Practical approach to analyse mine pneumatic drilling performance

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ABSTRACT

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South African deep-level mines were challenged over the last couple of years as production trends declined and the commodity price for PGM's and gold decreased from 2016. The labour costs and operational costs are also increasing, thus increasing mines' fixed costs. The profitability of South African mines is threatened as income decreases and fixed costs rise.

South African mines are also limited by the current infrastructure compared to the rest of the world. One such outdated technology used in most of South African mines is pneumatic rock drills. Optimising pneumatic rock drilling will help ensure South African mines remain profitable and competitive. Studies implemented to improve production, studies that investigated pneumatic rock drills, and studies identifying inefficiencies in a compressed air network were critically analysed.

The need was evident to develop a practical holistic approach to analyse mine production outputs against pneumatic drilling performance. The study's objectives were addressed by developing a methodology to holistically overview the mine's compressed air service delivery and production performance using key performance indicators. The most inefficient production levels, most likely affected by inadequate compressed air service delivery, were identified and further analysed to determine the effect of inadequate compressed air service delivery on production.

The effect of poor compressed air pressure could be analysed by comparing the calculated expected compressed air pressure with the production achieved for every active panel per day. The common drilling performance of every production panel was identified and compared to production realised when compressed air service delivery pressure was low.

The methodology was implemented at Mine A over five months, analysing all the production and compressed air service delivery data to identify production lost due to insufficient compressed air service delivery. The study's objectives were met and the study identified R3.5 million lost production due to inadequate compressed air supply at the production panels during a five-month period. Monitoring and addressing compressed air wastage in the compressed air network can prevent future production loss.

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ABBREVIATIONS

ROP	Rate of Penetration
GDP	Gross Domestic Product
M&V	Measurement and Verification
SCADA	Supervisory Control and Data Acquisition
NERSA	National Energy Regulator of South Africa
PGM	Precious Metal Group
ISRM	The International Society of Rock Mechanics
PIO	The Process Integration and Optimisation
MAPS	Mine Activity Performance System
HLP	Half-Level Planning
ERR	Energy Reduction Ratio

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CHAPTER 1. INTRODUCTION & BACKGROUND

1.1. Introduction

This introductory chapter provides background on challenges facing the South African mining industries and the general mining operations of deep-level mines. The chapter will elaborate on pneumatic drilling practices and factors influencing pneumatic drilling performance such as compressed air service delivery.

Previous studies on performance improvements in production outputs and methods used to identify inefficient compressed air reticulation will be explored. The need for this study and problem statement is developed based on the background, challenges and shortcomings of previous studies discussed in this chapter. Figure 1 shows this chapter's flow diagram linking the challenges facing the mining industry to the study's objectives.

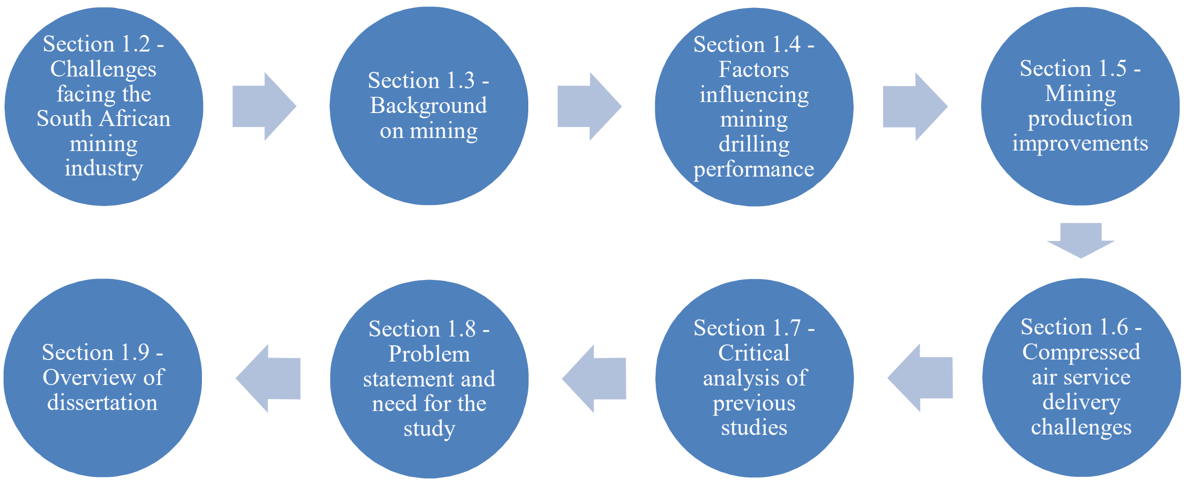

Figure 1: Section flow diagram

1.2. Challenges facing the South African mining industry

1.2.1. Operational and production challenges

The mining industry faces a variety of challenges in production and operations. The following areas are the most significant:

Production trends and commodity prices

Production trends and commodity prices play a crucial role in the profitability of mining industries. Production trends, shown in Figure 2, indicate that over the last 15 years manganese, iron ore and chrome are the only commodities that showed growth. Deep-level mining such as the PGMs and gold mining industries show long-term declines in production.

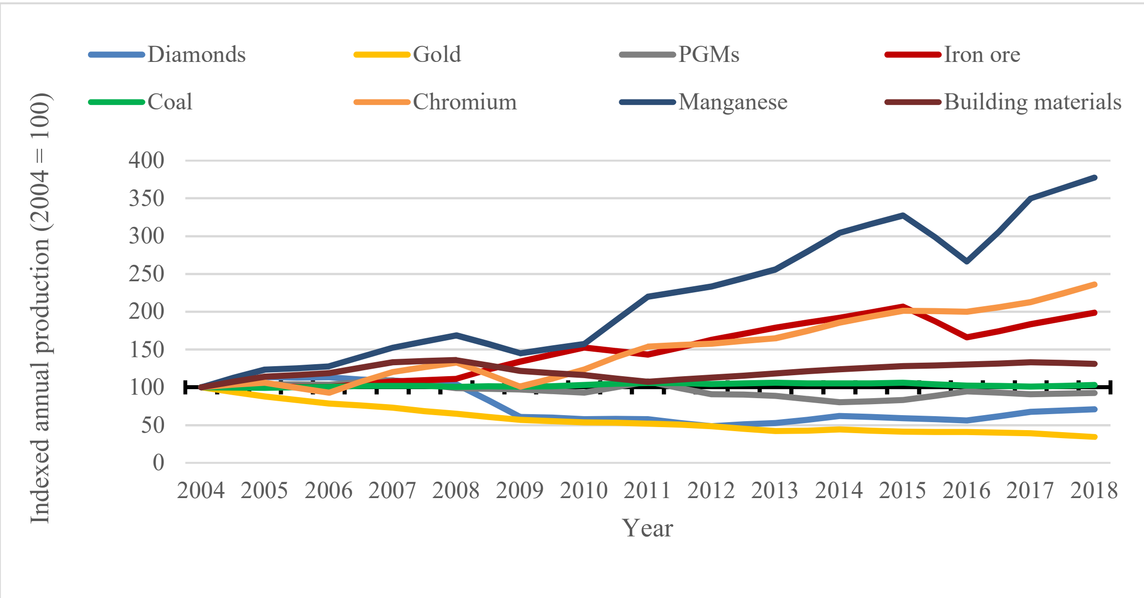

Figure 2: Indexed annual production per commodity, June 2004 - June 2018 (Adapted from [1])

The commodity prices for platinum and gold decreased from 2016 to 2018 and therefore indicated financial pressure on these mining industries, shown in Figure 3. If the production trend continues this will result in the unsustainability of the mining industry.

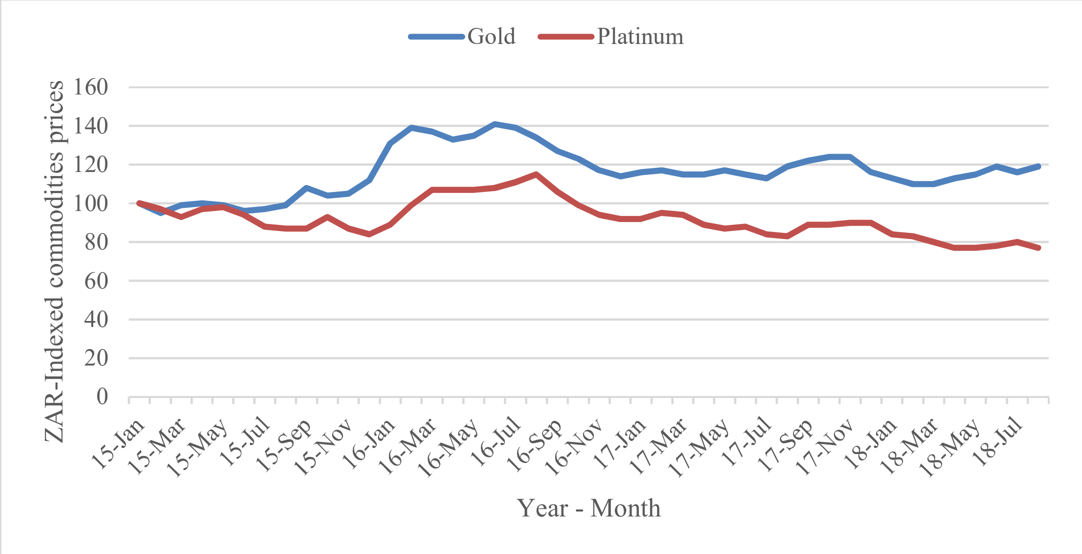

Figure 3: Commodity prices – ZAR-indexed (Adapted from [1])

Labour relations

In South Africa, labour relations and wage negotiations have a significant effect on the mining industry. Labour costs continue to be a substantial output cost of this industry, with value absorption of 47% [1]. As shown in Figure 4, the number of employees in the labour-intensive gold and platinum mining industries decreased by an average of 2% year on year, and the employee earnings increased on average by 11% year on year from 2007 to 2017 [2].

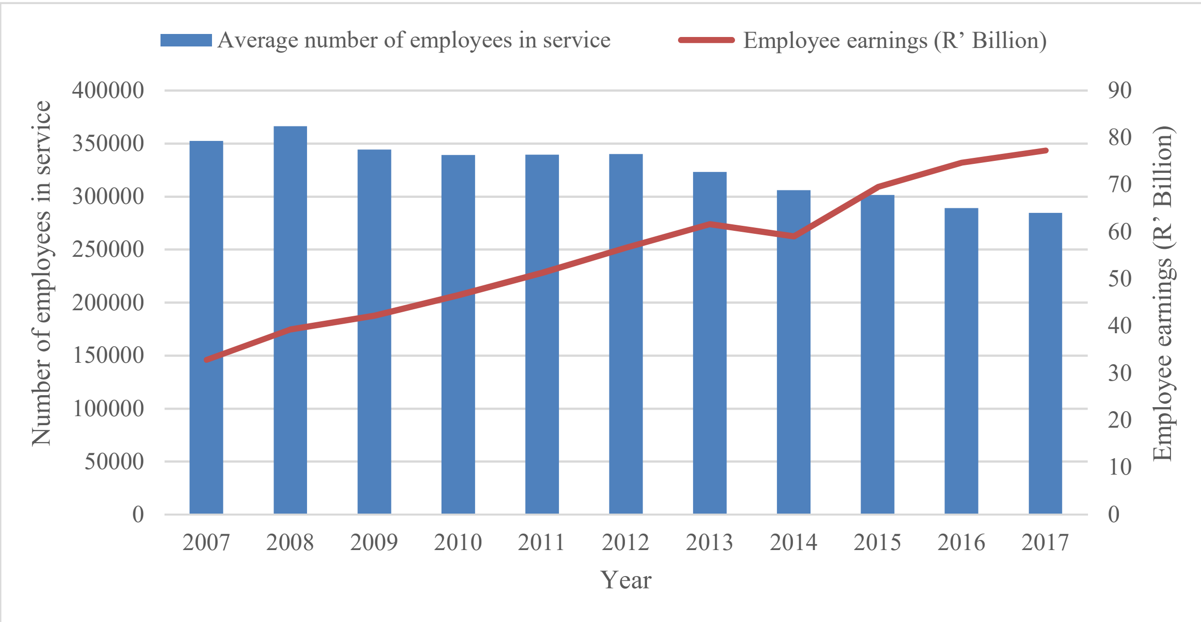

Figure 4: Combined platinum and gold employees and employees earnings [2]

Operational cost

Production costs of deep-level mines threaten the financial feasibility of the mining industry in South Africa. Figure 5 represents the breakdown of operating expenses. Utility costs such as electricity are a growing expenditure increasing production costs of deep-level mines, and contribute to 8% of total costs [1].

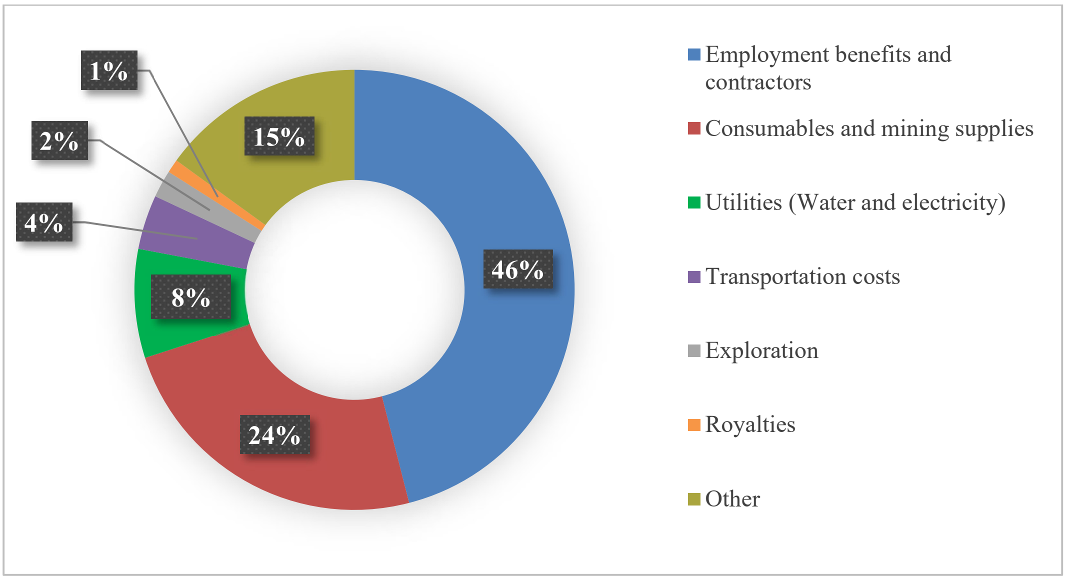

Figure 5 - Breakdown of total operating costs of mining in 2018 (adapted from [1])

The platinum and gold mining sectors consume 80% of the total electricity used by the mining industry [3]. Electricity tariffs between the period 2008/2009 and 2019/2020 for the mining sector are shown in Figure 6. The National Energy Regulator of South Africa (NERSA) approved an Eskom electricity tariff increase of 13.87% for the period 2019/2020 [4]. Operational efficiency of electricity consumption in mining systems is therefore mandatory for the financial feasibility of the mining industry in South Africa [5].

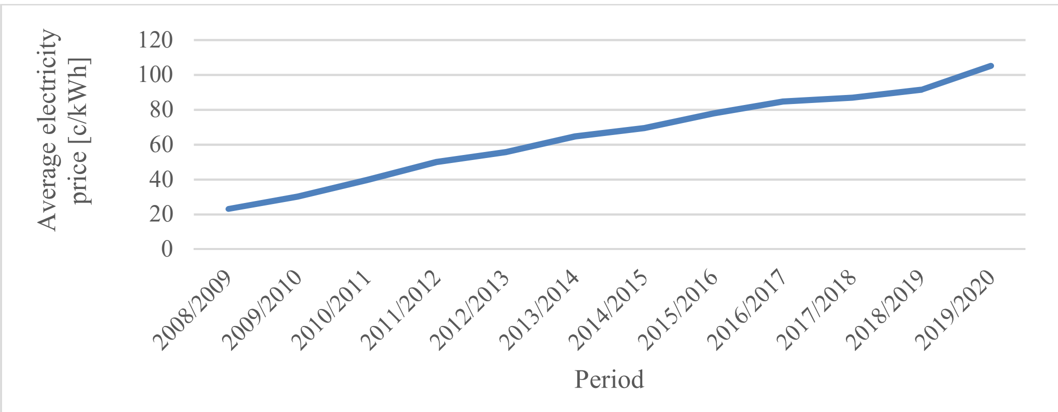

Figure 6: Annual average Eskom prices in the mining industry (2008/09-2019/20) [4], [5]

The energy breakdown of the South African mining sector according to Eskom shows that compressed air systems contribute 17% of the total mining energy expenses [3].

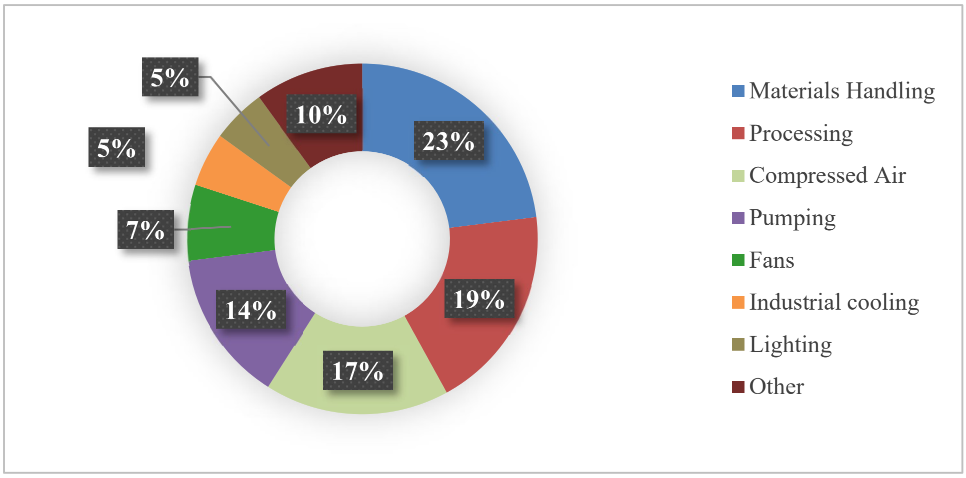

Figure 7 - Energy breakdown for mining services (adapted from [3])

In the mining industry compressed air is used for various purposes such as drilling. Compressed air is preferred due to its ease of use, reliability and relative safety, but this comes at the cost of increased energy losses. Only between 10-30% of generated compressed air reaches the consumer [6]. Not only are compressed air systems major energy consumers, but these systems are also operated inefficiently. Therefore, energy efficiency initiatives are required to improve compressed air service delivery. Efficiency improvements can be achieved in increased production output or energy savings.

