Improving demand-side pressure of compressed air distribution networks in mines

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

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Graduation: June 2023

Student number: 24286362

ABSTRACT

Title: Improving demand-side pressure of compressed air distribution networks in mines

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Faculty: Engineering

Degree: Master of Engineering in Mechanical Engineering

The Platinum Group Mining industry is a large contributor to South Africa's economy. Approximately 90% of the world's remaining platinum group metals are in South Africa, with 54% of the global palladium & platinum mined in 2019 from South Africa.

However, South Africa's PGM industry has been facing challenges due to decreased demand and escalating costs due to mines becoming deeper and electricity tariffs increasing annually. This encourages platinum mines to implement cost-saving initiatives on existing infrastructure.

From the literature, it was found that compressed air (CA) network inefficiencies offer enormous potential for optimisation. These studies showed that CA network inefficiencies result in low service delivery pressure being supplied to machinery, such as pneumatically operated drill rigs, pneumatic cylinders used to operate loading chutes, mechanical loaders, etc. These studies suggest that lowered demand-side pressure leads to longer drilling and loading times and higher consumption of compressed air, which contributes to higher operational costs, and affects the amount of ore hoisted. Research pertaining to demand-side pressure improvement initiatives on platinum mines is limited.

Therefore, a need exists to optimise the compressed air network to improve the demand-side pressure by mitigating network inefficiencies on platinum mines.

A methodology was developed to identify, evaluate, and address these network inefficiencies. With the use of this methodology, possible solutions were developed to increase demand-side pressure using an iterative process. These solutions were verified through simulation and

implemented on a case study mine, Mine A. The implemented solutions were then validated by comparing the simulation results with the actual results. After validation, the results were used to calculate and quantify the production increase.

An investigation performed on Mine A indicated a pressure drop of approximately 135 kPa from the compressed air supply on the surface to the main production levels. Three initiatives to improve demand-side pressure were identified during the investigation. The first initiative focused on reconfiguring the main compressed air supply line, the second initiative focused on wastages and leaks found on the compressed air distribution network, and the third initiative focused on removing condensate from the compressed air.

After implementation, the impact of the initiatives was validated, with results indicating an improvement in demand-side compressed air pressure. With the increased pressure, an increase in production is also expected.

Keywords: Compressed air network; Network inefficiencies; Demand-side pressure; Initiatives; Production; Compressed air leak fixing; Removing condensate from compressed air; Compressed air management plan

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to Dr Jean van Laar and Dr Johann van Rensburg for their guidance, advice and time that they provided.

I would also like to thank my mother, Elaine Botha, for the support and means provided to complete this degree.

To my girlfriend, Anneri Kapp, thank you for your support and understanding throughout the writing process.

Finally, I would like to thank Mr George Mathews and Prof. Edward Mathews from ETA Operations (Pty) Ltd for providing me with the funding and resources to be able to complete this dissertation.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF EQUATIONS

LIST OF ABBREVIATIONS

BIC	Bushveld Igneous Complex
CA	Compressed Air
CAMP	Compressed Air Management Plan
CH	Compressor House
DSM	Demand-Side Management
EDP	Engineering Design Process
GDP	Gross Domestic Product
HDPE	High-Density Polyethylene
KPI	Key Performance Indicator
PGM	Platinum Group Metals
PLC	Programmable Logic Controller
PTB	Process Toolbox
R	Rand (South African currency)
ROP	Rate of Penetration
SABS	South African Bureau of Standards
SCADA	Supervisory Control and Data Acquisition
UG2	Upper Group 2
VRT	Virgin Rock Temperature
WBS	Work Breakdown Structure
X/C	Crosscut

LIST OF TERMS

Baseline	Baseline simulation models are reference simulation models other simulation models are compared with. Usually, a baseline simulation model is a replica of a mining system for a specific time period.
Blast shift	Period when explosives are detonated to break the rockface underground.
Bypass valve	Regulating valve that allows one to open or close compressed air flow to various locations in the compressed air network.
Compressor house	Building that contains the compressors that supply compressed air to the end users.
Demand flow	Quantity of compressed air consumed by end users to perform various mining operations.
End user	Components/equipment that require compressed air to perform various mining operations.
Peak drilling period	Period when pneumatic rock drill activity and compressed air consumption are at their highest.
Supply flow	Quantity of compressed air supplied by the compressors to the mine compressed air network.
Supply pressure	Pressure at which compressed air is supplied to the mine compressed air network.

NOMENCLATURE

Celsius	°C
Cubic metre	m^3
Degree	°
Density	ρ
Diameter	Ø
Dimensionless	–
Division (per)	/
Hour	h
Kelvin	K
Kilogram	kg
Kilojoule	kJ
Kilometre	km
Kilopascal	kPa
Kilowatt	kW
Megawatt	MW
Metre	m
Millimetre	mm
Normal cubic metre per hour	Nm^3/hr
Number	#
Percentage	%
Seconds	s
Universal gas constant	R

Chapter 1 Introduction

1.1 Platinum mining in South Africa

The mining industry is one of the largest contributors to the South African economy with an 8.2% (or R362 billion) contribution made to the country's total gross domestic product (GDP) in 2020 [1]. The number of people employed in the South African mining industry totalled 451 427 in 2020 [1].

Platinum Group Metals (PGMs) was the largest contributor to the South African mining industry according to sales in 2020, with R171.3 billion in sales [2]. PGM consists of mining six noble metals: platinum, rhodium, palladium, osmium, iridium and ruthenium. South Africa contains 88% of the total known PGM reserves in the world and produces over 80% of the platinum and 60% of newly mined PGMs [3].

The Bushveld Igneous Complex (BIC), stretching from the North-West province to the Limpopo province in South Africa, is the largest reserve of PGMs found in the world [4]. The BIC consists of three reefs where the PGM ore deposits can be found, namely the Merensky Reef, the Upper Group Chromitite No.2 (UG2) Reef, and the Platreef [4].

Figure 1 illustrates the geographical location of the Bushveld Igneous Complex [5]. The BIC is split into three main limbs, namely the Northern limb, the Western limb, and the Eastern limb [5]. South Africa's major deep-level PGM mines, such as Impala Platinum, Anglo American Platinum and Sibanye Stillwater, are located on the Western limb of the BIC.

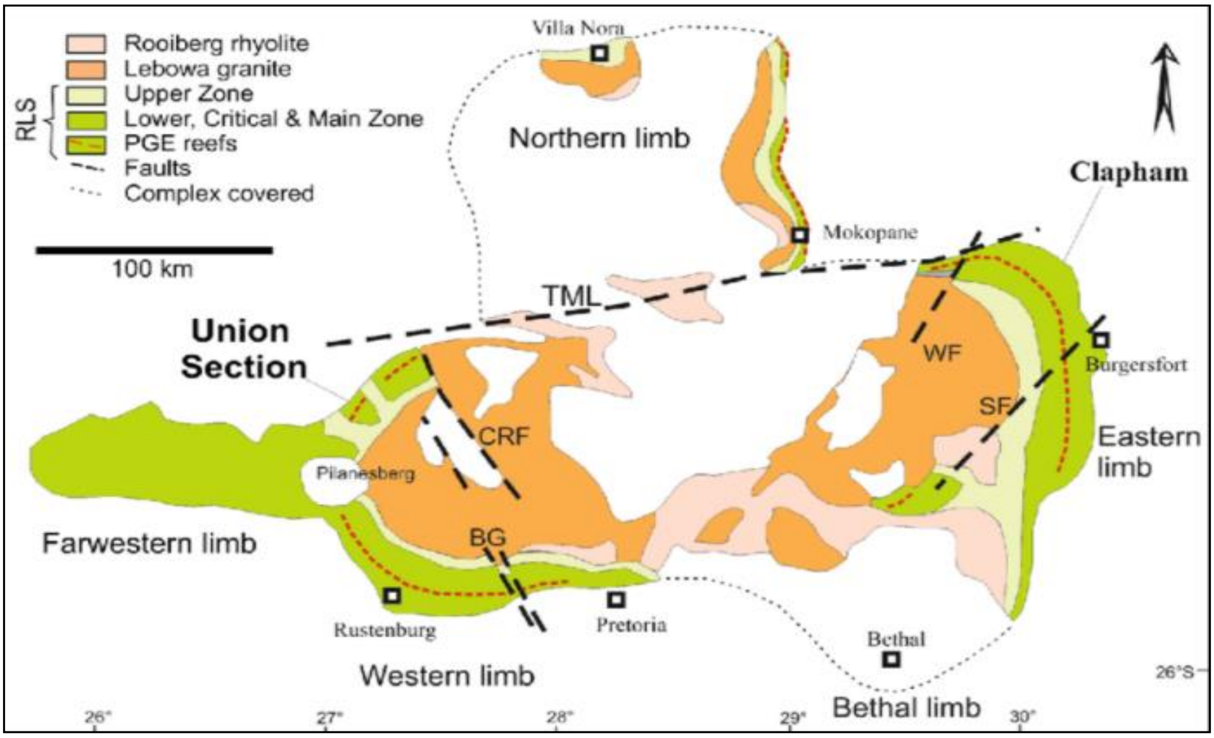


Figure 1: Geographical map of the Bushveld Igneous Complex (adapted from [5])

Platinum mines in the BIC are narrow reef-type mines [6]. The principal mining method for narrow reef mines is called "Room-and-Pillar" mining and is illustrated in Figure 2: Room-and-Pillar mining [7]. This method utilises pillars such as wooden logs or beams to support the hanging walls. The roof must stay intact and is reinforced using roof bolts [8]. Roof bolts function by promoting or retaining the natural self-supporting ability of the host rock mass [9]. The roof bolt expands within the rock and causes a lateral force, pushing the rocks tightly against each other.

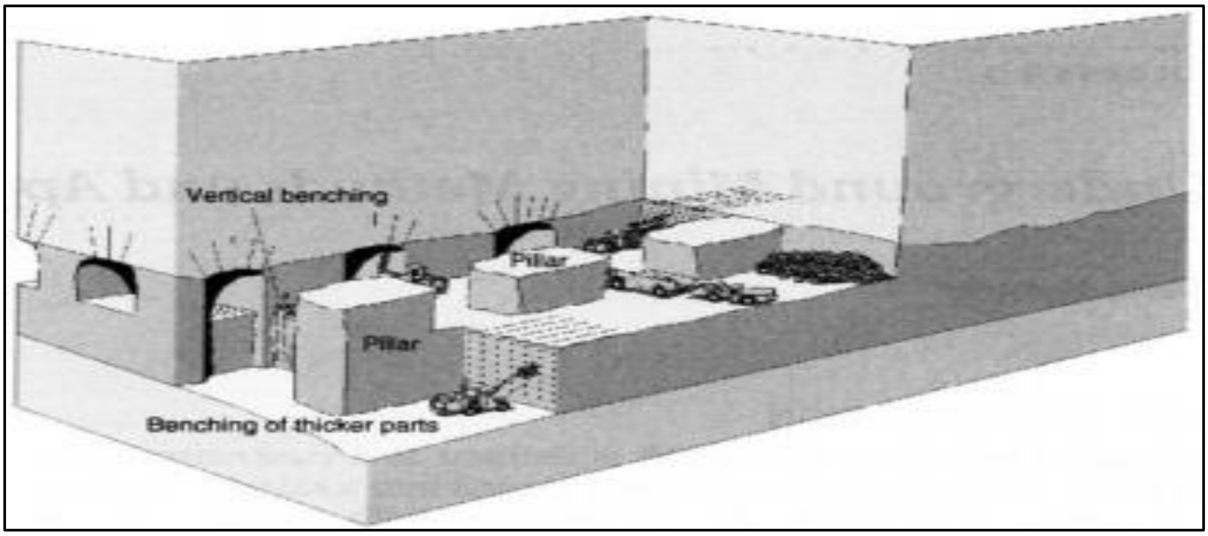


Figure 2: Room-and-Pillar mining [8]

1.2 An overview of compressed air networks on deep-level mines

The majority of the mining industry uses compressed air as the primary source of energy in mining operations [10]. Although using compressed air is critical to mining operations and directly affects production [11], compressed air is also regarded as one of the most inefficient and energy-intensive systems found on mines [12]. Several factors affect the efficiency of a compressed air network and will be addressed throughout this section.

Compressed air distribution networks found on deep-level platinum mines are highly complex systems. For ease of understanding deep-level mining compressed air distribution networks, the network can be divided into three main categories [13], namely:

- Supply-side (Section 1.2.2),
- Distribution network (Section 1.2.3), and
- Demand side (Section 1.2.4).

Each category consists of a wide range of components that differ in size, application and functionality.

Figure 3 illustrates a typical example of a compressed air network and all its intricate sub-systems [14]. From this illustration, it is clear how complex a compressed air network can become. This figure serves only as an illustration and does not necessarily appear as is in mining compressed air networks.

Understanding the compressed air network is the first step to developing solutions to optimise the use of compressed air on platinum mines.

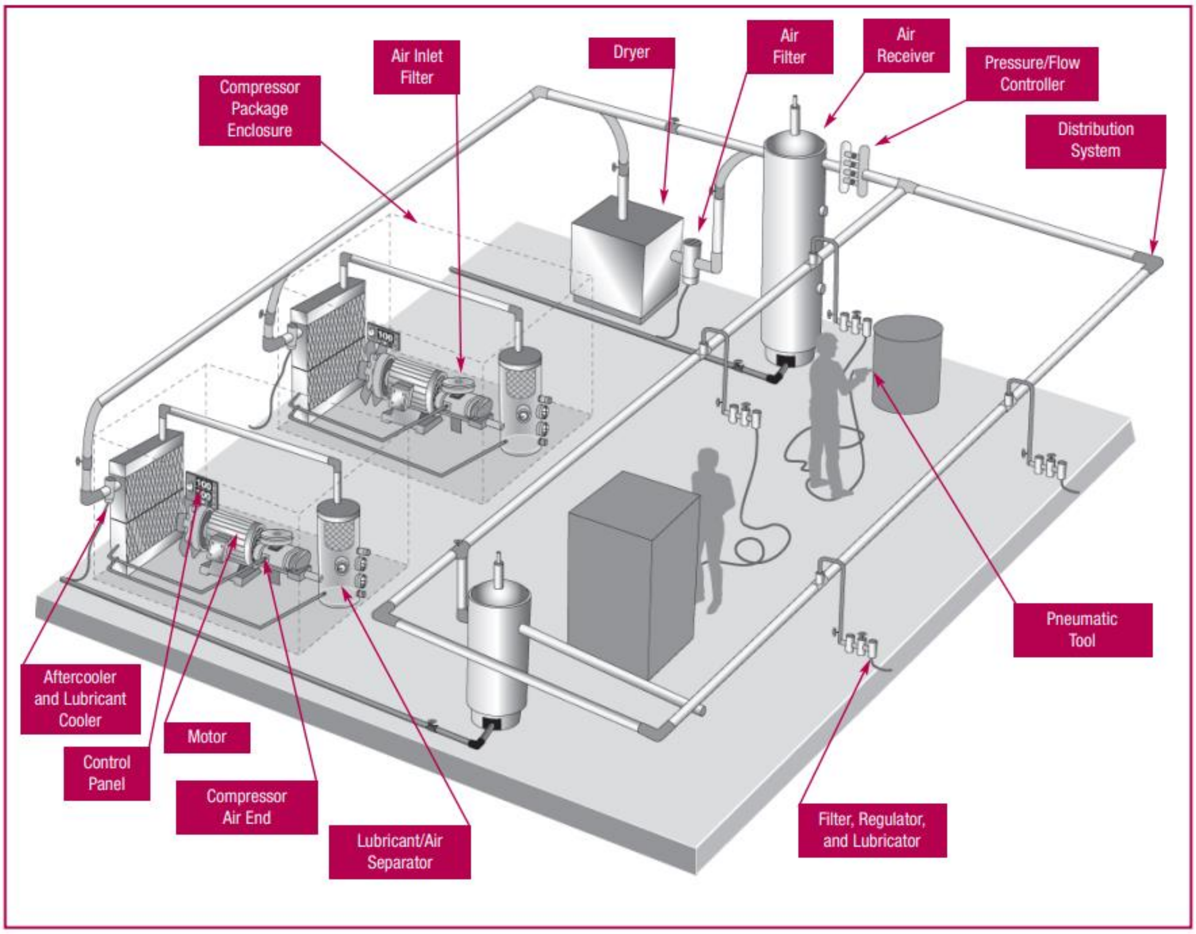


Figure 3: Illustration of a typical compressed air network/system [14]

1.2.1 Compressed air requirements

The mining of PGMs is a continuous operation that requires different processes. For these processes to be efficient, different compressed air requirements must be met. These processes are dependent on each other and cannot be performed simultaneously. Due to this limitation, mining operations are divided into separate shifts, namely:

- Pre-drilling Shift (06:00 – 08:00)
- Drilling Shift (08:00 – 14:00)
- Post-Drilling Shift (14:00 – 17:00)
- Afternoon Reduction Shift (17:00 – 18:00)
- Blasting Shift (18:00 – 21:00)
- Cleaning/Sweeping Shift (21:00 - 06:00)

Compressed air is required during all the shifts as the refuge bays, where miners and other personnel gather in case of an emergency, must always be supplied with air. Typically, the most compressed air intensive shifts are the drilling and cleaning shifts.

Drilling Shift

The term "drilling" is defined as the use of a machine to create a hole or holes for the purpose of exploration or loading with explosives [15]. On platinum mines, drilling describes the process of utilising pneumatic drills to create drill holes in the rockface being mined [12].

Drilling equipment capable of both rotation and percussion is the most effective when it comes to hard rock mining [16]. Optimal drilling rates can be achieved when no water is present [16]; however, this is not feasible as water is needed to 1) cool down the drill bit and 2) suppress dust and fine rock fragments formed when the drill bit grinds down the rockface.

Blasting Shift

Following the drilling shift, the blasting shift commences. The blasting procedure consists of miners/gangers placing explosive charges in the holes drilled in the rockface. The charges are then detonated remotely once all miners/gangers have been evacuated from areas of immediate danger, such as the stope areas [17].

The law requires mines to be ventilated for three hours after blasting occurs [18], to expel all the noxious gases, such as nitrous oxides, carbon monoxide and ammonia, and dust created by the explosives before cleaning/sweeping may commence.

Cleaning/Sweeping Shift and Ore Transportation

After blasting has occurred and the mine is properly ventilated, the cleaning or sweeping shift starts. See Figure 4; the process of sweeping and transporting ore involves:

- The use of scraper winches to transport the blasted ore from the stope panels to the centre gullies.
- Centre gully winches transport the blasted ore into ore passes.
- The ore pass transports the ore to lower levels, where the ore is collected in loading bins.

- With loading boxes/chutes, the ore is transferred from the loading bins into hoppers that are moved around using electrically powered locomotives.
- The locomotives transport the ore from the loading chutes, situated in crosscuts and haulages, to ore bins which feed underground conveyors.
- The conveyor belts transport the blasted ore to the central ore passes.
- The loading skip, located at the bottom of the shaft, is gravity fed by the central ore passes.
- The loading skip is then hoisted to the surface, where the ore is transferred into large hopper bins.
- Lastly, when the surface hopper is full, the ore is transported from the shafts via trains to the processing plants.

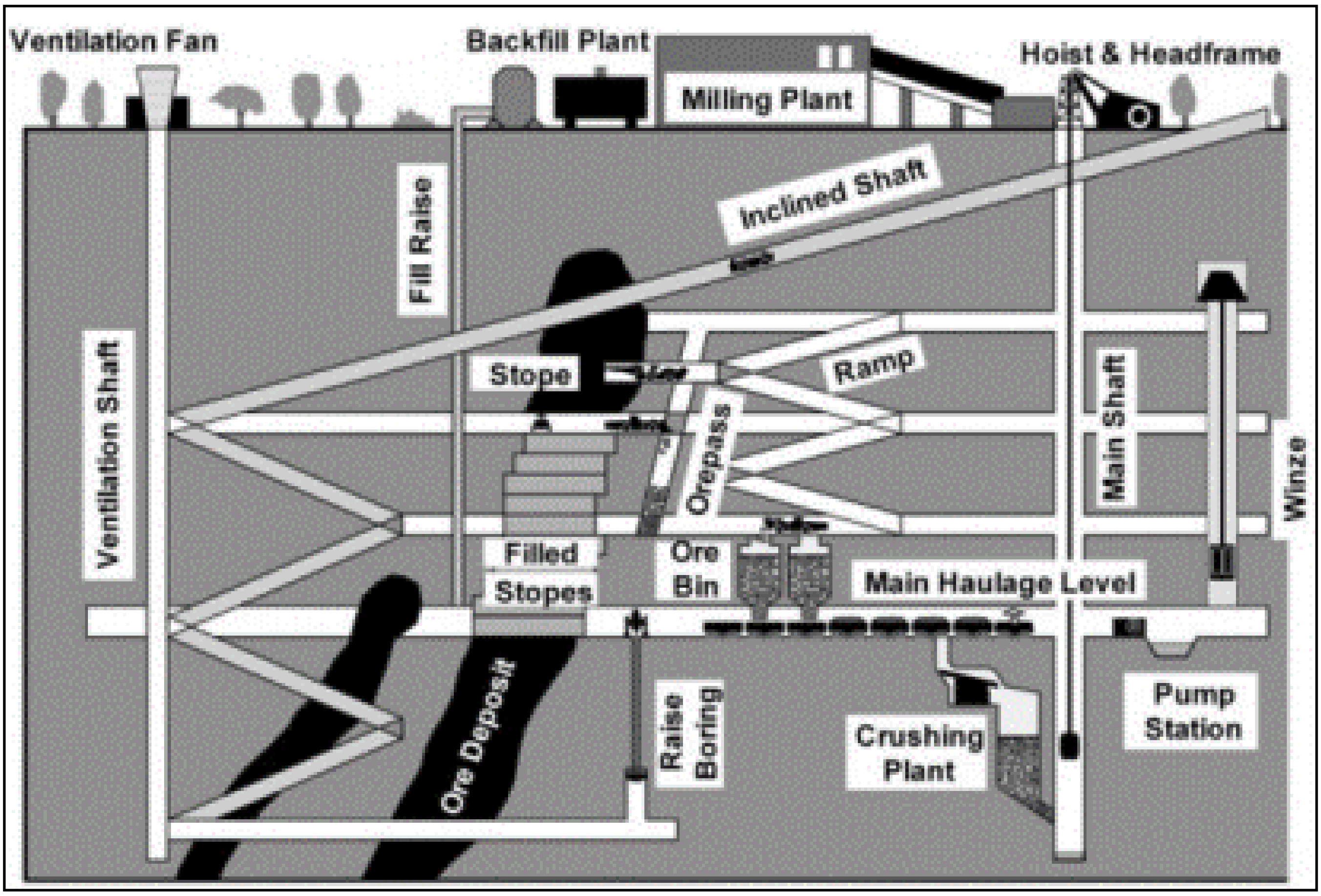


Figure 4: Underground transportation layout example [17]

From the descriptions mentioned above given for the different timeslots or shifts, it is clear that the compressed air consumption and requirement for a 24-hour period on a mine differs vastly according to the processes that operate during the different shifts.

Figure 5 gives a visual representation of the compressed air flow consumption and pressure supplied on a platinum mine during an average 24-hour period. The average pressure supplied to a shaft is at around 550 – 600 kPa daily. The pressure illustrated is within the normal operational range. The flow consumption on the graph is also typical of weekday operations.

The figure shows the required flow for the different shifts: approximately 60 000 Nm^3/h for the cleaning shift, approximately 78 000 Nm^3/h for the drilling shift, and no flow required for the blasting shift. The three spikes in flow observed is due to the opening/closing of the surface shaft CA valve. Production can be affected if the compressed air supplied to the shaft is at an insufficient pressure.

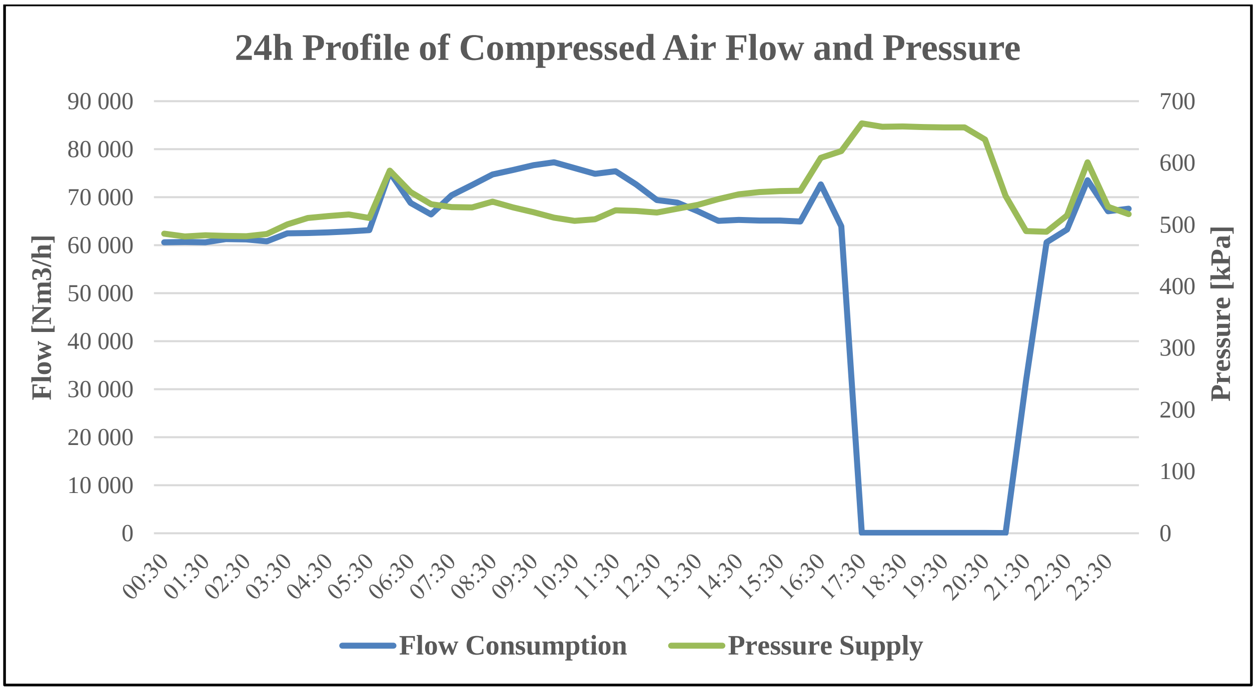


Figure 5: Typical compressed air requirement profile on a platinum mine

Due to inefficiencies in the compressed air network, end users such as the pneumatic drills, mechanical loaders and loading chutes typically receive compressed air at much lower pressures than that supplied by the surface compressors. Reduced pressures result in lower operational efficiencies of the machinery.

1.2.2 Supply-side

Compressors on surface generate the compressed air that is used to operate machinery underground. The function of a compressor is to increase the pressure of air at atmospheric conditions by reducing the air's volume [19]. There are different types of compressors namely, reciprocating, rotary, centrifugal and axial.

