could therefore be deemed verified [16].

3.5 Identification of compressed air inefficiencies

Figure 3-11 shows the characterisation curves for pressure and flow generated using the verified simulation. To simplify the calculation of pressure loss over the network, pressures and flows were evaluated at various points along the centre gully pipe. Node 1 represents the cross-cut intake, while Node 11 represents the furthest working place. It should be noted that there are several mining panels along the centre gully, not just at Node 11. The highlighted sections in the figure represent different areas inside the stope, while the red arrows indicate the pipe size along the different sections.

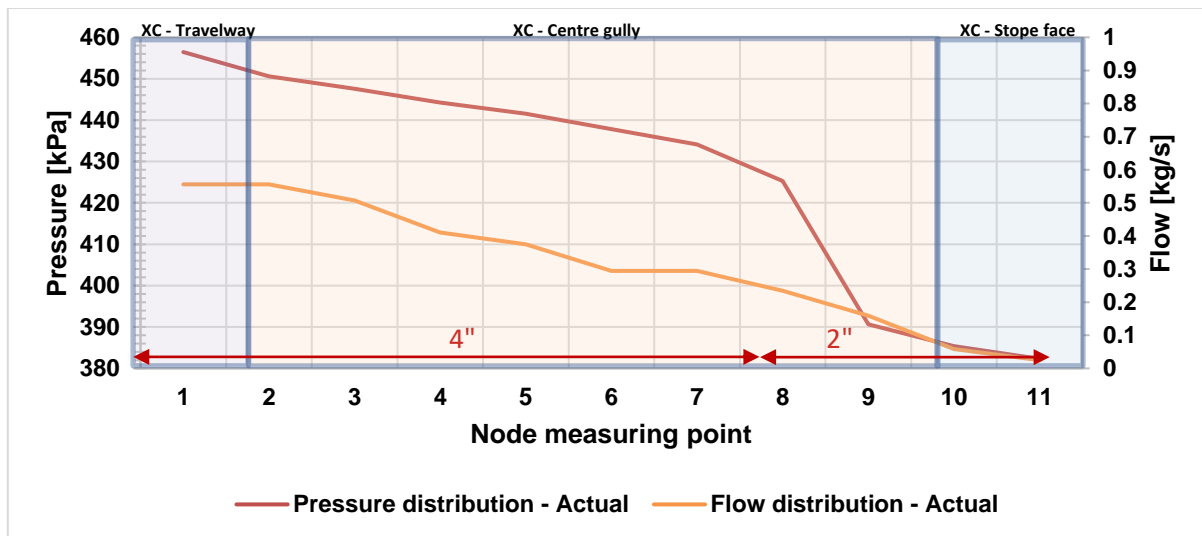


Figure 3-11: Case study – Baseline simulation results

According to the pressure characterisation curve in Figure 3-11, the case study stope experienced a total pressure loss of 75 kPa from the travelway to the stope face. The 4" pipe section exhibited a pressure loss of 32 kPa over its length, while the pipe reduction at Node 8 (4" to 2") inside the case study stope resulted in a pressure loss of 43 kPa.

3.6 Simulating improvement strategies

The simulation model can be used to simulate strategies to mitigate pressure losses from the identified inefficiencies. The total pressure loss over a network is typically defined by the sum of major and minor losses. Major head losses depend on factors such as pipe length, flow regime and fluid viscosity, while minor head losses are caused by flow disturbances created by components such as bends and connections in the pipe network.

Since the case study stope did not conform to the pipe size standard set out by Mine A, the pressure losses observed in Figure 3-11 may be due to major losses resulting from undersized pipes, as determined during the data-acquisition process.

Strategy 1

The first strategy worth simulating was the stoping standard that should have been used by Mine A. According to this standard, the travelway section should have used a 6" pipe, while both the centre gully and the stope face sections should have used 4" pipes. The simulated pressure and flow distribution using Mine A's standard are depicted in Figure 3-12, with the baseline curves shown for comparison purposes.