Limited infrastructure

South African mines exceed world-class standards, demonstrating their success in deep-level mining; however, the industry has not been innovative in its thinking to develop new methods of extracting certain metal groups. This leaves extraction methods similar over the last 100 years [7]. Rock drilling, blasting and cleaning remain part of everyday mining [7].

Studies have shown that the mining sector's future depends on modernisation. This is especially true for deep-level mining processes and equipment. Modernisation will lead to enhancement of processes by making use of new technology, examples being the implementation of mechanised mining equipment, new drilling technologies and integrating internet of things ('smart' technology) applications into the drilling cycle [8]. This mechanisation is beneficial, but its achievement has multiple challenges. Modernising is crucial to ensure profitability in the future of mining in the South African economy [7].

"Raise boring technology" that enables mining to be conducted without the use of explosives was developed by Master Drilling, a company established in South Africa in 1986 [9]. They now have operations across the world, ensuring mining safety, speed and efficient operational costs. This method creates round tunnels lowering the chances of rock falls as stone is not blasted. The method eliminates the use of explosives which reduces costs as ore bodies are reached in a fraction of the time [9]. However, this mining method can only be used for developing to the ore bodies and not for ore extraction.

South African mines are mainly using pneumatic handheld drilling. Handheld drilling technologies are improving and new drill implementation in South Africa faces many engineering and social challenges [10]. The operational cost of different drilling technologies was implemented and compared in a case study shown in Figure 8.

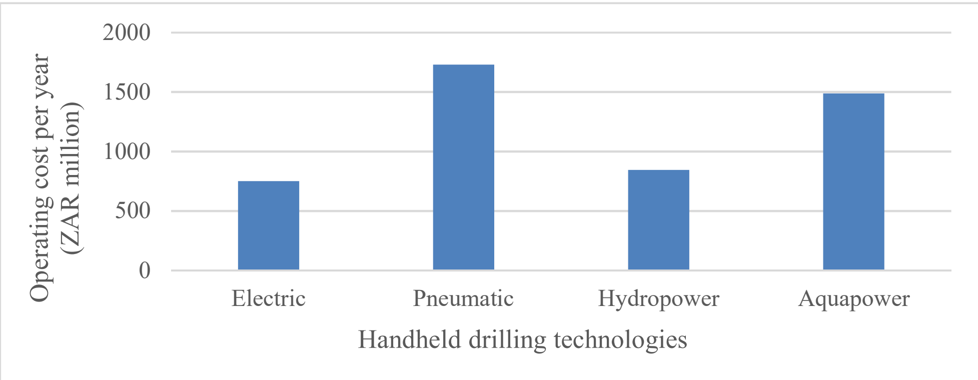

Figure 8: Operational cost of different drilling technology scenarios on a mine in 2013 (Adapted from [11])

1.2.2. Interpreting challenges mines in South Africa are facing

The life span of South African mines is threatened as production decreases and operational costs rise. Labour costs have a significant impact on this life span as they makes up 47% of costs and are continually climbing. Another challenge for the financial feasibility of the mines is electricity price increases of more than 400% over the last decade. The solution to the industry dilemma is a modernisation of mining infrastructure and procedures to increase efficiency, thus increasing production and decreasing operational costs. Economic and social issues need to be addressed to make productivity sustainable.

1.3. Background on mining operations

1.3.1. Introduction

In deep-level mines, ore deposits are far below the surface and underground access is only possible by using vertical shafts, as seen in Figure 9. In this chapter, the operations, procedures and infrastructure of deep-level mines are discussed.

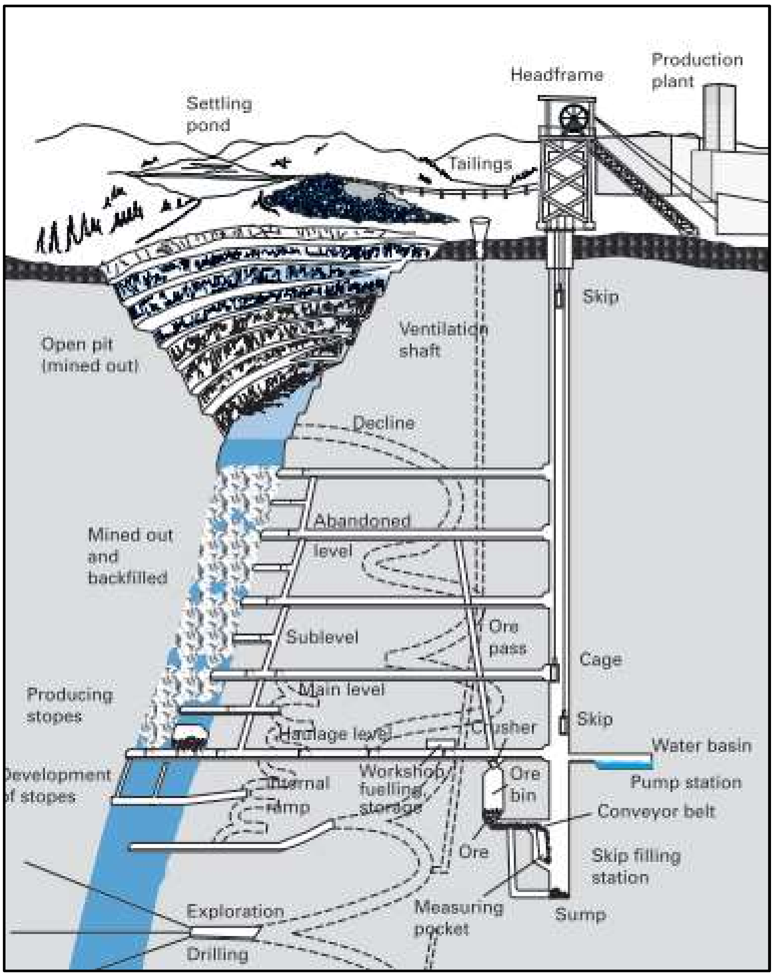

Figure 9: Underground layout of deep-level mine [12]

1.3.2. Mining operations

The mining cycle for deep-level mining consists of the following activities: support installation, drilling of the blast holes, charging-up of explosives, blasting and cleaning. The mining cycle can only continue if every activity of the cycle is completed. The mining cycle repeats every 24-hours and the time spent per activity is indicated in Figure 10.

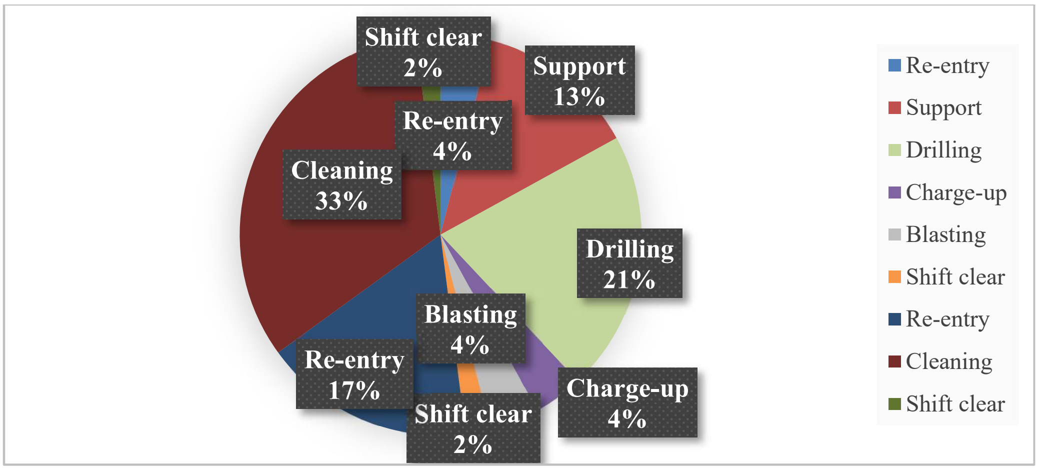

Figure 10: Mining cycle activities in a 24-hour cycle [Adapted from [13]]

Other operations are also required to support the mining cycle but do not affect the cycle directly. These activities are development, ledging, equipping, stoping, sweeping, vamping and reclamation [13].

The mining cycle consists of the following activities:

Support:

Mined areas need to be supported to prevent the rock roof from falling. Different mining methods require different support systems. Many different support systems are used: two commonly found support systems are wooden timber props and cement-grout packs. Face props are installed as temporary support along the face of the panel for the protection of the workers responsible for drilling and blasting [14].

Drilling:

In the deep-level mining cycle drilling makes up 21% of a 24-hour daily routine. Drilling refers to creating holes in the rock face to insert explosives. Drilling crews use handheld drills with a supporting airleg to drill a pattern of holes in the face. The airleg actuates the required thrust force onto the drill for increased penetration. Once the drilling is complete, the panel is ready to be charged for blasting [13].

Charge-up of explosives and blasting:

Charging-up of explosives and blasting takes up to 8% of a typical 24-hour deep-level mining day. The blasting process starts with the charging of drilled holes with explosive emulsion and an accompanying detonator. Mines in South Africa uses a blasting method called centralised blasting. Explosives are most commonly set off underground electrically from the surface while the mine is cleared [15].

Cleaning and sweeping:

Cleaning and sweeping make up 33% of a daily routine. This involves removing shattered ore caused by blasting and clearing the rock face. The cleaning starts by collecting ore with scrapers moving down the stope face and gullies that transfer ore into ore passes. The ore passes supply loading boxes in the haulage below the stoping panel where ore is collected. The ore is then transported with locos, ore passes and skips to the surface [14].

1.3.3. Pneumatic drilling practices

Pneumatic drills are used to create the blasting holes as discussed earlier in this section. Pneumatic drilling uses compressed air to operate. The compressed air is generally generated at the surface and supplied to the drills through large pipe networks.

Compressed air service delivery

Deep-level mines in South Africa use compressed air for pneumatic tools and machinery. The compressed air delivery system consists of multiple compressors, a compressed air network and compressed air consumers [16]. The compressed air network supplies compressed air to each working area underground. Underground levels have control valves and instrumentation to monitor compressed airflow and pressure on each level as shown in Figure 11. The most common underground consumers of compressed air are [17]:

- Pneumatic drilling and air leg
- Mechanical ore loaders
- Pneumatic cylinder actuated ore loading boxes
- Refuge bays
- Pneumatic rail switches
- Compressed air used for ventilation
- Leaks

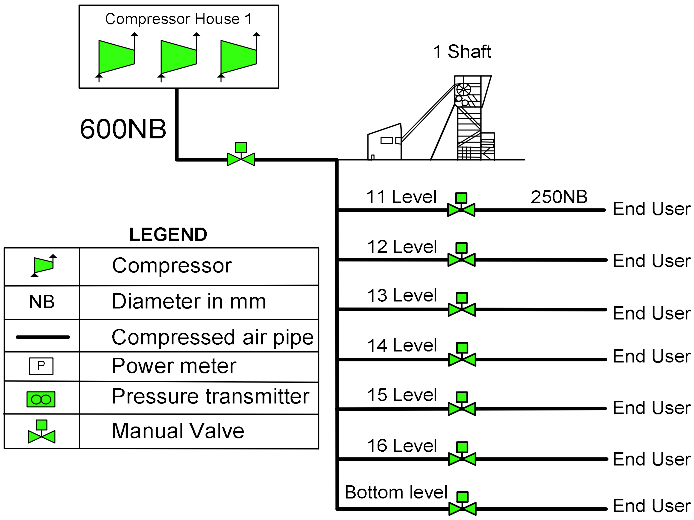

Figure 11 - Typical underground compressed air layout [18]

Surface compressed air networks have numerous compressor houses that distribute compressed air through a large surface pipe network. The network supplies more than one shaft or process plant simultaneously as shown in Figure 12.

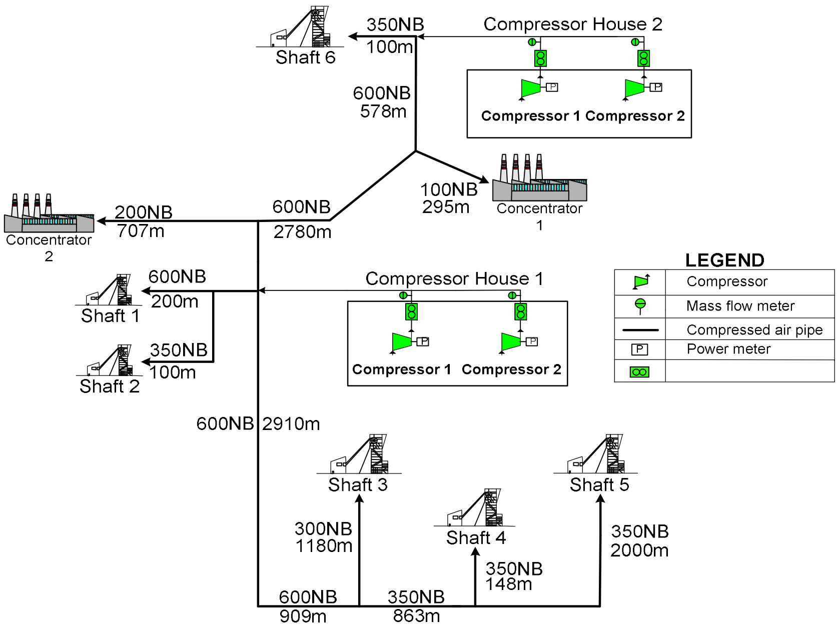

Figure 12 - Typical surface compressed air layout [18]

Drilling in the panels

Drilling of blast holes is essential in conventional mining. Active working panels need service water and compressed air supply continuously. The compressed air pipe layout for pneumatic drilling is shown in Figure 13.

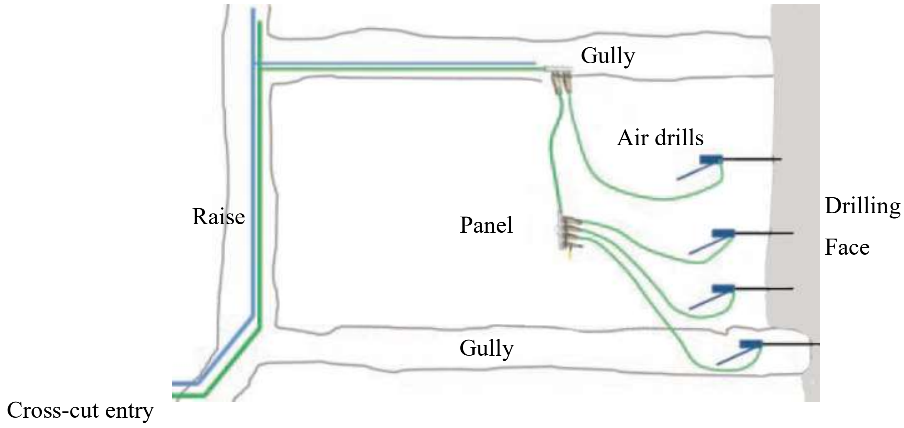

Figure 13: Panel and pipe layout for pneumatic drilling (Adapted from [11])

A variety of pneumatic handheld drills are available on the market. The main characteristics of handheld drills that are considered for specific mining conditions are the following [19]:

- Drill size
- Penetration rate
- Hole diameter ranges
- Low noise levels
- Weight
- Efficiency
- Durability
- Cost
- Mechanical method

Stope drilling in narrow reefs, mostly found in the platinum and gold mining industries, require a compact in size yet efficient rock drill. The development of the air leg supported drills started in 1935 [20]. By controlling the air supply to the air leg, the added air leg ensures that optimal forward thrust is maintained. Figure 14 shows the basic operation of a rock drill with an added airleg.

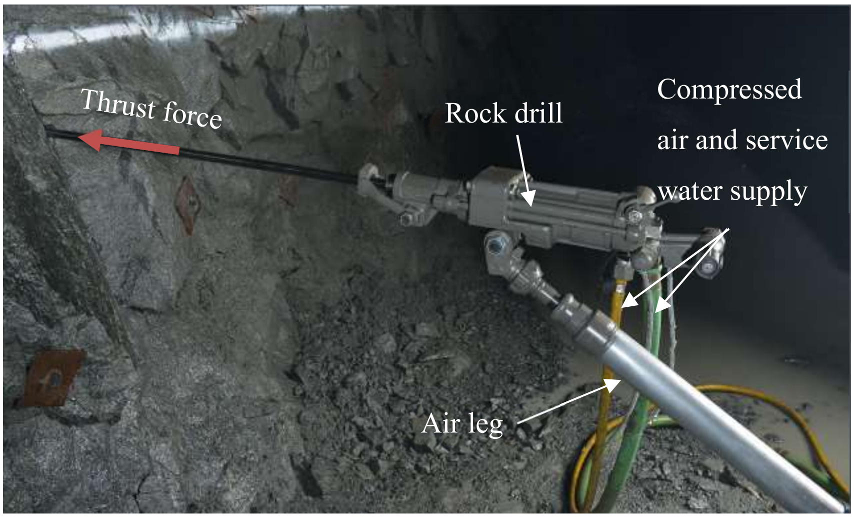

Figure 14: Rockdrill and air leg[1]

For successful drilling four actions are required: percussive impact to break the rock; feed force from the air leg to keep the drill bit in close contact against the rock; rotation to move the drill bit to a new position to make the next blow as effective as possible; and water flushing. Flushing uses water to remove the rock cuttings out of the hole and cool down the drill bit [20].

Different drilling patterns are used to effectively blast the production areas without causing damage to the structural integrity of the work area. Figure 15 shows an example of a drilling pattern used in the production area.

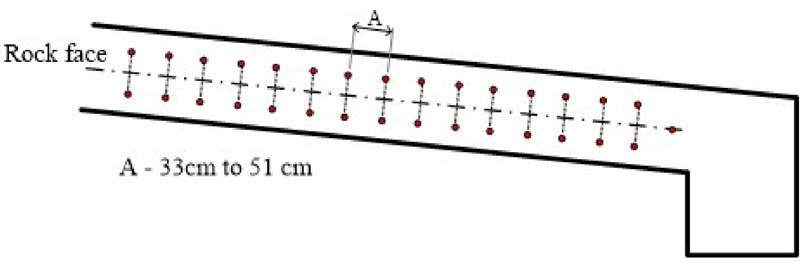

Figure 15: Example of a drilling pattern used in the production area (Adapted from [14])

[1] https://www.boartlongyear.com/product/hand-held-pneumatic-rock-drills/

1.4. Factors influencing drilling performance

1.4.1. Introduction

Two commonly used pneumatic drills, found in the platinum and gold mining industry, are replications of the S215 stoping jackhammer and the S25 rock drill originally designed by Boart Longyear.