The centrifugal compressor is the most common type of compressor used by gold and platinum mines. This type of compressor is used due to its large operating range and relatively small size when compared to an equivalent axial flow compressor [20].

An important factor in assessing a compressor's operational value is the pressure or compression ratio. The compression ratio can be defined as the ratio of the absolute discharge pressure to the absolute suction pressure, shown in Equation 1 [21].

Equation 1: Compression ratio formula

$$CR = P_2/P_1$$

Here,

- P_1 = Absolute suction pressure [kPa]
- P_2 = Absolute discharge pressure [kPa]

The centrifugal compressor is capable of reaching compression ratios of three or fewer per stage for multi-stage compressors [20]. Comparing the above-mentioned with industrial axial flow compressors, which can achieve compression ratios of 1.05 – 1.20 per stage [22], the centrifugal compressor is the best choice to generate the high-pressure compressed air that is required by mining applications. The impact on energy usage with the different compression ratios of the different types of compressors are irrelevant to this study.

These centrifugal compressors are typically found in pairs of two or more to prevent the mine from ceasing all operations in case of a breakdown or scheduled maintenance. Multiple compressors supplying compressed air from the same location are referred to as compressor houses.

The centrifugal compressors utilised on platinum mines vary in size from 1 MW to 5 MW, and supply compressed air at a flow rate between 30 500 Nm^3/h and 170 000 Nm^3/h at an approximate pressure of 5.5 bar, depending on the time of day [23]. Figure 6 shows a typical example of a centrifugal compressor on gold and platinum mines.

The compressed air generated from these centrifugal compressors is sent to the end-users through a distribution or reticulation network.

Figure 6: Photo of a centrifugal compressor found on a mine [20]

1.2.3 Distribution network

Preamble

This section aims to describe the compressed air distribution or reticulation networks on the surface as well as underground and will also highlight typical network inefficiencies and losses that are experienced on platinum mines. The distribution network is a critical component in the overall system as it must transport the compressed air generated by the compressors to the end-users with minimal pressure loss.

Surface network

The compressed air supplied by the compressors is transported to the end-users via a complex network of pipes referred to as the reticulation network. The compressed air network can be divided into three main sections, according to [24], which have been adapted to conform to a mining reticulation network, namely:

- **Risers** – the section of piping transporting the air from the compressor house to the shaft.
- **Distribution pipes** – the section of piping that splits the air across the different levels of the mine.
- **Service pipes** – The section of piping that routes the air from the distribution pipes into the working areas.

The distribution network's routing and dimensioning must be designed to mitigate network inefficiencies which will be discussed in a later section.

Two types of surface distribution network configurations are commonly used, namely, Stand-alone and Ring Feed networks [25], [26].

The stand-alone network consists of a single compressor house feeding the demand-side users and is typically connected directly with a network of compressed air pipes [25], [26]. Figure 7 shows a representation of such a network.

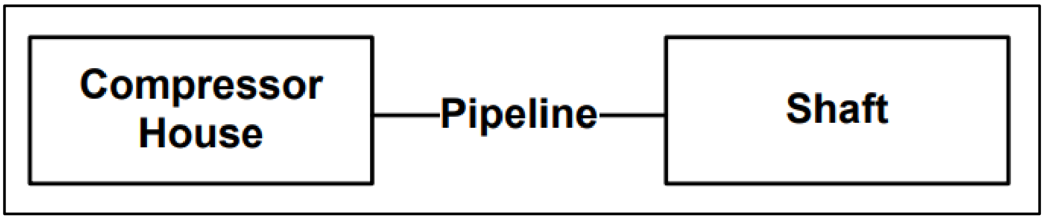


Figure 7: Stand-alone network example [23]

A ring feed network, however, consists of a network of interlinked compressor houses and shafts that is dependent on all the components in the network to function correctly [25], [26]. This type of network is more dynamic with the supply of compressed air to the shafts. It provides more possibilities to mitigate compressed air pressure loss that can be experienced at a shaft compared to a stand-alone network. Figure 8 shows a representation of such a network.

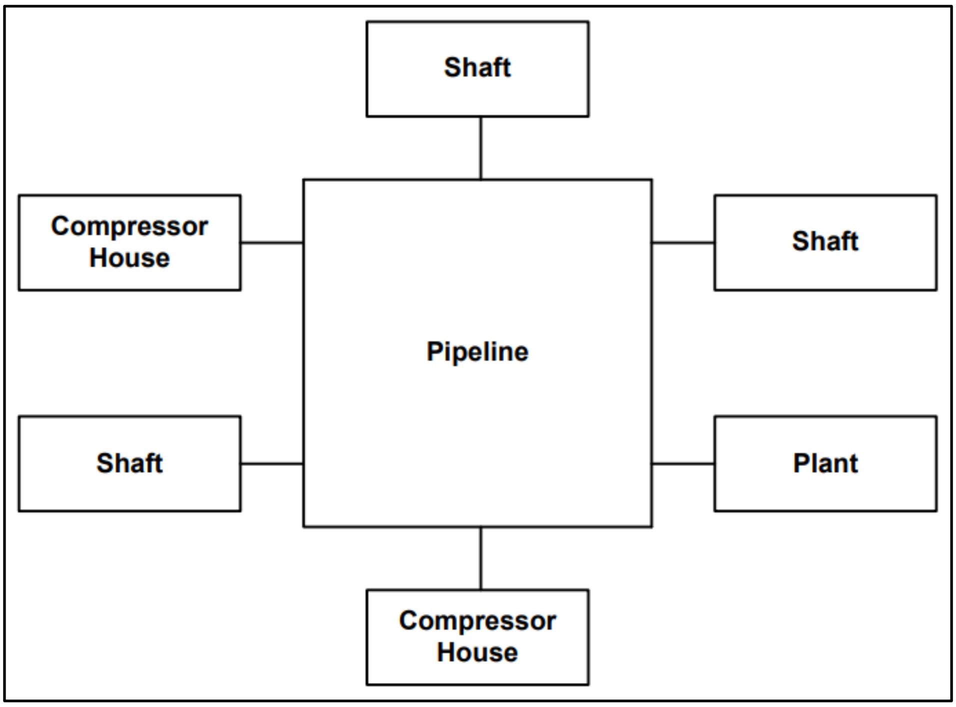


Figure 8: Ring feed network example [23]

Underground network

Platinum mines consist of underground sections to which the distribution network must split or tie off to supply the sections with compressed air at a required pressure and flow. A mine typically consists of a vertical and/or incline shaft that transports the miners from surface to the respective levels they work on. Each level consists of various workshops and bays.

From the level station, the level splits into the Merensky reef and UG2 reef. The reefs then split into two drives, namely North and South. On these drives, crosscuts are found that lead to the stopes, where drilling and blasting occur. Figure 9 is an illustration of a deep-level underground platinum mine's layout. The black lines represent haulages and travelling ways.

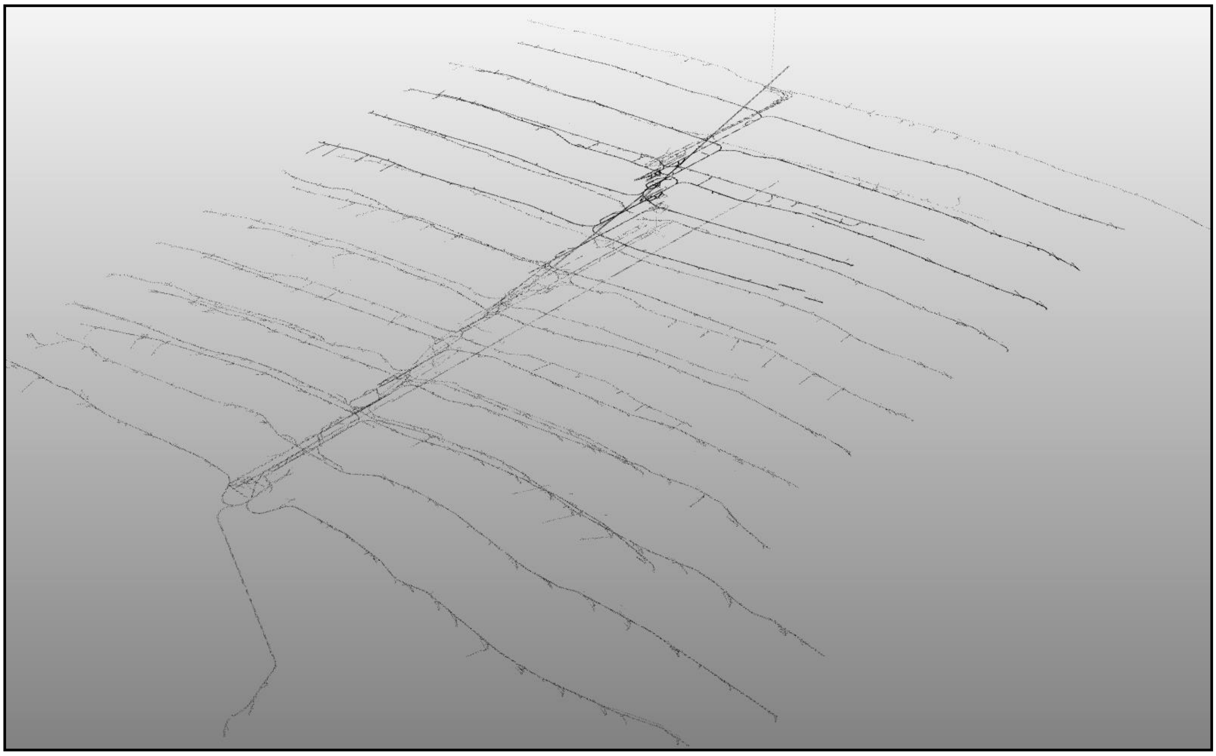


Figure 9: Illustration of an underground mining layout

Distribution network sizing

An observation of the distribution pipe sizes can be made as the network travels deeper underground. When the network splits from the main shaft column to the various levels, from the levels to the drive haulages, from the haulages to the crosscuts and from the crosscuts to the stoping areas, with each split, the compressed air pipes decrease in size.

The distribution network can be seen as a complex mass balance problem. Different demands, with different flow and pressure requirements, at various locations must be supplied with air from the main column, which is at a certain flow and pressure. Decreasing pipe sizes are utilised to limit air supply to a certain location. Reducing the cross-sectional area of a pipe reduces the volumetric flow of the air and increases the velocity of the air. Bernoulli’s principle shows that an increase in the velocity of the air leads to a decrease in the pressure of the air.

Network inefficiencies

Compressed air consumption is directly correlated to the production rate of ore since the most energy-intensive processes occur during the drilling shift [27],[28]. Compressed air, however, is regarded as one of the most inefficient systems implemented on deep-level mines [16].

When considering compressor and drill efficiencies and network losses such as outdated piping and CA leaks, the overall system efficiency can be as low as 2% [12]. The inefficiencies are further exacerbated when factoring in the sheer size and complexity of the network. Compressed air distribution networks can reach lengths of up to 40 km [29].

This section discusses and analyzes typical inefficiencies found on deep-level platinum mines.

Air coolers

The process of compressing air causes the air temperature to rise. A centrifugal compressor's average outlet air temperature is 107.2 °C for ambient inlet temperatures [30]. Air coolers are used to lower the increased temperature of the air after each stage of compression.

At these high temperatures, approximately 0.13 kg of water is present in a cubic meter of compressed air [26]. As the air travels through the distribution network to the end-users, the air will cool down, which causes the water vapour to condense and form liquid water. To mitigate the effect water will have on equipment and the piping itself, intercoolers and/or aftercoolers are fitted on compressors after each compression stage.

The aftercooler is a water- or air-cooled heat exchanger that reduces the air's temperature, causing the water vapour to condense [30]. The aftercooler allows for the water to be removed from the compressed air network at the supply side via a water trap [31]. The water trap will be discussed in more detail in Chapter 3.8.

According to a study [30] the main advantages of aftercoolers are the reduced moisture level in the compressed air, the equipment is protected from excessive heat, and the risk of hot compressed air pipes causing a fire is reduced.

However, aftercoolers cannot remove all the moisture from the compressed air. Couple this with the fact that with time the efficiency of the aftercoolers decreases, and if maintenance is not done regularly, the damaging effects of the water vapour entering the CA network become apparent.

Water in a compressed air network leads to [31]:

- Lower productivity,
- increased maintenance, and
- higher operating costs.

The loss of production can be experienced due to pressure drops when rust forms on the inside of the compressed air pipes, causing the friction between the air and the pipe to increase dramatically. The pressures that the demand-side users require to operate efficiently cannot be supplied, leading to a decrease in production (discussed in Chapter 1.3).

This section highlighted the importance of reducing water in the compressed air network as it can lead to damage that is difficult to identify and that can be costly to rectify.

Line losses

In a long, complex network of pipes, the air flowing in the pipes experiences pressure losses due to friction. As the distance the air travels increases, so does the loss in pressure [32]. The following factors also contribute to pressure losses [27]:

- The diameter of the pipes,
- the material of the pipes,
- bends in the network,
- the volumetric flow of the air,
- the velocity of the air, and
- the pressure of the air.

The Darcy-Weisbach equation can be used to calculate the pressure drop over large sections of compressed air networks [27].

Equation 2: Darcy-Weisbach Equation

$$\Delta P = \frac{f \rho L Q^2}{2D}$$

Here:

ΔP	=	Pressure loss	[kPa]
f	=	Darcy friction factor	[-]
ρ	=	Density of air	[kg/m^3]
L	=	Pipe length	[m]
Q	=	Volumetric flow rate	[m^3/s]
D	=	Inside pipe diameter	[m]

Another dimensionless parameter is required to calculate the dimensionless Darcy friction factor, namely the Reynolds number. This parameter Equation 3 illustrates the formula for the Reynolds number:

Equation 3: Reynolds number

$$Re = \frac{\rho v D}{\mu}$$

Here:

Re	=	Reynolds number	[-]
ρ	=	Density of air	[kg/m^3]
v	=	Flow velocity	[m/s]
D	=	Inside pipe diameter	[m]
μ	=	Viscosity of air	[kg/m.s]

The flow characteristic of the compressed air must be considered when determining the friction factor. For laminar flow, the friction factor can be expressed as:

Equation 4: Darcy friction factor for Laminar flow

$$f = \frac{64}{Re}$$

However, the flow characteristic of compressed air used in mining can be seen as turbulent [32]. To calculate the Darcy friction factor for turbulent flow, the Colebrook-White equation can be used:

Equation 5: Colebrook-White Equation

$$\frac{1}{\sqrt{f}} = -2\log_{10}[\frac{e}{3.7D} + \frac{2.51}{Re\sqrt{f}}]$$

Here:

f	=	Darcy friction factor	[-]
e	=	Surface roughness	[m]
D	=	Inside pipe diameter	[m]
Re	=	Reynolds number	[-]

The Colebrook-White equation, however, requires iterative solving with an initial guess value [33], [34]. To simplify the solving of the Darcy friction factor, the explicit Swamee-Jain equation can be used:

Equation 6: Swamee-Jain Equation

$$f = \frac{0.25}{\{\log[\left(\frac{\varepsilon}{3.7D}\right) + \left(\frac{5.74}{Re^{0.9}}\right)]\}^2}$$

Here:

f	=	Darcy friction factor	[-]
ε	=	Surface roughness	[m]
D	=	Inside pipe diameter	[m]
Re	=	Reynolds number	[-]

From the above equations, the influence of the characteristics of compressed air and the state of the network infrastructure on demand pressure is seen. No system is ideal; thus, line losses will always be present when investigating a network of pipes.

The age of the infrastructure also impacts the demand-side pressure. As mentioned, moisture is present in the compressed air, which causes the pipes to rust over time. The friction coefficient of the pipe increases as the pipe surface roughness increases. A study [27] shows the effect surface roughness of a pipe has on the compressed air pressure loss in Figure 10. The study illustrates this by varying air flow rate through 100 m of pipe with a constant diameter.

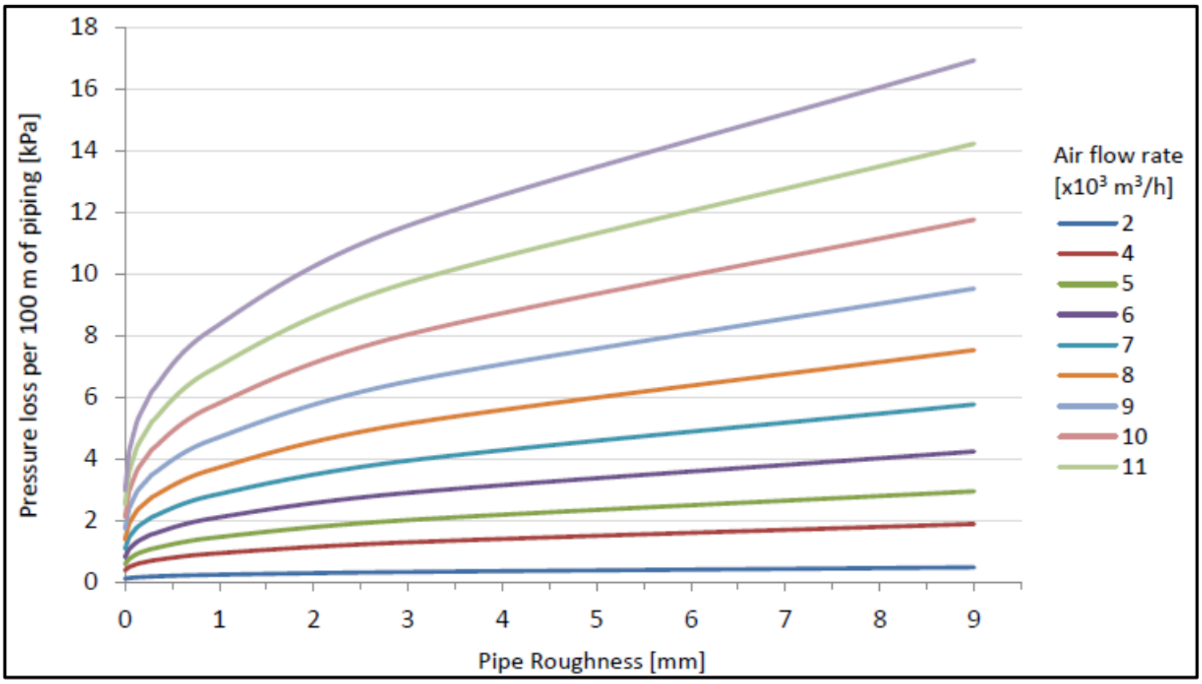


Figure 10: Pressure losses due to pipe surface roughness [27]

This study also shows how increasing the rate at which compressed air flows results in decreasing the pressure of the air.

The amount and severity of bends in the network also contribute to line losses experienced.

Compressed air leaks and wastages

Leaks and wastage occur on all mining compressed air networks due to the size and complexity of the networks. A leak is a localised event on a piping network where the working fluid, compressed air in this instance, escapes from the system into the atmosphere.

According to a study [28], up to 70% of the total underground compressed air demand for an underground mine were caused by leaks, wastages, and losses. This is supported by another study [29] that was performed on two mines namely, a 30-year-old mine and a 20-year-old mine. It was found that 52% of the installed compressor capacity were lost to leaks on the 30-year-old mine and 39% of the compressor capacity were lost to leaks on the 20-year-old mine.

From the study [29], 867 leaks were identified on the 20-year-old mine. The sources of the leaks are given in Figure 11.

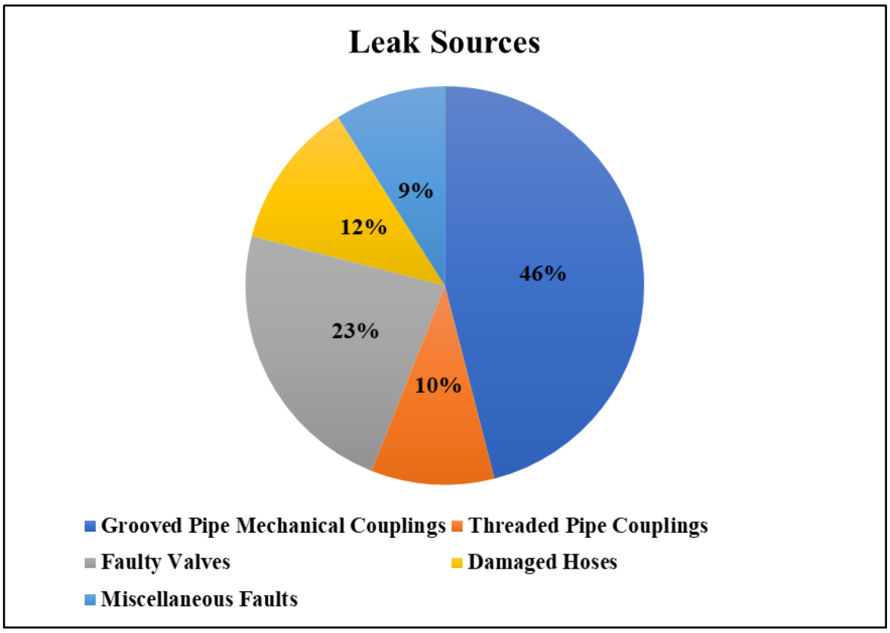


Figure 11: Breakdown of leak sources [adapted from 29]

The base load consumption of a shaft represents the rate at which compressed air is consumed when the shaft is in a minimum or non-operating mode. As discussed in a previous section, during drilling shift (6am – 2pm) the highest number of air consumers are operating. As seen in Figure 12, the base load represents 70% of the peak or drilling shift load [28].

The flow data used for compiling the base load are measured upstream from all the consumers and thus a high base load is indicative of an inefficient network. The causes for such a high base load compared to the peak load includes, but are not limited to, the following system losses [28]:

- Air leaks on distribution and stoping networks.
- Excessive unauthorised ventilation.
- Inefficient refuge bay ventilation control.
- Ineffective water traps causing build-up of moisture in the network.

Typically, high base loads correlates to under-performing rock drills due to pressure loss experienced at the demand-side. The aforementioned leaks and wastages in the network cause this pressure loss.

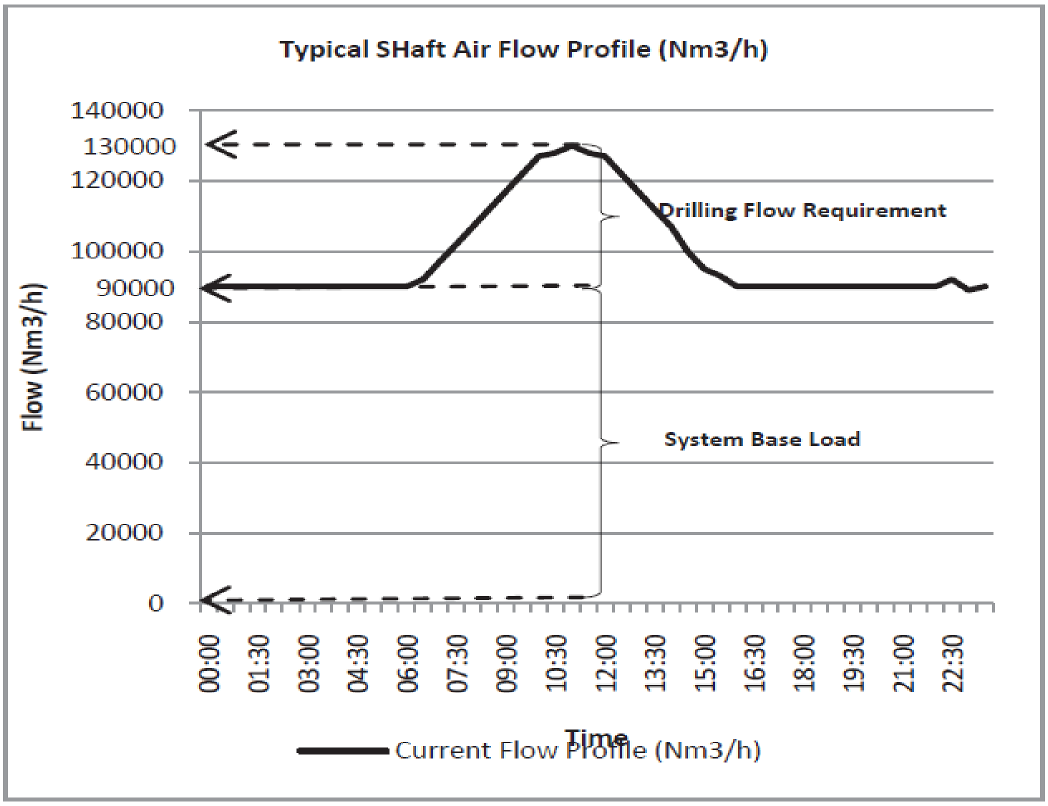


Figure 12: Compressed air consumption profile [28]

Compressed air wastages, in principle, have the same effect on the downstream pressure as does leaks. However, with wastages, compressed air is consumed and lost due to unauthorised usage.

One of the biggest challenges faced in deep-level mining is the high temperatures experienced underground. The virgin rock temperature (VRT), or the heat trapped inside the earth, increases as the depth of the mine increases. A study [29] found that the VRT of the Bushveld Complex can reach up to 70 °C at a depth of 2.2 km. Surface refrigeration plants are utilised to lower the temperatures underground. For mines exceeding a depth of 2 km, secondary (underground fridge plants) and tertiary (cooling carts either on the haulages or inside the crosscuts) cooling are utilised.

Platinum mines, however, rarely exceed the 2 km mark; thus, only surface cooling is required. These high temperatures, coupled with inadequate mining ventilation (as the mining operations expand underground, the demand on the installed ventilation infrastructure increases) and other factors such as water being used for the suppression of dust in the working areas (increases the humidity of the ambient air), results in miners abusing compressed air to ventilate their working places and cool themselves.

As ventilation air travels from the station into the level, the air picks up heat from various sources such as diesel engines, water pumps, workshop equipment, return air from crosscuts mixing with the cool intake ventilation air etc. and therefore the hottest area of a level is typically found deeper into the level. Most active crosscuts and thus stopes where drilling occurs are usually near the developing ends (furthest away from the station).

Miners use compressed air as a means to cool themselves and to ventilate their working areas. This unauthorised use of compressed air is one of the largest contributors to a loss of pressure at the demand-side. Typically, 1-to-2-inch hoses are used, or holes are punched in the compressed air pipes for ventilation, which causes large compressed air pressure drops.

The compressed air supplied to this unauthorised usage is at pressures of anything between 100 kPa and 400 kPa, depending on the severity of the hole or size of the hoses.

Substandard piping

As discussed, the distribution network is a vital component in supplying the end-users with compressed air. The network is designed following specific standards set by the mining group or governing body to ensure that the demand-side receives compressed air at the required flow and pressure to operate the various pneumatic equipment efficiently [35].

At the developing ends, however, incorrect pipe sizes or pipes made of a different material than specified by the standards are frequently installed. This can be due to:

- a shortage of the correct pipe or pipe size,
- certain type of pipes being easier to install than others, or
- servicemen and riggers who are unwilling to transport pipes up a travelling way due to the weight of the pipes.