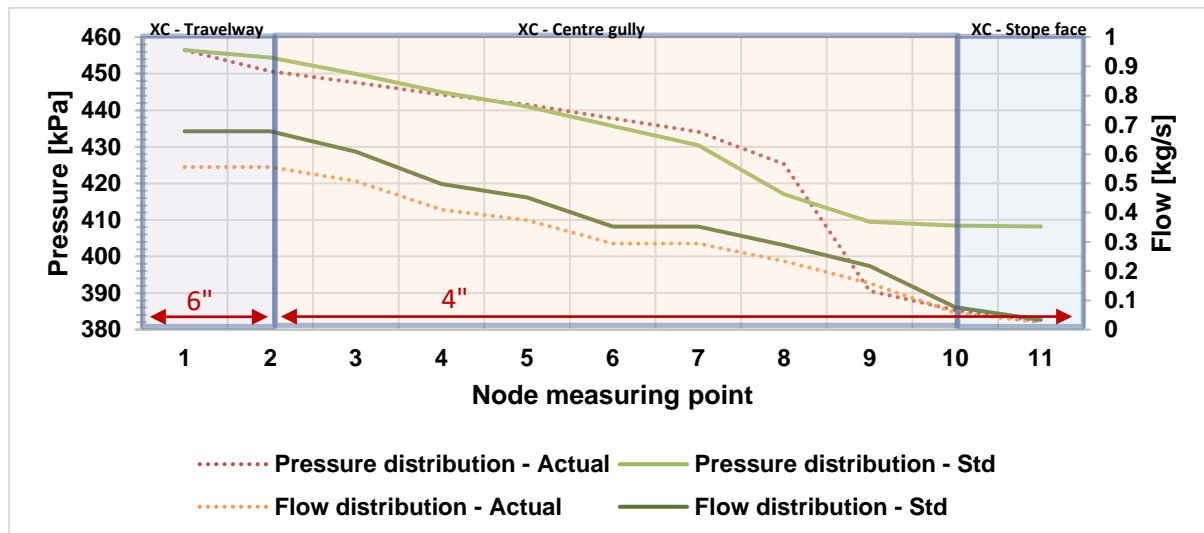


Figure 3-12: Case study – Simulated working pressures (standard pipe configuration)

The simulation results indicate that increasing the pipe size could reduce pressure loss over the network, indicating a lower system resistance. However, it is important to note that increasing the pipe size could lead to higher flow rates through the network and ultimately result in pressure losses once again.

The first strategy that was simulated, which involved implementing Mine A's standard, showed a significant reduction in pressure loss at Node 8 where the 2" pipe was replaced with a 4" pipe (26 kPa). This increase in pipe size also resulted in an increase in flow from Node 1 to Node 11. To achieve further improvements in pressure loss, the increase in pipe size should be significant enough to overcome the pressure loss caused by the increased flow rate from the rock drills. Overall, it is important to strike a balance between pipe size and flow rate to minimise pressure losses and improve system performance.

Strategy 2

Strategy 1 showed an increase in flow but no increase in pressure up to Node 10. Strategy 2 simulated a 6" centre gully. The results are shown in Figure 3-13.

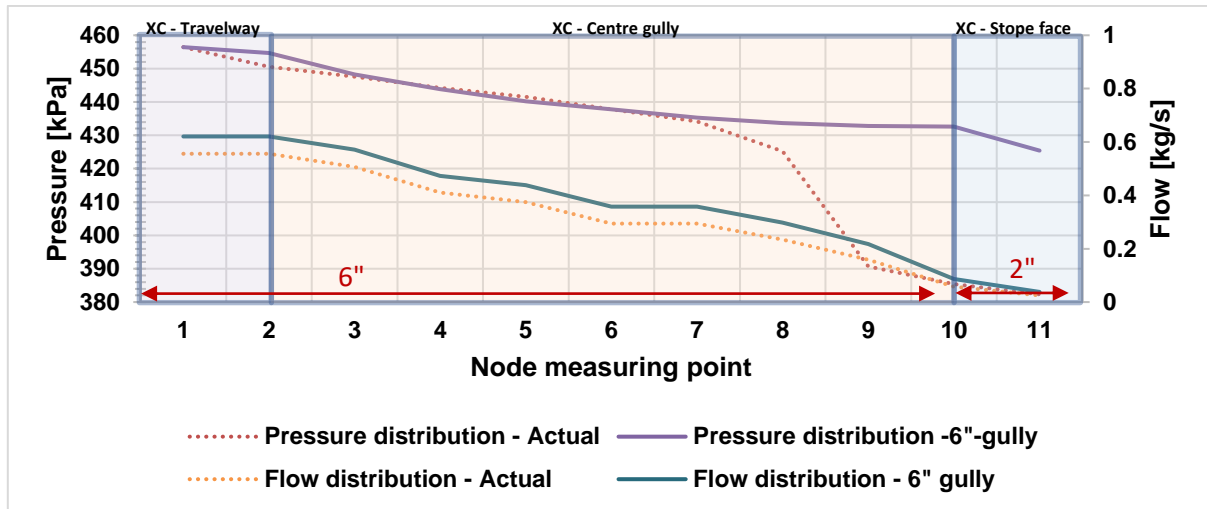


Figure 3-13: Case study – Simulated working pressures (6" centre gully configuration)

An improvement in pressure loss (43 kPa) was seen from Node 8 to Node 11. Furthermore, an increase in flow was observed due to the larger pipes from Node 1 to Node 11. As with Strategy 1, the increase in pipe size did not yield lower pressure loss between Node 1 and Node 7. This shows that the increase in flow rate through the larger pipe contributed to the same pressure loss as the current pipe network.

Strategy 3

Strategy 3 simulated an 8" centre gully. The results are shown in Figure 3-14.