Direct factors influencing drilling performance apart from using different drill rigs and drill bits will be explored. Compressed air pressure, service water supply and correct thrust force applied by the operator-controlled air leg are factors that directly influence drilling performance. Studies modelling the operation of a pneumatic drill through experimental testing will be discussed in this chapter.

1.4.2. Drill performance

Pneumatic rock drills performance is measured by the rate of penetration (ROP) which is the progress of the drilling bit into the rock in a particular time [21]. Apart from the pneumatic drill's design characteristics such as percussive power output, the ROP is affected by three main categories: drill bit characteristics; characteristics of rock; and operational variables.

The characteristics of rock that need to be drilled are the physicomechanical properties of the rock, which affect the penetration rate of drilling. They form the resistance that the bit must overcome before penetration can be achieved. These include hardness, strength, texture, elasticity, plasticity, abrasiveness, structure and the characteristic of breakage [22]. Drilling performance will always be affected by rock properties, which are uncontrollable in the mining environment.

The operational variables for rock drills are: drill percussive and rotation power due to compressed air pressure; thrust force effectiveness (in-line, minimal drill steel bending or friction in the hole, rebound energy absorption) and flushing needed to ensure optimal penetration is accomplished [21], [23]. The power output performance of the S215 rock drill in relation to the supply air pressure is shown in Figure 16.

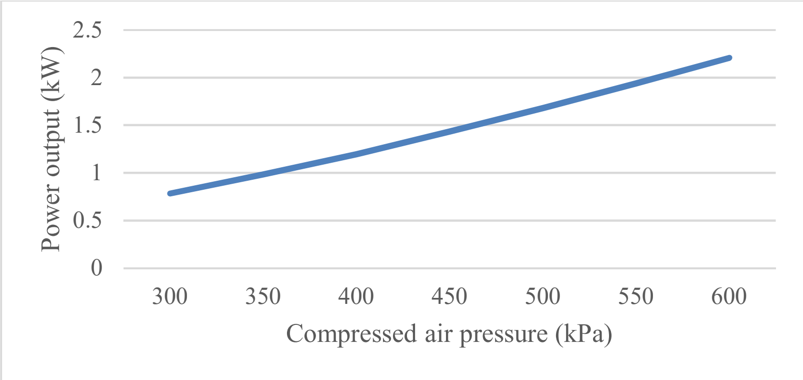

Figure 16: S215 rock drill output power in relation to supply air pressure [24]

The importance of the correct drilling thrust force applied by the operator-controlled air leg is illustrated in Figure 17. If the rock drill is under-thrust the drill bounces on the drill steel reducing ROP. If the rock drill is overthrust the drill tip grinds rock chippings in the bottom of the hole, rotation slows down, reducing ROP and the rock drill eventually stalls [24]. The ROP increases as the compressed air pressure increases, as shown in Figure 17.

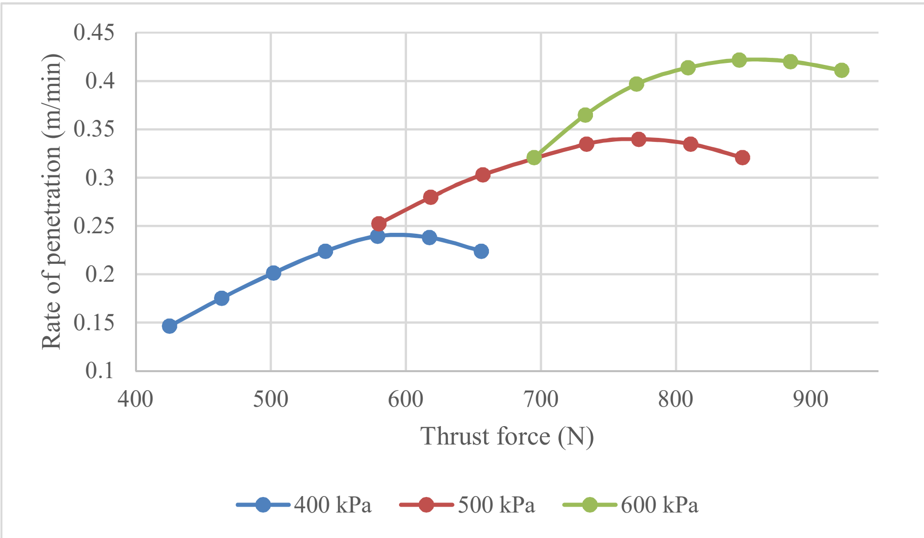

Figure 17: S215 rock drill ROP in relationship to different thrust forces at 400, 500 and 600 kPa air pressure supply [24]

Drilling performance is dependent on a variety of variables that affect the ROP. However, the only operational variables that can improve the ROP are compressed air supply, applying the correct thrust force and ensuring the drilling hole is always flushed.

1.4.3. Drilling penetration rate studies

A variety of studies and equations were evaluated to establish an understanding of drills, penetration rates, drilling performance and the strength of rock. The following drilling penetration rate studies are discussed:

Study 1 (2010) [25]:

Fraser's study "The energy and water required to drill a hole" compared and tested different rock drills on the market in South Africa. Figure 18 shows how the penetration rate increases with an increase in compressed air pressure for different pneumatic drills.

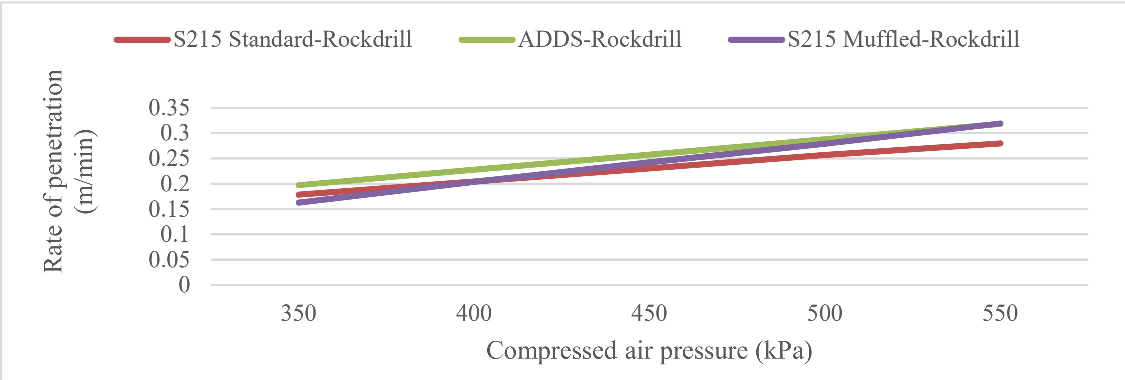

Figure 18: Pneumatic drill rate of penetration (ROP) in norite (adapted from [25])

Study 2 (2003) [23]:

A study was conducted by Kahraman titled "Performance analysis of drilling machines using rock modules ratio" which correlated the modulus ratio with the penetration rate of a variety of drills. The modulus ratio refers to the ratio of elastic modulus to compressive strength indicating the deformability. The penetration rates of diamond and rotary drills decrease with increasing modulus ratio and the penetration rates of percussive drills increase with increasing modulus ratio. The study concluded that the correspondence between the rock modulus ratio and penetration rate for a percussive drill is strong and can be used as a measure of rock drilling penetration rate.

Study 3 (2015) [21]:

The study "Experimental investigations on penetration rate of percussive drill" was done by Kivade, Mrthy and Vardhan to construct an explicit equation to predict the rate of rock penetration on sedimentary rock types in the mining industry. The International Society of Rock Mechanics (ISRM) covered the experiments. A pneumatically driven drill rig subject to a variety of forward thrusts, supply pressures and drill bit sizes was used in the study. Ten different standard rock samples were evaluated to measure rock penetration rate, and a model was constructed. Equation 1 represents the model.

Equation 1: Predictive rate of rock penetration

$$\mathbf{PR} = 0.0879242 + 0.0111569 \cdot A - 0.246978 \cdot B + 0.0070986 \cdot C - 0.0000100938 \cdot \boldsymbol{A^2} + \mathbf{0.003057 \cdot B^2 - 0.00000760976 \cdot C^2 + 0.0000103687 \cdot A \cdot C - 0.0000546415 \cdot B \cdot C}$$

Where:

PR	Poisson ratio [-]
A	Drill bit diameter [mm]
B	Air pressure [kPa]
C	Thrust [N]

Study 4 (2011) [26]:

Kelessidis conducted a study titled ”Rock drillability prediction from in situ determined unconfined compressive strength of rock”. The outline of this study was to evaluate the correlation between the rate of rock penetration and the unconfined compressive strength of the rock using various methods. The model relies on specific mining areas and uses Teales’s equation to construct a rough penetration rate model. The model is described in the equation below:

Equation 2: Rock penetration rate

$$R= \frac{\frac{\pi \cdot RPM \cdot \mu \cdot D \cdot W}{90 \cdot A}}{\frac{UCS}{eff} - \frac{W}{A}}$$

Where:

R	Rate of penetration [mm/s]
RPM	Revolutions per minute [rev/min]
μ	Friction coefficient
D	Bit diameter [m]
W	Weight on drill bit [N]
A	Bit area [m²]
UCS	Unconfined compressive strength [MPa]
eff	Efficiency of transferring

1.4.4. Conclusion

The pneumatic rock drill's performance is dependent on a variety of variables. From the studies discussed in this section, the rock penetration rate of pneumatic rock drills is affected by compressed air pressure. All the previous studies on rock penetration were done experimentally or theoretically and were not conducted in the mining environment. Further investigation is needed to determine the effect of insufficient compressed air supply on production.

1.5. *Mining production improvements*

1.5.1. Improved production strategies

Mining performance and profitability are directly related. Lost blasts occur when various circumstances prohibit operators form blasting the rock face and therefore not completing the production cycle. A study was done to determine the reasons for lost blasts. The results are shown in Figure 19. Insufficient compressed air service delivery is responsible for 4 % of the total missed blasts due to incomplete drilling [13].

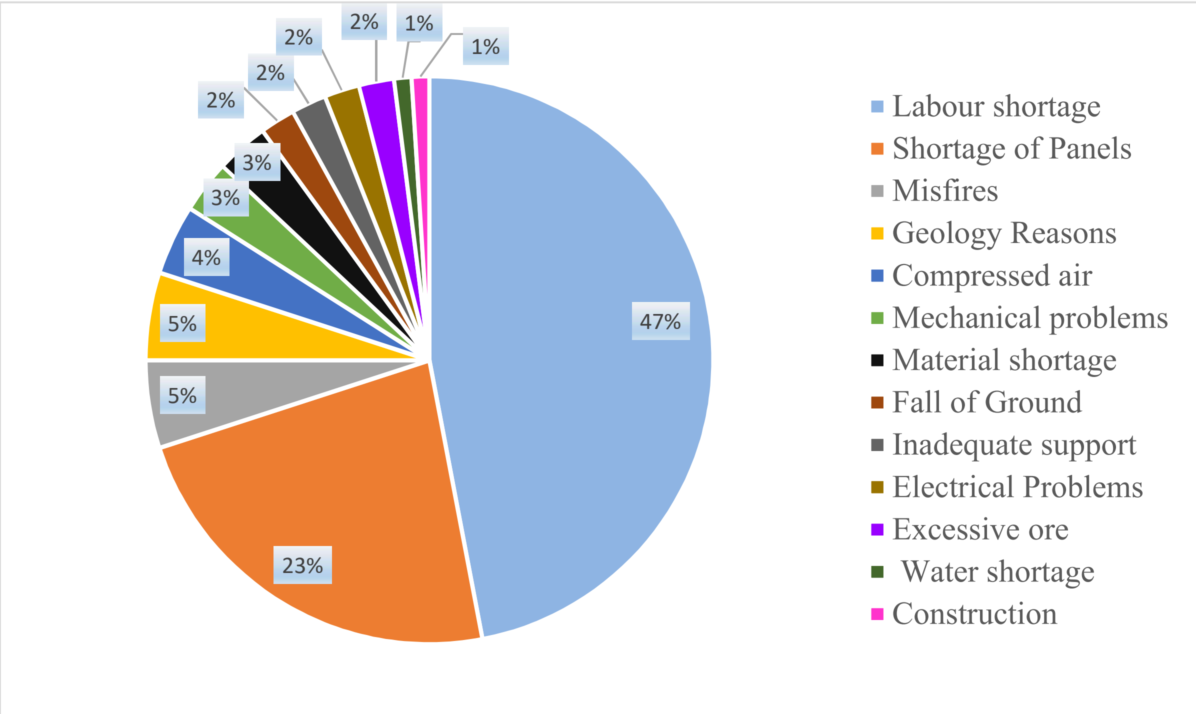

Figure 19: Reasons for lost blasts [Adapted from [13]]

The reasons for not blasting in Figure 19 can be summarised into five main categories:

1) Labour, 47% – Shortage in labour (Absence, sickness, training, leave)

2) No panel to drill, 29% – Miners cannot drill as no panel is available (Inadequate planning, previous misfire, construction).

3) Mining support, 7% – Miners cannot drill as the panel is not ready for drilling (Inadequate support, material shortage, excessive ore in the stope).

4) Mine geology, 7% – Miners cannot drill as the mine's geology is not in a mining condition or unsafe to mine (Geology reasons, fall of ground).

5) Drilling issues, 10% – Miners cannot drill (Compressed air problems, water shortage, electrical issues, mechanical issues).

The following studies focus on enhancing production output in mining:

Study 5 (2002) [27]:

Vermeulen did a study titled "Methods to Optimise Underground Mine Production" to investigate the current underground conventional mining systems used in the platinum mining industry. Vermeulen addressed the labour problem by designing a mine production planning system to optimise conventional operations referred to as the Half-Level Planning (HLP) model. The output levels of underground mines were determined from a mining and engineering perspective to be used in the HLP model.

Shortcoming:

Vermeulen's HLP model addresses labour issues, but non-labour related reasons for not blasting need to be further investigated.

Study 6 (2011) [28]:

Valery and Jankovic's article titled "New methodology to improve productivity of mining operations" explains a methodology called: The Process Integration and Optimisation (PIO) methodology to increase efficiency. The mining process is optimised by assessing the whole mine operation and not a specific system or process in isolation. PIO projects involve rock characterisation, site auditing, data collection, modelling, simulation and implementation of integrated operations on site. Implementation of the modified blast design and improvements to the operation of crushing and grinding circuits have resulted in a 25% increase in concentrator production quantity.

Shortcoming:

The effect on production and drilling performance was not assessed by the PIO methodology.

Study 7 (2006) [29]:

Strong, Terblanche, Göhre and Andrews did a study titled "A symphony of collaboration between mining and engineering" at Modikwa Mine. Management collaboration was needed to improve mechanised mining productivity. A system called MAPS (Mine Activity Performance System) measures the activities associated with every piece of equipment and allowed management to obtain a clear view of all the activities. Mining and engineering management could identify and address the issues that hampered productivity to improve efficiency and reduce costs.

Shortcoming:

The study was done for a mechanised mine where activity data could be collected for the MAPS system, whereas most South African mines' conventional mining techniques are used with little activity data.

Study 8 (2015) [30]:

Durrant-Whyte, Geraghty, Pujol and Sellschop conducted a study: "How digital innovation can improve mining productivity". The potential of digital and technology innovations in mining is discussed. The implementation of digital and technology changes in mining can build a more comprehensive understanding of the resource base, optimise material and equipment flow, improve expectancy of failures, increase mechanisation through automation, and monitor performance in real-time.

Shortcoming:

The South African mining industry is lacking in digital innovation. This will only be developed in the future.

Study 9 (2017) [31]:

Nell did a study to improve production through optimising compressed air reticulation, titled "Optimising production through improving the efficiency of mine compressed air networks with limited infrastructure". Lower compressed air pressure results in an increase in drilling time and an increase in compressed air usage which contributes to operational costs. Addressing inefficiencies in the reticulation network will increase compressed air pressure resulting in an increase in theoretical rock penetration rate on pneumatically operated drill rigs. This will lead to reduced drilling times.

Shortcoming:

Production outputs of specific working areas were not accurately monitored before and after compressed air network improvements were implemented. More focus should be placed on the effect of compressed air pressure service delivery on production in the mining environment.

1.5.2. Conclusion

Studies focusing on improving the mining industry's production together with shortcomings were presented. Only one study improved compressed air pressure at the working areas to enhance production. However, the effect of increased compressed air service delivery on the productivity of crews needs to be further analysed.

1.6. Compressed air service delivery for pneumatic drilling

1.6.1. Introduction

Compressed air inefficiencies need to be addressed for energy savings opportunities and improved service delivery through enhancing drilling performance. In this section, different methods used to address compressed air inefficiencies are discussed together with shortcomings.

1.6.2. Service delivery challenges

A compressed air network consists of demand and supply. The supply is the compressed air network that supplies the underground levels (compressor and pipe network) and the demand is the usage of air in underground levels where mining activities are taking place.

Service delivery challenges arise when the supply and demand of compressed air are not equivalent. Compressed air networks in mines are very dynamic in terms of configuration and size. Compressed air networks may develop outside the initial design specifications [31].

Inadequate supply

A lack of sufficient compressed air from the network can limit the compressed air supply to the production areas. Figure 20 below illustrates the compressed air supply pressure and power profile of a 5 MW capacity compressor undersupplying the demand. During the peak drilling shift, when the compressed air demand is high, the supply pressure cannot be sustained as the compressor ramps up to its full capacity. As a result, the compressed air network's pressure drops and the compressed air demand cannot be met.