The pipe's size and material influence the compressed air pressure supplied to the end-users such as the pneumatic drills. Typically, the incorrect pipes are found from the crosscuts up until the rock face. Therefore, the effect of substandard piping directly influences the performance of the pneumatic drills and in turn, the production of the shaft.

Incorrect pipe size

Bernoulli’s principle can be used to explain the relationship between the velocity and pressure of the air flowing inside a pipe [36]. As the pipe diameter decreases, the velocity of the air increases. To abide by the law of conservation of energy, the pressure of the air must decrease. However, this assumes that the flow is laminar and no energy is lost due to dissipative forces such as friction between the air and the pipe walls. Equation 7 shows the relationship between the pressure and velocity at two points, where point 1 is at a larger diameter than point 2.

Equation 7: Bernouilli's Equation

$$P_1 + 0.5\rho v_1^2 + \rho g h_1 = P_2 + 0.5\rho v_2^2 + \rho g h_2$$

Here:

P	=	Pressure	[Pa]
ρ	=	Fluid density	[kg/m^3]
g	=	Gravitational acceleration	[m/s^2]
v	=	Fluid velocity	[m/s]
h	=	Fluid elevation	[m]

When undersized pipes are used, which is typically more likely to be found at the development end than oversized pipes, the downstream pressure will be lower, directly affecting the equipment's performance. Another consequence of undersized pipes to be considered is that due to a higher velocity, there exists a greater risk of erosion of the pipe’s inner walls and an increase in noise [37].

Pipe material

The platinum mining industry's standard material for compressed air pipes is schedule 40 carbon steel [38]. This pipe material can be found from the surface to the flat or development ends of the various levels.

However, the use of HDPE (High-Density Polyethylene) pipes is mostly found in crosscuts nearing the development end of a level. Compared with the carbon steel pipes used, the HDPE pipes cost less and are made of a flexible, lightweight material, resulting in faster and easier transportation and installation.

Due to the lack of rigidity in the HDPE pipes and pipes hanging due to insufficient pipe supports in the crosscuts (usually held up by single chains), the pipes tend to sag and form troughs in the line. These troughs are also caused when pipe sections are not cut to the correct length. This causes unnecessary bends, which increases the K-value or resistance coefficient to the piping network and can result in pressure losses. Due to gravitational forces, water or moisture in the pipes will accumulate at the lowest point in the pipeline. When water accumulates in a certain spot, it effectively reduces the area where the compressed air can flow. As previously mentioned, reducing the diameter, or more accurately, the cross-sectional area of a pipe, will decrease downstream pressure.

1.2.4 Demand side

Compressed air and the use thereof are critical components in the operations of a wide variety of equipment in mining. It is used in both the mining and processing of ore. The success of a mine is dependent on how efficiently compressed air is 1) supplied to the demand-side and 2) utilised by the equipment consuming the air. The following are examples of typical mining applications that require compressed air to function [28]:

Pneumatic drills

As discussed earlier in this section, pneumatic drills are used to create blast holes. They are an essential component in the mining industry as they are used to advance the rockface in stoping areas, to extract the PGM containing ore, and in the haulages and working places to expand mines for new development. Pneumatic drills come in many different shapes and sizes, each suited for a specific application or designed to operate in certain conditions.

The preferred drilling rig for narrow reef mining, which is also used on South African platinum mines, is a compact handheld pneumatic drill supported on a stand. The small size allows a single user to operate the drill.

Pneumatic drills operate at pressures of between 400 kPa to 600 kPa [39].

Mechanical loaders

Mechanical loaders are machines that are operated with the use of compressed air to remove and transport newly blasted rock away from working areas and development ends. This must be done before development crews can continue drilling and laying tracks for locomotives to operate in the development ends of a haulage.

Mechanical loaders operate at pressures between 400 kPa and 500 kPa [39]. Due to these loaders being operated at development ends, typically the furthest point away from the compressed air supply to the level, most loaders struggle to operate efficiently due to the pressure loss that exists over the span of the half-level pipe network. This loss in pressure will be discussed in the following section.

Loading boxes/ Loading chutes

After blasting, electrical winches and scrapers are used to transport the blasted rock to ore passes in the stopes. These ore passes feed the loading boxes on a lower level. The loading box serves as a temporary storage unit for the blasted ore. During the cleaning shift, hoppers (driven around by locomotives) are positioned under the box in front of the loading box. Pneumatic actuated cylinders are then operated to open the loading boxes to fill the hoppers and empty the loading boxes.

The loading boxes operate at pressures between 350 kPa and 450 kPa [39].

Refuge bays

Refuge bays are areas throughout the mine that are used in case of emergencies such as fall of ground incidents, fires occurring underground and/or when incidents occur causing inadequate ventilation in working areas. These areas are used as assembly points in emergencies and are generally seen as a “safe zone” when miners get exhausted from heat exposure or other ailments.

The South African Mine Health and Safety Act requires refuge bays to always have an uninterrupted supply of compressed air [40]. In emergencies, the compressed air provides oxygen and cooling to the miners that assemble in these areas.

The compressed air is supplied at a pressure of 200 kPa [39].

1.3 Correlation between pressure and production

The primary method of producing ore on platinum mines are by drilling holes into the rockface and blasting the rock containing the platinum ore into smaller, more manageable and transportable sizes. Pneumatic drills are mostly used to accomplish this task.

A key indicator of determining the drill's performance is called the rate of penetration (ROP) which is the time elapsed to progress a certain depth into the rockface [41]. The ROP is affected by three factors, namely,

- drill bit characteristics,
- rock characteristics, and
- operational variables.

For this study, the first two factors are negligible. The operational variables of a drill includes the percussive and rotational power generated due to compressed air pressure, the thrust force applied by the operator-controlled air leg and the efficiency of flushing the drill hole of debris [41], [42].

Studies [12] and [43] were conducted to compare and test different rock drills to determine the most effective type of rock drill. Figure 13 illustrates the effect of increasing the compressed air pressure supplied to the drill on the rate of penetration of the pneumatic drills. The data displayed in the graph was obtained from measurements made underground on the UG2 platinum reef, which aligns with this study. The shaft where this study was conducted is situated on the UG2 reef and utilises the S215 rock drills.

The S215 rock drill is most found on deep-level platinum mines. Figure 13 shows the rate of penetration significantly improves when the compressed air pressure supplied to the drills is more than 450 kPa.

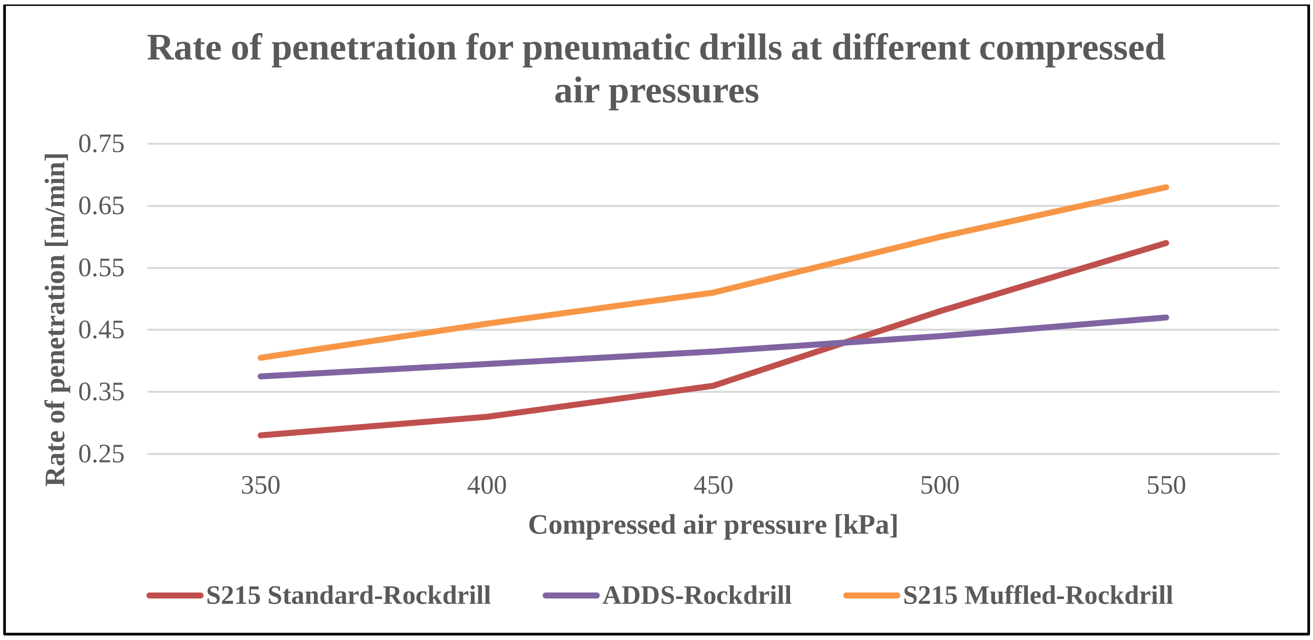


Figure 13: Rate of penetration comparison (adapted from [12])

A study [33] was conducted to determine the impact on production when the rate of penetration for the drills were improved. The study found that improving the rockdrills' ROP, which leads to less time to drill a hole, resulted in an increase in the number of holes that could be drilled per shift. This, in effect, leads to more ore that can be blasted, resulting in an increase of production for the shaft.

Another study [44] was conducted to determine the effect on production due to insufficient compressed air pressure supplied at the rock drills. The author assumed production as the total area mined per day on a face and compared the days with inadequate compressed air pressure supply (lower than the minimum required drilling pressure of 400 kPa) to days with sufficient drilling pressure (average of 450 kPa). The study found that days with less than 400 kPa CA pressure on average resulted in 30% less area mined.

Therefore, by improving the compressed air pressure supplied to the demand-side, the production of the shaft will improve.

1.4 Simulation software

Simulations are extremely useful tools that can be used to determine the feasibility of a project before implementation and can accurately depict various flow and pressure scenarios [45]. The following table compares different flow simulation packages to determine the best suited for simulating the flow and pressure of compressed air in a mining network.

Table 1: Simulation software functionality comparison

Simulation package	Network analysis	Dynamic analysis	Optimisation	Scenario investigation
Flownex[1]				
KYPipe[2]				
Solidworks[3]				
Process Toolbox [45]				
Thermoflex[4]				
Ansys[5]				

From Table 1, it is clear that a number of simulation packages meet the requirements to accurately simulate a mining compressed air distribution network. However, Process Toolbox (PTB), a thermohydraulic semi-transient simulation software package, is in-house software; thus, no additional licensing is required. For this study, PTB will be used for the required simulations.

[1] www.flownex.com
[2] www.kypipe.com
[3] www.solidworks.com
[4] www.thermoflow.com
[5] www.ansys.com

1.5 Literature review

The previous sections give an overview of the utilization of compressed air in deep-level underground platinum mines and how inefficiencies in the network can impact the demand-side pressure. This section will review existing literature to identify possible solutions to the loss of compressed air pressure over a distribution network.

The following key aspects were determined as the main criteria of the literature review:

1. **Pressure drop reduction** – What are viable methods to reduce pressure drops found in compressed air distribution networks?
2. **CA network inefficiencies** – Do the studies identify and address any inefficiencies on the network?
3. **Demand-side initiatives** – What has been done in the engineering field to address the issue of reduced service delivery performance at the end-users?
4. **Compressed air infrastructure** – How does the compressed air get distributed to the end-users, and are there any inefficiencies that can be identified?
5. **Production benefits** – How, if possible, does improving service delivery affect the mine's production?

The following studies were identified using various online libraries and databases such as Elsevier, Scopus and ScienceDirect. Keywords used to search the databases included terms such as 'compressed air', 'demand-side', 'energy', 'optimisation', 'pressure', 'production', 'mining', 'networks', and many others. However, not all studies having a high correlation to the keywords were used. Studies chosen were narrowed to only the mining industry as they would have the most relevancy to this study.

Study 1: Reconfiguring mining compressed air networks for cost savings (2014) [27]

Overview

The study focuses on generating cost savings in the form of cost payback and total savings over the life of mine as well as decreasing maintenance costs by proposing strategies to reconfigure surface compressed air networks. The author highlights the importance of, and incorporates the impact of line pressure losses in the development of solution.

Shortcomings/Recommendations

However, the scope of the study does not include the line losses' effect on production. The author recommends implementing reconfiguration strategies on underground distribution networks to eliminate inactive areas being supplied with compressed air.

Study 2: Local benchmarking in mines to locate inefficient compressed air usage (2019) [46]

Overview

The study provides a methodology for identifying levels with compressed air inefficiencies. The methodology correlates compressed air supply and production. By implementing the proposed methodology, the author was able to identify inefficient levels and reduce the compressed air consumption of the shaft. A slight increase in production was realised with repairing leaks and reducing wastages.

S***hortcomings/Recommendations***

The study, however, does not include improving the demand-side compressed air pressure.

Study 3: Energy efficiency opportunities in mine compressed air systems (2009) [31]

Overview

The study proposed various demand-side management strategies to achieve compressed air savings. The study focused pre-dominantly on compressor selection strategies, pressure control strategies and leak detection to reduce the load on compressors, which leads to a reduction in electricity usage.

Shortcomings/Recommendations

The study focused on energy savings and not quantifying the impact on production. The author recommended that future work include minimising pressure drops on the distribution network.

Study 4: An integrated approach to optimise energy consumption of mine compressed air systems (2012) [29]

Overview

The study focuses on various methods to reduce compressed air energy consumption on mines such as reducing components dependent on compressed air, maintaining compressor air filters, and repairing leaks.

Shortcomings/Recommendations

The study mainly focused on high-level initiatives to increase potential savings but the author recommended investigating initiatives on the distribution network to further increase savings potential.

Study 5: Simulating operational improvements on mine compressed air systems (2018) [47]

Overview

The study aims to improve the efficiency of a compressed air network by developing a simulation methodology. The simulation model methodology considers a range of network inefficiencies such as air leakages, faulty valves, pipe losses, obstructed compressor intake air filters and inefficient equipment. With the methodology, a scenario where compressed air flow into refuge bays is regulated was simulated and it was found that potential energy savings and an increase in pressure are achievable. This study suggests that simulation is a powerful tool to determine the feasibility of a possible solution.

Shortcomings/Recommendations

The study, however, does not implement the simulated results but only shows that it is possible to find possible solutions through simulation.

Study 6: Optimising production through improving the efficiency of mine compressed air networks with limited infrastructure (2017) [33]

Overview

The study focuses on optimising the production of a gold mine by investigating the compressed air network and improving the demand-side pressure. The study's results show that a sizable production improvement is possible when improving the pressure supplied to the end-users.

Shortcomings/Recommendations

The study, however, focuses solely on improving sub-standard piping to increase network efficiency. The author recommends developing a leak quantification model and investigating alternative methods to mitigate system fluctuations.

Study 7: Improving efficiency of a mine compressed air system (2017) [48]

Overview

The study focus on implementing initiatives such as fixing leaks, adjusting compressor pressure setpoints and reducing pressure demand with control valves.

Shortcomings/Recommendations

This study solely focused on the implemented initiatives' effects on the mine's power consumption and did not include production benefits. However, the author developed a leak auditing procedure that simplifies the process of identifying problem areas. The author recommended line loss improvement be investigated for future work, which could potentially increase end-user pressure and production.

Study 8: Cost and time effective DSM on mine compressed air systems (2010) [49]

Overview

The study focuses on implementing demand-side management initiatives to reduce the electricity consumed by mines. Initiatives such as leak fixing and controlling air consumption with valves were investigated to lower the compressed air consumption.

Shortcomings/Recommendations

This study, however, does not include effects on production when network inefficiencies are improved. The author recommends repairing and maintaining air leaks as this will further enhance the efficiency of the compressor control strategy that was developed during the study.

Study 9: Practical approach to analyse mine pneumatic drilling performance (2019) [44]

Overview

The study focuses on improving production by developing a holistic overview methodology that analyses the case study mine's service delivery and production performance using key performance indicators. The study found that R3.5 million lost production occurred due to inadequate compressed air supply over a period of five months.

Shortcomings/Recommendations

The study, however, did not implement initiatives to reduce network inefficiencies on the supply side. The author recommends monitoring and addressing compressed air wastage to prevent future production loss.

Study 10: Methods to optimise underground mine production (2002) [50]

Overview

The study focuses on improving production by analysing the required facilities such as equipment, services, and infrastructure to achieve optimised production. A mine production planning system (Half-Level Planning) was designed to optimise conventional operations. The development and implementation of this system involved continuous input from the engineering and mining departments. The output of this model was to provide the potential sustainable capacity per half level for increased production.

Shortcomings/Recommendations

The Half-Level Planning model mostly addresses issues regarding labour and does not provide reasons for production loss due to network inefficiencies.

Summary

A state of art matrix can be created from the studies mentioned above. The state of art matrix is simply a summary of the above studies with key aspects highlighted. These key aspects are chosen with relevance to this specific study.

Table 2: State of the art matrix of the literature study conducted

Study	Pressure Drop Reduction	CA Network Inefficiencies	Demand-side Initiatives	CA Infrastructure	Production Benefits
1	[green]	[green]	[red]	[green]	[red]
2	[red]	[green]	[green]	[red]	[green]
3	[red]	[red]	[green]	[green]	[red]
4	[red]	[red]	[green]	[red]	[red]
5	[green]	[green]	[red]	[red]	[green]
6	[green]	[green]	[red]	[green]	[green]
7	[red]	[red]	[green]	[green]	[red]
8	[red]	[green]	[green]	[red]	[red]
9	[red]	[green]	[red]	[green]	[green]
10	[red]	[red]	[red]	[green]	[green]

The green blocks indicate that the specific reference researched and/or incorporated the relevant aspect into their methodology and results.

The tabulation of the literature findings in Table 2 indicates that the majority of the research focuses on implementing demand-side initiatives and improving the compressed air network inefficiencies. However, only two studies were done where both these aspects were considered, and from the two, only one study (focusing on only one initiative) correlated the two aspects with a production benefit. Most of the studies focus on implementing demand-side initiatives with the objective of making the system more energy efficient.

Table 2 shows a gap in the available literature regarding the effect a reduction in the overall compressed air pressure drop from the surface to the demand side will have on production when considering the entire distribution network from the supply side to the demand side.

1.6 Need and objectives for the study

1.6.1 Problem and need for the study

From the literature, it was found that one of the most inefficient systems on a platinum mine is the compressed air distribution network. These networks are fraught with leaks, ageing and substandard pipes, redundant and abandoned pipelines, faulty valves etc. Due to the limited monitoring capabilities on the mines, identifying these inefficiencies is often difficult and time-consuming, resulting in poor service delivery and production targets not being met.

Therefore, a need exists to identify, implement and test various initiatives to improve demand-side pressure losses in deep-level mining compressed air networks.

The potential improvement in pressure can then be used to quantify a potential production benefit with the application of methodologies found in research.

1.6.2 Objectives

To ensure the compressed air distribution network inefficiencies are reduced and an improvement in demand-side pressure is achieved, the following objectives must be accomplished:

1. Identify and evaluate compressed air network inefficiencies in deep mines.
2. Develop a generic methodology to identify and reduce compressed air network inefficiencies, which can be applied on any mine utilising compressed air.
3. Identify and implement feasible solutions that will improve the efficiency of the network and reduce pressure drops found from the supply side to the demand side.

1.7 Study overview

Chapter 1

Chapter 1 describes the background to the study and provides context of the problems faced on platinum mines with all relevant components involved. This section also provided literature that is relevant to the study. From this background and literature, a problem was identified, and a need for this study was identified.

Chapter 2

Chapter 2 describes a generic seven-step method to identify, evaluate and address network inefficiencies to reduce the pressure drops experienced on the distribution networks to improve demand-side working compressed air pressures.

Chapter 3

The seven-step methodology developed in chapter 2 was applied to different case studies. The process and main findings of the case study are discussed in detail in this chapter. This chapter serves as the results section of the study.

Chapter 4

Chapter 4 summarises the study and give recommendations for future work and study fields. This chapter serves as the conclusion of the study.

Chapter 5

Reference section.

Chapter 2 Methodology

2.1 Introduction

This chapter focuses on developing a methodology that identifies network inefficiencies through evaluation and data acquisition with the purpose of reducing pressure loss at the demand-side. This methodology aims to develop a generic approach to the process of improving demand-side compressed air pressure. A generic approach allows for greater versatility in problem-finding and solution development. Therefore, the practical relevance of the methodology will increase as it can be applied to all mines that utilise compressed air.

The demand-side pressure improvement methodology follows a seven-step process. The first step of the methodology focuses on identifying the scope of the problem. The next step focuses on evaluating and analysing the current state of the compressed air distribution network. After the network has been evaluated, operational data must be collected, which leads to the development of a baseline for the current system with which to do comparisons for any changes made to the system in the later part of this methodology.

When the first four steps have been completed, enough information and data will be available to formulate and propose a solution to the problem/s identified. The next step in the process is to verify the feasibility of the proposed solution by means of simulation (only if the necessary data is available to allow for simulation). Theoretical results are obtained during this step and allow for optimisation of the solution before implementation on practical systems. When the proposed solution has been implemented, tests can be conducted to validate the theoretical results. The steps the methodology consists of are as follows:

- Identify compressed air network inefficiencies.
- Evaluate the compressed air network.
- Data acquisition.
- Baseline development.
- Proposing solutions.
- Implementation.
- Verification and validation.

The methodology for this study was derived from the Engineering Design Process (EDP) [51] and will be adapted for specific use on mines with compressed air networks. The EDP is an iterative process that allows for problem identification, evaluation of the problem, refinement of the variables required to develop a solution and to implement, test and optimise the final solution. Therefore, this method is ideal for the challenges faced in this study.

Figure 14 illustrates the methodology that will be developed visually by way of a flow diagram. The details of each step will be discussed in depth in the following sections.

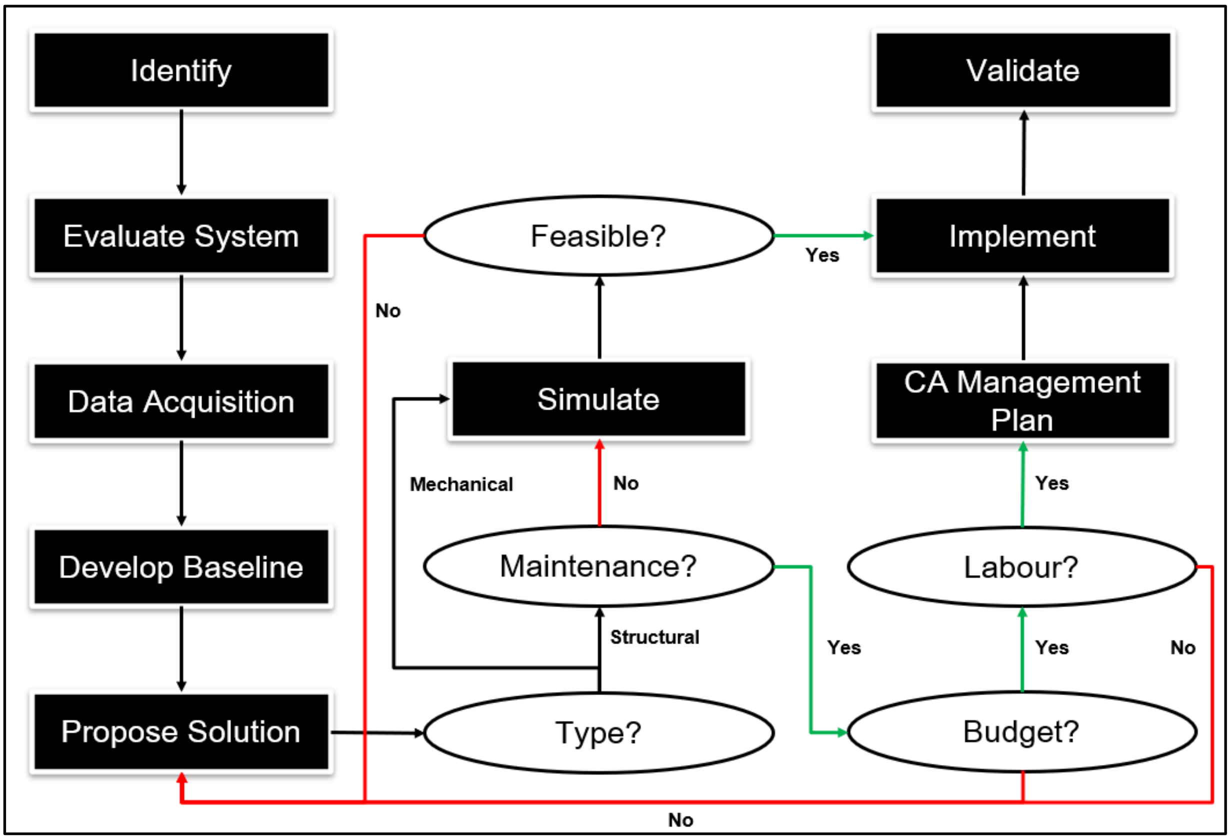


Figure 14: Methodology flow diagram for implementing feasible solutions to identified network inefficiencies

2.2 Identifying compressed air network inefficiencies

Chapter 1 discusses the size and complexity of deep-level mines' compressed air networks. The dynamic nature coupled with the complex and sometime intricate layouts of piping of such a network makes identifying network inefficiencies a daunting and difficult task to accomplish.

Before any problem or inefficiency can be identified, investigations must be launched on the desired network. To fully understand a mine's network can take months of investigation.

However, limiting initial investigations to high-level information gathering will reduce the time spent investigating.

2.2.1 Mining Layouts

Layout drawings can be a useful tool when acquiring data on a certain system within a mine [52]. Layout drawings can typically be found at a shaft's mine planning offices. These drawings are used to detail the entire system and will usually include, but are not limited to, the main components within the system. Examples of this detail includes where the compressors are, the piping infrastructure of the network, locations of workshops, working bays, working areas and any other additional information deemed necessary. These layout drawings can be found for the compressed air network, electrical reticulation systems, water reticulation systems and ventilation systems.

The compressed air network layout drawings can be of use when navigating a mine as well as provide information such as:

- The number of levels per shaft.
- The number of crosscuts per level.
- The length of the entire piping network.
- Active and inactive working areas.
- Redundant pipelines/infrastructure.
- Ring feeds.
- Number of panels per stope.

The layouts, however, only provide quantitative geographical information. To better understand the physical and mechanical properties of the compressed air utilised on a mine, other sources such as the SCADA system must be investigated, discussed in the following section.

2.2.2 SCADA

Supervisory control and data acquisition (SCADA) systems can typically be found on mines [53]. These control systems are required to remotely operate, monitor and collect data from various interconnected devices and sensors located underground and on surface [54]. Each mine has a dedicated centralised control room where operators are responsible for monitoring or controlling real-time data which is displayed textually and/or graphically on the SCADA software.