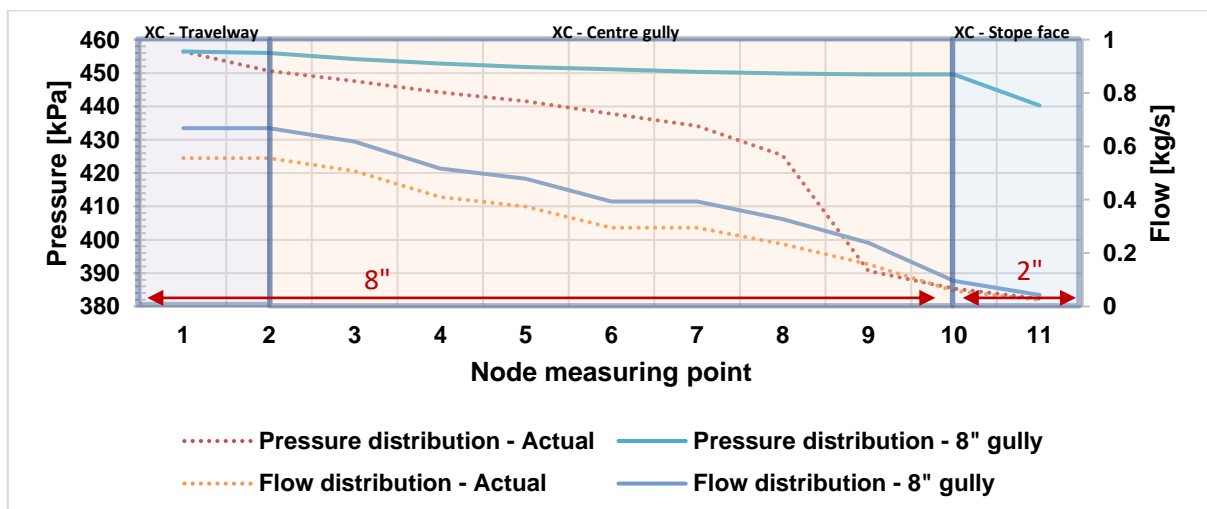


Figure 3-14: Case study – Simulated working pressures (8" centre gully configuration)

A significant improvement in pressure loss (58 kPa) was seen from Node 1 to Node 11 where the 4" pipe was replaced with an 8" pipe. An increase in flow was observed from Node 1 to Node 11 due to the larger pipes. The increase in pipe size yielded lower pressure loss over the network. This shows that the pressure loss due to higher flow rates did not outweigh the lower system resistance of the 8" pipe.

Strategy 4

Strategy 4 simulated a 10" centre gully to obtain as little as possible pressure losses. The results are shown in Figure 3-15.

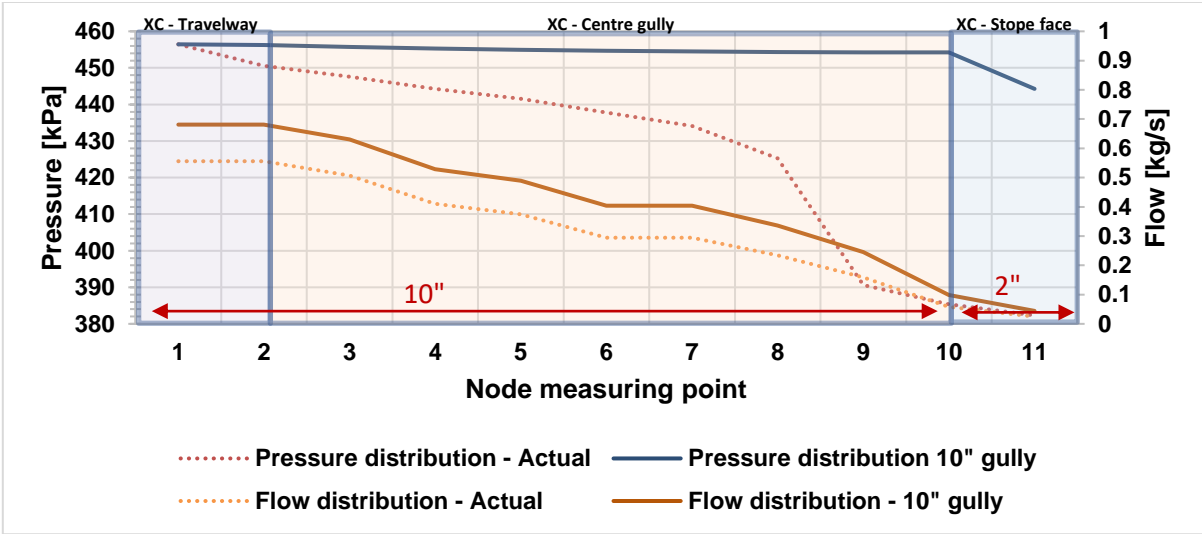


Figure 3-15: Case study – Simulated working pressures (10" centre gully configuration)

The pressure loss from Node 1 to Node 10 was almost completely overcome in this strategy. An increase in flow was observed from Node 1 to Node 11 due to the larger pipes. A pressure improvement of 62 kPa was observed.

Strategy 5

Strategy 1 showed that replacing the 2" section from Node 10 to Node 11 eliminated the pressure loss across the section. Therefore, Strategy 5 simulated a 10" centre gully with a 4" pipe to the stope face. The simulated pressure and flow distribution are shown in Figure 3-16.

The pressure loss from Node 1 to Node 11 was eliminated in this strategy. An increase in flow was observed from Node 1 to Node 11 due to the larger pipes. A pressure improvement of 70 kPa was observed.