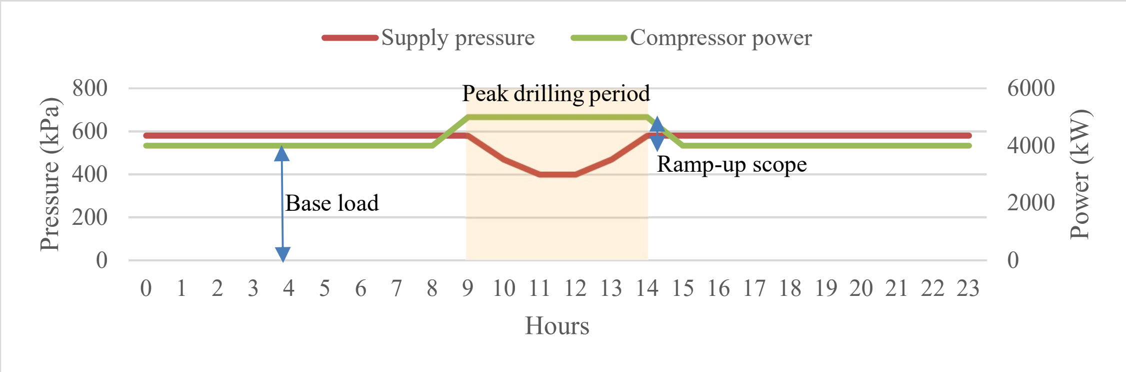

Figure 20: Inadequate supply of compressed air [31]

Over demand

An over-demand of compressed air or insufficient reticulation of compressed air causes low compressed air pressure at the working areas. Figure 21 below illustrates the compressed air supply pressure at the start of an underground level and measured pressure at the last production area. The line loss is the decrease in pressure which is caused by an over demand of compressed air.

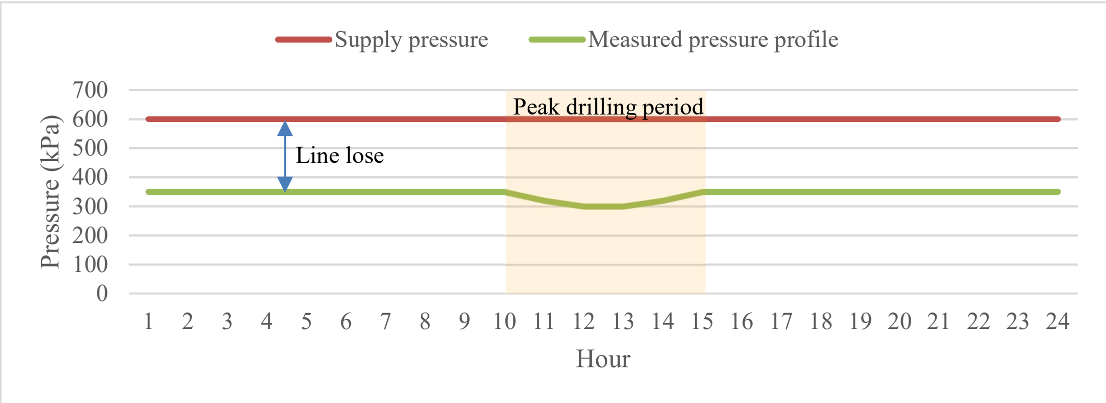

Figure 21: Compressed air demand-side concern [31]

The air demand required can be determined by totalling all the compressed air equipment requiring airflow. The required will be compared to the actual flow. If the calculated required airflow is less than the actual flow, compressed air abuse might be present causing an over demand.

Air leaks

Air leaks are a significant problem for mines and are difficult to repair as production downtime is required [32]. A study performed on two mines showed that as much as 39% and 52% of the installed compressor flow capacity was wasted on leaks [21]. Reducing wastage will increase compressed air service delivery pressure in production areas.

Insufficient reticulation

The reticulation network can be inadequate for compressed air demand. Nell's study increased compressed air pressure by 45 kPa by replacing a 400 m 6-inch pipe section with an 8-inch pipe. As seen in previous sections a rock drill's ROP may increase as air pressure increases depending on external factors.

Inadequate reticulation can be determined by calculating the pressure drop over a pipe length with certain airflow. Inadequate reticulation will have a substantial pressure drop negatively affecting the pressure in working areas. The Darcy–Weisbach equation is used to calculate the pressure drop over the pipe length.

Equation 3: Darcy-Weisback

$$\mathbf{Dp} = \mathbf{F}\left(\frac{L}{D}\right)\left(\frac{pV^2}{2}\right)$$

Where:

Dp	Pressure drop [Pa]
F	Friction factor
L	Pipe length [m]
D	Hydraulic diameter [m]
ρ	Fluid density [kg/m³]
V	Average velocity [m/s]

Equation 3, the Darcy–Weisbach equation requires the friction factor and fluid density. The Swamee–Jain equation can be used to calculate the friction factor, Equation 4. The Reynolds number must also be calculated to determine the friction factor in the Swamee-Jain equation, Equation 5.

Equation 4: Swamee-Jain

$$f = 0.25\left[\log 10\left(\frac{e}{3.7D} + \frac{5.74}{Re^{0.9}}\right)\right]^{-2}$$

Where:

f	Friction factor [-]
D	Hydraulic diameter [m]
e	Surface roughness [m]
Re	Reynolds number [-]

Equation 5: Reynolds

$$Re = \frac{pVL}{\mu}$$

Where:

ρ	Density of air [kg/m³]
V	Average velocity [m/s]
L	Pipe length [m]
μ	Dynamic viscosity of the fluid/gas [Pa·s]

Equation 6 is used to calculate the fluid density at a certain pressure and temperature used in the Darcy–Weisbach equation.

Equation 6: Ideal-gas equation of state

$$\rho = \frac{P}{R(T + 273.15)}$$

Where:

ρ	Density of air [kg/m³]
P	Absolute pressure [kPa]
R	Gas constant (Air = 0.2870) [kJ/kg·K]
T	Fluid temperature [ºC]

1.6.3. Operational improvements on compressed air systems

Inefficiencies need to be identified, evaluated and addressed to ensure compressed air systems are effectively operated. Operational improvements for air supply and demand are listed below as well as shortcomings related to these operational improvements.

Supply:

- **Load sharing [33], [34]:**
  Energy can be saved if the most efficient compressors share the load of the compressed air demand from compressed air networks. Compressors vary in sizes and efficiency.
- **Compressor selection [33], [35]:**
  Oversupply of compressed air is avoided by scheduling compressors, as demand is not constant. Compressor schedules are therefore designed to run the least number of compressors for the demand required.
- **Guide vane control [32], [36]:**
  Individual compressors' air supply can be controlled. This is done by regulating the guide vane angels on the air intake of the compressor. Less energy generation is obtained by adding less strain on the driving motor by lowering the discharge airflow rate.

Demand:

- **Control valves [34]–[37]:**

  Underground or surface control valves can regulate air demand. Control valves are regulated to determine the downward pressure of a compressed air network. These control valves prevent an oversupply of compressed air and limit wasting of air when the demand drops.
- **Reducing Wastage [34], [37], [38]:**

  An increase in compressed air demand is significantly influenced by the wastage which results in compressors consuming more energy and in turn increasing generating costs. Leaks are an opening in the compressed air system where air is released without intention. In the mining industry, a lack of maintained systems is a big concern and can lead to 50% of air wastage through leaks and could negatively affect production.

- **Reducing friction losses [16], [31]:**

  Friction in pipes may cause a loss of compressed air pressure with a greater loss seen in pipe sections with higher airflow rates. Bends, blocks, corrosion and a change of diameter can cause increased friction. The only solution for air losses through friction is replacing the pipe in certain parts of a pipe network.

Shortcoming:

Compressed air supply and demand in the mining industry can be optimised in various ways to improve the efficiency of compressed air systems as explained above. However, these improvements are focused on the saving of electricity and do not include optimisation of compressed air service delivery at working areas. Compressed air inefficiencies that influence drilling performance must be the primary indicator of where the compressed air systems need to be optimised.

1.6.4. Studies on identification of compressed air service delivery inefficiencies

Previous studies on methods used to identify insufficient compressed air delivery are discussed below. The shortcoming associated with each of the studies is mentioned to identify possible improvements needed. The studies are categorised as follows:

Compressor characterisation:

Study 10 (2019) [39]:

A study by Shaw titled "Using specific energy as a metric to characterise compressor system performance" characterises the performance of compressors in terms of the air supplied and energy consumed. The method uses a single metric to determine the performance of a compressed air system relative to the compressor's air supply and energy consumption. This simplified method gives a good indication of the performance change in a compressed air system.

Shortcoming:

The study only characterises a compressor's performance. An elaboration on the correlation between compressor outputs and drilling performance is required.

Scope identification:

Study 11 (2012) [32]:

A study titled "An integrated approach to optimise the energy consumption of mine compressed air systems" was developed by Marais. An estimation model was determined that predicts power changes in generating compressed airflow by investigating the change in the pressure of the system. Power consumption will change between 1.6X%-1.8X% for every X% change in system pressure according to this model. Practical measurement and theory are used to develop the model.

Shortcoming:

This model predicts the power consumption change as the pressure supply is changed. This study focused on the reduction of compressed air pressure outside the drilling shift. The effect that decreased pressure will have on production is not taken into account in this study.

Study 12 (2015) [17]:

A study named "Benchmarking electricity use of deep-level mines" was developed by Cilliers where a mathematical benchmarking model was suggested to determine the efficiency of energy usage systems on deep-level mines. A best-practice method for compressed air systems formed part of this thesis. Depth of mining shafts and the tons of ore mined per shaft were found to impact the efficiency of a compressed air system.

Shortcoming:

The study benchmarked the compressed air electrical consumption of an entire mine. Further studies are needed to benchmark individual working areas.

Study 13 (2018) [40]:

Vermeulen's study titled: "Simplified high-level investigation methodology for energy-saving initiatives on deep-level mine compressed air systems" developed multiple tools to determine the expected power savings on compressed air systems during a specific period. These tools are based on the concept of the Energy Reduction Ratio (ERR), which is the relationship between the peak and off-peak power usage recorded by the compressed air system.

Shortcoming:

The ERR relationship is used to identify potential inefficient mines and cannot be used to determine the effect of compressed air wastage on production.

Simulations:

Study 14 (2017) [35]:

Pascoe's study was titled: "Improving mine compressed air network efficiency through demand and supply control". Control philosophies for the compressors were developed, implemented and optimised to ensure a decrease in electricity consumption. Control valves decreased air demand in working areas. A simulation was constructed to test the effect of the improved control philosophy and control valves.

Shortcoming:

The simulation was only used for the surface compressed air network and not for underground networks.

Study 15 (2017) [41]:

Maré, Bredenkamp, and Marais did a study titled: "Evaluating compressed air operational improvements on a deep-level mine through simulations". According to the study, an insufficient supply of compressed air can result in production losses. The dynamic nature and size of compressed air systems make the evaluation of proposed operational efficiency solutions complex.

A new easy-to-use method for simulations was developed on compressed air systems to evaluate operational improvement. Process Toolbox was the software used to model and simulate the compressed air systems of a mining complex. After the simulation is calibrated within 5% accuracy, the simulation model can be used to determine the compressed air pressures and flows in different scenarios.

Shortcoming:

Simulating and calibrating a whole underground compressed air network requires a large amount of data and resources to model the network. Also, possible improvement opportunities must be identified before simulation, which requires experience and knowledge of the compressed air system.

Benchmarking:

Study 16 (2018) [38]:

Du Plooy's study: "Development of a local benchmarking strategy to identify inefficient compressed air usage in deep-level mines" developed a methodology to locate and manage factors that contribute to compressed air network inefficiency. The methodology benchmarks compressed air consumption against production output tons to determine the indicator for inefficiencies, Equation 7. The methodology proved to be less time consuming compared to a comprehensive audit of compressed air networks underground.

Equation 7: Inefficient compressed air section indicator [38]

$$\text{Indicator} = \frac{F_{section}}{P_{section}} \cdot \left(\frac{\frac{F_{section}}{F_{shaft}} + \frac{P_{section}}{P_{shaft}}}{2} \right)$$

Where:

$F_{section}$	Section compressed airflow rate [m³/h]
F_{shaft}	Shaft compressed airflow rate [m³/h]
$P_{section}$	Section production [t]
P_{shaft}	Shaft production [t]

Shortcoming:

The benchmarking technique is limited to benchmarking mining sections and not individual workplaces. The production data is for a whole mining section and not for individual end-users. Compressed air pressure at the end-users will be more accurately determined if production is affected by inefficient compressed air.

1.6.5. Conclusion

Compressed air service delivery challenges in the mining industry and different methods used to address compressed air inefficiencies were explored by various studies. Service delivery inefficiencies at individual working areas are not identified. Analysing compressed air pressure in individual working areas will provide more accurate data to determine optimal solutions for compressed air inefficiencies.

1.7. Critical analysis of previous studies

Compressed air inefficiency improvement, drilling penetration rate and production enhancement in the mining industry were studied numerous times in the past. The previously discussed studies are critically analysed below to determine the need for the study.

Pneumatic drilling penetration rate studies 1-4:

Drilling penetration rate studies are compared in Table 1 below to highlight the key variables that influence drilling performances. Compressed air pressure is used in studies 1, 3 and 4 to determine the expected penetration rate of handheld pneumatic rock drills. Studies 1 – 4 are experimentally or theoretically conducted. Additional studies are needed to determine what the production output effect will be if compressed air service delivery pressure is increased in a mine.

Table 1: Variables that influence the pneumatic penetration rate

Variables that influence the rate of penetration	Study 1	Study 2	Study 3	Study 4
Compressed air pressure or drill rotational speed	✓		✓	✓
Rock characteristics	✓	✓	✓	✓
Drill bit characteristics			✓	✓
Thrust force applied on the drill			✓	✓
Friction and efficiencies				✓
Drill type	✓			

Production improvement studies 5-9:

Production improvement studies can be divided into two groups. Table 2 below summarises studies 5 - 9 according to these two groups by either improving the production through better management or by improving the mining operations.

Table 2: Production improvement studies

Production improvement strategies	Study 5	Study 6	Study 7	Study 8	Study 9
Improved management	Improved labour planning		Improved communication	Improved understanding of the process	
Improved mining operations		Improved rock blasting		Improved mining using mechanised mining	Increased air pressure for enhanced theoretical drilling performance.

Only one study improved compressed air service delivery. However, the effect of inefficient compressed air service delivery on production needs to be evaluated in a real case study.

Identify inefficient compressed air operations studies 10 - 16:

Previous compressed air operational improvements studies have used different methods to identify potential operational improvements for supply and demand. The methods used to identify the compressed air inefficiency are listed in Table 3 below. The shortcomings associated with each method is also listed in Table 3.

Table 3: Methods used to identify compressed air inefficiencies

Methods used to identify compressed air inefficiencies	Study 9	Study 10	Study 11	Study 12	Study 13	Study 14	Study 15	Study 16	Shortcomings
Manually measure workplace compressed air pressure	✓							✓	Compressed air audits are time-intensive and compressed air networks change constantly. No historic data to determine the effect on production.
Characterise compressor performance		✓							Compressed air inefficiency at the end-users is not identified.
Identify scope for compressed air efficiency improvements			✓	✓	✓				The scope for energy improvements are determined using best-case models but problematic factors are not identified. These factors may include location of inefficiencies, the effect on production and the root casue of inefficiencies.
Simulations of the compressed air network						✓	✓		Simulating and calibrating an underground compressed air network requires a large amount of data and resources to model the network. The compressed air network changes constantly while the simulation model is static and does not account for changes.
Benchmarking production output against compressed airflow								✓	Inefficient sections are identified, however the service delivery pressure at the production ends are not part of the study.
Daily estimate compressed air pressure for every work area and compare with production	No study analysed and compared the compressed air service delivery pressure at the production end with the production achieved.								

Conclude critical analyses of studies 1-16:

Studies 1-4 identified that the effect of service delivery pressure on the production of pneumatic rock drills must be analysed in the mining environment.

Studies 5-9 showed that management and operational improvements can lead to better production. Only one study improved compressed air pressure to obtain better service delivery and more production. However, the production and compressed air service delivery pressure need to be monitored daily to determine the effect of increased compressed air pressure on production.

Studies 10-16 showed that different methods have been used to identify compressed air inefficiencies, but a method is needed to monitor the pressure at every working area daily.

1.8. Problem statement and need for the study

Need for the study

Conventional deep-level mines in South Africa are threatened by the following:

- Platinum and gold production decreases and rising operational costs.
- Compressed air systems are one of the largest electricity consumers in the mining industry and are essential in conventional mining using hand-held pneumatic drills.
- The electricity price hikes increase operational costs in the mining industry and energy efficiency measures are needed to reduce operational costs for deep-level mines.

Ineffective drilling is the primary concern in mining. Mine profits are fundamentally determined by production outputs after deducting the fixed costs. Compressed air costs contribute an estimated 1.4 % of the total fixed costs in deep-level mining [1], [3].

Many studies have implemented compressed air initiatives to reduce energy expenditure and increase service delivery, discussed in chapter 1.5.2. Studies identifying compressed air inefficiencies have implemented various strategies. The previous studies' shortcomings are listed in Table 3. The main shortcoming is identifying service delivery issues in working areas. Previous studies are too broad to identify service delivery specific issues in individual working areas or involve audit processes and data simulation that are time-consuming. A new practical method is needed to identify service delivery issues in working areas.

Pneumatic drilling performance is dependent on a variety of variables that affect the ROP. The pneumatic drilling power or rotational speed is dependent on the compressed air supply pressure. Multiple drilling penetration rate studies use compressed air pressure or the rotational speed of the drill bit as a variable to determine the ROP. Thus, it is necessary to ensure optimal compressed air pressure is delivered to working areas for effective pneumatic drilling.

There is a need for a practical method to locate inefficient compressed air supply that affects production output, in the underground network, for every drilling area. Determining when production is affected by insufficient compressed air pressure will determine the effect of improved compressed air service delivery.

Problem statement

A practical holistic approach is needed to analyse mine production outputs against pneumatic drilling performance derived from compressed air supply pressure.

Study objectives

The following study objectives will ensure that a practical approach is developed to analyse mine pneumatic drilling performance:

- Develop daily KPIs to monitor working areas' production outputs and compressed air service delivery.
- Develop a methodology to analyse pneumatic drilling performance to identify possible compressed air service delivery inefficiencies that affect production.
- Verify the methodology by validating the results in a case study.
- Determine the percentage production lost due to insufficient compressed air service delivery.

1.9. Overview of dissertation

Chapter 1: Introduction & background

This chapter serves as an introduction and background to the study. An overview of the current challenges faced in the deep-level mining industry of South Africa is presented. An overview of the mining process and previous implemented studies on production and compressed air inefficiency improvements are discussed. From the challenges and shortcomings of previous studies in the field, a problem statement and need for the study are formulated. Finally, the study objectives are provided.

Chapter 2: Methodology to analyse mine drilling performance

Chapter 2 presents the developed methodology to analyse mine pneumatic drilling performance. The methodology focuses on identifying, prioritising and analysing inefficient drilling performance caused by insufficient compressed air supply.