The devices are normally flow and pressure sensors, control valves, fan power switches, etc., controlled with a programmable logic controller (PLC). The PLC can be remotely controlled to switch the various equipment on or off, close or open certain valves, but is mainly used to log data from sensors that is then sent to the SCADA software in the control room.

These measurements are given as tags. Tags are unique codes or identifiers that bundles certain data such as flow of compressed air from a specific sensor at a specific location such as the outlet of a compressor. These tags can also be used to extract historic data for a specified period from an on-site database that enables the user to trend historic profiles of the required data for comparison, maintenance planning and problem identification.

Important measurements required to analyse the compressed air network of a mine include the following:

- Compressed air flow rate.
- Compressed air pressure.
- Valve position.
- Run statuses of the compressors.

However, the SCADA is not always a comprehensive data collection and analysis tool. The level of integration varies from mine to mine; thus, the required data will not always be present. When the required data is not available, data must be collected manually. Manual data collection can consist of retrieving data directly from sensors, usually older technology, such as mechanical pressure gauges, collecting written daily/weekly monitoring logs from relevant personnel (not always available or reliable) and/or manually installing equipment such as pressure and flow meters that log the data for a specified period due to a lack of measuring equipment, which is usually the case at older mines.

2.2.3 Network specifications

The best strategy to identify a problem on a complex and dynamic system such as a mine's compressed air distribution network is to fully comprehend the scope of the system. This can only be done by gathering as much information as possible. As more information is gathered and analysed, more variables can be eliminated and thus the likelihood of problem identification increases [55].

All information regarding the network will aid fault finding and thus to identify opportunities for improvement. The following information is also of importance:

- Various pipe sizes of the network
- Pipe material and installation methods used
- Condition of the pipes
- Network maintenance strategies
- Network development strategies
- Operating limits and design specifications
- Compressed air consumption and control strategies
- Compressed air demand during a 24-hour period across a mine
- Compressed air requirements per level/per haulage/per crosscut/per stope/per crew
- Miners' discipline surrounding usage of compressed air

The information mentioned above can all be factored in when identifying discrepancies in data. This will be important when identifying problems as some of these factors may mislead the investigation if not properly analysed.

2.2.4 Known historical problems

A lot of problems or issues that exist on a mine has been present for years. When starting an investigation, a reliable source of information is that of the experience of long-time employees at a mine. Engineers, managers, supervisors, foremen, overseers etc., are most often aware of specific issues that impact production or service delivery quality [50]. To narrow down an investigation to a particular system or sub-set of systems, it is wise to consult with people with experience on the mine in question.

Table 3: Mining personnel and responsibilities

Personnel	Area of Responsibility
Engineer	Surface and shaft (end at the start of a level)
Mechanical Foreman	Level station and haulages (end at the start of crosscut)
Mine Overseer	Crosscuts and stopes

2.3 Evaluating the compressed air network

When the scope of the compressed air pressure loss has been determined, and the requirements for demand-side pressure have been established, the next step will be to evaluate the current system. This step encompasses the main fault-finding process and network diagnostics.

This step aims to inspect and analyse the network to discover and investigate possible network inefficiencies that could be a cause for a loss of compressed air pressure at the end users. This step is also necessary to narrow the focus of the investigation by identifying the worst-performing areas. By identifying the worst performing levels or areas, less time is wasted on investigating areas and systems that may not have any issues that could impact the compressed air pressure.

2.3.1 Baseload tests

Baseload tests are conducted during periods when no mining activity occurs, typically during the blasting shift. These tests are performed to accurately evaluate the compressed air demand of each mining level [55]. This allows for easy identification of any unusually high demands leaks and wastages can cause. Continuous testing is a great tool to monitor the performance of a level over time if instrumentation such as level flow meters are not installed. Thus, baseload tests are ideal for identifying large consumption areas without conducting in-depth audits on the entire CA distribution network [57].

Baseload tests are performed by supplying the mine with compressed air as during normal operations. The isolation valve at the level station with the highest production (assumed that this level would have the highest demand) is closed first, effectively cutting off all compressed air entering the level. After the valve is closed, a drop in shaft flow and an increase in shaft pressure will be observed. When the flow and pressure has stabilized (normally within 20 minutes), the next level's valve must be closed. This process is repeated until all the levels are closed.

When all the levels are closed, the valves must be opened from the bottom up, with pressure and flow stabilizing after each opening. This is to verify the top-down test. The drop in flow seen by closing the isolation valve is the amount of compressed air that level consumes. Ideally, the test must be performed at the same compressed air pressure, but due to constant changes in operations at different shafts, the pressure will fluctuate. With the closing of each isolation valve, the supply pressure will also increase.

Due to the supply pressure influencing the flow, normalisation calculations are utilised to normalise the recorded flow to a new flow at a specific reference pressure. This allows the baseload flows to be comparable at the same pressure. The reference pressure that will be used during this study is 500 kPa, as this is the operational supply pressure of a platinum mine.

The formula used for normalising the flow is given in Equation 8.

Equation 8: Normalised flow

$$Nomalised\ Flow = \frac{Measured\ Flow}{Surface\ Pressure} \times Pressure_{Reference}$$

The procedure that will be followed is described below:

1. Abort control on the surface valve if the surface valve is a control valve set to a certain lowered pressure setpoint.
2. Ensure that all level valves are fully open and not throttled.
3. The level with the highest production should be closed first.
    a. Record the time at which the valve was closed. This serves as the start of the baseload test for the level.

b. Wait 15 - 20 minutes for the shaft pressure and flow to stabilise. This can be monitored using the SCADA live view.
c. After the allotted time has passed and the flow and pressure graph has reached a stable trend, a minimum of 5 minutes of data should be recorded, serving as the average baseload.

4. If step 3 has been completed, keep the valve closed and move on to the next valve in level order.
    a. As in step 3, record the time the valve was closed. This serves as the start of the baseload test for the level and serves as the baseload end time for the previous level.
    b. Repeat step 3 at the next valve.
5. Repeat step 3 for all the remaining levels of the shaft.
6. It is important to note that if, for any reason, there is a sudden change observed in flow and pressure, the test should be paused. When the flow and pressure has stabilised, the test can continue. These changes are typically due to compressors on the surface ring being switched on or off. These changes should be noted.

Extending the time for the system to stabilise will improve the accuracy of the results.

2.3.2 Visual inspection of levels

To determine the condition and the operational specifications of the compressed air network, a visual inspection of the different levels' piping must be completed. A visual inspection consists of walking and examining all the pipes while noting all components connected to the pipeline, changes in the pipeline, faults on the pipeline and any other type of discrepancy that might influence the behaviour of the compressed air inside the pipe [16],[58].

Visual and auditory inspections are one of the easiest and most efficient methods of finding leakages on the pipeline as an easily recognisable hissing noise accompanies the leaks. The following is important to note when doing a visual inspection:

- Faulty or broken valves
- Size and type of valves
- Valve locations
- Measuring points that will be used for level audits (typically a 1-inch ball valve)

- Sizes of the pipes
- Material of the pipes
- Changes in pipe sizes
- Tie-off pipes from main haulage line (size, type and material)
- Rust
- Leaks on pipes, flanges, valves, couplings etc. (location and severity)
- Possible blanking locations
- Illegal connections for ventilation
- Possible abandoned areas where pipes are running into.
- Active and inactive crosscuts
- Manifold locations and types
- Redundant or unnecessary bends in the pipeline

The network layouts of the levels and half-levels obtained in the first step are of utmost importance as this assists with reporting the findings since the locations of the leaks and other inefficiencies can be indicated visually. This will save time during repairs as the assigned personnel will not have to search for the leaks themselves or mistakenly repair an incorrect or less severe leak.

2.3.3 Measuring point identification

Measuring points should be identified holistically. This can be done by examining the incoming supply columns at different levels to easily identify problematic levels. Once the problematic levels are identified, further measurements can be conducted to determine whether attention should be given to points before or after a split [33].

The final measurement should then be placed at the initiation of a crosscut (X/C) and the end of the X/C, where air delivery will be (drills, etc.). The figure below illustrates the measuring point process. Measuring points are areas where a 1-inch ball valve is typically installed on the compressed air line where measuring equipment can easily be installed.

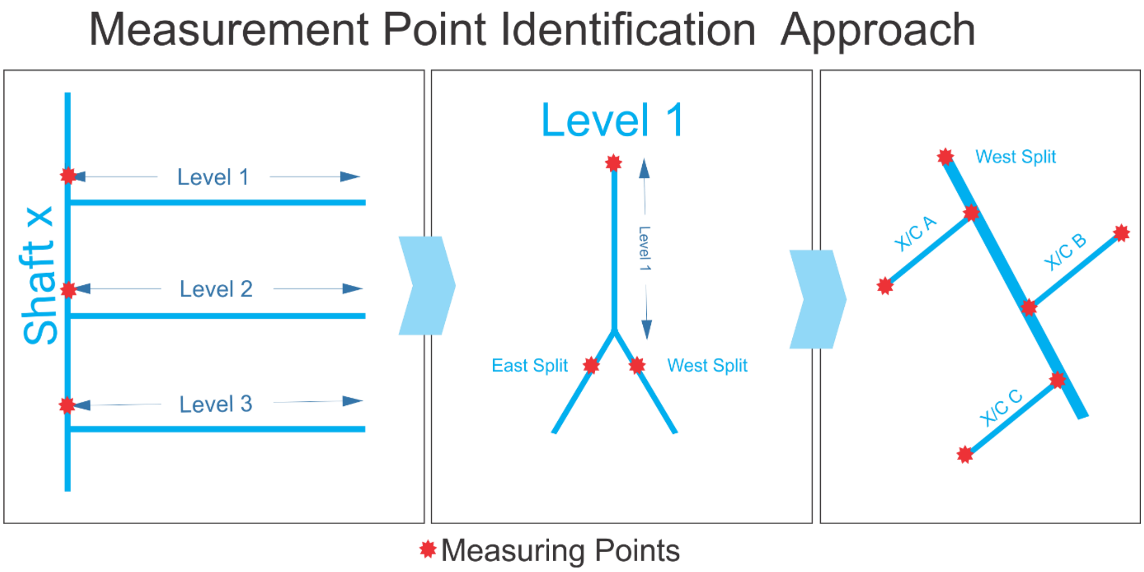


Figure 15: Measuring point identification (adapted from [33])

Some instruments are sensitive to line disturbances, for example, flow meters installed downstream of a valve. Thus it is important to take this into consideration when installing instruments and to read data from them. Understanding the limitations of each instrument will help ensure accurate data is collected.

2.4 Data acquisition

After the scope of the compressed air pressure loss has been determined and the compressed air network has been evaluated to determine which area/s of the shaft is the worst performing, the next step will be to start acquiring data.

This step aims to obtain real-world, operational measurements that can be utilised in calculations and simulations to transform the data into valuable and usable information that can be beneficial to the relevant responsible persons [59].

2.4.1 Equipment needed

For the purpose of this methodology and study, pressure loggers will be the most relevant equipment required as this is the thermophysical property of air that is the focus. However, when gathering data for simulation, other mechanical properties of the compressed air at certain locations must also be included and measured.

The compressed air properties required for simulation and that must be logged include flow and mass rates, temperature, density and velocity. Sophisticated compressed air flow meters are able to measure and record this data. Table 4 below gives the common equipment required for auditing compressed air networks.

Table 4: Equipment to be used for auditing the CA networks

Name	Equipment	Description
Kimo Pressure Logger[6]		An instrument for measuring and storing real-time data. This instrument can also record environmental data such as temperature and pressure.
Wika Pressure Logger[7]		A precision digital pressure logger. This instrument can be controlled remotely for real time monitoring.
CS Instrument Flow Sensor (VA 500)[8]		A sensor used to measure the flow rate of a liquid or gas. This single device is used to monitor consumption and analyse leakage flows. This instrument is used in conjunction with the PI 500 handheld logger.

[6] KP 320 Differential Pressure Data Logger & Pressure Store Data (kimoinstruments.com)
[7] Precision digital pressure gauge - CPG1500 - WIKA South Africa
[8] Flow meter for compressed air and gases - VA 500 (cs-instruments.com)

CS Instrument Flow Logger (PI 500)[9]		This is an all-purpose hand-held measuring instrument used in conjunction with the VA 500. Data recorded can be instantly analysed with graphs and tables compiled on the device.

[9] Portable flow meter with integrated data logger - PI 500 (cs-instruments.com)

2.4.2 Shaft compressed air audits

A pressure audit should be conducted on the main compressed air line feeding all the levels. Ideally, pressure loggers should be installed on the main compressed air line before and after each level's split to determine the pressure drop over the level.

The installed pressure loggers should log the compressed air pressure simultaneously to accurately indicate how the compressed air is utilised throughout the mine. This is due to a mine's ever-changing and dynamic nature. When comparing the pressure at each level to the supply or upstream pressure on the surface, the data can be used to determine any inefficiencies, such as leaks, blockages or open ends on the main compressed air line.

However, measuring points are not readily available; thus, conclusive data will not always be obtained. Typically, there could be only two to three measuring points on the entire length of the main compressed air line feeding all the levels. Thus an approximation of how the compressed air is utilised should be expected when conducting this test.

2.4.3 Compressed air flow and pressure audits (level baseload test)

The next step is to investigate the worst performing levels as determined from the baseload test performed. Every detail of the compressed air system is noted when performing level investigations and audits. This can be crosscuts that are not blanked off or sections of the levels that has been abandoned that is still being supplied with compressed air, sub-standard piping, the condition of the infrastructure such as leaks, rusted pipes, broken valves etc.

With the investigations, half-level crosscut baseload tests are also performed. This follows the same principle as the above-mentioned baseload test. With half-level baseload tests, a pressure logger is installed on the half-level split to determine the pressure of the compressed air supplying the half-level. The next step is to install a compressed air flow meter on the secondary split or drives (usually North or South). When all the measuring equipment is installed, the crosscut isolation valves are closed one by one, with a delay of around 10 minutes, to allow flow and pressure to stabilise.

After all isolation valves have been closed, the process is repeated in reverse. The drop in flow recorded per crosscut valve being closed is the compressed air consumption of that crosscut.

After all crosscuts are closed, the remaining flow indicates the amount of compressed air consumed by leakages on the haulage line.

2.5 Developing the baseline

This step in the methodology focuses on developing a baseline or 'snapshot' of the current network before any project, or infrastructural change has been implemented. After the proposed solution has been approved and implemented on the network, more tests or audits will be conducted, which is identical to the audits and data acquisition before implementation.

The baseline that is developed in this step will then be used to compare the results after implementation to validate the effectivity of the solution.

It is recommended to develop baselines for each identified parameter that has been investigated [60].

Operational baselines:

- Pressure (measured at compressor outlets and identified measurement points on the distribution network)
- Flow (measured at compressor outlets and identified measurement points on the distribution network)

Figure 16 illustrates a typical 24-hour average operational pressure baseline.

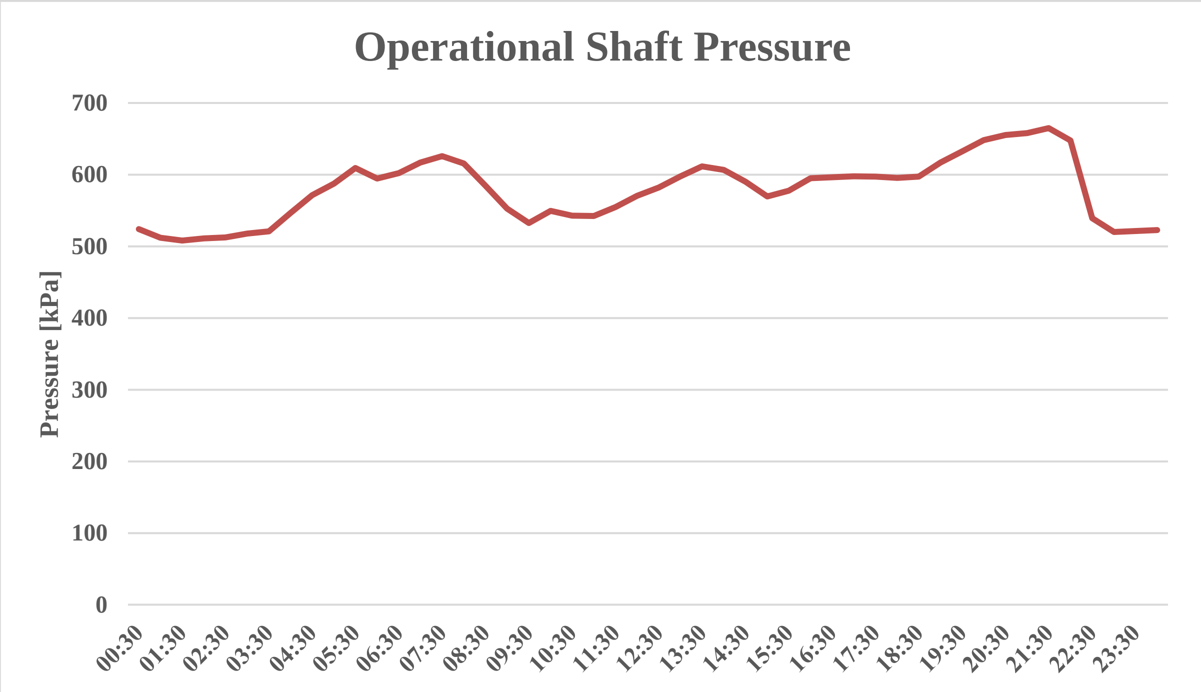


Figure 16: Baseline development example

2.6 Proposed Solution

After the above-mentioned steps have been completed, a solution can be proposed to solve the identified inefficiency. In this step, the first thing that must be considered is will this proposed solution add a new component to the network, change the layout of the network or leave the network unchanged and only maintain the current network?

If the network is changed in any way, the best method of determining the feasibility of the solution is to simulate the scenario/change on the case study mine's distribution network. A theoretical result can be obtained before any capital cost is incurred as well as the possibility of refining and optimising the proposed solution without causing any down time on the continuous operation of the shaft or losing valuable resources on unnecessary labour that could've otherwise be used to improve or maintain the existing network.

If the proposed solution does not entail any changes to the network, be it reconfiguration or additional components, and solely focuses on maintenance or optimisation of the existing network, then the need for simulation does not exist. With maintenance, the key factors that could affect the progress is:

- resource availability,
- time constraints,
- limited budget,
- planning.

It is then essential to have a detailed plan which prioritises the maintenance and repairs of the areas with the highest severity leaks and wastages.

2.6.1 Simulation

It is important to note that a simulation model does not provide a flawless representation of the results and effects on the network; rather, it indicates the feasibility of the proposed solution by delivering the desired results, if possible.

As stated in Chapter 1.4, the simulation software that will be used to verify the proposed solution is Process Toolbox (PTB). De Jager [61] created a methodology for compiling a simulation model for compressed air systems using PTB. Similarly, the same components and data will be required for a compressed air pressure simulation.

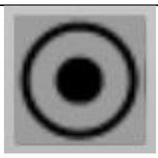
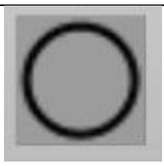
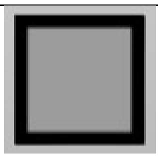
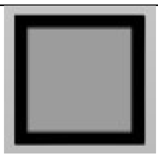
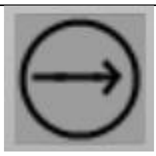
Data required

The accuracy of the model depends on the understanding of the simulation software. PTB allows the modelling of thermohydraulic systems with various components relating to water, steam and air. To create a compressed air network model, the following components will be used:

- Air Boundaries.
- Air Nodes.
- Air Demands.
- Pipes.
- Valves.
- Air Mass Flow.

Table 5 indicates the data required for each component below and shows what is calculated after running the simulation model. This data would have been acquired during the identification, evaluation and data acquisition steps of the methodology.

Table 5: PTB component specifications

Component	PTB icon	Data required	Calculated outputs
Boundary		Ambient pressure Ambient temperature Elevation	Ambient pressure Ambient temperature Gauge pressure
Node		Ambient pressure Ambient temperature Gauge pressure Elevation	Ambient pressure Ambient temperature Gauge pressure Humidity Temperature Wet bulb
Demand		Pressure Flow	Flow
Pipe		Hydraulic diameter Flow area Surface roughness Length	Mass flow Volume flow Velocity
Valve [modified pipe component]		Hydraulic diameter Valve type Valve fraction Kv coefficient Dynamic loss coefficient	Mass flow Volume flow Velocity
Mass Flow		Flow	Air flow

2.6.2 Compressed air management plan (C.A.M.P.)

Aim of the C.A.M.P.

The C.A.M.P. is a reporting tool sent weekly to all relevant shaft personnel indicating the performance of the compressed air utilisation. This is also used to track and plan all required compressed air infrastructure repairs and maintenance with the goal of reducing compressed air wastages such as leaks on pipes, flanges and valves, crosscut and half-level blanking, as well as tracking the progress of projects improving the compressed air network.

Data required to compile the C.A.M.P.

In order to determine and track the performance of the compressed air, at least three months' worth of compressed air data is required. The report tracks daily, weekly and monthly compressed air usage. The data is necessary to compare the current time period, be it a day, week or month, with the previous time period. This gives an accurate indication of improvement or deterioration in compressed air performance.

The data required for this report is the upstream pressure and supply flow on the surface to the shaft. Therefore, this report tracks the total performance of the shaft and not the performance of specific sections or levels of the shaft. This data is typically found on the SCADA.

Another set of data is required to compare the month-on-month resource and monetary impact of compressed air usage. This data is obtainable from internal mine resources such as accountants and project managers.

Action tracking/ Actions required from the shaft

The C.A.M.P. is also used to track all compressed air infrastructure maintenance and projects that pertain to the compressed air network. The action tracking can be broken up into three sections, namely:

- Main priorities and completed actions
- Outstanding work to be completed by responsible personnel
- Completed work by responsible personnel

The first section summarises the top-priority tasks that must be completed before continuing to the next set of tasks. These priority tasks are usually tasks that should be completed by the end of the current week. This breakdown of smaller tasks is more achievable and managed than setting a larger goal that can quickly become over-complicated and easily mismanaged, which in turn can result in slow progress. The second part of this section is to show what has been completed in the past two weeks. This is helpful as it can be used to plan future steps and keep employees motivated.

The second section describes all the tasks that are not of priority that should also be completed. This also keeps a record of all the planned tasks, outstanding tasks or tasks that are in the process but not complete by the end of the week. This section is split per level to give a clear indication as to where the work is required.

The third section keeps track of all the tasks that have been completed since the start of the year. It indicates the value added by the employees.

Accountability

All tasks listed in the report also indicate the person/s responsible for completing the task. This serves to:

- Keep the responsible person accountable for the task,
- Provide a backlog of who to talk to if anything occurs that assistance is required on or if anything goes wrong after completion of the task,
- Provide the people consulting the report that is not knowledgeable of the operations of the shaft with the relevant personnel for the relevant skill set. This is useful when new personnel are added to the compressed air network projects.

2.7 Implementation

The successful implementation of a proposed solution consists of various factors that must be considered and planned for. The following are the main factors to be considered [33]:

Procurement

If new infrastructure, equipment or components are required, the sourcing and procurement of the required items must be prioritised. This process should be done in advance as lead times for the required items could be several months, which could lead to costly delays.

Resource allocation

Thorough planning and communication with the project managers should be ensured to avoid bottlenecks or inefficient use of the required labour when there is time available for maintenance or installations of key project milestones.

Strategic planning and scheduling of smaller tasks using a work breakdown structure (WBS) would ensure the continuous progress of the project. The WBS should include each person's role, responsibilities and what is expected of them.

Installation procedures

Approved installation procedures should be in place to ensure the safety of the workers, high quality of work and efficient performance.

Logistical constraints

The transportation of parts and equipment to the installation site is one of the largest challenges faced by the mining industry. The only way to transport items from the surface is by using shaft slinging. Thorough planning and scheduling are required to ensure optimal transportation. A loss in production is possible if there are delays during shaft slinging.

2.8 Results and Validation

The impact of the proposed solution is validated by comparing the measured data after implementation with the baseline data obtained during the evaluation and data acquisition steps.

During the validation step, it is important to consider any changes made to the distribution network and supply side as this could skew the results obtained during after-implementation testing. These changes, if any, must be accounted for to accurately determine the proposed solution's effect.

To account for changes on the supply side, the results obtained during testing can be normalised to the supply side conditions during the baseline data acquisition period. By normalising the input parameter (supply-side compressed air pressure), the difference in baseline and measured output (demand-side compressed air pressure) will accurately determine the effect of the implemented solution.

2.9 Verification

The method developed in this chapter addresses the five aspects, namely pressure drop reduction, CA network inefficiencies, demand-side initiatives, compressed air infrastructure and production benefits determined during the literature study conducted. Through the use of literature and adaptation of proven engineering processes, the method was developed. Implementing the method will result in feasible solutions to improve the demand-side pressure on compressed air distribution networks.

2.10 Conclusion

This chapter presented an approach to identifying, evaluating, improving network inefficiencies found on mining compressed air distribution networks and quantifying the impact the proposed solutions have on the demand-side compressed air pressure. The steps in the method were derived from observations made in literature and the adaptation of the Engineering Design Process. Implementing the method will improve demand-side compressed air pressure and potential production increases.

Chapter 3 Results and Discussion

3.1 Preamble

In Chapter 2, a methodology was developed to identify network inefficiencies and implement possible solutions to improve the demand-side compressed air pressure. In order to test and verify this methodology, it was implemented on two South African platinum mines, Mine A and Mine B.

In this section, three case studies will be presented to showcase the developed methodology's versatility as well as aim to prove that the initiatives implemented met the objectives of the study, given in Chapter 1.6.2, which includes increasing the demand-side compressed air pressure which in turn will have a beneficial effect on the production of the case study mines.

3.2 Identifying compressed air network inefficiencies

In August of 2020, an investigation was launched at Mine A to determine the cause of high energy consumption coupled with low production rates. From initial talks with the personnel working at Mine A, it was clear that the cause for this inefficient use of compressed air was due to drills and loading boxes on the three main production levels, namely, 18 Level, 19 Level and 20 Level, struggling to perform as per manufacturer's specifications due to insufficient CA pressure supply.

The focus of the investigation shifted from optimising the energy usage of the compressors for savings to auditing the CA distribution network to identify inefficiencies that could cause a decrease in downstream pressure. Due to insufficient demand-side pressure at full compressor capacity, energy-saving initiatives (which involve reducing compressor capacity) would not yet be feasible.

Mine Layouts and SCADA data availability

After the scope of the problem at Mine A was determined, the first step to identifying the network inefficiencies was to gather high-level information regarding the distribution network and determine what data was available on the SCADA system. Figure 17 is the network layout of Mine A on SCADA.