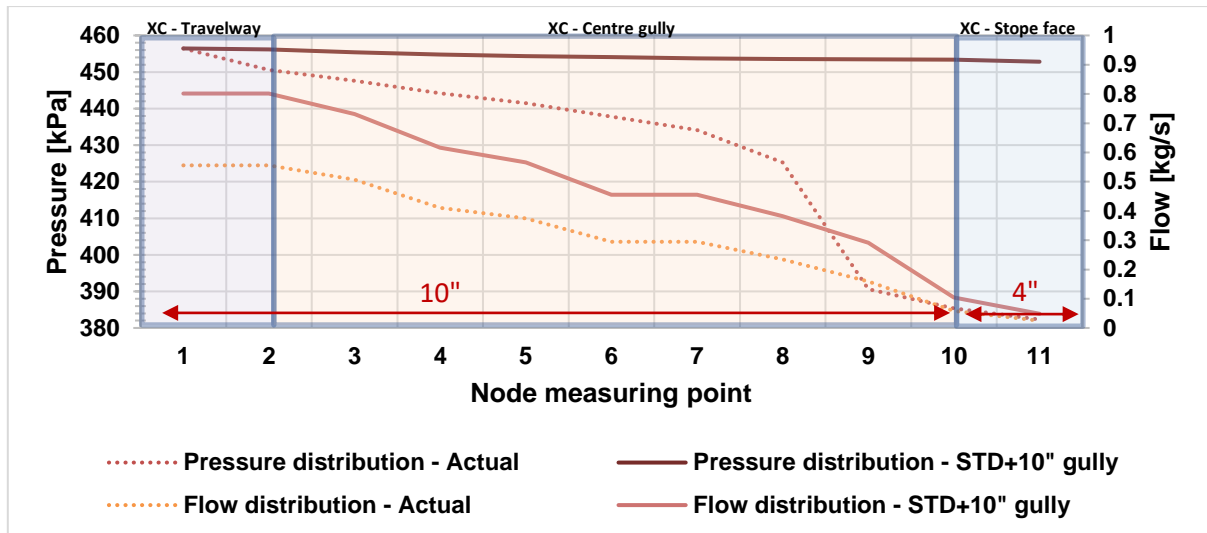


Figure 3-16: Case study – Simulated working pressures (10" centre gully + 4" slope configuration)

Strategy 6

A final strategy was simulated where only the most significant inefficiency was addressed. The 2" pipe section from Node 8 to Node 11 was replaced with a 4" pipe section. The simulated pressure and flow distribution is shown in Figure 3-17.

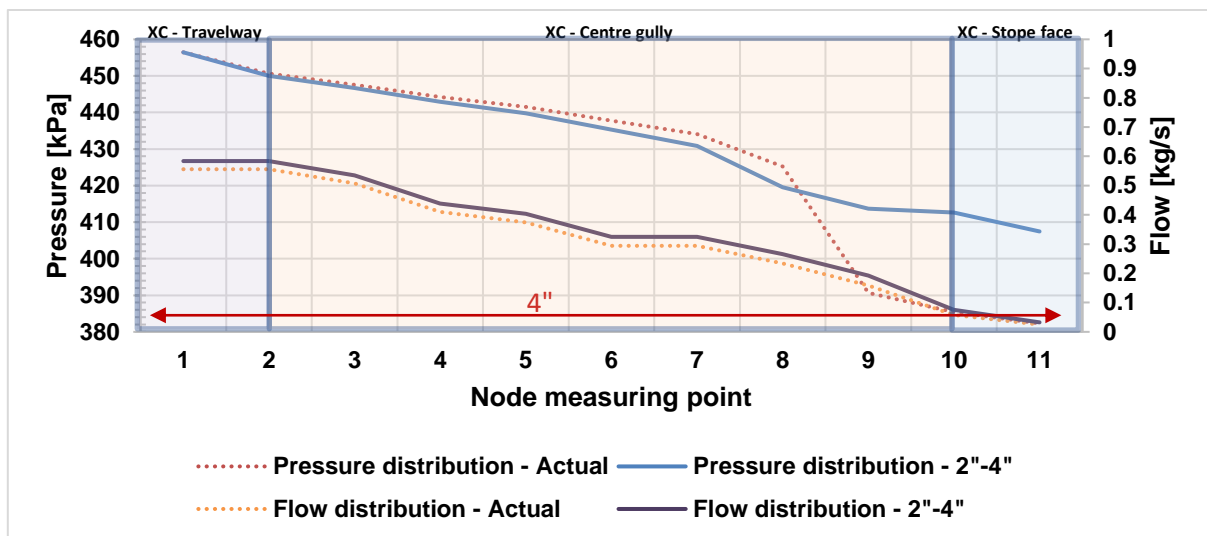


Figure 3-17: Case study – Simulated working pressures (2" to 4" pipe configuration)

Only replacing the 2" pipe with a 4" pipe showed an increase in pressure of 26 kPa from Node 8 to Node 11. However, the network was still showing pressure losses from Node 1 to Node 11.

The effectiveness of the different simulated strategies was evaluated by comparing their pressure improvement with the baseline. Table 3-7 summarises the different strategies and their respective pressure improvements.