Chapter 3: Implementation & validation

This chapter validates the developed methodology with real-life case studies and determines the effect of insufficient compressed air pressure on production. The results and limitations of three case studies are discussed in this chapter.

Chapter 4: Conclusion & recommendations

This chapter concludes the results of the study and compares the outcome with the study's objectives. The main conclusions of the study are presented. The need for the study and problem statement are addressed. Finally, recommendations for further studies are discussed.

CHAPTER 2. METHODOLOGY TO ANALYSE MINE DRILLING PERFORMANCE

2.1. Introduction

This chapter focuses on developing a methodology to identify, prioritise and analyse inefficient drilling performance caused by compressed air supply. Figure 22 illustrates the simplified layout of the developed solution.

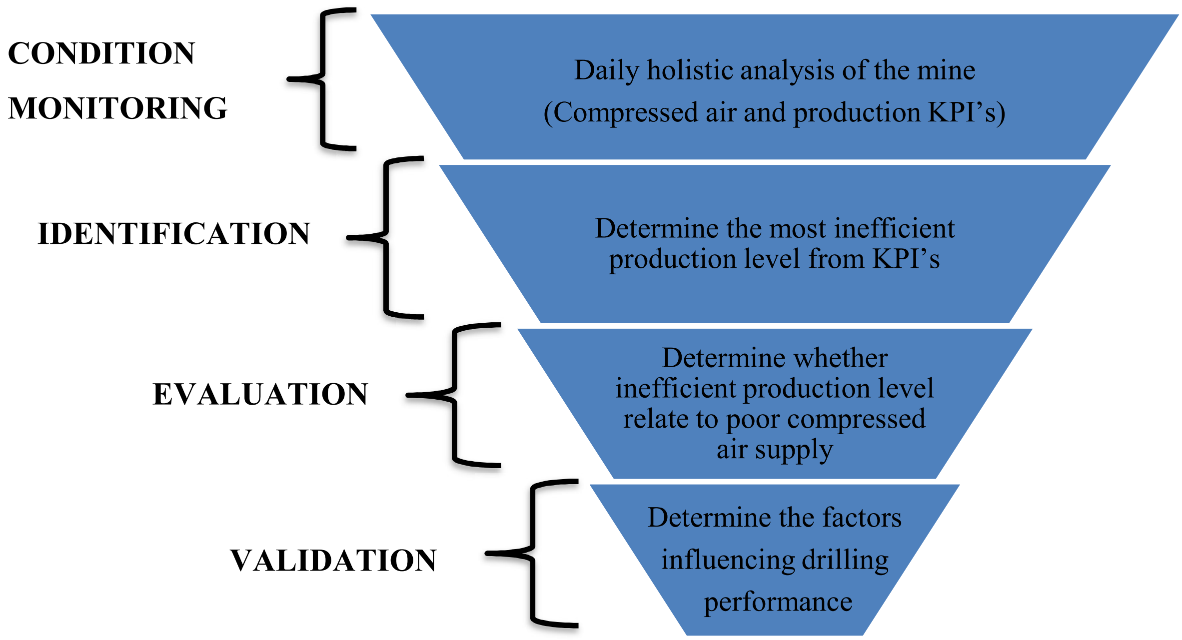

Figure 22: Simplified methodology layout

Condition monitoring

The first step is a holistic analysis of the mine's compressed air system, production outputs and external factors. To simplify the monitoring of the mining conditions, KPIs are developed to track performance over time for each production area.

Identification

Developed KPI trends are analysed over time to identify inefficient production levels. The working areas will be ranked according to the possibility of drilling performance being influenced by insufficient compressed air service delivery.

Evaluation

Inefficient production levels will be analysed to evaluate if inefficiencies relate to poor compressed air service delivery. The working areas' pneumatic drilling performance compared to the production will be examined. Production loss due to inefficient compressed air supply will be quantified.

Validation

The quantified production loss due to insufficient compressed air supply must be validated. The compressed air network will be analysed to determine whether compressed air service delivery could be influencing the drilling performance. The compressed air supply and demand on ineffective working days will be compared to productive days to determine if losses are caused by inadequate air supply to drilling areas.

2.2. Condition monitoring

2.2.1. Introduction

The layout of deep-level mines expands over a large area connecting multiple workplaces thus making performance monitoring complex. The mining environment is dynamic in both service delivery and production areas.

The number of mining crews changes over time affecting the service delivery of mining infrastructure. Mines typically have compressed airflow and pressure instrumentation installed at the start of production areas. This can be used to identify inefficiencies. However, to interpret the instrumentation's output measurements without full knowledge of all external factors will be misleading interpretation.

KPIs are thus needed to monitor production areas' performance while taking all the external factors into consideration. The first step will be to collect data and formulate the data to KPIs.

2.2.2. Collect & process data

Mines collect vast amounts of data. Data utilisation to improve service delivery and production outputs in the mining environment is still lacking. Mines only compare monthly compressed air usage to production to evaluate the performance of the entire shaft. An in-depth correlation between production data and operational data is required to analyse the pneumatic drilling performance.

Data collection

The minimum data required to analyse pneumatic drilling performance is listed in Table 4 below. Data collected can be divided into three categories: production data, operational data and site information. Mine instrumentation is monitored through an active control system (SCADA) and stored in large databases.

Miners and surveyors report daily on the production achieved or the reason for not blasting on the mine's management system. The transfer of data acquired from production and operations to a local database is required to analyse the data. Production data and operational data are time-dependent and need to be updated daily. Site information only needs to be updated if infrastructure changes are made.

Table 4: Site data required

Production data	Operational data	Site information
• Area mined (m^2 per panel)	• Compressed air supply pressure	• Underground haulage layouts
• Development advanced (m)	• Compressed air pressure per level	• Compressed air reticulation network layouts
• Active stoping panels	• Compressed air supply flow	• Compressed air pipe diameter, material type and condition
• Active development panels	• Compressed airflow per level	• Compressed air control setpoints and schedules
• Reasons for not blasting, e.g. Poor air pressure; Absent worker; Unsafe	• Compressed air control valve statuses	
• Number of working crews allocated		
• Total tons hoisted (tons)		

Data conversion

Collected data from compressed airflow meters needs to be expressed as a mass flow rate. The measurement of compressed airflow output is dependent on the type of flow meter and calibration. Compressed airflow can be expressed as a volumetric-, standardised- or mass-flow rate.

- Volumetric flow rate (m^3/h) is a measurement of the volume (m^3) that the compressed air occupies as it flows past the flow meter under measured pressure and temperature conditions.
- Standardised (or normalised) volumetric flow rate (Nm^3/h) is a measurement of the volume (m^3) that the compressed air would be measured under standard temperature and pressure conditions. Standard conditions for temperature and pressure are 0 °C and 100 kPa, respectively.
- Mass flow rate (kg/s) is a measure of the number of molecules that flow through the instrument, regardless of how much space those molecules occupy.

Compressible-flow theory will be used to calculate pressure differences and quantify air leaks. Converting the output of the flow meter to a mass flow rate is required. Some compressed airflow meters only measure the volumetric flow rate and convert it to standardised volumetric flow rate by assuming the flow pressure to be constant.

The standardised flow measurement calculated using an assumed fixed pressure must be recalculated by using the actual flow pressure. Figure 23 explains the conversion process for any compressed airflow meter to volumetric and mass flow rates.

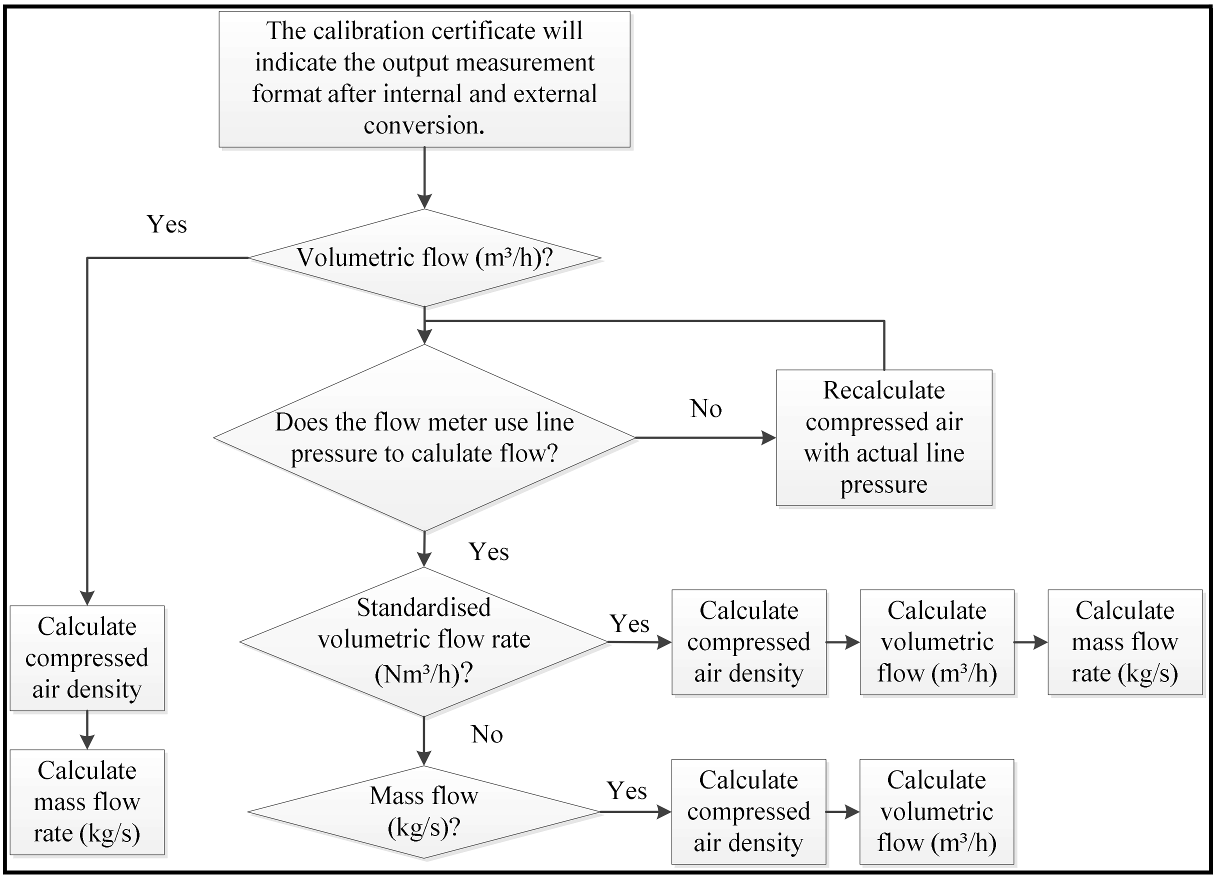

Figure 23: Covert compressed airflow output to volumetric and mass flow rates

Instrumentation verification

Compressed air pressure sensors and flow meters need to be maintained and calibrated. In the mining industry, the maintenance of compressed airflow meters is often neglected and needs to be verified individually.

The compressed air mass flow to the different levels must be equivalent to the total mass airflow supplied to the shafts. Three methods can be used to test level flow meters.

Method 1: Inline flow measurement verification

The compressed airflow meter can be verified with a secondary portable flow meter. A measuring point is needed before or after the flow meter without any tie-offs between the installed compressed airflow meter and the verification flow meter. Figure 24 illustrates a simplified layout of this verification method.

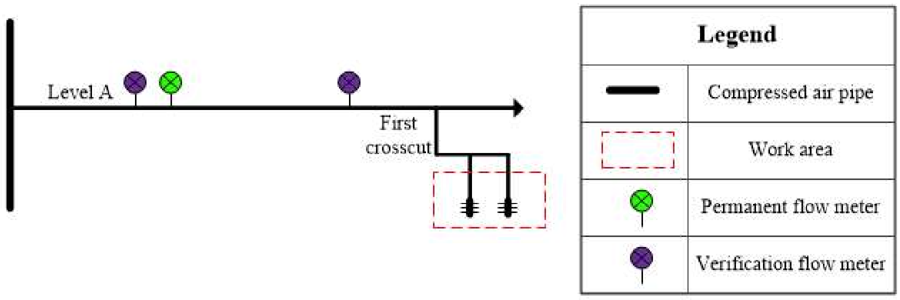

Figure 24: Inline flow measurement verification layout

Method 2: Pressure difference flow measurement verification

The compressed airflow meter can be verified by measuring the pressure drop over the pipe length, thereby calculating the compressed airflow. Figure 25 illustrates a simplified layout of this method. The level compressed air pressure transmitter is usually close to the flow meter and can be used as one of the pressure points. A pressure reading down the line is required to determine the pressure drop over the pipe length.

Equation 3 is the Darcy–Weisbach equation discussed in Section 1.4.3 that is necessary to calculate the compressed airflow taking into account the pipe length, pipe diameter, pipe surface roughness and pressure drop over the pipe. The surface roughness table is in Appendix A.

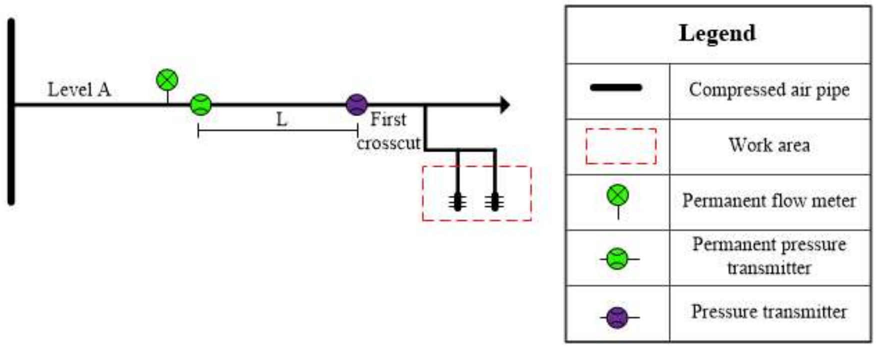

Figure 25: Pressure difference flow measurement verification layout

Method 3: Upstream flow measurement verification

An upstream flow meter can be used to verify flow meters downstream if the verifying flow meter is not directly in line. The compressed air supply for the level flow meter needs to be closed to determine the change in compressed airflow. The difference in the level flow meter must correlate to the difference in the upstream flow meter. When the level is closed, the flow meter reading should be zero to ensure accurate reading. Figure 26 illustrates a simplified layout of this method.

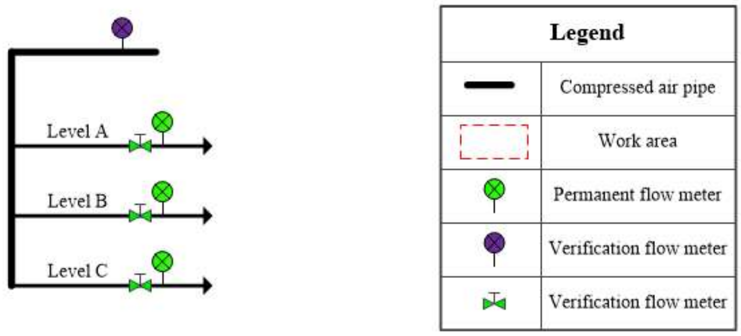

Figure 26: Upstream flow measurement verification layout

2.2.3. Developed KPIs

Once all operational and production data have been verified and collected, daily analysis can commence. KPIs will be calculated daily to determine inefficient production areas and to identify trends in mining performance. KPIs will be used to prioritise inefficient compressed air and production levels. The production and compressed air KPIs are discussed below.

Production trends (m^2)

Production output is a standard KPI used to determine productivity. Production trends for every production area need to be monitored daily. The production areas can be divided between levels and reef types.

Production areas with increasing production trends indicate increased profit from the production area. Increased production can also increase the strain on resources. Increased production can be the result of more mining crews, better productivity, better service utilities, overtime or incentives. Decreasing production trends is always a concern in any industry and further investigation will be required.

The working areas consist of mining panels that will be drilled for production. The production output per working area is expressed as the number of centare blasted per day. A centar is a mining measurement term used for the volume rock of a meter by a meter area at the height of the reef. Figure 27 below shows the working area and the drilling markings for the daily production output.

Figure 27: Production working area[2]

Total production for a shaft including multiple working areas is usually recorded as tons ore hoisted. A delay in time is expected between area mined recorded in working areas and recorded tons hoisted as the ore needs to be transported and hoisted out of the shaft before the ore is recorded.

Area mined per crew allocated (m^2 per crew)

The productivity KPI of the area mined per crew is calculated as the total area mined divided by the number of allocated crews assigned to a specific production area during the drilling shift.

Mining crews have a daily target to achieve. The KPI will thus decrease below the daily target because of crews underperforming. The closer the KPI is to the target the better the productivity of the production area.

Area mined per crew worked (m^2 per crew)

The KPI for area mined per crew differs from the previous KPI as only the crews that blasted at the end of the shift are taken into account. The KPI excludes the crews that could not blast due to various factors and measures the productivity of working crews. The KPI 'area mined

[2] Chamber of Mines of South Africa, "Drilling and blasting in hard rock narrow tabular mines," Johannesburg, 2016.

per working crew' is expected to decrease below the daily production target or typical drilling performance as the pneumatic rock drills performance decreases.

Percentage crews worked (%)

The number of working crews is compared to the total number of crews assigned to the working area. Every crew assigned to a production area has to report on the area mined or the reason for not mining.

Number of production crews missed blasts per reason category

Reasons for not blasting need to be reported by crews. The reasons for missed blasts fall under one of the following categories listed in Table 5. The number of missed blasts per category in each working area will be used to identify ineffective working areas.

Table 5: Missed blast categories

No blast reason category	Description
No power supply	Mining equipment is out of order due to no electricity supply, e.g. winches etc.
Breakdown	Infrastructure breakdowns preventing the production cycle, e.g. Broken fan, winch, pumps, loco etc.
Support failure	The work area is not fully supported. Supporting has to be done before the mining process can continue.
Labour	Absent crew members, e.g. absent without cause, training, crews declared unfit for work.
Compressed air	No compressed air for pneumatic drills, e.g. Compressed air pressure too low, water in the compressed air causing mist in the work area preventing miners from mining productively.
Water	No water supply in the working area, e.g. broken pipes, water mismanagement, low water pressure
Drilling	Problems with drilling operations, e.g. drill breakdown, air-leg breakdown
Mining conditions	The mining conditions don't allow crews to continue mining, e.g. Off reef, potholes, water intersection, bad ground conditions, slipping etc.