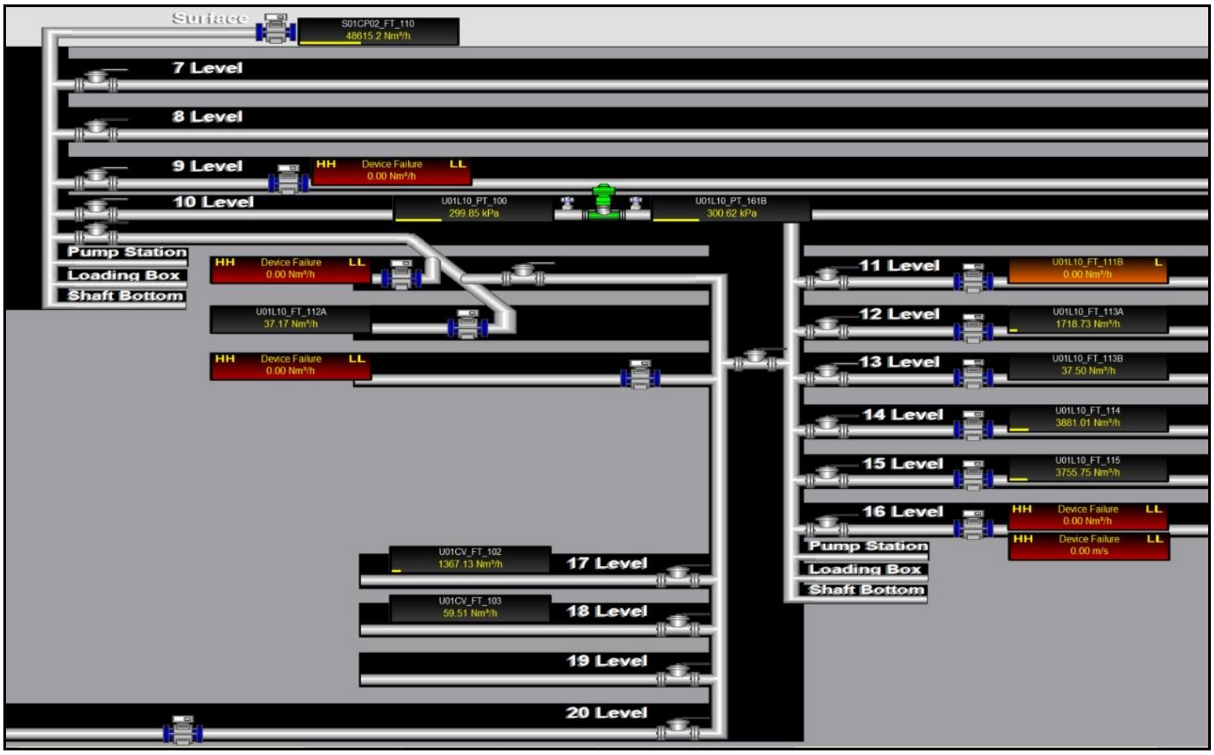


Figure 17: Mine A's SCADA network layout

From Figure 17, the total amount of levels can be determined, which levels have flow meters installed at the station and what the real time flow into that level is, the layout of the main CA supply line from surface to the lowest level, what type of valve is used at the stations and where control valves are installed.

Levels 7 – 10 are on the vertical shaft, Levels 11 – 16 are on the sub-vertical shaft and Levels 17 – 20 are on the decline shaft. The main production levels where drilling occurs are Levels 18 – 20, which are also the lowest levels of the mine. This is where the CA demand is the highest and where the pressure is the lowest. Any open end, leak or other inefficiencies on the network upstream from these levels will impact the CA pressure supplied to these levels.

Due to Mine A being one of the oldest mines on the platinum mining complex, the availability of CA flow and pressure instrumentation required for comprehensive and accurate monitoring are lacking. From the SCADA, the two highest producing levels, 19L and 20L, do not have any flow or pressure meters installed. Thus, no historical data is available for analysing the consumption and performance of the compressed air from before the investigation was launched.

Therefore, all the measurements and reading will have to be done manually, which leads to all the results from this study being based on instantaneous readings or average readings based on the specific time the instrumentation were installed for. The data acquired will be averaged over the span of a shift or a day and not for extended periods of time, such as a week, due to the battery life of the portable instrumentation that will have to be used.

3.3 Evaluating the network

After high-level information regarding the network was gathered, the next step was to start evaluating the network by means of baseload testing to determine and prioritise the worst performing levels, i.e., levels with the highest flow consumption, and doing level audits to start gathering half-level flow and pressure data as well as collecting data on the condition and configuration of the half-level network.

Baseload test

Following the procedure described in the methodology, a baseload test was done on Mine A to determine the levels with the highest baseload demand. Below are the results obtained from the baseload test.

Table 6: Top-down baseload results

Baseload Analysis						
Level	**Time Valve Closed**	**Time Flow Recorded**	**Flow (Before Closed)**	**Flow (Valve Closed)**	**Baseload**	**% Usage**
13 Level	06:34	06:46	64298.08	63864.96	433.11	**1%**
14 Level	06:57	07:05	71155.45	70997.83	157.62	**0%**
15 Level	07:12	07:28	72297.68	60898.58	11399.11	**17%**
16 Level	07:43	07:58	81774.22	78003.22	3771	**6%**
17 Level	08:10	08:24	80985.21	70411.28	10579.93	**16%**
18 Level	08:24	08:39	70411.28	56499.61	13911.67	**21%**
19 Level	08:39	09:02	56369.49	47407.63	8961.86	**13%**
20 Level	09:01	09:15	47074.47	28498.93	18575.54	**27%**
				Baseload Total	**67783.84**	

Table 7: Top-down baseload results (Normalised)

Normalised Baseload Analysis				
Level	Total flow	Flow (Valve Closed)	Baseload	% Usage
13 Level	69346.16	68148.77	1197.39	2%
14 Level	71094.08	67808.83	3285.25	6%
15 Level	67818.42	64760.41	3058.02	5%
16 Level	69792.81	64465.76	5327.05	9%
17 Level	65209.66	54652.41	10557.24	18%
18 Level	54652.41	45252.52	9399.89	16%
19 Level	45246.08	36785.48	8460.61	15%
20 Level	36569.17	20365.36	16203.81	28%
		Baseload Total	57489.26	

Table 6 illustrates the raw data obtained during the test, indicating at what time the valves were closed and the surface flow before and after the valves were closed to calculate the baseload for the levels. The result for 15 Level seems to be too high as the engineer indicated this level as a non-production level.

Table 7 indicates the normalised results of the baseload test. It is seen that 20L has the highest baseload consumption of 28% of the total flow consumed by the shaft, which is expected, as this is the level with the highest production. 17L is the second largest consumer of air, which was not expected as this level has the fourth-highest production.

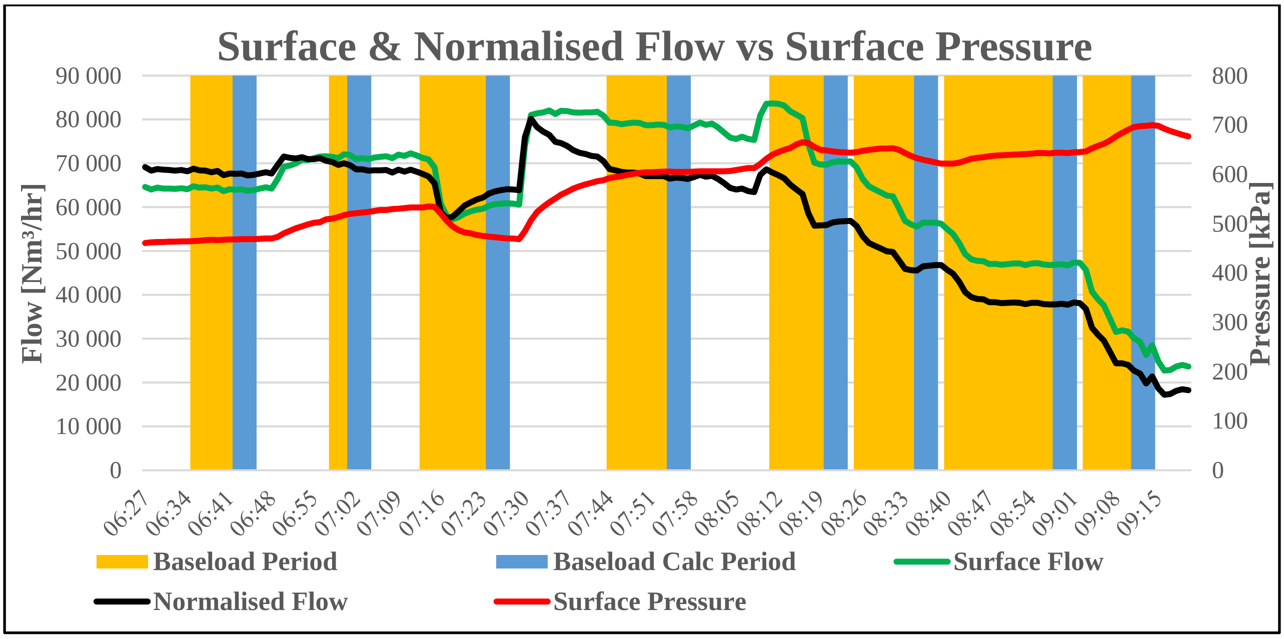


Figure 18: Surface flow and pressure during baseload test

When consulting Figure 18, during the baseload period for 15L, something happened on the surface CA ring, causing both the pressure and flow to drop. This could've been a result of cutting back on a compressor. After the 15L baseload period, a large increase in flow and pressure is observed. This could also have been caused by a shaft closing their surface valve, or, more likely, a compressor being switched on.

Figure 18 also gave an unexpected result. When all the valves on the shaft are closed, a baseload of 0 Nm^3/h is expected. However, about 20 000 Nm^3/h was unaccounted for. Later investigations revealed that there was a CA line that splits away from the main line, which feeds the sub-vertical shaft section (11L – 16L).

From this baseload test, the worst-performing levels were identified and prioritised. This also furthered the understanding of how the shaft's distribution network is configured.

Level audits

The next to evaluating the network was to do audits of the levels, starting with the worst performing. A compressed air audit was conducted on Mine A in October 2020.

During the audit, flow and pressure readings were taken at the start of the half-level and at the station to determine how much air each half-level was consuming. During the audit, several key components of the network were noted, as listed in the methodology. An example of how the audit report is captured the findings will be given in this section.

Table 8 below identifies the active and inactive crosscuts on the half-level. The purpose of this was to find any inactive crosscuts that could still be consuming air and which had to be isolated by means of blanking to ensure that compressed air is not wasted.

Table 8: Mine A - 20L Merensky North audit results

Crosscut	Mining Status	CA Isolation Status	Pipe size tap off [mm]	Comment	Responsible Person	Commitment Date
2017	Inactive.	Blanked off.	N/A	No comment.		
2018	Inactive.	Blanked off.	N/A	No comment.		
2019	Inactive.	Blanked off.	150	No comment.		
2020	Inactive.	Blanked off.	N/A	No comment.		
2022	Inactive.	Blanked off.	N/A	No comment.		
2023	Inactive.	Closed valve.	150	Walled off, not blanked		
2024	Inactive.	Open	150	Active Refuge Bay. Must blanked off after RB whistle.		
2026	Inactive.	Open	150	Must be blanked.		
2027	Active	Partially closed	150	No comment.		
2028	Active	Open	100	No comment.		
2029	Active	Open	150	No comment.		

Table 9 below summarised the severity and locations of the CA leaks identified during the audit.

Table 9: Summary of identified leaks

Leak ID	Severity	Comment	Responsible Person	Commitment Date
L.1	3/10	CA leak on 1inch ball valve at X/C 2019.		
L.2	3/10	CA leak 15 meters before X/C 2023 (rust).		
L.3	3/10	CA leak 20 meters before X/C 2023 (rust).		
L.4	4/10	CA flange leak 70 meters after X/C 2023.		
L.5	3/10	CA leak on valve at X/C 2027.		
L.6	5/10	CA leak on valve at X/C 2028.		
L.7	5/10	CA leak on flange 100m after X/C 2029.		
L.8	4/10	CA leak on flange adjacent to L.7 leak.		
L.9	7/10	CA leak on tie-off manifold at end of development.		

Figure 19 illustrates the crosscuts and all the identified leaks and wastages visually. Representing the locations of the leaks and wastages visually can greatly improve finding and repairing them.

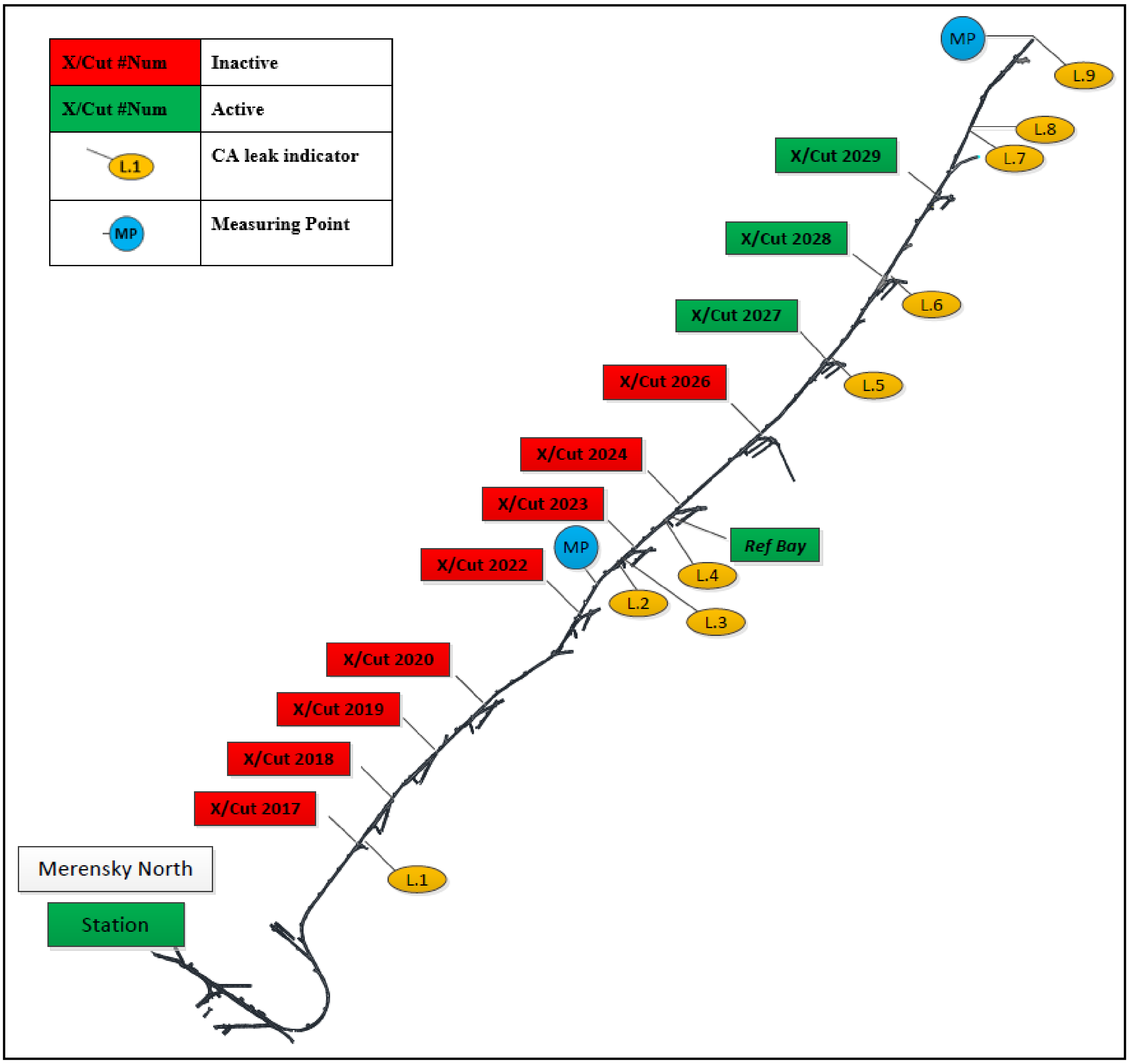


Figure 19: Mine A - 20L Merensky North layout

During the audit, pressure sensors were also installed at the locations on Figure 19 marked as 'MP'. The results of these pressure measurements are seen in Table 10 below.

Table 10: Audit vs surface pressure comparison

Time	Shaft Pressure [kPa]	Station [kPa]	North Drive Pressure [kPa]	Location
02:41	571.7	436.1	392	X/C 2022
03:20	575.5	439.3	380	End of Development

The results obtained during this audit revealed that several major leaks resulted in a high consumption rate of air and a decrease in pressure as you near the end of development throughout the shaft. The audit only entailed investigating the main haulages and crosscuts and did not include the stoping areas.

During the audit, rushing air could be heard at the top of the travelling ways to some of the stopes, indicating either large leaks or open ends used for ventilation as the stopes are areas with high temperatures. Miners cool themselves off with the compressed air used for drilling and sweeping as Mine A’s ventilation in the stopes is inefficient.

This result led to doing crosscut baseload tests to determine which crosscuts are consuming the most air when no machines are operating, which will be discussed in the following section, ‘Data Acquisition’. If a crosscut has a high flow consumption rate, the pressure within the pipes will be low due to the air escaping into the atmosphere due to leaks or open ventilation hoses.

Another important result from this audit was obtained when the pressure at 20L station was measured and compared to the shaft pressure at the same timestamp. A pressure drop of approximately 135 kPa was experienced between the surface and the lowest production level. This led to a shaft main line pressure audit to determine if there were any major leaks, open ends or blockages present on the line feeding all the levels. These results will be given in the next section.

3.4 Data Acquisition

After evaluating the condition of the network and determining a more focused area of investigation, the next step was to start gathering data on the CA flow and pressure trends of the shaft for analysis and developing a solution for the results obtained. This was done using the equipment mentioned in the methodology.

Shaft pressure audit

The first avenue of investigation was to determine what was causing the 135 kPa pressure drop between the surface and 20L station. A pressure audit was conducted on the main line at locations where a measuring point was available.

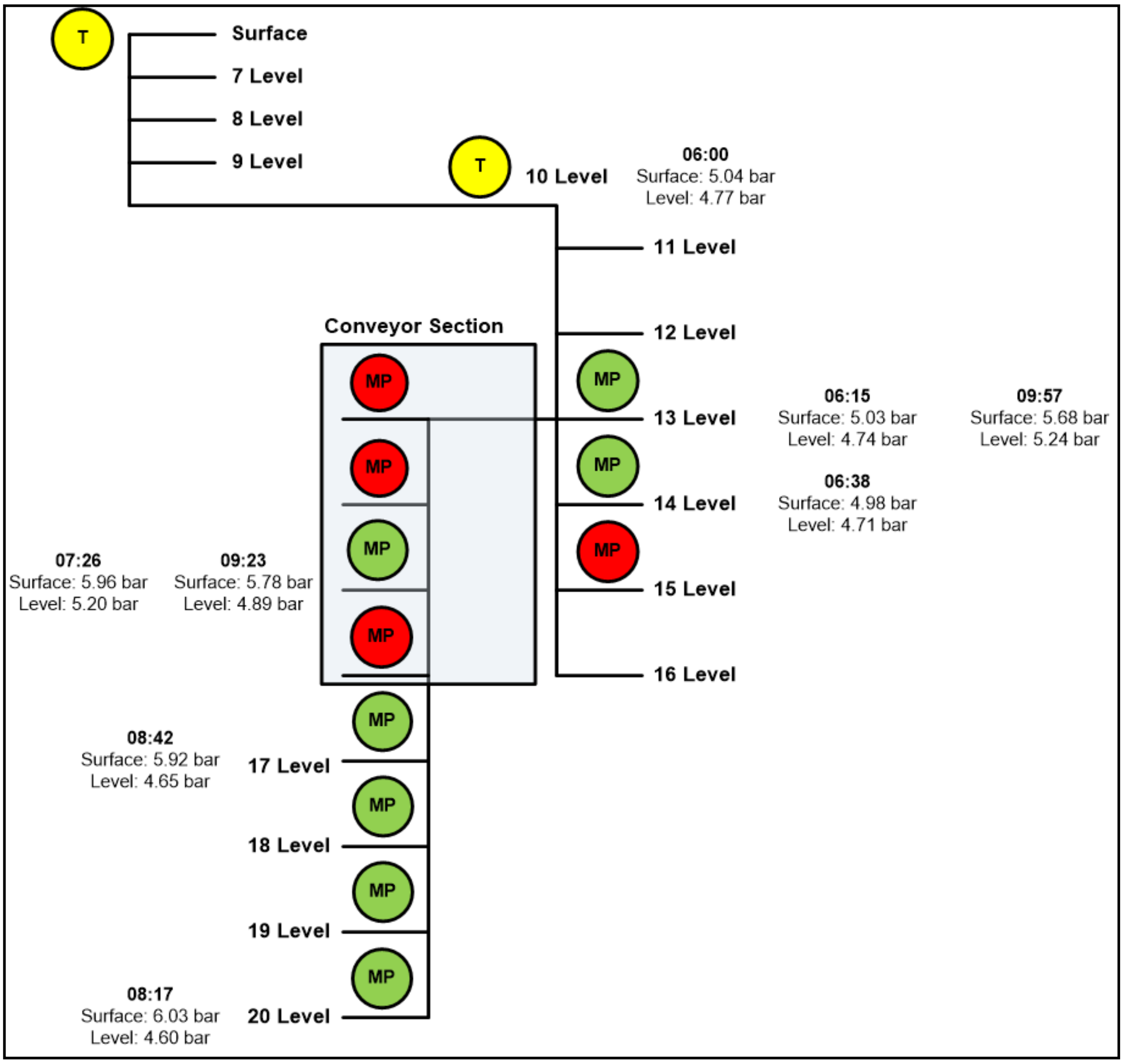


Figure 20: Mine A - Shaft pressure audit layout and results

Figure 20 shows a breakdown of the audit results with all the locations where measuring points were available on the main compressed air line and the pressure measured at those locations at the starting time it was measured. The green symbols indicate the available measuring points; the red symbols indicate locations where measuring points should be installed, which would assist with identifying the problem area more accurately, and the yellow symbol indicates the locations of the SCADA pressure meters.

The measurements were taken for a period of 5 minutes and were averaged to give the value seen in Figure 20. This was also done for the shaft pressure. The values obtained during the audit were compared to the shaft pressure to determine the pressure drop between the surface and the measurement location, as seen in Figure 21.

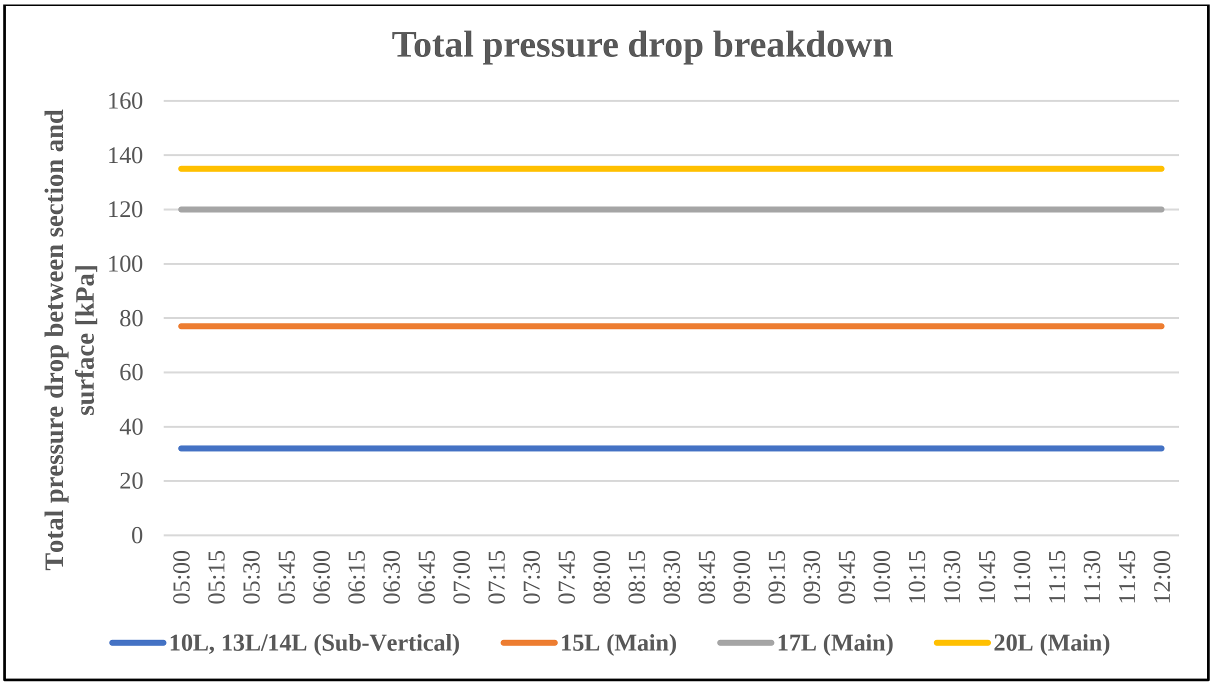


Figure 21: Pressure drop analysis

Figure 21 shows that the low pressure experienced at 20L is due to a gradual drop in pressure over the length of the main line. Three sections are clearly causing the bulk of the pressure drop; therefore, no single point, such as a blockage or large reduction in the line could be causing the drop in pressure seen at 20L station. Table 11 gives a breakdown of the three sections mentioned above.

Table 11: Sections with largest pressure drops

	Location	Pressure Drop
1	Between Surface and **10 Level.**	**32 kPa**
2	Between **14 and 15 Level.**	**45 kPa**
3	Between **17 and 15 Level.**	**43 kPa**
	Total shaft pressure drop.	135 kPa

Further investigation of the line between 14L and 15L found that the main line has two 90º bends within 3 to 5 meters of each other for the purpose of switching what side the line runs down the conveyor decline section, see Figure 22 (the other bend is on the right out of frame). These bends in such close proximity to each other will result in turbulent air flow and in effect, reduce the downstream pressure inside the pipe. Also, note the trough created at the pictured 90° bend. This location is a prime spot for water to collect and cause blockages.

Figure 22: Main line 90° bends over conveyor

Another important finding from this was that a large amount of water was found accumulating on the first 90º bend. A 1-inch ball valve was installed on the pipe's bottom half on the 90º angle piece. The valve was opened, and a large amount of water escaped. This was also observed at the pumping level past 20L when a valve was opened on the main line with water shooting out, see Figure 23 below.

Figure 23: Water in CA line

The water could be accumulating at certain areas inside the line which could cause blockages, effectively lowering the pipe's cross-sectional area and decreasing the downstream pressure. It could be causing rust to form on the pipes' inside wall, which would increase the friction between the air and the wall and also decrease the air's working pressure.

The water observed in the compressed air at Mine A could be due to inefficient and old compressor aftercoolers and air-dryers as this shaft is one of the oldest on the platinum mining complex this study was done at. This is then exacerbated due to the layout of the CA distribution network at Mine A. The CA temperature at the compressor outlet is about 60ºC, and the main line transporting this warm air is routed in the same sections as the surface bulk air cooler's refrigerated ventilation air, which is cooled to about -1ºC. This cold atmospheric air temperature on the outside of the pipe will result in a high percentage of moisture in the compressed air to form condensate inside the main line.