Table 3-7: Mine A – Strategy pressure comparison

Simulated scenario	Pressure gain [kPa]
Strategy 1	26
Strategy 2	43
Strategy 3	58
Strategy 4	62
Strategy 5	70
Strategy 6	26

According to the findings in Table 3-7, Strategy 5 proved to be the most beneficial in terms of pressure improvement, closely followed by Strategies 4, 3 and 2. Strategies 1 and 6 both showed a similar pressure improvement of 26 kPa. However, it is important to consider the behaviour of mine employees who tend to ventilate the stoping areas using the compressed air pipes [37]. This means that although the larger diameter pipes used in Strategies 5, 4, 3 and 2 effectively reduce frictional losses and enhance pressure, they also facilitate increased air leakage when used for ventilation. Furthermore, the increased air leakage through these larger pipes will contribute to higher frictional losses and necessitate higher compressor power due to the greater number of leaks [38].

3.7 Validation

The developed method is validated through this case study as follows:

Objective 1

The method evaluated the supply, demand and reticulation sections of the compressed air system simultaneously to interpret in-stope compressed air inefficiencies effectively. The systematic evaluation of the compressed air system showed that the stoping section was the highest priority area for compressed-air-related inefficiencies in the case study mine. These results align with findings from Bester [37] that suggested most inefficiencies are located inside of stoping area.

Using simulation and characterisation, the method identified the following inefficiencies:

1. The 4" pipe section exhibits a pressure loss of 32 kPa over its length.
2. The pipe reduction (4" to 2") inside the case study stope results in a pressure loss of 43 kPa.

The method successfully identified in-stope-related compressed air inefficiencies and, therefore, achieved the objective.

Objective 2

The characterisation curves presented in Section 3.5 showed the case study stope experienced a total pressure loss of 75 kPa from the travelway to the stope face. The 4" pipe section exhibited a pressure loss of 32 kPa over its length, while the pipe reduction at Node 8 (4" to 2") inside the case study stope resulted in a pressure loss of 43 kPa. To determine whether the simulation model identified the inefficiency correctly, pressure sensors were installed strategically throughout the stope to measure for a full week.

Sensor 1 was placed just before the stope in the cross-cut, and this pressure reading served as the reference pressure. Sensor 2 was positioned on a 4" compressed air pipe, while Sensor 3 and Sensor 4 were placed on 2" pipes. Furthermore, the test was conducted under similar compressed air demand from both the 2" and 4" pipelines, ensuring a fair comparison. The positions of these sensors can be observed in Figure 3-18.

In Figure 3-19, the difference in compressed air pressure between the cross-cut intake, and 4" and 2" pipes are shown. The blue line represents the pressure at the inlet of the cross-cut, while the grey line represents the pressure in the 4" compressed air pipe, and the orange line represents the pressure in the 2" compressed air pipe.

During the drilling period, the 4" pipe experienced a 37 kPa pressure loss from the cross-cut intake while the 2" section experienced a further 43 kPa pressure loss. The case study stope experienced an average total pressure loss of 80 kPa during their drilling shift. This was measured from the cross-cut intake to the face. These results align with the 75 kPa simulated pressure loss.

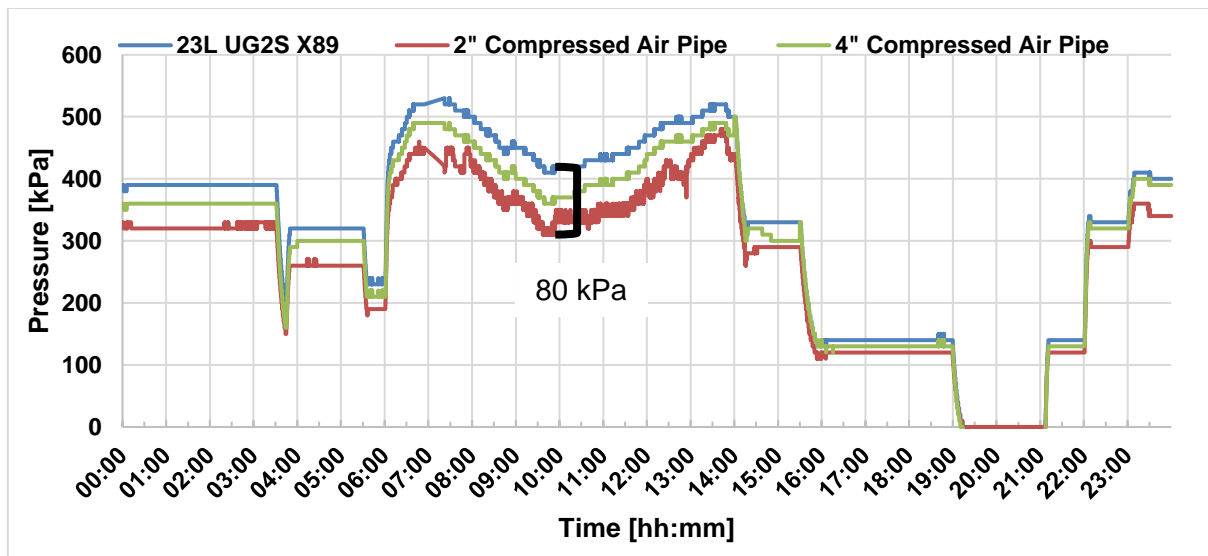


Figure 3-19: Mine A – Pressure difference between the cross-cut, 4" pipe and 2" pipe at the stope face

The simulation predicted an expected improvement of 26 kPa if the 2" pipe section were to be replaced. However, it is crucial to note the distinction between the simulation's prediction and the measured results. The simulation estimated the pressure improvement that would have been achieved if the 2" pipe section were replaced with a 4" section, accounting for the frictional losses of the 'new system'.