Safety	The working area is too unsafe to continue mining, e.g. rockfalls, air quality
Blast	Blasts missed due to poor charging up, explosive shortage or misfire.
Planning	Poor planning, therefore, mining crews cannot work e.g. no working place assigned to crews.
Mining survey	Mining crew could not work due to surveyor's incomplete assessment.
Ventilation	Mining crews cannot work in substandard ventilation conditions.

Percentages missed blasts of the total blasting opportunities per reason category

The number of missed blasts per category in Table 5 is divided by the total number of blasting opportunities for a working area. This percentage will enable comparison for production areas for the different missed blast categories.

Development trends

Development is required to prepare the working area for mining crews. The development consists of drilling and blasting of tunnels for ore transport, passageways and ventilation. The development of the haulage to extend the level is also part of development operations.

Development crews report on daily development in meters progressed. The total meters developed per day per working area KPI will be used to identify a change in development trends.

Development per crew allocated (m per crew)

Total meters developed for every working area divided by the number of crews allocated will indicate the productivity of each area. Unproductive development in working areas can be identified to be further analysed.

Missed blasts by development crews per reason category

Development crews also report on missed blasts. The reasons for missed blasts can be categorised according to Table 5 discussed above. Unproductive development working areas can be further analysed according to the reasons for missed blasts.

Total percentage of crews worked (%)

The number of working crews is compared to the total number of crews assigned to the work area for both development and production areas.

Peak compressed air consumption per working area (kg/s)

The KPI peak compressed air consumption per working area is the maximum compressed airflow during the drilling shift to a working area. High compressed air consumption will affect compressed air pressure due to friction losses in the compressed air pipe.

The compressed airflow measured per level is split between the working areas according to the number of stoping and development crews allocated. This is shown in Equation 8 below.

Equation 8: Compressed air split

$$F_{workarea} = F_{level} \cdot \frac{C_{workarea}}{C_{level}}$$

Where:

$F_{workarea}$	Compressed airflow per work area [kg/s]
F_{level}	Compressed airflow for the entire level [kg/s]
$C_{workarea}$	Number of crews allocated per work area
C_{level}	Number of crews allocated per level

Benchmarked compressed air usage (kg/s per m²)

Benchmarked compressed air usage is the total compressed air used per day versus the total area mined for a working area. Low productivity with high compressed airflow will identify inefficient compressed air usage.

Expected compressed air pressure during drilling shift at the first active panel per work area (kPa)

Compressed air pressure at the start of a level is not a representation of the compressed air pressure at the drills. The station pressure and compressed airflow are used to calculate the pressure drop from the station to the first active panel. Some of the older levels' haulages are much longer, which will result in a more significant pressure drop from station to drills.

Equation 3 - Equation 6 discussed in Section 1.4.3 are used to calculate the pressure drop to the first working area. Equation 9 incorporates all of the above equations to calculate the pressure drop.

The first working area's panel location can be used to calculate the pipe length. The surface roughness of a commercial steel pipe, most often used underground, is 0.09 mm. The compressed airflow dedicated to the work area can be estimated by the percentage of crew allocated to the work area as shown in Equation 8. The fluid temperature used in the pressure drop equation is the same as the calibration of the flow meter.

Equation 9: Pressure drop over a pipe

$$Dp = \frac{2LPQ^2}{\pi^2 D^5 R(T+273.15)\left(\log_{10}\left(\frac{e}{3.7D} + \frac{5.74}{\left(\frac{4PQL}{\pi\mu R(T+273.15)D^2}\right)^{0.9}}\right)\right)^2}$$

Where:

Dp	Pressure drop [Pa]
L	Pipe length (25m per panel) [m]
P	Absolute pressure at the start [kPa]
Q	Volume flow rate [m³/s]
D	Pipe hydraulic diameter [m]
R	Gas constant (Air = 0.2870 kJ/kg·K) [kJ/kg·K]
T	Fluid temperature (Same a flow meter calibration) [ºC]
e	Surface roughness [m]
μ	Dynamic viscosity of the fluid/gas (Air = $18.6*10^{-6}$ Pa·s) [Pa·s]

Peak wastage compressed air (kg/s)

Determining the compressed air wastage per working area KPI will identify possible compressed air inefficiencies. Compressed air wastage is the compressed air supplied to a working area while no or minimal mining operations consume compressed air.

To determine the compressed air wastage, the mass flow and expected working area pressure before the shift starts is used to calculate the leak constant - Equation 10. It is expected that the leak constant will be persistent during the drilling shift. The compressed air wastage can be recalculated using the leak constant and the new expected pressure at the working areas during the peak drilling shift.

Equation 10: Mass flow rate through a leak [42]

$$\dot{m} = C_{discharge} \left(\frac{2}{k+1}\right)^{\frac{1}{(k-1)}} \frac{P_{line}}{R \cdot T_{line}} A \sqrt{kR\left(\frac{2}{k+1}\right) \cdot T_{line}}$$

Reduced:

$$\dot{m} = C \cdot P_{line}$$

Where:

$\dot{m}$	Mass flow rate [kg/s]
C	Leak constant
P_{line}	Line pressure [kPa]

Figure 28 shows the compressed airflow profile of a working area. The compressed air leak constant, C, is calculated at point A on the graph with the mass flow and line pressure during a time period when no compressed air is used for production. During the peak compressed air consumption period in the drilling shift, the compressed air wastage is calculated at point B. The compressed air consumption is calculated with the line pressure and the leak constant calculated on the same day.

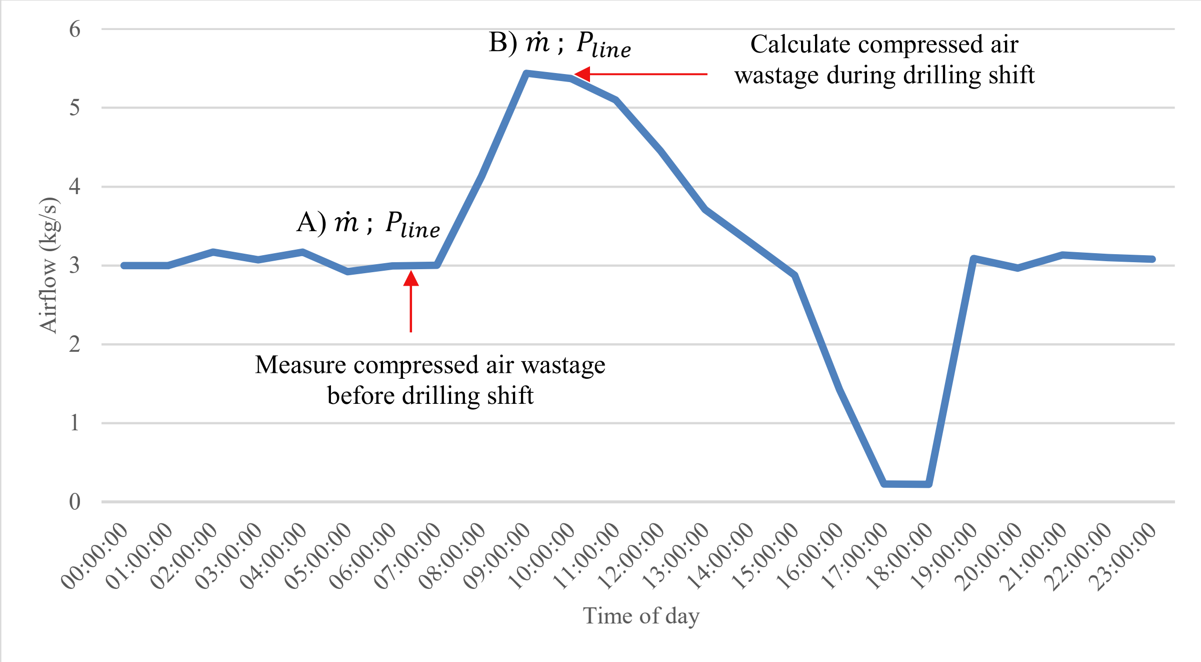

Figure 28: Compressed air wastage calculation example

Peak production compressed air (kg/s)

The peak production compressed air KPI is the compressed air used for drilling in the peak compressed air consumption timeslots excluding the wastage determined in Equation 10.

Utilised compressed air percentage (%)

Production compressed air divided by the peak compressed air consumption will indicate the percentage of compressed air utilised for drilling.

2.2.4. Conclusion

The methodology's first step is to condition monitor the mine's production and compressed air data. The instrumentation used needs to be verified to ensure accurate monitoring of working areas. The mines' production and operational compressed air data can be analysed by comparing multiple developed KPIs. The KPIs will be used to identify inefficient working areas and further analyse the performance of working areas daily.

2.3. Identify inefficient working areas

2.3.1. Introduction

Compressed air and production KPIs are used holistically to analyse pneumatic drilling performance. The developed KPIs will be interpreted to rank working areas according to the possibility of drilling performance being influenced by insufficient compressed air service delivery. Working areas' KPIs can be analysed and compared, or a weighted table method can be used to determine the unproductive areas.

2.3.2. Working area KPI analysis

Compressed air service delivery varies over time as demand or infrastructure changes. Breakdowns can also influence compressed air service delivery. Compressed air KPIs need to be analysed over time to identify changes in production areas' compressed air service delivery.

Production areas with underperforming service delivery KPIs need to be analysed to determine whether compressed air has affected productivity. Figure 29 describes the KPI analysis process.

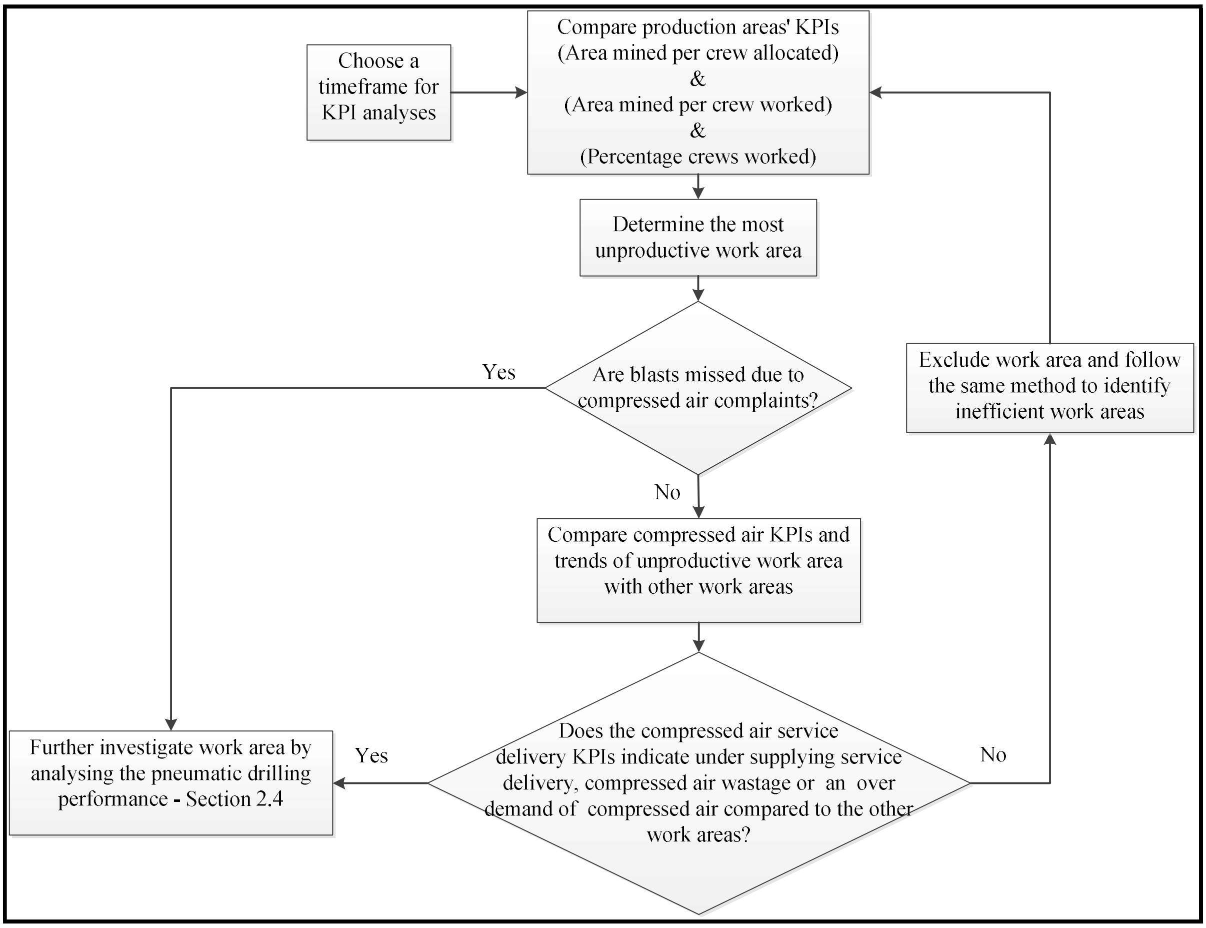

Figure 29: Simplified KPI analysis process

2.3.3. Overall performance weighted table

Production, compressed air service delivery and missed blasts KPIs are compared in an overall performance weighted table. The average of the KPIs over a period are normalised and weighted to score every working area. The working areas' performance scores will identify possible working areas affected by insufficient pneumatic drilling performance. Equation 11 describes how the weighted overall performance value is calculated. The higher the weighted score, the high is the possibility that the work area may be affected by insufficient compressed air.

The overall performance value of all the working areas is compared in a performance weighted table. Table 6 shows the weighted percentages and KPIs used in the overall performance score. The KPI are weighted in accordance to the possibility that the KPI will identify working areas where production may be affected by insufficient compressed air. The expected pressure at the first working area has a good possibility of identifying areas affected by insufficient pneumatic drilling performance and is thus weighted high. The average area mined per crew worked has a good possibility of identifying areas affected by insufficient pneumatic drilling performance and is thus weighted high. The average area mined per crew allocated KPI can be due to numerous reasons and is thus weighted low.

Equation 11: Weighted overall performance value score

$$Weighted\ Score\ (Higher\ is\ optimal\ ) = W \cdot \frac{P - P_{min}}{P_{max} - P_{min}}$$

$$Weighted\ Score\ (Lower\ is\ optimal) = W \cdot \left(1 - \frac{P - P_{min}}{P_{max} - P_{min}}\right)$$

Where:

W	Weight
P	Performance
P_{min}	Minimum performance score of all the work areas
P_{max}	Maximum performance score of all the work areas

Table 6: Overall performance weighted score table

Category	KPI	Weight	Calculation	Weighted score
Production & Development KPI's	Average area mined per crew allocated	0.5	Higher is optimal	
	Average area mined per crew worked	1.5	Higher is optimal	
	Average development per crew allocated	0.5	Higher is optimal	
	Average percentage of crews worked	1	Higher is optimal	
	Average number of crews allocated	1.5	Lower is optimal	
Compressed air complaints	Percentages missed blasts of the total blasting opportunities due to compressed air	1	Lower is optimal	
Compressed air KPI's	Average benchmarked compressed air usage (kg/s per m²)	1	Lower is optimal	
	Average expected compressed air pressure during drilling shift at the first working panel per work area (kPa)	2	Higher is optimal	
	Average utilised compressed air percentage (%)	1	Higher is optimal	
			Score:	**/10**

2.4. Analyse pneumatic drilling performance

2.4.1. Introduction

Inefficient working areas are identified by overall weighted performance values or by working area KPI analysis. These areas need to be analysed in more detail by examining the pneumatic drilling performance of every panel. The pneumatic drilling performance is the production achieved with a certain supplied compressed air pressure.

The common drilling performance of a working panel must be identified and used as a reference to determine whether production is affected by compressed air service delivery pressure. An example is shown in Figure 30. Reported reasons for not blasting are required to validate typical drilling performance constraints not related to inefficient compressed air service delivery.

The expected pressure per working area is calculated according to the Darcy–Weisbach equation and plotted against the production achieved. The graph in Figure 30 illustrates the expected correlation between production outputs and compressed air pressure supply. Low production output with low compressed air pressure can be an indication of inadequate production due to poor service delivery.

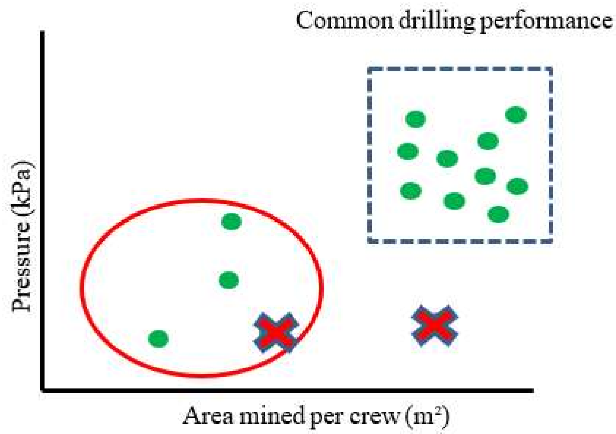

Figure 30: Pneumatic drilling performance illustration

The expected pressure at each active panel is calculated and compared to the production realised to determine the pneumatic drilling performance. The expected pressure calculated at each production panel and determining the factors influencing the drilling performance will be discussed in this section.

2.4.2. Expected panel air pressure calculation

One of the KPIs, developed in Section 2.2.3 is the expected air pressure at the first working panel. The same method will be used to calculate the pressure drops between each panel to estimate the working pressure supplied to the drills.

Typically, the compressed air to the different panels is supplied from the haulage pipe through the crosscuts, as indicated in Figure 31-A. Multiple panels can be supplied through an individual crosscut and often the panels are supplied from multiple cross-cuts to form a ring feed. Thus, calculating pressure drop to every panel will require resources, time and complex calculation.