Thus, this finding was another cause for the low demand pressure on Mine A, with the leaks and wastages found during the level audits being the other. The moisture content of the CA can thus explain the pressure drop between the surface and 20L station. The pressure drop between 20L station and the development end of the half-level drive (about 60 kPa, as seen in Table 10) is caused by leaks and wastage on the haulage line and unused crosscuts that should be blanked off.

Half-level baseload tests

A half-level baseload test was conducted on the level with the highest baseload (20L) to determine the crosscuts with the highest flow consumption. This test was only conducted on the 20L Merensky North and South haulages due to the Chrome North and South haulages not having measuring points available. These measuring points were identified during the full shaft audit but were not installed by the time this test was conducted.

A pressure and flow logger were installed on the haulage line towards the Merensky half-level near the station. The results are shown in Table 12.

Table 12: 20L Merensky test summary

	Average Flow	Average Pressure	Comment
Shaft	81 712 [Nm³/hr]	568 [kPa]	Average shaft flow and pressure were measured during the test.
20 Level Merensky	24 219 [Nm³/hr]	438 [kPa]	On average, Merensky consumed 30% of the Shaft's CA during the test.

The next step was to install the flow and pressure logger on the Merensky North drive near the split. Unlike the shaft baseload test, the crosscut isolation valves could not be kept closed due to testing during normal operations. Thus, one valve would be closed for about 7 minutes and be re-opened. The drop in flow measured near the North and South drive split would then be taken as the crosscut's baseload. Table 13 and Figure 24 illustrates the results.

Table 13: 20L Merensky North test summary

	Average Flow	Average Pressure	Comment
Shaft	81 712 [Nm³/hr]	568 [kPa]	Average shaft flow and pressure measured during the test.
20 Level Merensky North	13 738.55 [Nm³/hr]	438 [kPa]	On average, Merensky North consumed 16% of the Shaft's CA during the test.

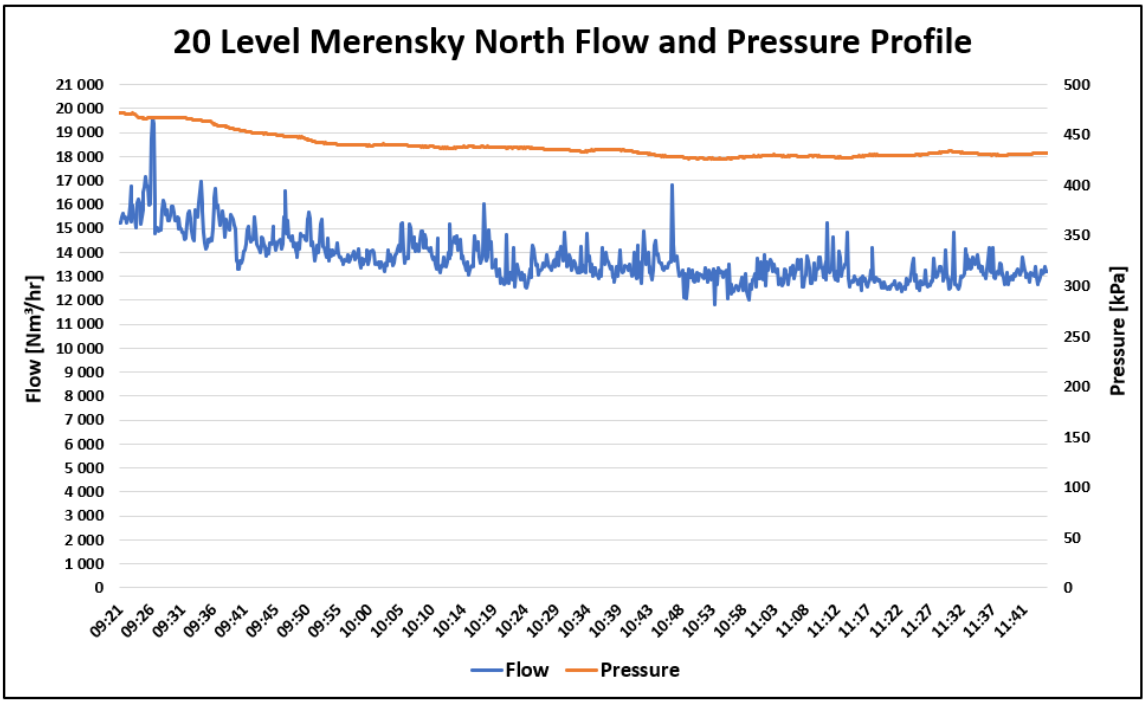


Figure 24: 20L Merensky North test profile

At 09:41, 10:09 and 10:39, the three active crosscut isolation valves were closed. However, no discernible change in flow could be determined, as seen in Figure 24. The reason for this was faulty isolation valves that did not close properly. The same process was repeated on Merensky South drive.

Table 14: 20L Merensky South test summary

	Average Flow	Average Pressure	Comment
Shaft	81 712 [Nm³/hr]	568 [kPa]	Average shaft flow and pressure measured during the test.
20 Level Merensky South	10 481 [Nm³/hr]	484 [kPa]	On average 13% of the Shaft's CA was consumed by Merensky South during the test.

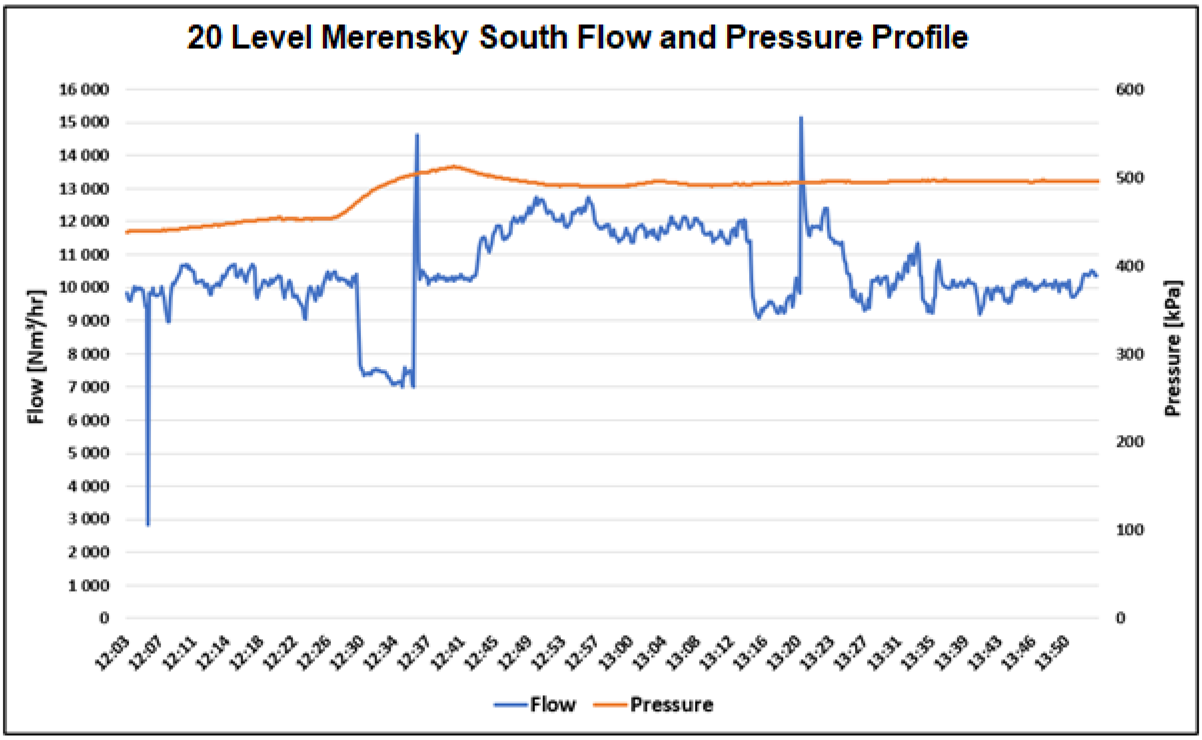


Figure 25: 20L Merensky South test profile

The South Drive test was more successful than the North. This drive has four active crosscuts, with two of four valves giving good results during this test. From Figure 25, the first of the two crosscuts had a baseload of 3 100 Nm³/h and the other a baseload of 2 300 Nm³/h. What is also important to note was the increase in pressure in the line when the first crosscut was closed.

3.5 Baseline development

The initial distribution network evaluation and data acquisition audits were started in October 2020. Thus, the shaft's operations in October and the results from these audits and investigations will be used as this study's baseline. The results obtained from the implemented initiatives will be compared to this baseline to determine the effect the initiatives had on the flow consumption and demand-side pressure of the shaft.

The average shaft flow consumption and pressure of Mine A for October 2020 is given in Figure 26.

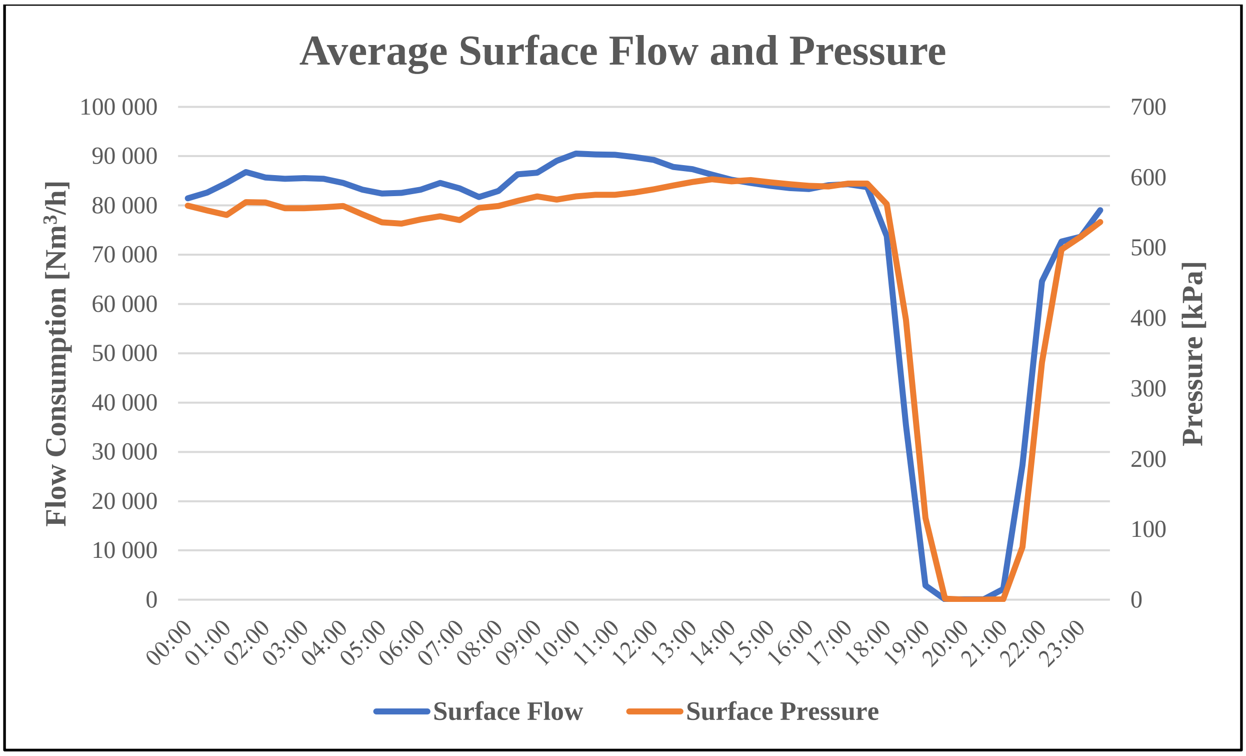


Figure 26: Mine A's average flow and pressure profile for October 2020

The expected profile for the shaft pressure should be a relatively flat trend fluctuating between 500 kPa and 600 kPa throughout the 24h profile, but in Figure 26 shows it following the flow trend. After consulting the shaft's engineer, it was determined that the pressure logger on the surface, used to measure the supply pressure from the compressed air surface ring network, was installed downstream of the shaft's surface isolation valve. This, however, does not affect the pressure readings (except for the slight pressure drop over the valve itself) as it is still upstream of any air consumer.

After investigations were finished, it was determined that Mine A's compressed air network had great potential for improvement. In the following section, compressed air initiatives will be proposed to reduce or mitigate the effects of the network inefficiencies found during the investigation phase on the demand-side pressure.

3.6 Initiative A – Reconfiguring the distribution network layout

Initiative A was determined when the network layout drawings and SCADA drawings were studied. It was found that the main compressed air line split on 10L.

The main branch of the split travels down the sub-vertical shaft, down the conveyor decline and eventually down to the bottom production levels, where it supplies the levels with the compressed air used for mining operations.

After an underground visit, it was determined that the secondary branch travelled down the first chairlift decline and fed 11L, 12L Chrome, and 13L Chrome. However, after further investigation, it was found that on 11L, the line had no tap-off points and reconnected with the main branch of the compressed air line at the 13L conveyor section landing. At 11L station, two isolation valves were found, one isolating 11L Chrome section and the other isolating the line that reconnects with the main line.

Both valves were closed and rusted shut. After consulting the engineer and mechanical foreman regarding the findings, it was determined that the original purpose of this line and the reason for its' closure were unknown. This, therefore, led to the first initiative.

3.6.1 Proposed solution

The first solution proposed for this study was to reinstate the bypass line between 11L and the main line at the 13L conveyor landing. The main concern for re-opening the line was that the pressure inside the main line would cause a high enough back pressure that could lead to one of two scenarios:

- The back pressure would overcome the pressure supplied in the bypass line which could divert air away from the bottom levels and result in a ring-feed.
- The pressure in the bypass line equals the pressure in the main line resulting in no additional flow and thus no improvement in downstream pressure supplied to the production levels.

In order to determine the feasibility of this solution, before implementing any changes, a simulation was compiled to test the effects opening this line would have on the distribution network. The objectives the simulation would have to achieve to prove feasibility were the following:

- No ring feed had to occur, meaning a drop in flow and pressure downstream of the reconnection point and a flow and pressure reading above baseline upstream from the reconnection point.
- A clear increase in supply pressure at 20L station.

A simulation was built to scale for Mine A's compressed air distribution network. PTB factors in pressure drop over the length of a pipe, and thus this was important for accurately modelling the system. The simulation model was built and then calibrated to reflect the real network. This was done by using the data acquired during the shaft baseload test and shaft pressure audit, as described in Sections 3.3 and 3.4.

The pressure drop over the network was simulated by manipulating the valve fraction value of the pipes, which reduces the pipe's cross-section to induce the pressure drop. The air demand of each level was also incorporated into the simulation to accurately depict how the supplied air will split off to the relevant level.

The simulation model can be seen in Figure 27. The simulation results are shown in Table 15 below, with a reference shaft pressure of 575 kPa. This shaft pressure was chosen as this was the pressure during the audit done on 20L. This allows for comparing the actual 20L station pressure and the simulated pressure to determine the simulation's accuracy.

Table 15: Simulation results

Location	Pressure [kPa] [Bypass Closed]	Pressure [kPa] [Bypass Open]	Pressure [kPa] [Actual]
10L	544.7	532.8	-
17L	445.7	475.9	-
20L	432.9	463.5	438

The theoretical results from the simulation proved the feasibility of opening the bypass as there was no increased pressure at the point where the line splits, and it showed a clear improvement of the downstream supply pressure. Comparing 20L station's actual and theoretical pressures at 575 kPa surface pressure indicates that the simulation was within 2% accurate to the actual value.

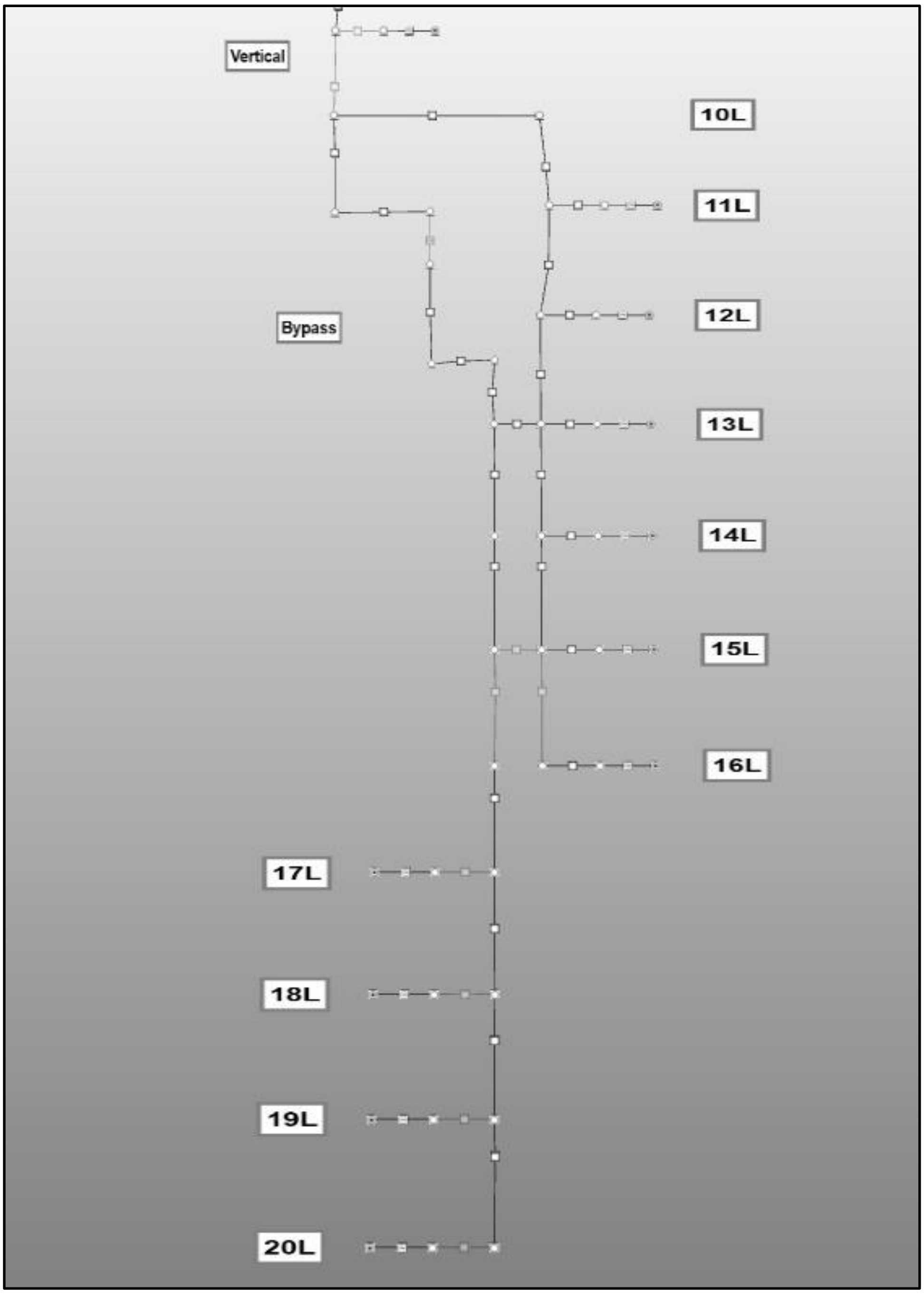


Figure 27: Network reconfiguration simulation using PTB

3.6.2 Implementation

After the solution was proven to be feasible, the next step was to implement the solution by running tests to obtain the results and validate the solution.

The isolation valve on 11L was old and rusted and had to be replaced before any tests could be conducted. An engineering drawing of the installation first had to be created to determine the valve and surrounding pipes' sizes and the type of valve, see Figure 28 below.

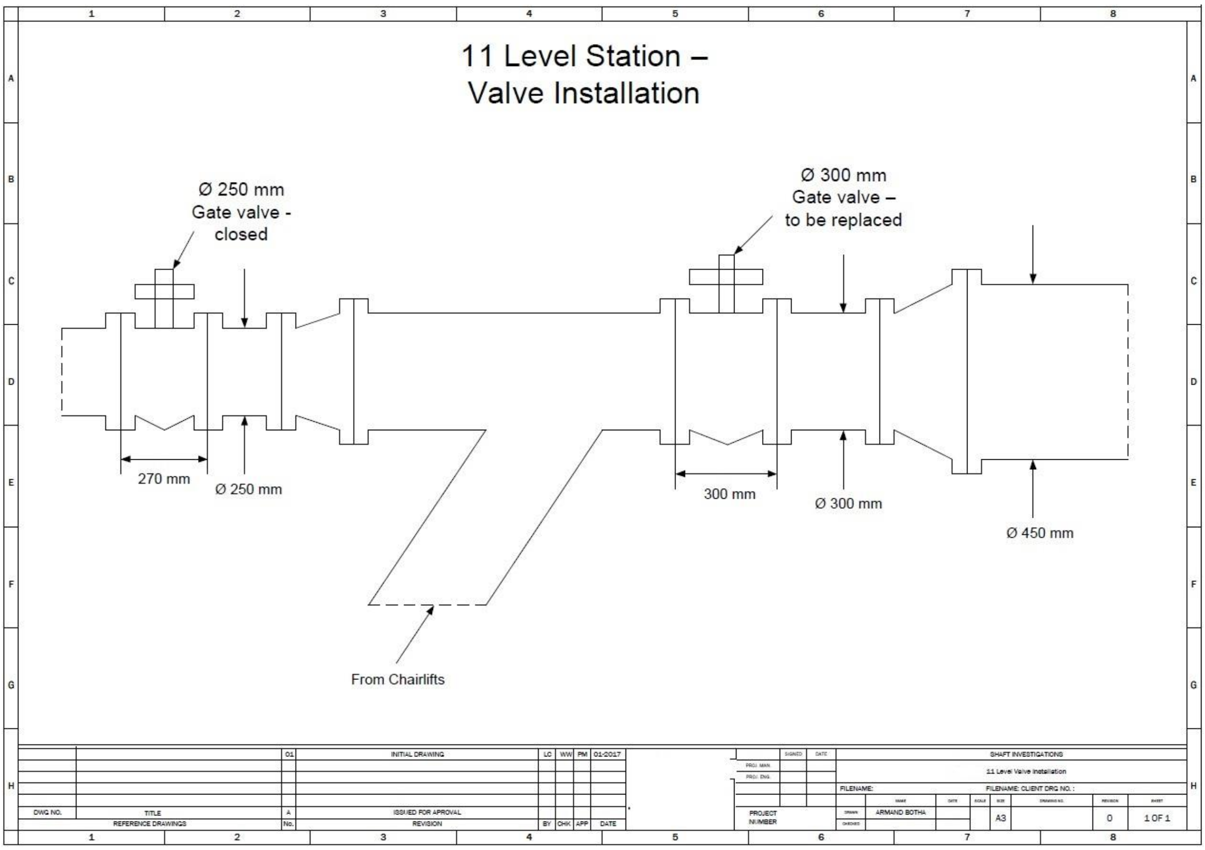


Figure 28: 11L valve installation drawing

With this, a new valve was ordered and later installed. The installation process required an off weekend at the mine, during which no operations took place to close the surface valve. After installation, the first test was conducted but with no results, as this test determined that a major leak (two pipe flanges were pulled away from each other) was present on the bypass line. After this fix, it was discovered that there were blank flanges installed further down the line. These blank flanges were removed before the test could be conducted.

3.6.3 Results and validation

After installing the valve and opening the line, a test was conducted to validate the solution. The test was conducted to quantify the effects of three different running configurations of the 11L and 13L isolation valves on the total compressed air flow of the shaft and the downstream supply pressures.

Configurations

The measuring points and isolation valve locations used in this investigation are given in Figure 29. Three different valve running configurations were used to determine which configuration would be the best solution for increasing the compressed air supply pressure to the lower production levels. Each configuration was implemented for 45 minutes during the test.

For Configuration 1, the bottom section was supplied with compressed air through the main compressed air line that travels down the sub-vertical shaft and conveyor section with the 11L valve closed. This configuration can be seen as the baseline to which the other two configurations will be compared. Before the 11L isolation valve was replaced, this configuration was used.

For Configuration 2, the bottom section was supplied with compressed air by both the 11L compressed air line and the main compressed air line that ties into one on 13L conveyor landing. The 11L isolation valve was open, as well as the isolation valve on 13L conveyor landing.

For Configuration 3, only the 11L compressed air line supplied the lower production levels with compressed air. The isolation valve on 13L was closed. This configuration determined the effect of the 11L compressed air line on the supply pressure of the lower levels and allowed determining how much-compressed air was being consumed by the sub-vertical section.

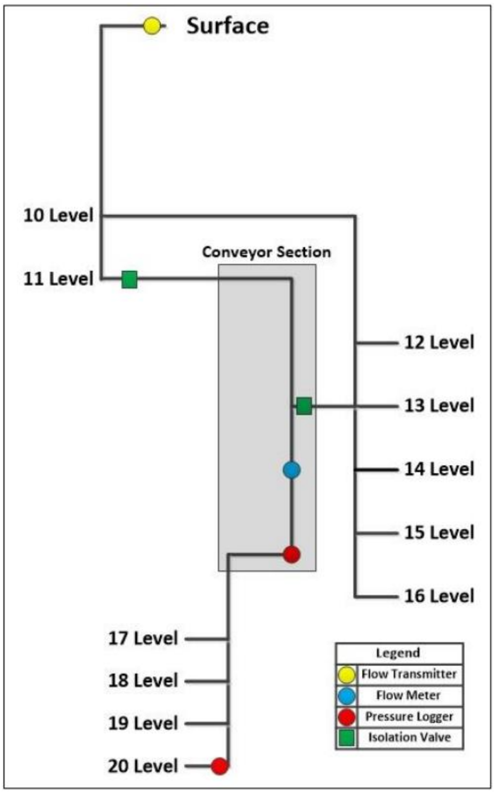


Figure 29: Isolation valve and measuring point locations

The outcome of this test is given in Figure 30 and Table 16 below.