On the other hand, the measured results solely indicate the pressure loss between the 4" and 2" pipe sections without considering the potential frictional losses that would have still occurred had the 2" pipe been replaced with a 4" pipe. Therefore, the measured results confirm the identified inefficiencies, and the objective is validated successfully.

Objective 3

Using the simulation model of the case study stope, six mitigation strategies were developed. The efficacy of these strategies was determined based on the simulated pressure improvement they achieved. If the mitigation strategy yielded a pressure improvement, the strategy would be

deemed effective. The six strategies each had a pressure improvement with the lowest being 26 kPa and the highest 70 kPa. The method successfully developed and evaluated different improvement strategies and therefore achieved the objective.

3.8 Conclusion

In this chapter, the method derived from existing literature was applied to analyse different sections of a compressed air system, aiming to identify in-stope inefficiencies. A Likert scale enabled the assessment of various sections to ensure accurate representation of stope inefficiencies. Through this method, it was determined that the stoping section emerged as the top priority area for improvement in this case study.

To gain further insights, a verified baseline simulation of the stope was developed using reliable simulation software. This allowed for the creation and evaluation of characterisation curves, aiding in the identification of pressure losses in the stoping pipeline. The identified inefficiencies were proved using practical measurements.

The simulation was used to develop six distinct mitigation strategies that were assessed for their efficacy based on their simulated pressure improvement. The method successfully achieved the study objectives and can be deemed valid.

4 CONCLUSION

4.1 Study summary

South Africa's deep-level mines are currently witnessing a decline in platinum production. These mines, known for their depth, are grappling with soaring electricity expenses, making efficient production more crucial. Furthermore, the size and nature of these mines present significant infrastructural challenges that hinder productivity. Among these challenges, the compressed air network stands out as a particular area of concern. Compressed air systems have low mechanical efficiency (as low as 2%), and the distribution network is a major contributor to this inefficiency. Causes of poor system efficiency include leaks, ineffective water traps, ventilation with compressed air in working areas, and insufficient pipe sizing and connections.

Several studies have investigated compressed air inefficiencies in mining operations and have proposed various strategies for improving efficiency. These strategies included optimising set-point control and compressor selection, interconnecting compressed air pipelines to form a ring, installing an additional compressed air supply pipeline, sealing inactive sections off, limiting refuge bay air consumption, implementing set-point control on control valves, and replacing undersized pipes.

Some studies have used simulation and root cause analysis to identify inefficiencies and evaluate potential solutions, while others have used numerical methods, local benchmarking methods or underground audits. However, from the thirteen core literature studies presented, only one addressed inefficiency inside the stope, and the majority of the studies did not consider improving underground working pressures. Instead, the studies focused on saving energy by reducing compressor load because of improved efficiency. A detailed literature survey revealed the initiative to investigate in-stope compressed air inefficiencies and the effect thereof on drilling pressure.

A need for a method that identifies and evaluates in-stope compressed air inefficiencies that lead to reduced drilling pressures was established. The study objectives for the method included:

1. The identification of compressed air inefficiencies inside the stoping area using a systematic evaluation approach.
2. The verification of the identified inefficiencies with actual measurements.
3. The development and evaluation of various approaches to address in-stope compressed air inefficiencies through simulation-based evaluation.

A method was developed that systematically evaluated in-stope inefficiencies by establishing flow and pressure baselines for the supply, demand and reticulation network of a compressed air system. The severity of inefficiencies for the different compressed air sections was compared and prioritised using a Likert scale.

After the compressed air system was characterised by means of flow and pressure baselines, the method showed how to develop a baseline simulation of a deep-level mine stoping area. The method discussed simulation time, parameters, components, and accuracy. The method provided a theoretical approach to verify the stope simulation model against the pressure and flow baseline, using the MAE method.

Using the verified simulation, the method used literature studies and theory to highlight how a typical compressed air inefficiency would present itself in a stope network. The method showed how to practically verify a compressed air inefficiency inside a stope network using measurement instrumentation. Finally, the method discussed generic simulation strategies that aimed to mitigate compressed-air-related inefficiencies.

The method was implemented on a case study mine where it was used to analyse different sections of a compressed air system, aiming to identify in-stope inefficiencies. The use of a Likert scale enabled the assessment of various sections to ensure accurate representation of stope inefficiencies. Through this method, it was determined that the stoping section emerged as the top priority area for improvement in this case study.

A baseline simulation of a case study stope was developed using simulation software. The characterisation curves showed the case study stope experienced a total pressure loss of 75 kPa from the travelway to the stope face. The 4" pipe section exhibited a pressure loss of 32 kPa over its length, while the pipe reduction at Node 8 (4" to 2") inside the case study stope resulted in a pressure loss of 43 kPa.

To verify the identified inefficiencies, pressure sensors were installed throughout the stope. The case study stope experienced a total pressure loss from the cross-cut intake to the face of 80 kPa. During the drilling period, the 4" pipe experienced a 37 kPa pressure loss from the cross-cut intake while the 2" section experienced a further 43 kPa loss in pressure. These results align with the simulated pressure loss.