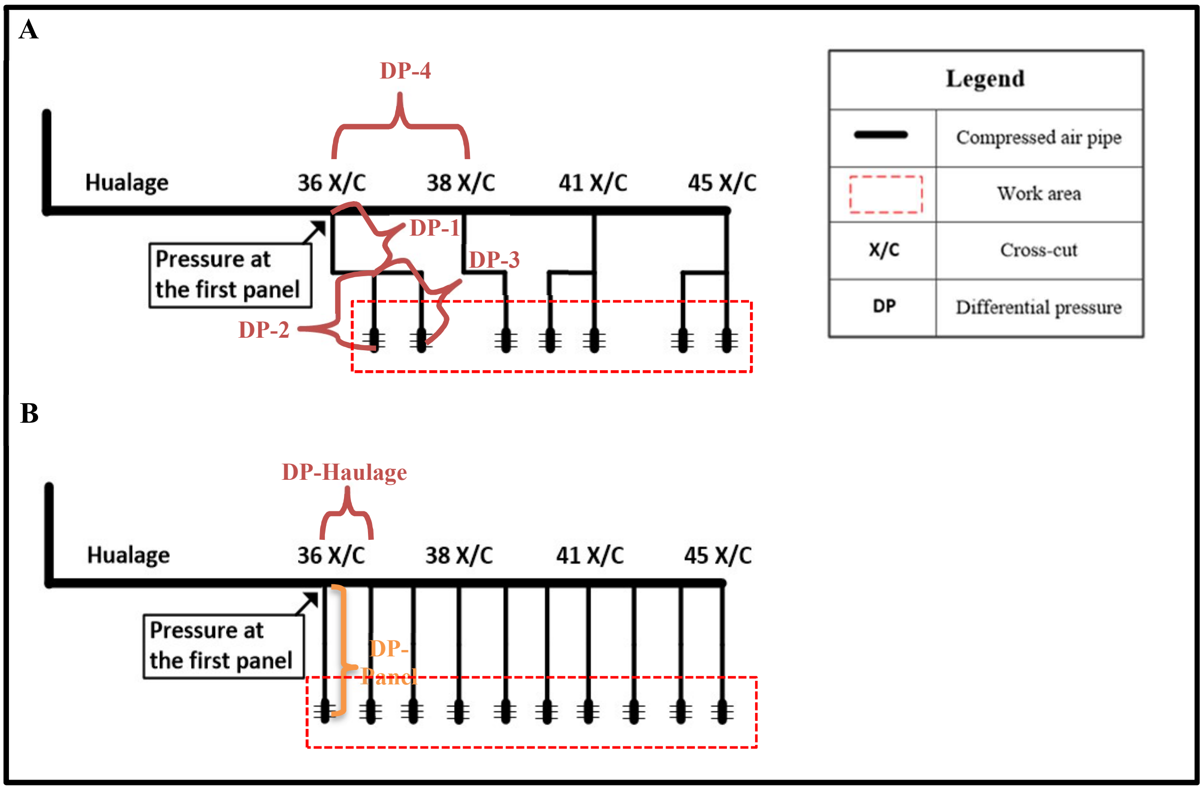

Figure 31: A - Compressed air network to working panels; B – Simplified compressed air network calculation

For a practical approach, the simplification is made that every panel connects directly to the haulage pipe and not through the crosscuts. The assumption is also made that all the panels are connected with a fixed pipe diameter and pipe length to the haulage pipe. Figure 31-B shows the simplified pipe network for calculating the expected pressure at every panel.

To calculate the expected pressure at every panel, Equation 9 is used to determine the pressure drop from panel to panel. From the haulage to the panel, the pressure drop is calculated using Equation 9 with the only unknown variable being the flow rate expected at every panel. The expected flow for every panel is the wastage- and production-air proportionally allocated to the active panels according to the area mined or developed.

The wastage compressed air is allocated to the active and inactive panels as some of the wastage is due to haulage leaks or pipe leaks in the panel. A commonly found mining practice is to ventilate development ends with compressed air as the confined development areas are typically not ventilated appropriately. Equation 12 describes how the compressed airflow is allocated to every panel. The haulage and panel pressure drops are indicated in Figure 31-B.

Equation 12: Compressed air allocated per panel

$$M_{panel} = \frac{M_{wastage}}{n_{panels}} + \frac{M_{production}}{C_{Total\ stope} \cdot 3 + C_{Total\ development}} * \left(C_{stope} \cdot 3 + C_{development}\right)$$

Where:

M_{panel}	Panel compressed airflow [kg/s]
$M_{wastage}$	Peak wastage compressed airflow [kg/s]
$M_{production}$	Peak production compressed airflow [kg/s]
$C_{Total\ stope}$	Total number of stoping crews working at the work area
$C_{Total\ development}$	Total number of development crews working at the work area
C_{stope}	Number of stoping crews working at the panel
$C_{development}$	Number of development crews working at the panel

2.4.3. Determine the factors influencing drilling performance

The production outputs versus expected compressed air service delivery pressure need to be plotted to determine underperforming production panels. Interactive data visualisation tools can make the identification of underperforming panels easier to identify.

Pneumatic drilling performance is analysed by comparing the production outputs or number of crews worked with the expected compressed air pressure. The pneumatic drilling performance can be summarised as the average by day or month. It can also be expressed as an average of all production panels or as individual panels. The more the drilling performance analysis is broken down per panel per day the easier insufficient compressed air service delivery can be identified.

The common drilling performance is the service delivery pressure required for a production area to realise the production target without being affected by insufficient compressed air pressure. Production below the target due to insufficient compressed air pressure leads to underperforming production areas.

Pneumatic drilling performance analysis can be done by comparing productivity with service delivery pressure in three methods:

1) ***Production per crew worked compared to compressed air service delivery pressure***

Only crews that produced production are used in the analysis to identify underperforming production caused by undersupplied compressed air pressure.

The advantage of excluding crews that did not realise production from the performance analysis is that crews with valid reasons for not drilling are excluded. Thus, the area mined per crew will not be affected by valid reasons for not drilling and the productivity of working crews can be compared to the service delivery.

2) ***Production per crew allocated compared to compressed air service delivery pressure***

Another way to analyse pneumatic drilling performance is by using all the crews allocated to a panel and not only production crews as above. The crews that produce no production will lower the production per crew realised.

The disadvantage of including all the crews, whether they achieved production or not, will be that valid reasons for not realising production will be included. The advantage is that crews who do not record production but assist other crew allocated to the panel will be taken into account when analysing performance.

3) ***Number of crews worked and number of missed blasts compared to compressed air service delivery pressure***

The productivity of a production panel or working areas can also be determined by comparing the number of crews that achieve production and the number of crew that did not blast with the compressed air service delivery pressure.

2.4.4. Conclusion

The pneumatic drilling performance of every panel is determined by calculating the expected pressure at every panel during the peak drilling period and comparing it with panel productivity. Three methods to identify underperforming production panels were discussed. The expected air pressure is compared to productivity measured as:

- Area mined per working crews
- Area mined per allocated crews
- Number of crews worked

The common drilling performance is the production productivity most regularly achieved with commonly supplied air pressure. Mining panels where productivity and air pressure supply is lower than the common drilling performance will be identified as unproductive due to insufficient compressed air pressure.

2.5. Investigate inefficient compressed air service delivery to validate the results

Panels with insufficient expected compressed air pressure influencing production must be investigated. This will assist in determining the reason for compressed air inefficiency. Two procedures can be followed to determine compressed air supply inefficiency.

1) Daily compressed air supply and demand analysis

Over-demand of airflow and undersupply of compressed air pressure will lead to service delivery inefficiency. The supply compressed airflow and pressure over a 24-hour period can be compared to the average flow and pressure of a specific month. If the compressed airflow demand increases, the compressed airflow will exceed the average for the month while the supply pressure stays constant. If the supply air pressure decreases, the supply pressure will be less than the average monthly pressure.

Insufficient compressed air pressure at the working areas can be caused by an increased demand for compressed air. This can occur when crews are motivated to achieve maximum production due to incentives or bonus targets. When all drills are operating simultaneously, it causes an over demand in compressed airflow resulting in insufficient pressure at working areas. The pressure drops over the pipe length with the increased compressed airflow that causes the rock drills to underperform.

Insufficient compressed air pressure at the working areas can be caused by a decrease of supply pressure to production levels. This can be caused by an increase in demand of other production levels or underperforming compressors generating pressure.

2) Compressed air wastage audit

Air wastage will lead to insufficient compressed air pressure at working areas. A compressed air wastage audit can be done to identify where compressed air is wasted through leaks or open ends. Wasted compressed air leaks or open-ends will be repaired when identified to prevent future production losses due to insufficient compressed air supply.

A wastage compressed air audit is done during downtime when compressed air consumers in a production level are at a minimum. The compressed airflow is measured at the start of the working area while individual crosscuts valves are closed to isolate sections of the compressed air network. As sections of the compressed air network are isolated the flow reduction can be observed on the flow meter. This will identify panels with high wastage causing other panels to have insufficient compressed air supply during a drilling shift.

The audit procedure and work area layout are shown in Figure 32. The steps follow below:

1. Install the flow meter at point A or use the mine’s permanent flow meter.
2. Close all crosscut valves individually for five minutes before opening the valve. Annotate open and closing times and crosscut numbers for every open crosscut valve. The crosscut valves are indicated in Figure 32 as points B. Before continuing to the next open crosscut, allow five minutes for the flows to stabilise.
3. Identify haulage leaks and estimate the hole size. Annotate location and hole size for leakages with a diameter greater than 3 mm. Small leaks are not essential to record as these are not feasible to repair.

4. After the audit is complete, analyse the flow data recorded together with the valves' closing time to determine the wasted airflow in every crosscut.
5. Report the compressed air wastage to the mining personnel to ensure reduced compressed air wastage. This will increase compressed air pressure at pneumatic drills.

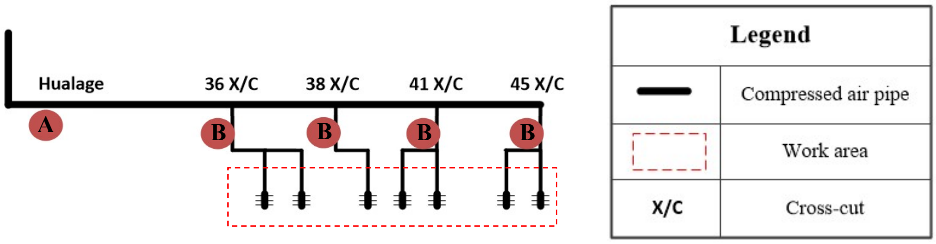

Figure 32: Compressed air pipe network in a work area

2.6. Determine the cost of lost production

Production lost due to insufficient compressed air service delivery was identified and validated in the previous section. This can be expressed as a percentage of the total production or as a Rand value. The equation to calculate the Rand value of the production loss is shown in Equation 13. The variables needed to calculate the production loss value can be found in any mine's mineral resource and reserve statement.

Equation 13: Production rand valve

$$PV = P \cdot 0.035274 \cdot C_{gram\ per\ ton} \cdot C_{ton\ per\ area\ mined} \cdot h \cdot A$$

Where:

PV	Production value [R]
P	Rand basket price [R/ounce]
$C_{gram\ per\ ton}$	Ore per ton rock [g/ton]
$C_{ton\ per\ area\ mined}$	Weight per volume rock [ton/m^3]
h	Reef height [m]
A	Area mined [m^2]

2.7. Verification of approach to analyse pneumatic drill performance

The evaluation of whether or not the developed methodology proposed is accurately implemented will be discussed. The methodology compares the productivity of every working area with the expected compressed air pressure to identify production loss due to insufficient compressed air pressure.

Literature studies that tested pneumatic rock drills, experimentally and theoretically, to determine the effect of compressed air pressure on the pneumatic rock drills' rate of penetration was analysed [21], [25], [26]. These studies verified the correlation between compressed air pressure and the rate of penetration (ROP).

The developed methodology calculates the expected compressed air pressure during peak production times and compares it with the production realised per crew at each working area. The effect of different supplied compressed air pressures at the working areas on productivity can be analysed.

The compressed air pressure estimations and the production realised per day are an essential part of the developed method. The verification of both these aspects will be discussed below.

Compressed air pressure at each working area

The method used to calculate the expected compressed air pressure at the working area makes use of assumptions, listed below, that could influence the accuracy of the pressure expected at each working area.

- Compressed airflow is proportional to the number of crews working
- Pipe surface roughness is 0.09 mm
- Pressure drops are only calculated for the haulage pipe. The pressure drop from the haulage pipe to the working area is insignificant
- Compressed air wastage airflow is distributed equally between all working areas
- All the rock drills are operational during the peak periods

The assumptions made to calculate the expected air pressure at every working area are a practical method to compare the effect of different compressed air pressures on production. The developed method only compares the expected pressures of each working area individually at daily intervals and does not take actual pressure into account. The calculated pressure is not compared to other working areas but each area is evaluated individually. The inaccuracy of assumptions made is thus reduced by only assessing the pressure change for each individual area.

A decrease in the expected pressure supplied to the drills in each working area can be compared to the production realised. The change in expected pressure is analysed to determine whether it caused ineffective drilling and therefore less production.

Production realised per day

The productivity of the miners in every working area can only be determined by calculating the area mined per crew for every working area. Total tons hoisted or extracted per production level is too broad and the effect of insufficient compressed air on each working area cannot be determined.

The production realised in the area mined per crew directly correlates to the number of holes drilled [43]. Insufficient compressed air will reduce or stop the pneumatic rock drills from penetrating the rock and reduce the number of blast holes. Thus a smaller area mined per crew will be achieved for production days affected by insufficient compressed air supply. The equation below describes the correlation between area mined and the number of holes drilled.

Equation 14: Estimating the number of drilled holes required per area mined [43]

$$N = 2.2A + 16$$

Where:

N	Number of holes to be drilled
A	Rock area to be blasted [m²]

The proposed developed method to identify production loss due to insufficient compressed air supply was verified for accurate implementation to be achieved. The compressed air pressure estimations and the production realised per day as an indication of productivity is analysed to determine the common drilling performance and identify production loss due to insufficient compressed air supply.

2.8. Conclusion

A methodology was developed to analyse mine pneumatic drilling performance to determine when production is affected by insufficient compressed air service delivery. Developed compressed air and production KPIs can be used to identify and prioritise working areas that might be affected by insufficient compressed air service delivery.

KPIs for both compressed air service delivery and production performance was developed. The KPIs developed can be monitored on a daily interval to identify a change in compressed air service delivery or production. The KPIs can also be used to track changes in the number of crews allocated to a working area. The KPIs give a holistic overview of the compressed air efficiency and production performance of the mine.

The methodology is developed to identify inefficient production areas due to an undersupply of compressed air. A weighted score is developed that combines production performance KPIs and compressed air service delivery KPIs. By using KPIs all factors influencing production are taken into account. The weighted scores are used to determine the working areas that need to be analysed for possible production loss due to insufficient compressed air delivery. The weighted score also incorporates other KPIs like number of crews allocated to a working area and the number of missed blasts reported.

The methodology is developed to identify inefficient drilling performance due to insufficient compressed air pressure by comparing common drilling performance with undersupplied production day. The developed methodology was verified through literature to ensure accurate implementation. The compressed air pressure at the drills affects the penetration rate and thus the production achieved.

The identified days affected by compressed air can be validated by analysing the supply compressed airflow and pressure of inefficient days compared to the monthly average. The production loss due to insufficient compressed air supply at the production panels can be expressed as a production percentage or as a production loss rand value.

CHAPTER 3. IMPLEMENTATION & VALIDATION

3.1. Introduction

In this chapter, the methodology developed to analyse the mine's pneumatic drilling performance will be applied to a well-instrumented platinum mine. The purpose of this chapter is to validate the methodology with real-life case studies and determine the effect of insufficient compressed air pressure on production. The developed methodology's objectives are listed below to determine the effect of inefficient compressed air service delivery on production outputs.

- Monitoring of all working areas' production and service delivery KPIs.
- Identify the working areas where production outputs might be affected by an under-supply of compressed air.
- Analyse pneumatic drilling performance of all workplaces' production outputs that might be affected by insufficient compressed air service delivery.
- Determine the production lost due to insufficient compressed air service delivery.

3.2. Mine A: Case study identification

3.2.1. Introduction

The methodology was implemented on a platinum mine and three case studies were identified and analysed in detail. The overall performance of the mine's working areas was analysed based on production and compressed air service delivery. The case studies were identified by evaluating the developed KPIs of the different working areas and identifying the areas most likely to be affected by poor compressed air service delivery.

3.2.2. Site background

The methodology was implemented on Mine A which is a conventional deep-level platinum mine. The mine has been productive for ±30 years with an estimated ten years of production remaining. The mine's compressed air network dynamic changes constantly as the number of crews, active areas, compressed air demand and supply pressure change over time.

The production outputs also varied as management, seasons and production demand changed. This mine is the ideal mine to analyse pneumatic drilling performance due to the production and compressed air service delivery's dynamic environments. Due to confidentiality and the sensitivity of the data, the name of this mine is not disclosed.

The underground compressed air network reticulation and compressed air instrumentation are shown in Figure 33 below. The compressors only supply compressed air to Mine A and an additional small shaft.