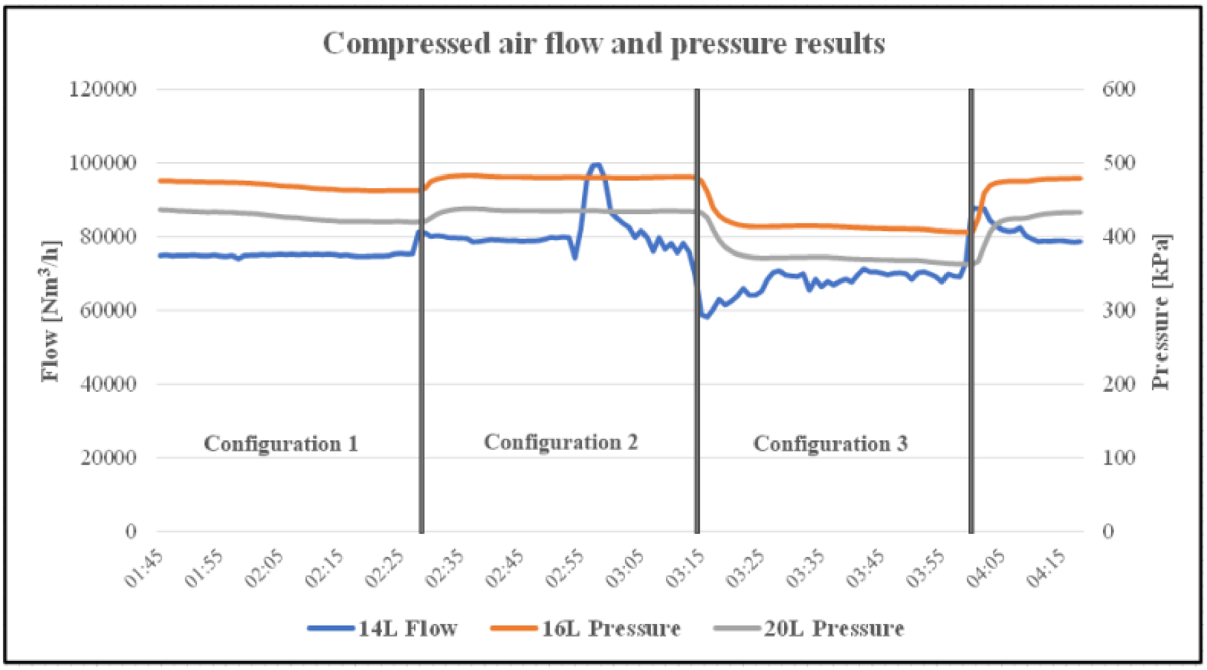


Figure 30: Test results

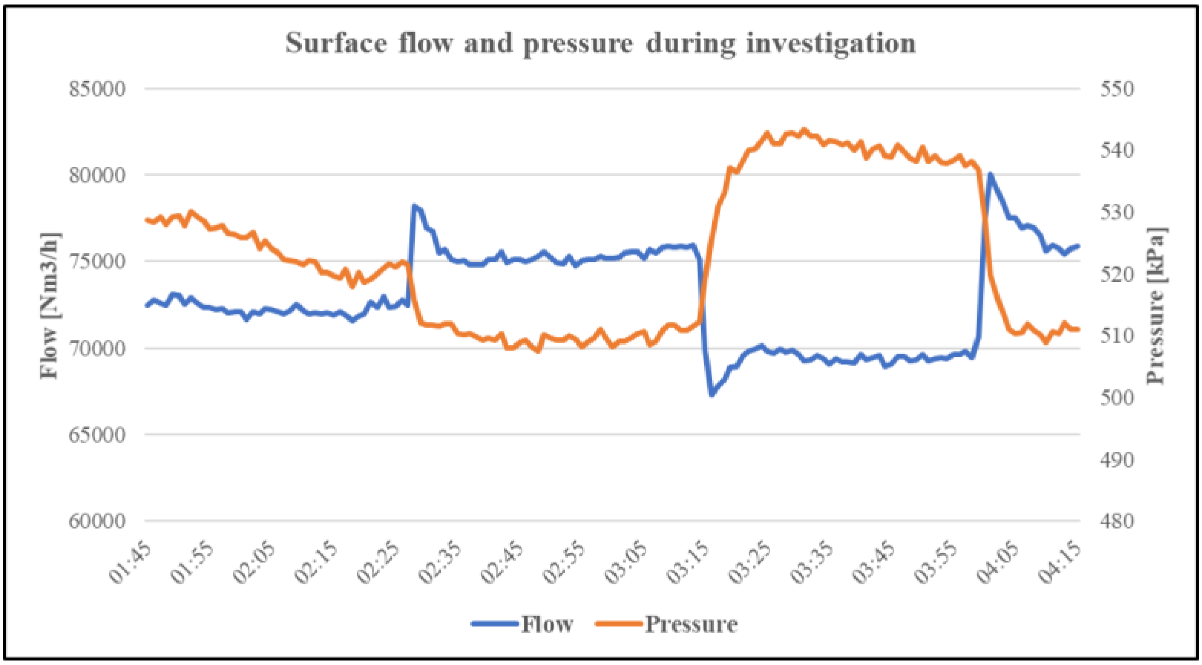


Figure 31: Surface flow and pressure during test

Table 16: Average pressure recorded during test

	Average Shaft Pressure [kPa]	Average 16 Level pressure [kPa]	Average 20 Level pressure [kPa]
Configuration 1	524	469	427
Configuration 2	510	481	435
Configuration 3	539	416	374

The cause of the spike in flow observed during Configuration 2 is not known. However, due to the erratic nature of the flow recorded with the installed flow meter after the spike, it is assumed that water in the air could have started to accumulate on the sensor, which could lead to the observed readings. This spike, however, did not affect the outcome of this initiative.

From the results obtained during the test, it was clear that Configuration 2 was the best option to improve the compressed air pressure to the lower levels at Mine A. The configuration caused a decrease of 27.2% pressure drop from the surface to 20L station. Therefore, this result validates the solution of reconfiguring the network by opening the bypass line.

3.7 Initiative B - Distribution network maintenance

Initiative B was determined during the compressed air audits done on the various levels of Mine A. It was found that the piping infrastructure was in a state of disrepair and required extensive maintenance. Severe leaks on valves, pipe flanges and pipes, open-ends used for ventilation, walled-off and inactive crosscuts and inactive half-levels were identified during the audits.

No additional audits were conducted inside the stopes, but it was assumed that there would be many unauthorised ventilation locations where the ambient temperature was the highest and where most miners worked. These wastages were excluded from the proposed solution as this problem can only be solved by improving the miners' discipline surrounding compressed air usage, for example, by implementing incentives that will motivate miners to reduce unauthorised ventilation, such as awarding bonus pay for the crosscut that used the least compressed air per ton ore blasted.

3.7.1 Proposed solution

The second solution proposed for this study was to develop an action tracker/management plan to assist Mine A personnel to plan and keep track of priority maintenance issues and projects regarding compressed air improvements. This management plan doubles as a performance tracker by indicating daily, weekly and monthly changes to the pressure and flow consumption of the shaft.

This Compressed Air Management Plan (CAMP) is intended to be sent out weekly to all the relevant personnel on Mine A. The first section of the CAMP consists of the priority tasks that must be completed during the week. Table 17 illustrates the given information of this section.

Table 17: List of priority tasks

Priority	Section	Action	Identification date	Commitment date	Responsible person
1.	Surface	Distance piece fabrication order on tender	2021/07/16	2021/09/28	
2.	20L UG2	Install measuring points to do crosscut baseload	2021/09/30	TBD	
3.	20L UG2	Audit half-level	2021/09/30	TBD	
4.	Surface	Installation quote	2021/06/18	2021/07/02	

Table 17 indicates the priority index, where the task is located, what action must be taken, when the task was identified, when resources would be allocated, and who the responsible party is. This allows the person/s in charge to know what needs to be done, how long the task has been outstanding and who is to be held accountable for the completion of the task. Table 18 below is given after the weekly priority tasks to provide feedback as to what has been done during the previous two weeks.

Table 18: List of completed tasks in the previous two weeks

Section	Work Completed	Completion date	Responsible person
Shaft	Baseload test	2021/09/30	

The second section of the CAMP consists of graphs showing the shaft's historic performance regarding the compressed air flow consumption and pressure. The aim with this is to determine the effect of the compressed air initiatives implemented. Daily, weekly and monthly figures should be given, but for illustrative purposes, only the weekly and monthly graphs will be given in this document. The first set of graphs illustrates Mine A's flow consumption, the second set illustrates the supply pressure, and the third set illustrates Mine A's KPI. The profiles plotted on the Weekly consumption graphs are the average flow/pressure for the corresponding week of the year.

The KPI is a measurement of the overall performance of the shaft. It is the amount of flow (measured in m^3) per hour divided by the pressure (measured in kPa) of the compressed air. This will give an indication of the resistance of the shaft. The lower the KPI, the better the shaft performance. When leaks are fixed, the flow will drop, and pressure will rise, resulting in a lower KPI.

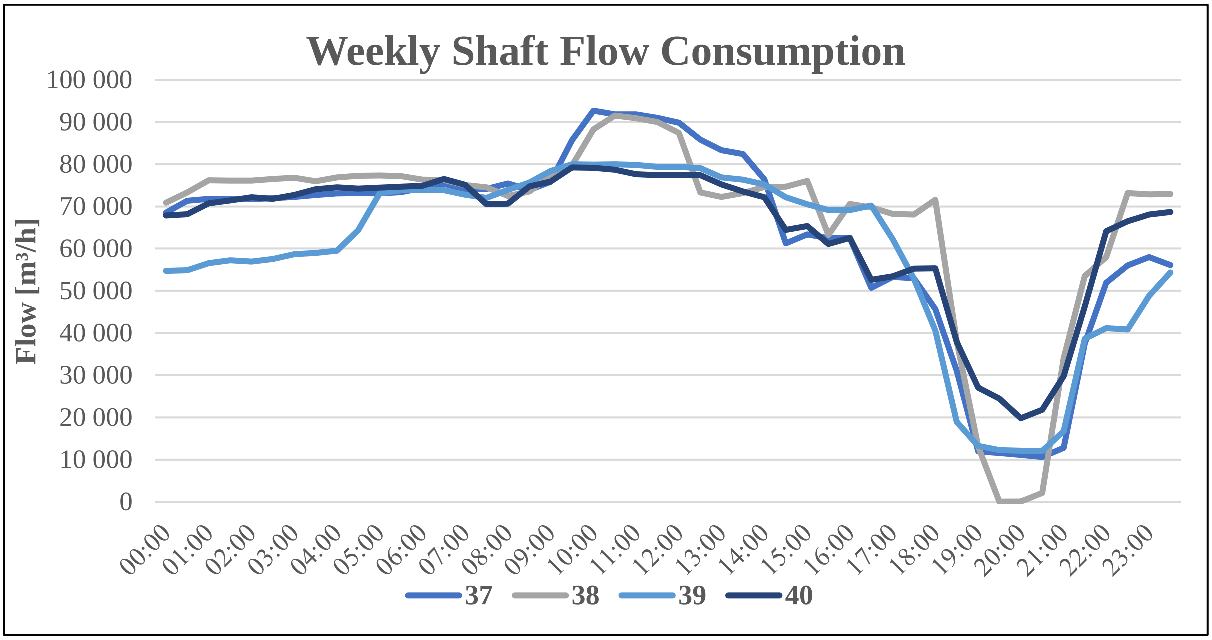


Figure 32 : Historic weekly flow consumption (previous 4 weeks)

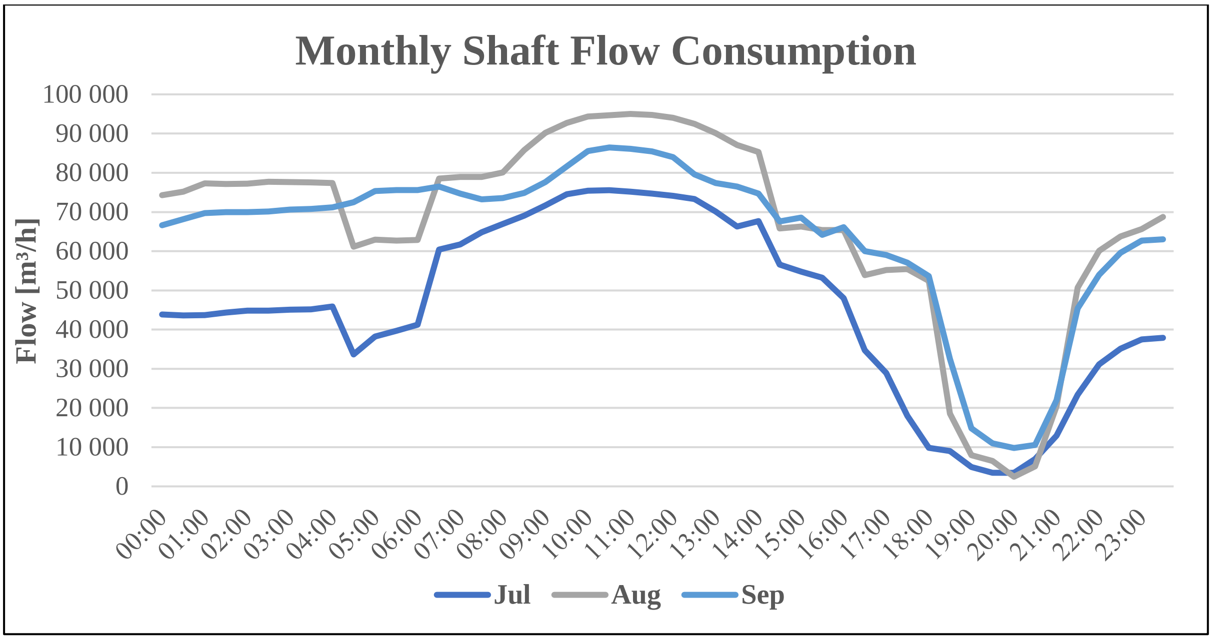


Figure 33: Historic monthly flow consumption (previous 3 months)

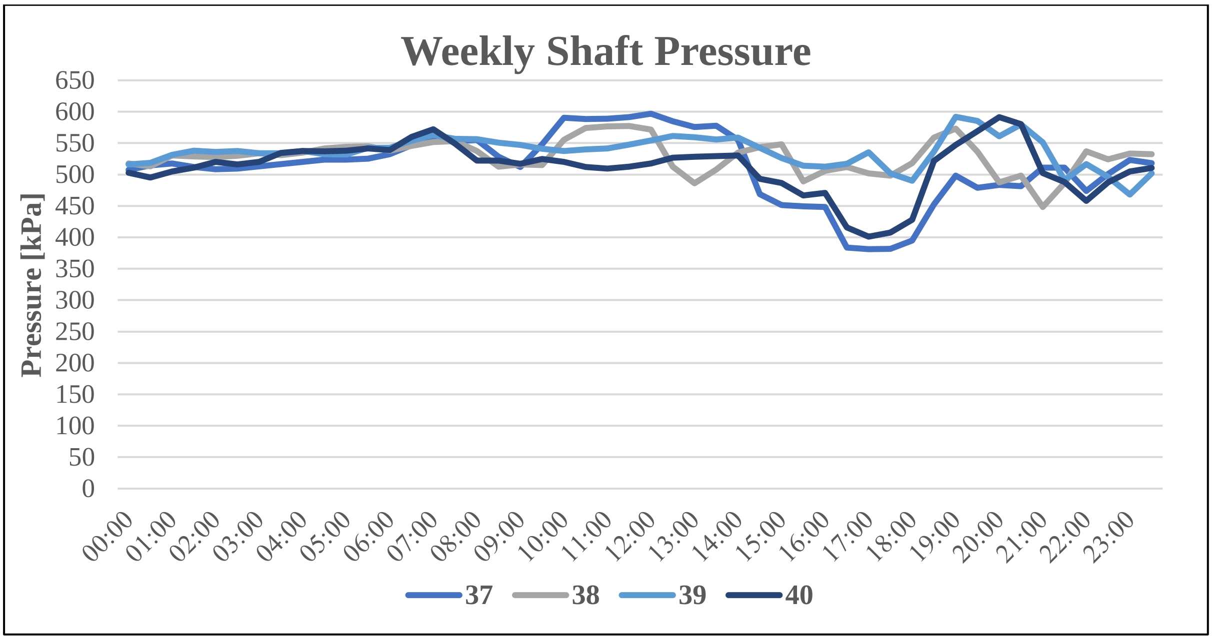


Figure 34: Historic weekly shaft supply pressure (previous 4 weeks)

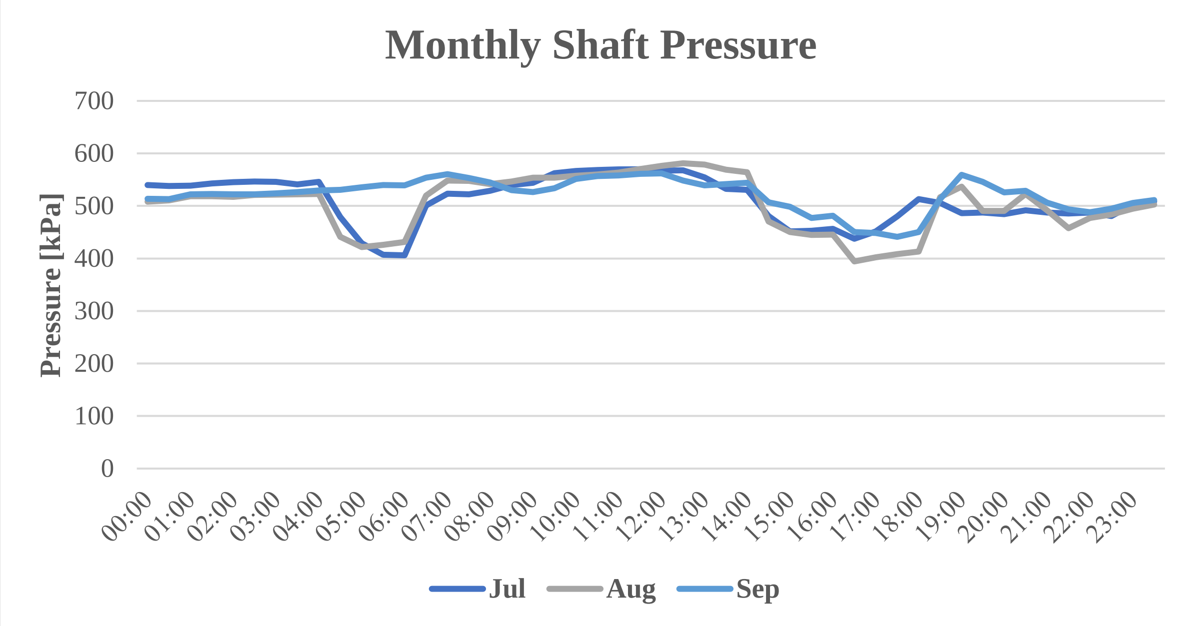


Figure 35: Historic monthly shaft supply pressure (previous 3 months)

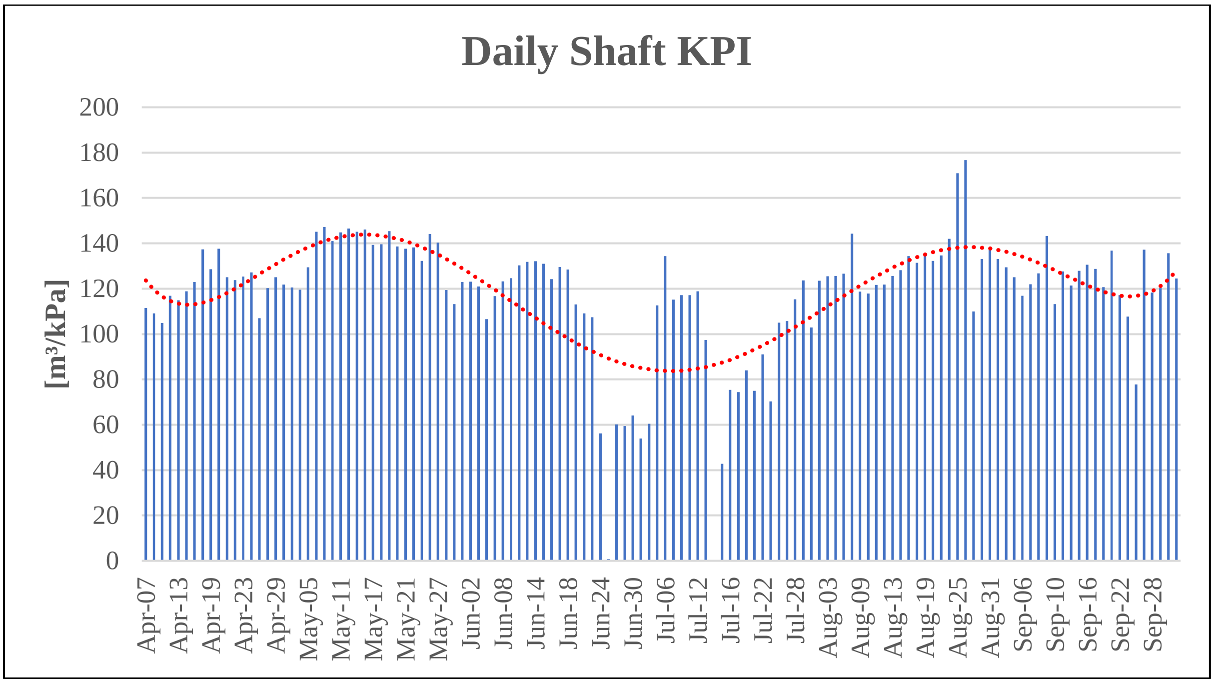


Figure 36: Historic daily KPI

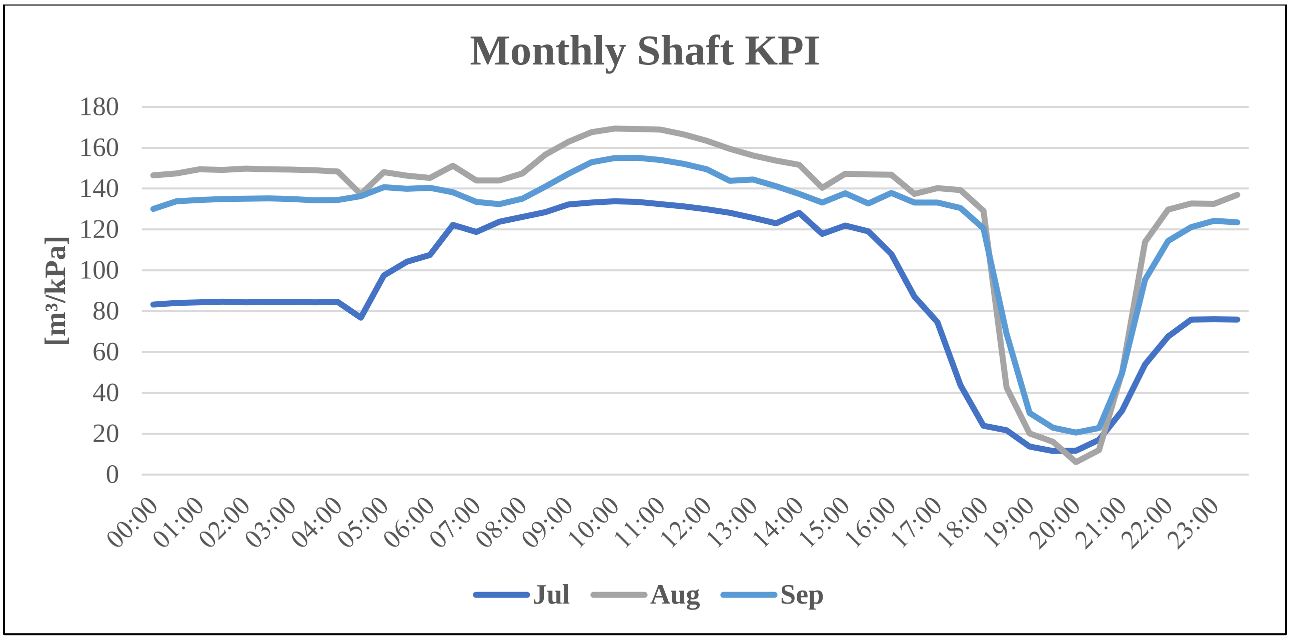


Figure 37: Historic monthly KPI

Figure 36 and Figure 37 are the best indicators of the shaft's performance as it illustrates the flow and pressure ratio known as the KPI of the shaft. From the figures, the shaft performed the best during July. However, during this month, the shaft experienced multiple strike actions due to labour wage disputes, therefore, context is needed when looking at these types of graphs.

The third section of the CAMP entails work that is still outstanding. Reasons for tasks on this list may be due to insufficient budget, labour availability issues or pre-requisite tasks not yet completed. See Table 19 below; for illustrative purposes, only 20L is given, all levels are included.

Table 19: Level specific priorities

Priority	Section – Area	Action	Identification date	Commitment date	Responsible person
20 Level					
1.	Chairlift	Distance piece fabrication	2021/04/28	TBD	
2.	Chairlift	Water trap installation	2021/04/28	TBD	
3.	MN, MS	X/C 2023, 2026 and 2010 must be blanked.	2021/02/08	TBD	

The last section of the CAMP is used to archive all the work completed. This records the work done on the shaft to improve compressed air performance. This also indicates who the responsible personnel were, giving the reader the necessary information to follow up with the parties involved in emergency maintenance or additional required actions. See Table 20 below; for illustrative purposes, only the first three entries are shown.

Table 20: Work completed by responsible personnel

Section	Work Completed	Completion date	Responsible person
14L	Chrome South blanked off. Two major CA leaks fixed on Merensky split	2021/03/13	
15L	X/C 15C28 blanked-off.	2021/03/13	
16L	X/C 16C10 and X/C 16C07 blanked off.	2021/03/13	

3.7.2 Implementation

The CAMP was implemented following the full audit of Mine A. It was sent out weekly with updated tables and figures and was discussed with the shaft engineer and the mine manager. The CAMP was also discussed at the weekly mine planning meeting, where all the people involved were responsible for assigning tasks to the relevant personnel.

The implementation of the CAMP resulted in a more organised and structured approach in dealing with the inefficiencies on the distribution network.

One of the biggest benefits of the report was assisting the engineer and mine manager with prioritising important repairs and projects that would have otherwise been pushed to the bottom of the long list of tasks they needed to complete. This report also shed light on multiple areas that required improvement on the network, which the engineer and mine manager were unaware of.

3.7.3 Results and validation

Due to the intermittent nature of labour availability for maintenance, the lack of installed measuring points or monitoring instrumentation and the fact that compressed air had to be shut off for either the entire shaft or certain sections when performing the repairs, no direct results could be obtained to validate the statement that repairing leaks and blanking inactive crosscuts would lead to a higher compressed air pressure at the end users for this study.

To determine the effects of repairing leaks and blanking off inactive crosscuts for this study, the repairs and maintenance were 'simulated' on a half-level drive during cleaning shift by means of a baseload test. This was done by installing a flow meter at the start of the drive, installing a pressure logger at the development end of the drive and closing crosscuts upstream of the installed logger. The crosscuts were considered the leaks during this test as it consumed air which was required for operations at the measuring point ('end-user') for the purpose of this test.

This test was conducted during an audit on 24L Merensky South at Mine B. As this test was only intended to determine the effects of flow reduction on downstream compressed air pressure when leaks were repaired, the half-level or even, shaft is negligible. Figure 38 gives the complete breakdown of this test.