Six mitigation strategies were developed using a combination of theoretical principles [41] and simulation software. The simulated strategies indicated that the identified inefficiencies can be mitigated by increasing the pipe size of the compressed air network to accommodate the flow demand of the network.

Considering the study objectives, the method successfully identified compressed-air-related inefficiencies inside the stoping area and provided valuable insight to mitigate them. The study outcome solidifies the findings of previous authors that undersized pipes result in significant pressure losses. The study contributed to the existing research by including the evaluation of the stoping sections in deep-level mine compressed air networks.

4.2 Future recommendations

- While the objective of the study was to identify compressed air inefficiencies, the study did not verify the actual impact on the rock drills. Future studies could aim to implement mitigation strategies and measure the drilling improvement due to increased pressure.
- It is recommended to expand the Likert scale from a three-variable scale to a five-variable scale or a scale with more variables. This expansion would enable better identification of factors and lead to more accurate and reliable results.
- The study highlights the importance of considering the behaviour of mine employees, who tend to use compressed air pipes for ventilation in stoping areas. Increasing the pressure in the pipelines may inadvertently result in increased air leakage during ventilation. This means that the initial benefits gained from using larger pipes for pressure improvement would be offset by higher electrical costs, making the overall impact negligible. To fully leverage the results presented in this study, a comprehensive investigation into leakages within the stoping area is recommended.
- Future studies could aim to relate the improvement in drilling pressure to production figures. This could aim motivation behind replacing undersized pipes in stoping areas.

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APPENDIX A: CALCULATING PRIORITY FACTOR WEIGHTS

Saaty [69] proposed an analytical hierarchical process for establishing weights of multiple factors. The process can be summarised as follows [16]:

1. Determine the problem.
2. Create a discission hierarchy by defining the goal, defining the objective and defining the relevant factors to the problem.
3. Generate matrices for pairwise comparison, where each element at the highest level is used to compare the elements in the subsequent level directly beneath it.
4. Use the comparisons to assign weights to the measures of significance in the levels immediately below.

For example, Item *i*, Item *j* and Item *k* can be compared by using the following pairwise comparison matrix. This matrix can be expanded to include more items.

	<i>i</i>	<i>j</i>	<i>k</i>
<i>i</i>	1	Importance of <i>i</i> over <i>j</i>	Importance of <i>i</i> over <i>k</i>
<i>j</i>	Importance of <i>j</i> over <i>i</i>	1	Importance of <i>j</i> over <i>k</i>
<i>k</i>	Importance of <i>k</i> over <i>i</i>	Importance of <i>k</i> over <i>j</i>	1

Table A-1 shows a scale of 1 to 9 for determining the importance of one item over another [66].

Table A-1: Ranking factors

Importance	Definition	Explanation
1	Similar importance.	The two items make an equal contribution to achieving the end goal.
2	Weak.	
3	Moderate importance.	One of the items has a slightly greater contribution to achieving the goal.
4	Moderate plus.	
5	Strong importance.	Experience strongly favours one item over the other.
6	Strong plus.	
7	Very strong or demonstrated importance.	One item is very strongly favoured.
8	Very, very strong.	
9	Extreme importance.	The evidence confirms that one item should be preferred over the other.

Importance	Definition	Explanation
Reciprocals of assigned importance	If Item <i>i</i> has one of the integers above assigned to it when compared with Item <i>j</i> , then Item <i>j</i> has the reciprocal value when compared with Item <i>i</i> .	It is reasonable to assume that the preference for Item <i>i</i> over Item <i>j</i> is the inverse of the preference for Item <i>j</i> over Item <i>i</i> .

If one item's dominance over other falls within the predetermined ranges, then the item importance values of 2, 4, 6 or 8 are used.

To analyse the long-term behaviour of the system, the matrix is typically raised to a high power. For the sake of simplicity, the matrix was squared in this study, but the method remained the same. The pairwise comparison matrix discussed above was used to calculate the weights of the factors used in this study. The priority factors are:

- Pressure loss
- Volatility
- Cost

Each of these priority factors were compared as Saaty [69] suggests using Table A-1. The factors were compared and assigned scores by using available relevant literature and by talking to experienced mining personnel.

Pressure loss vs volatility

The magnitude of pressure loss resulting from inefficiencies in a section determines the feasibility of mitigating the pressure loss. If the pressure loss stems from a volatile section and is negligible, then there is little incentive to pursue a solution. Conversely, if the pressure loss is significant, the mine would prioritise rectifying it even if the section is volatile [11], [20], [37]. In essence, the severity of pressure loss is the primary determining factor. Therefore, pressure loss was ranked as a *strong importance* (5) over volatility.

Pressure loss vs cost

From the literature presented in this study, the pressure improvement of a project was used to underline the success thereof [37]. Once the payback period of the project is reached, the production benefits will still be seen and the cost of a project is no longer considered [16]. However, the cost of a project is a key factor when considering the overall profitability of a mine [70]. Therefore, pressure loss was ranked as *similar importance* (1) than cost.

Volatility vs cost

Since pressure loss is of strong importance over volatility, and the cost of a project is of similar importance to pressure loss, the cost was ranked as *strong importance (5)* over volatility.