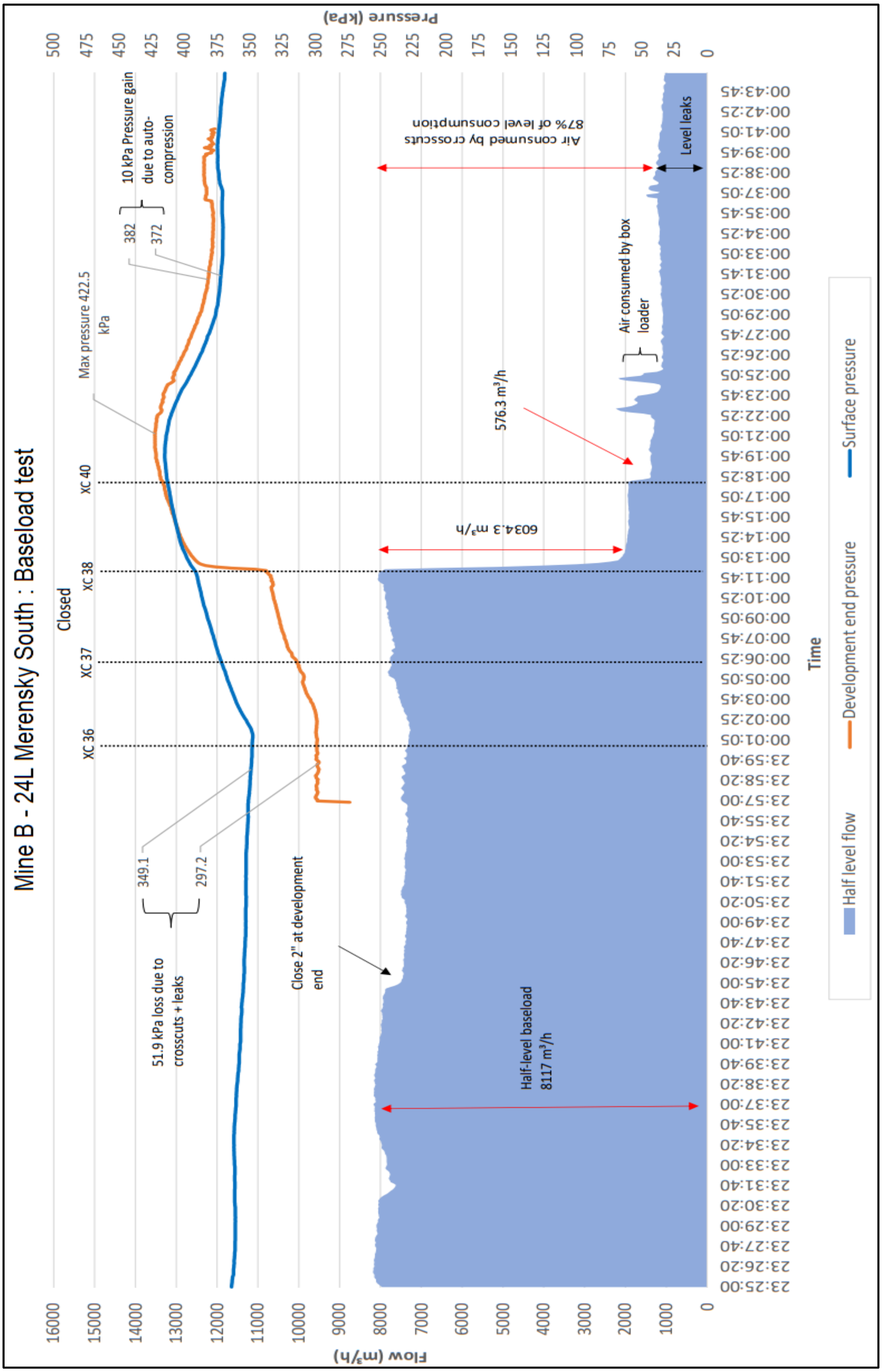


Figure 38: Mine B - leak repair test results

Figure 38 provides clear and valuable insights into how the compressed air reacts in a distribution network. The following insights and results are obtained from the graph:

- Compressed air flow rate is directly proportional to the pressure.
    - From 00:01 – 00:12 the supply flow rate (compressed air feeding the drive) increases as the surface pressure increases.
- Reducing the upstream demand (flow consumption) results in an increased downstream pressure.
    - Closing X/C 38, with a demand of 6034 m^3/h, had a dramatic effect on the downstream pressure at the measuring point, increasing the pressure by approximately 70 kPa. Another pressure increase of approximately 10 kPa was measured when X/C 40, with a demand of 576 m^3/h, was closed. This result is also validated by the slight decrease in pressure observed when the two pneumatic loading boxes consumed air from 00:22 to 00:27.

For this specific drive, it can also be seen that around 50 kPa is lost to leaks on the haulage line supplying the development end.

The results obtained during this test validate Initiative B as reducing the inefficient flow consumption on the supply side - such as repairing leaks, blanking off inactive crosscuts that could be consuming air unnecessarily and mitigating any other types of wastages on the distribution network, such as unauthorised ventilation points, will lead to higher demand pressures. The CAMP was utilised successfully, with many network inefficiencies being repaired or optimised.

The increase in pressure expected on the demand side from the reduced flow consumption could lead to an increase in production, as discussed in Chapter 1.

3.8 Initiative C: Condensate removal

As discussed in the 'Data Acquisition' section, Initiative C was determined during the shaft pressure audit. It was found that water rushed out of a measuring point (1-inch ball valve) installed on the main compressed air line. During the level audits, it was also found that moisture would be present on the instrumentation when the flow and pressure meters were removed after use.

3.8.1 Proposed Solution

From the literature, it was found that removing condensate from the compressed air network would greatly improve the system's efficiency. Moisture in the system can cause corrosion on the inside of the pipes, leading to rust forming, which in turn, causes friction between the compressed air and the inside surface of the pipes to increase, which can lead to a lower pressure at the demand side. Other effects moisture in the system can have:

- unplanned maintenance on pneumatic equipment (leading to downtime and a potential loss in production),
- ice formation in cold temperatures causing blockages on valves, and
- it can affect control instruments from reading and actuating correctly and accurately.

The discovery of water in Mine A's compressed air network led to a discussion with the shaft's engineer as to the best method to remove/reduce the moisture. Two options were presented: in-line water traps or installing new aftercoolers on the two compressors feeding the shaft. It was determined that the aftercoolers would not be feasible as it would be too expensive and require too much downtime for the shaft.

The engineer opted for the in-line water trap option as it was relatively inexpensive, it was tested and approved by SABS (South African Bureau of Standards) to remove 96.85% of the moisture content of the air that flows through it with a 0.03% pressure loss over the instrument and the installation would be a quick process.

The in-line water trap consists of a tube with static radial vains inside which is connected in-line with the compressed air network. The air inside the water trap is then essentially spun dry as it moves through the water trap. The condensate is then gravity fed to a water collection vessel, where it can be continuously drained via an automatic draining valve. See Figure 39 for an illustration of the water trap [62].

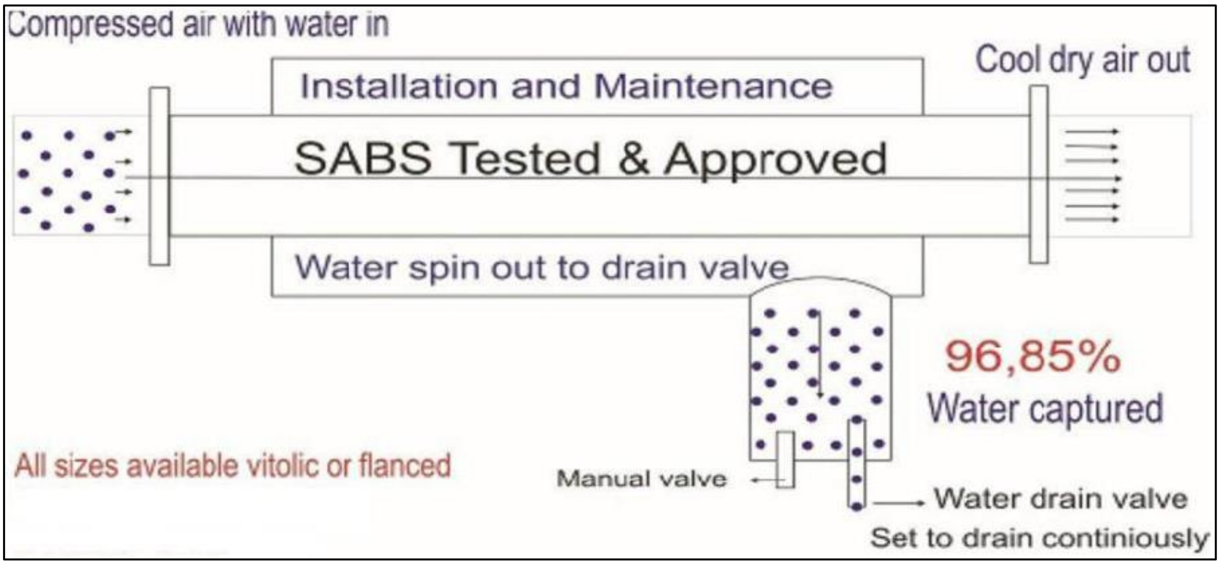


Figure 39: In-line water trap schematic to be used [62]

The data required to simulate the effects of removing moisture from the air was not available, and thus no simulation could be compiled to determine the initiative's feasibility. Nonetheless, the engineer approved the initiative.

3.8.2 Implementation

It was decided that three water traps would be installed on the main compressed air line. The installation locations were strategically determined for the optimal moisture removal in the distribution network. With the assistance and guidance from the shaft’s engineer, the locations were approved and signed-off.

The first installation location was determined as the 13L sub-shaft station. The main CA line runs down the sub-shaft into the conveyor decline section, which in turn feeds the lower production levels. Ventilation air cools the main line running down the sub-shaft, increasing the probability of condensation forming inside the pipe. The first water trap would be installed to remove some of the condensate formed between the compressor outlet and the first working level at this location.

The second location was determined at the 15L conveyor decline section before the two 90° bends on the main line over the conveyor belt. From previous investigations, this location was known for large water build-ups. The water trap at this location would reduce the risk of water causing a narrowing of the main line’s effective cross-sectional area and blockages at the trough formed by the first 90° bend. Refer to Chapter 3.4 - Figure 22.

The third location was determined as the entrance to 20L station. With 20L being the largest production level for the mine, it was determined to be the highest priority for dry air to reach the rock drills. The third water trap would be installed to remove any excess moisture that the other water traps did not remove.

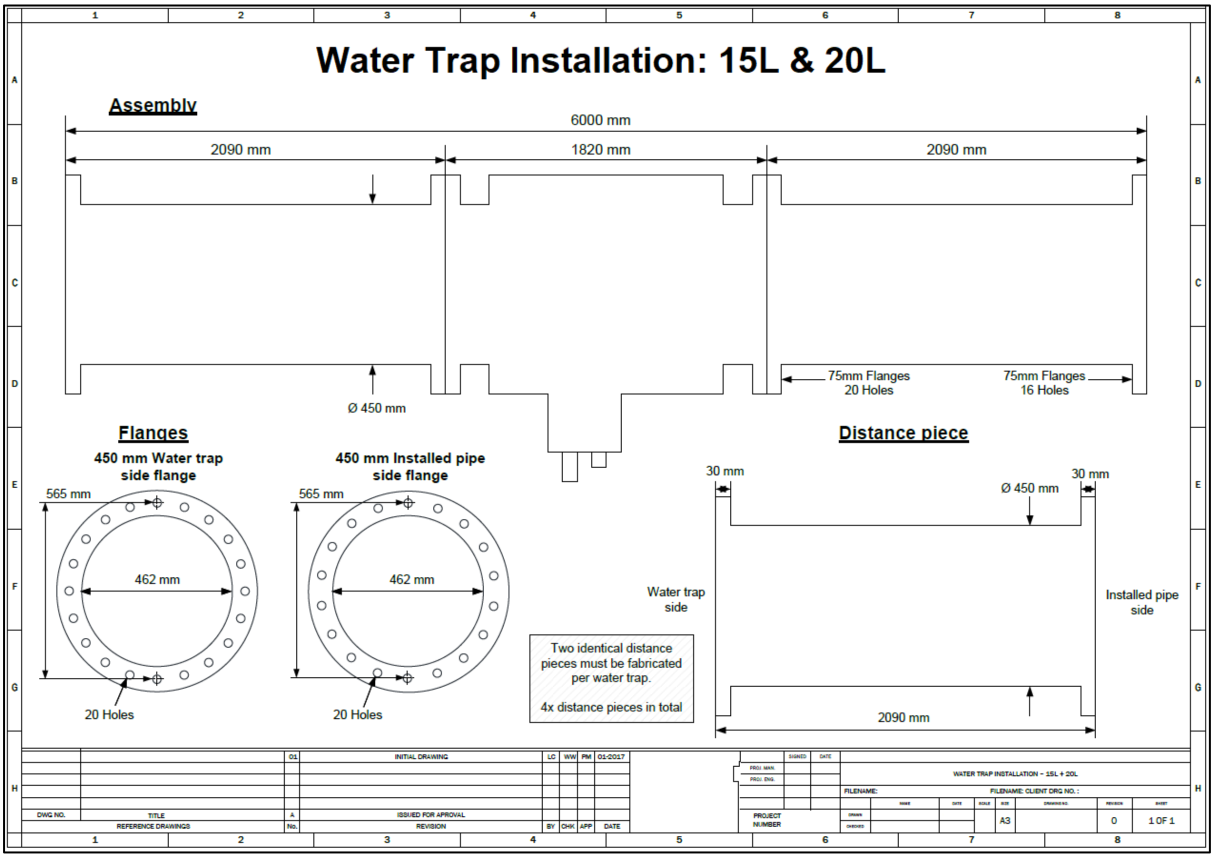


Figure 40: Water trap installation drawing

Figure 40 illustrates the water trap distance piece drawings and Figure 41 illustrates the installed water trap. Two distance pieces were fabricated per location and were attached to the water traps on either side on the day of installation. The assembly took place at the installation location as it is easier to transport the separate components than the full assembly. A pipe section was removed, and the water trap/distance piece assembly was installed.

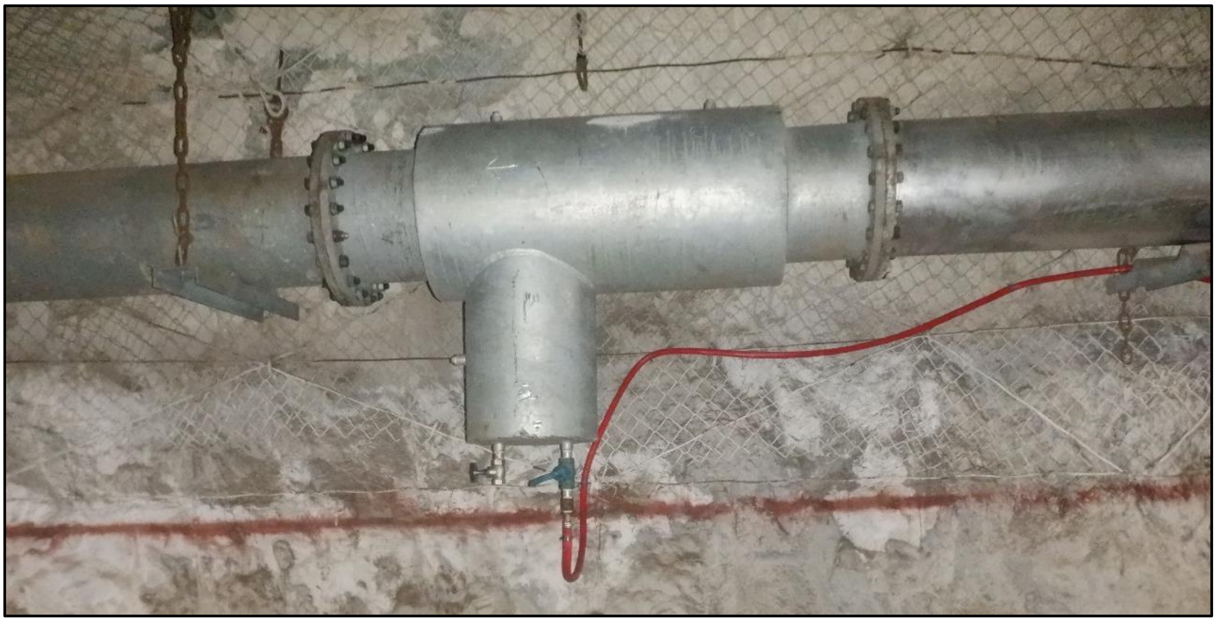


Figure 41: Installed water trap at 13L station

Many challenges were faced during the implementation of Initiative C. The project took over a year to complete, as there were budget constraints, delays on the distance piece fabrications, delays on the auto drain valve delivery, ongoing strikes at Mine A during 2021 and 2022, and scheduling issues with transportation and labour availability for installation. However, all these issues were kept track of with the assistance of the CAMP developed during Initiative B, which led to a systematic approach and resolution to the issues faced.

3.8.3 Results and validation

After installation, another main line compressed air audit was done to determine the effect the water traps had on the downstream compressed air pressure and to determine if it had reduced the 135 kPa pressure drop experienced from the surface to 20L.

Ideally, a pressure audit should have been done a week before the water traps started removing moisture from the air. This would have given a more accurate result as to the effectivity of the water traps by comparing what the pressure drop was close to implementation as the compressed air network is a dynamic system that changes constantly. However, this wasn't possible due to the short notice given by the mine for the installation of the water traps.

A pressure audit was conducted after implementation. Pressure loggers were installed at the same locations as during the initial pressure audit (see Figure 20). The pressure loggers were installed for a week to obtain average pressures. However, when the pressure loggers were retrieved, it was found that the pressure logger installed at 13L did not log more than a day due to dead batteries and the data from the pressure logger at 15L became corrupt and could not be extracted from the memory card. Both these loggers' data was excluded from the results and only the pressure logged at 20L station was used. At the time of the study, no additional audit was scheduled to remeasure the data. Figure 42 illustrates the results obtained during this audit.

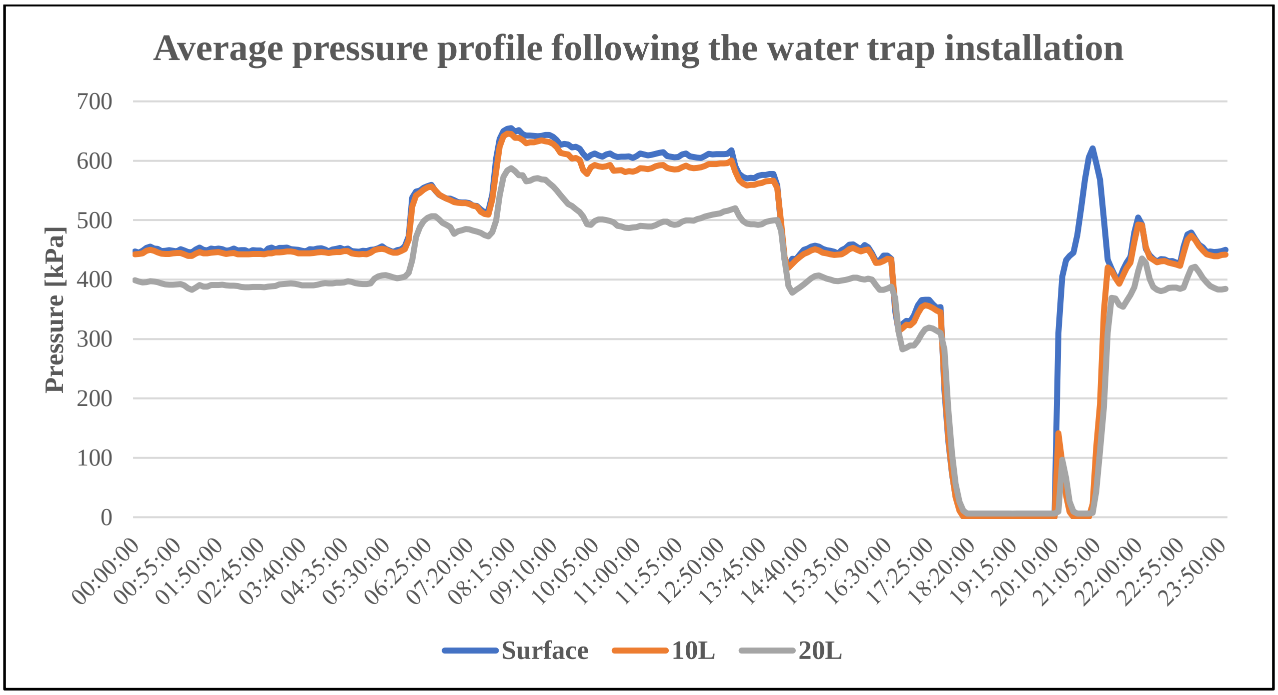


Figure 42: Pressure audit results after implementation of Initiative C

Note the 'steps' in the 24h pressure profile. A surface control valve was installed on Mine A during the implementation of Initiative C. The control valve uses different pressure setpoints throughout the day for the different shifts. This was installed for the purpose of energy savings as this reduces the amount of air supplied to the mine during times when a fully open surface valve is not required. This, however, does not affect the operations of the water traps. Table 21 below summarises the pressure drop between surface and 20L for the different shifts.

Table 21: Results of average pressures obtained during audit

Shift	Surface Pressure [kPa]	20L Station Pressure [kPa]	Pressure Drop [kPa]
Cleaning	453	380	73
Pre-Drilling	537	482	55
Drilling	613	516	97
Post-Drilling	434	396	38
Afternoon Reduction	300	278	22
Overall Average	451	375	76

It is important to note that the pressure audit was conducted with the 11L bypass line closed, as implemented during Initiative A, for the purpose of comparison, as this line was also closed during the initial audits conducted in October 2020.

Comparing the results from this audit to the constant pressure drop of 135 kPa observed during the initial audits, the water traps improved the 24-hour average pressure supplied to 20L by around 60 kPa, and an increase of around 40 kPa was observed during the drilling shift.

Therefore, these results validate Initiative C as there was a clear improvement in the compressed air pressure supplied to 20L. According to the literature, the increased pressure supplied to the level will also lead to improved pressure at the drills, causing the rock drills to operate more efficiently. It is expected that an increase in production could be expected following this increase in supply pressure.

3.9 Conclusion

Three initiatives were identified during this study. All three initiatives were implemented and delivered results proving that increased pressure to the demand side was achievable by reducing network inefficiencies on the distribution network.

A summary of the initiatives and the increase in compressed air pressure each achieved is seen in Table 22 below. The results shown are the expected improvement seen at the rockdrills on 20L. This study could not obtain actual compressed air pressure at the face.

Table 22: Summarised results for all three initiatives

Initiative	Demand-side pressure increase [kPa]
A	36
B	50
C	40
Total pressure increase	**126**

The result from implementing the three initiatives at Mine A shows a clear improvement in compressed air pressure supplied to 20L and thus, by extension, to the rockdrills in the stopes. However, it is important to note that the increase in pressure from Initiative A and C will not equal the value in Table 22 at the rockdrills and pneumatic loaders as inefficiencies on the network from the station to the demand could affect the pressure. Initiative B focused on the inefficiencies between the level station and the demand.

From the literature, an increase in compressed air pressure supplied to the rock drills will result in,

- higher rock drill power output,
- an increase in the rate of penetration,
- a decrease in the time it takes to drill a hole,
- an increase in the number of holes that can be drilled per shift,

and thus, an increase in production can be expected.

Chapter 4 Conclusion and Recommendations

4.1 Summary

Platinum mines in South Africa are under financial pressure due to the rising cost of energy and a decline in production trends. Most South African platinum mines operate with ageing or outdated infrastructure with limited monitoring capabilities. To ensure production targets are being met, the current infrastructure should be used as effectively as possible.

Platinum mines utilise compressed air as the main source of energy to power equipment required for production. Compressed air networks are considered to be the most inefficient systems in the mining industry.

From the literature, it was found that compressed air network inefficiencies offer a large potential for optimisation. These studies showed that CA network inefficiencies results in low service delivery pressure being supplied to machinery such as pneumatically operated drill rigs, pneumatic cylinders used to operate loading chutes, mechanical loaders etc. These studies suggest that lowered demand-side pressure leads to longer drilling and loading times, and higher consumption of compressed air, which contributes to higher operational costs and affects the amount of ore hoisted.

The need for the study to identify, implement and test various initiatives to improve demand-side pressure losses in deep-level mining compressed air networks was identified. The study's objectives were:

1. Identify and evaluate compressed air network inefficiencies.
2. Develop a generic methodology to identify and reduce compressed air network inefficiencies, which can be applied on any mine utilising compressed air.
3. Implement feasible solutions that will improve the efficiency of the network and reduce pressure drops found from the supply side to the demand side.

The methodology developed focused on identifying the most inefficient areas of the network with techniques such as base load testing and compressed air network audits.

The methodology was implemented on Mine A. Various tests and audits were performed on the compressed air distribution network to identify possible inefficiencies. A pressure drop of 135 kPa between the surface and 20L (the lowest production level geographically) was found. Further tests were conducted to determine the cause of this pressure drop.

Three initiatives were determined to improve the network inefficiencies found during the evaluation stage that could potentially cause the low demand-side pressure experienced at Mine A.

The initiatives included,

A. Reconfiguring the compressed air network to allow more air to be supplied to the lower production levels,
B. Reducing the number of leaks, wastages and inactive areas still receiving air with the assistance of a compressed air management plan developed to systematically approach the repairs and maintenance of the network, and
C. Removing moisture from the compressed air by installing in-line water traps.

The compressed air pressure at 20L station was used as the performance indicator for these initiatives. Both Initiative A and C resulted in an increase of 20L station’s pressure. These initiatives were implemented on the main CA distribution line before it split into the levels.

The exact pressure increase for Initiative B could not be determined. However, from a simulated test, it was seen that reducing air consumption upstream of the demand resulted in increased pressure at the demand.

Therefore, all the objectives were successfully achieved to address the need for this study. This study was thus successful, and the methodology can be implemented on other mines to identify and reduce network inefficiencies with the goal of improving demand-side compressed air pressure.

4.2 Recommendations

The recommendations for future studies are as follows:

- A more comprehensive compressed air monitoring system will add value. Installing compressed air flow meters and pressure loggers at the start of production levels, half-levels, drives, and crosscuts will simplify the network inefficiencies identification process.
- The method developed in this study could also be implemented on other mining systems, such as the water reticulation system.
- The focus should be placed on improving ventilation systems when conducting investigations regarding inadequate service delivery, as unauthorised use of CA by miners in hot areas leads to decreased pressures at the rock drills/mechanical loaders.
- Half-level isolation control valves could be investigated as a possible initiative to improve demand-side pressure. Typically, miners do not close the isolation valves at the crosscuts at the end of their shifts. Closing off abandoned sections would improve the downstream pressure during the cleaning shift when the mechanical loaders load ore into the hoppers.
- Further investigations should be done on the effects unnecessary or over-complicated bends have on the downstream compressed air pressure.
- If a large pressure drop over a few lengths of pipes is found and it is not caused by a blockage, it could be caused by an orifice plate installed between two flanges. Mines used orifice plates to measure the CA flow rate at certain points. An orifice plate effectively reduces the cross-sectional area of the pipe.
- The effect of rust inside old pipes should be investigated further.
- The effect of sub-standard piping or incorrectly sized pipes on the downstream compressed air pressure.

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