With consideration of the comparisons above, the following pairwise matrix was defined:

	Pressure loss	Volatility	Cost
Pressure loss	1	5	1
Volatility	1/5	1	1/5
Cost	1	5	1

The weights were determined by raising the matrix to a higher power, summing the rows and dividing the summations by the total sum of the matrix [69].

	Pressure loss	Volatility	Cost	
Pressure loss	3	15	3	21
Volatility	3/5	3	3/5	4.2
Cost	3	15	3	21
				46.2

The weight for each priority factor is presented in Table A-2 below:

Table A-2: Priority factor weights

Priority factor	Weight
Pressure loss	45.5
Volatility	9.0
Cost	45.5

APPENDIX B: DETERMINING PRIORITY FACTOR SCORES

Each factor is assigned a score between 1 and n with 1 being the worst score and n being the best score. The score range is determined based on the number of compared sections, as all priority factors can be compared numerically to establish the best and worst scenarios. For example, if the supply, demand and compressed air pipe network sections are being compared, the maximum score that can be achieved is 3, indicating the best out of the three. Conversely, a score of 1 is considered the worst score possible among all the sections being compared.

For the case study presented in this study, the baseline sections under evaluation are the supply, demand, Pipe Section 1, Pipe Section 2 and Pipe Section 3 baselines. The scores for the priority factors relevant to the different sections were determined as follows:

Pressure loss

From the baselines shown in Section 3.3, the pressure loss for each section was obtained. Table B-1 displays the scores for each section based on the magnitude of pressure loss.

Table B-1: Sectional pressure loss summary

Section baseline	Maximum pressure loss	Score
Supply	100 kPa	5
Demand	100 kPa	5
Pipe Section 1	0 kPa	1
Pipe Section 2	77 kPa	2
Pipe section 3	92 kPa	3

Volatility

The volatility of various sections was assessed by evaluating their interaction with mine employees, maintenance schedules and environmental conditions. In the case of the supply section, which comprises the compressor, there is minimal interaction with employees. The surface compressors at the case study mine are subject to a maintenance schedule, and thus maintenance is not expected to be a significant issue. Furthermore, the compressors are situated in a compressor house, which protects them from harsh environmental conditions. Based on these factors, the supply section was deemed to have a volatility rating of 5.

The demand section encompasses all compressed air users, including underground working equipment and leaks. This section is subject to significant employee interaction, but there is currently no maintenance schedule in place at the case study mine to, for example, address leaks.

Moreover, the network that supplies compressed air to the underground equipment is exposed to harsh environmental conditions due to the underground mining environment. As a result, the demand section was deemed to have a volatility rating of 1.

The first segment of the pipeline, known as Pipe Section 1, runs from the surface supply point of the case study to the level and is situated inside the shaft. Except during maintenance operations, mine employees have no interaction with this section of the pipeline. Although it endures severe conditions, it undergoes weekly maintenance to ensure its upkeep. Therefore, this section of pipeline was deemed to have a volatility rating of 4.

Pipe Section 2 extends from the level station to the cross-cut intake in the main haulage, which serves as a frequent throughfare for employees when traveling to their workstations. While the pipeline does not come into direct contact with personnel, it is susceptible to occasional collisions with machinery during transit. Additionally, the pipeline is exposed to adverse environmental factors, thus warranting a volatility rating of 3.

Pipe Section 3 stretches from the cross-cut intake to the rock drills located in the stope, where it undergoes substantial handling by employees. Given the high noise levels present in this environment, detecting leaks proves challenging. Furthermore, based on prior literature, it has been observed that mineworkers employ this pipeline for ventilation purposes. Consequently, this section merits a volatility rating of 2.

In summary, the different section volatility scores are shown in Table B-2.

Table B-2: Sectional volatility scores

Section baseline	Volatility score
Supply	5
Demand	1
Pipe Section 1	4
Pipe Section 2	3
Pipe Section 3	2

Cost

In relation to the supply section, rectifying the pressure loss would involve the installation or enhancement of additional compressors. As outlined in section 0, the case study exhibits an excessive air consumption of 40 000 m³/h. While one possible solution is to install a VK50 compressor, it should be noted that this approach would incur substantial upfront and ongoing expenses. Consequently, the supply section was given a cost rating of 1.

To address the demand section effectively, it is necessary to address multiple leaks, close valves and minimise unnecessary venting caused by mine employees throughout the entire shaft. By implementing these measures, the supply compressors will be capable of maintaining a pressure of 600 kPa. However, it is important to consider that rectifying the demand section involves addressing the entire shaft, which means the costs associated with replacing broken pipelines will accumulate. Therefore, the demand section was assigned a cost rating of 2.

The replacement of Pipe Section 1 will incur the highest cost among the three pipe sections. This is primarily since Pipe Section 1 has the largest diameter compared with the other two sections. Following Pipe Section 1, the next highest cost is associated with Pipe Section 2, as the pipe size decreases at that point. On the other hand, Pipe Section 3, being the shortest and smallest in size, will have the lowest capital cost among the three sections. Consequently, the three sections were ranked with a cost score of 3, 4, and 5, respectively.

In summary, the different section cost scores are shown in Table B-3.

Table B-3: Sectional cost scores

Section baseline	Cost score
Supply	1
Demand	2
Pipe Section 1	3
Pipe Section 2	4
Pipe Section 3	5