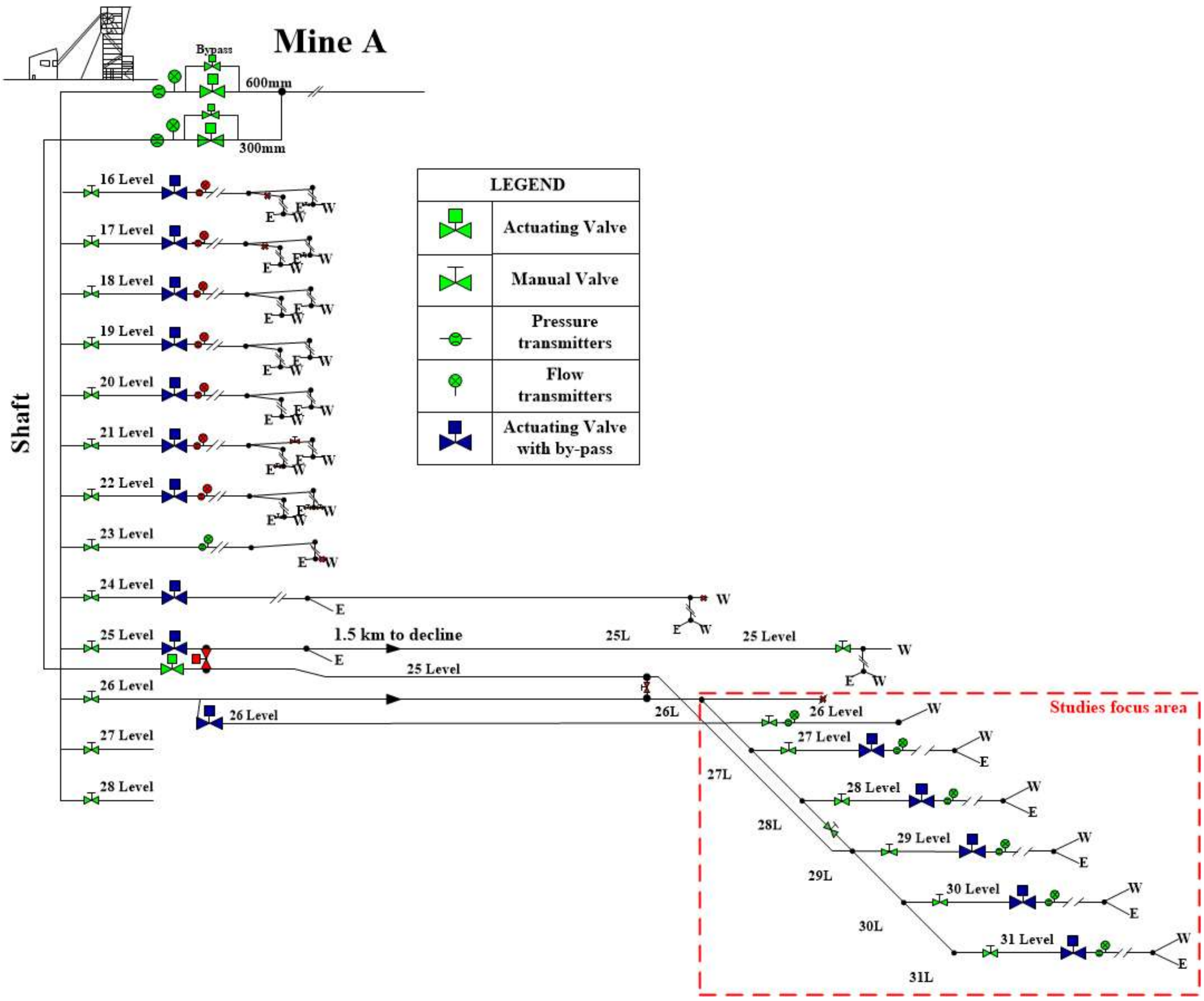

Figure 33: Simplified compressed air network

The compressors are automated to control the supply pressure at a setpoint of 600 kPa during the drilling shift and will dynamically adapt the supply airflow to match the demand. However, the shaft's compressed air demand can be more than the capacity of the installed compressors, thus the supply pressure reduces during the drilling shift to 550 kPa. The installed compressors, therefore, cannot supply the full demand of pressure required affecting compressed air service delivery at production ends.

3.2.3. Holistic condition monitoring of Mine A

Mine A was holistically monitored to gain insights into the overall compressed air service delivery and the production achieved. The instrumentation's accuracy was first verified before implementing the developed KPIs.

Instrumentation verification and data acquisition

Data required to analyse pneumatic drilling performance in Mine A, listed in Table 4, were obtained daily from the mine's SCADA and management system. The compressed air data is captured hourly. The upper levels, namely level 16 to 23, are mined by contractors or are closed off and will not form part of this study.

As indicated in Figure 33, there are no compressed airflow meters installed at level 24 and 25. The remaining levels, level 26 to 31, are the shaft's main production levels and will be the focus of this study. These levels have compressed airflow meters and pressure transmitters installed at the start of each level.

The flow meters measured compressed airflow at a constant flowing pressure and did not calculate the compressed airflow according to the pressure transmitter's output. The compressed airflow meter's output was recalculated, taking the line pressure into consideration.

The differential pressure flow meters were calibrated and verified. The flow meters were also verified using method three developed in section 2.2.2. The results proved that the flow meters were calibrated correctly, shown in Appendix B. The compressed airflow meters' readings were converted to volumetric and mass flow rates using the conversion diagram in section 2.2.2.

Condition monitoring

Levels in the focus area were monitored over a time period of five months to determine how compressed air service delivery and production outputs changed over time. The KPIs discussed in section 2.2.3 were implemented to gain insights into compressed air service delivery and production achieved. The condition monitoring shows the need for further investigation into the effect of compressed air supply on production with pneumatic drilling performance analyses.

Figure 34 & Figure 35 show how the compressed air and production changed over time. The area mined increased by 27% and meters developed increased by 10% from March to July. However, the average compressed air consumption during the peak drilling shift decreased by 7% and the compressed air wastage decreased by 11% from March to July. Figure 35 shows the average airflow used for production and the average airflow wasted during peak drilling shift. The calculations are derived in section 2.2.3.

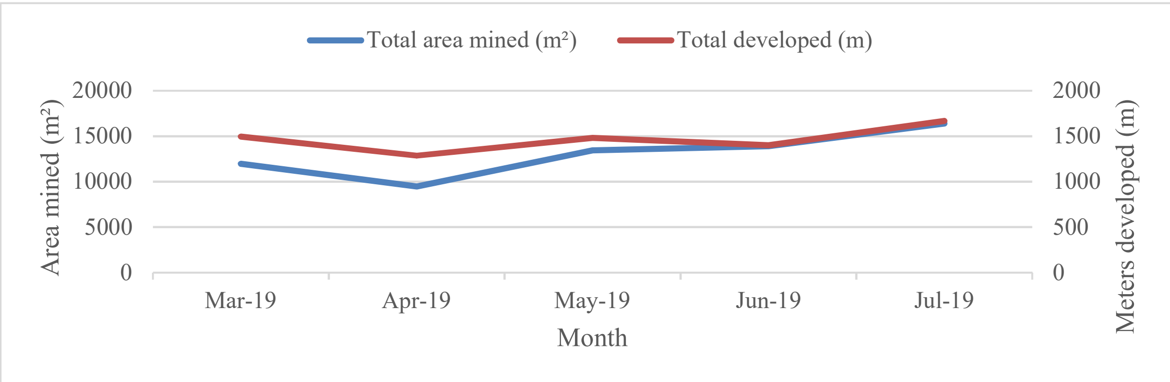

Figure 34: Mine A's production

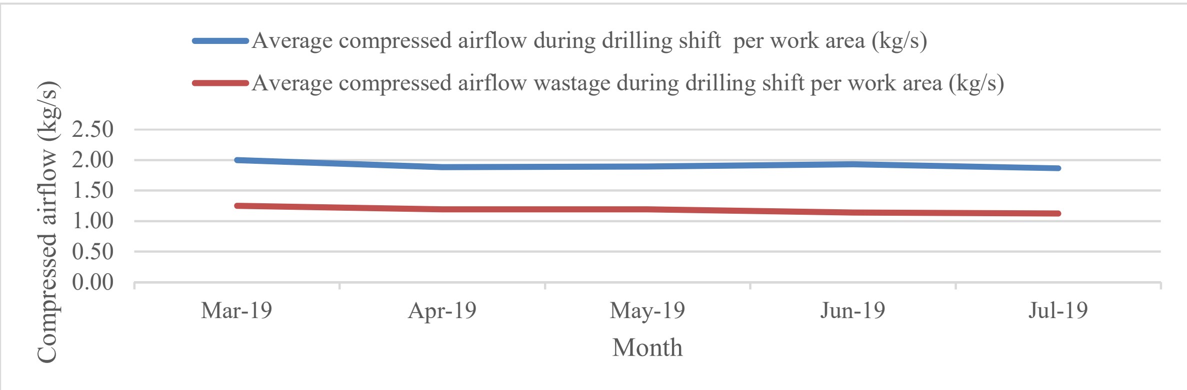

Figure 35: Average production and wastage compressed airflow air

Mine A's production increased as the total compressed air consumption decreased. It would be expected that the compressed air consumption will increase as the production increases due to more drilling activity.

The decrease in compressed air consumption should have an effect on the overall pressure at the start of each working area as well as on the service delivery pressure at the first working area. Figure 36 shows the average pressure at the start of each working area and at the first active panel.

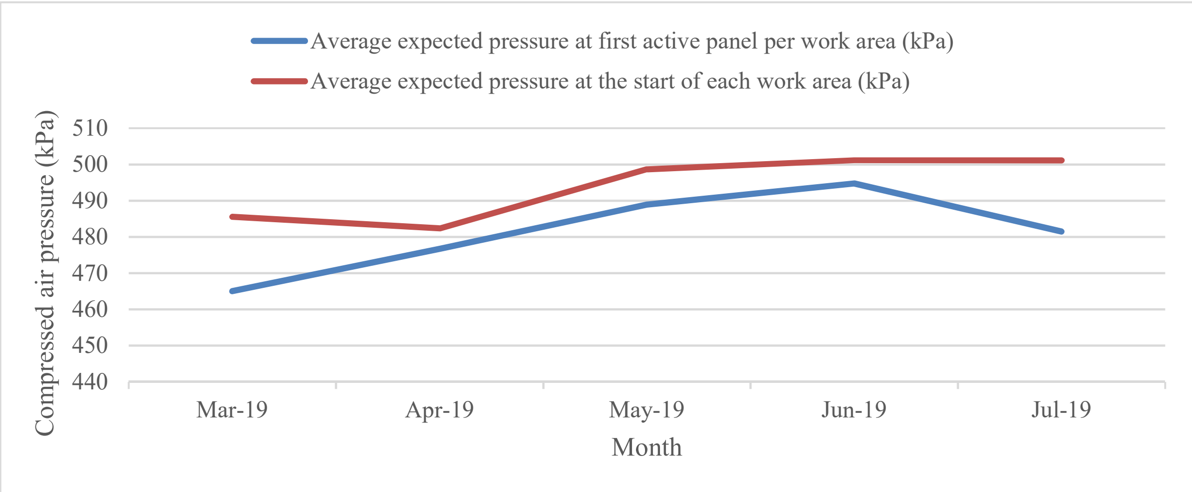

Figure 36:Average expected pressure at each work area

The average compressed air pressure at the start of each working area increased by 3% and the average expected pressure at the first active panel of every working area also increased by 3% from March to July.

The average pressure at the start of each working area was 482 kPa during April, the lowest for the five months. The production achieved was also the lowest during April. Further investigation will be done in this study to determine whether compressed air service delivery could affect production.

The improvement of compressed air efficiency can be seen in the compressed air usage per area mined shown in Figure 37. Working area '26WUG2' has the largest compressed air consumption per area mined. However, only two crews worked at the working area and compressed air is unlikely to be affecting production. All KPIs need to be evaluated to determine the working areas with the highest chance of being affected by compressed air service delivery.

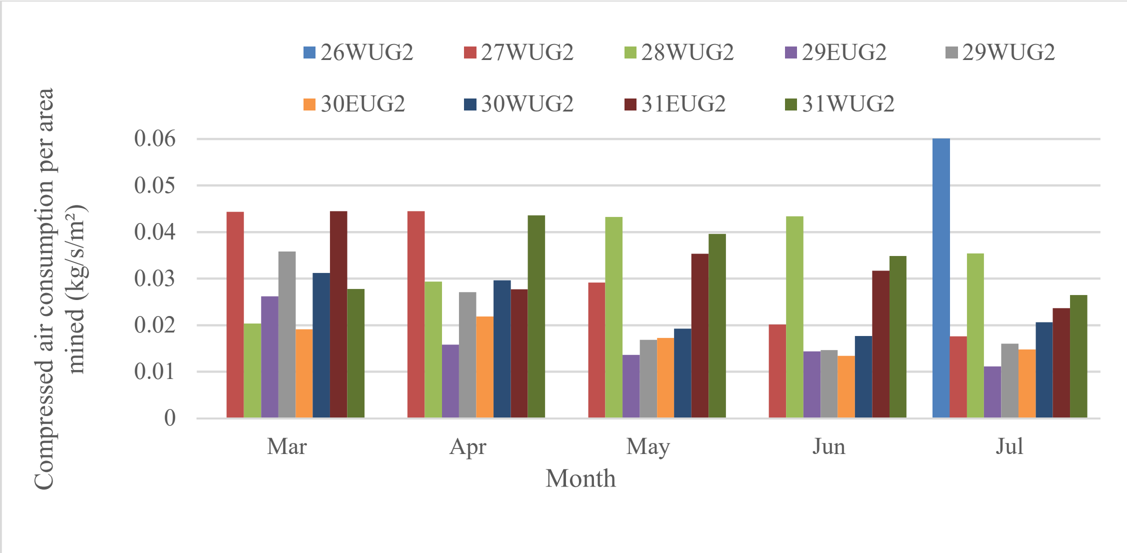

Figure 37: Benchmarked compressed airflow per area mined for each work area

3.2.4. Inefficient working area identification

Working areas with the most significant chance of being influenced by insufficient compressed air pressure were first identified for further drilling performance analysis.

The KPIs developed for every working area were weighted according to production outputs, compressed air complaints and compressed air service delivery. The average overall performance of all the working areas is compared in Figure 38.

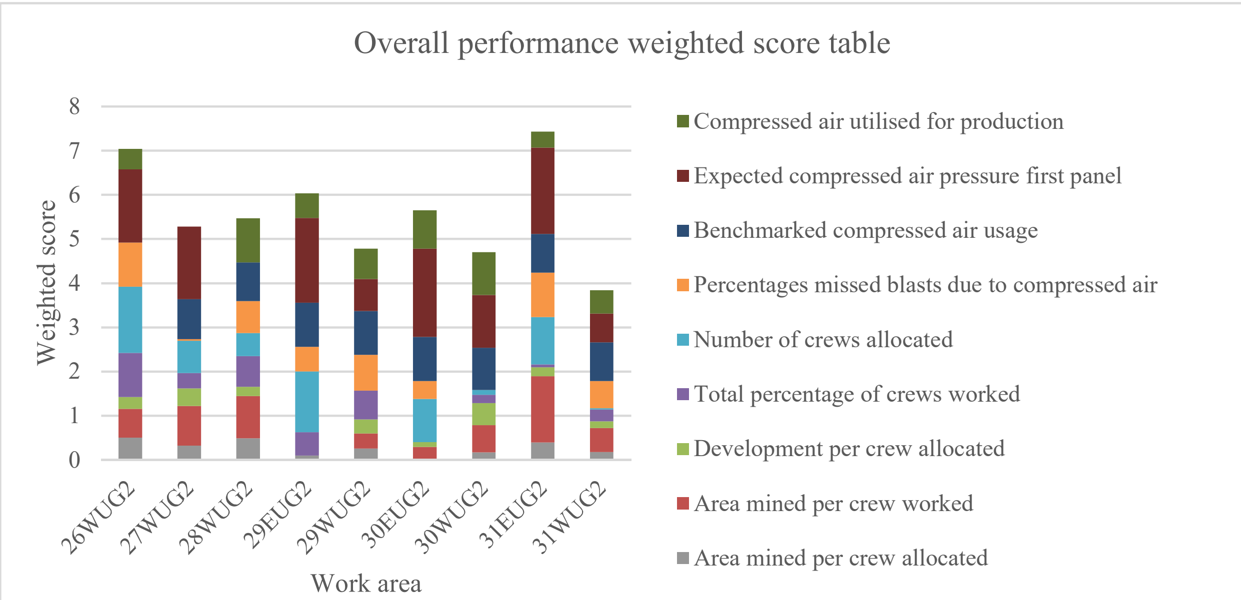

Figure 38: Overall performance weighted score

The lowest weighted score represents the underperforming working areas due to less production per crew and inefficient compressed air service delivery. Working area "30WUG2" had the most compressed air complaints per blasting opportunity.

Working areas: "31WUG2", "30WUG2" and "29WUG2" achieved the lowest overall performance weighted score. The pneumatic drilling performance analysis of these working areas will be discussed in three case studies.

3.3. Case Study A: Level 31 UG2 West

The identified working area's production performance and compressed air service delivery were analysed before the pneumatic drilling performance analysis was done on each active panel. Compressed air service delivery was compared to production realised to identify production loss due to insufficient compressed air pressure supplied to the drills. The factors influencing the drilling performance were validated by comparing the compressed air demand and supply of the affected day to non-affected days. The total production loss due to compressed air service delivery was valued at R1 million for the analysed five-month period.

3.3.1. Working area performance analysis

Working area "31WUG2" is the bottom level of the shaft with the highest compressed air consumption. The working area's compressed air consumption is expected to be higher than other production levels as the bottom level has more production panels. Pneumatic pumps installed in this area also use compressed air for pumping accumulated water from lower areas.

Figure 39 shows the compressed air consumption and the pressure at the start of the working area during peak periods. The graph also shows the calculated expected pressure at the end of the working area.

The peak compressed air consumption increased at the end of March and then reduced over time. The expected compressed air pressure at the end of the working area increased over time, especially during June and July. If the expected pressure at the end of the working area increased, the supply pressure to the pneumatic drills would also have increased. This is due to pneumatic drills connected before the end of the working area.

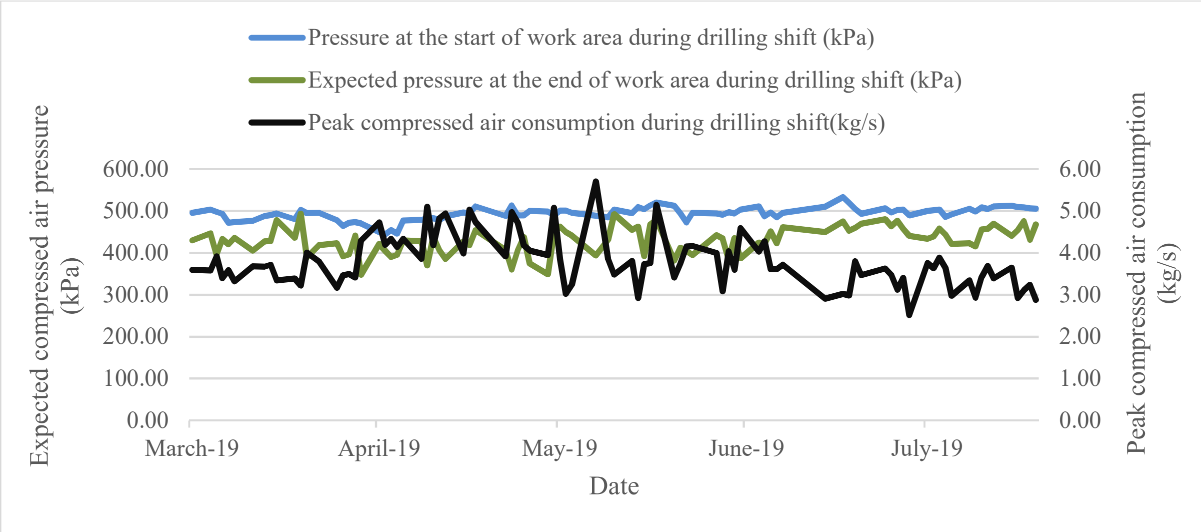

Figure 39: Work area "31WUG2" peak compressed airflow and pressure

The decrease in air consumption during June and July is the reason for the increased pressure at the working panels. It is expected that compressed air may affect production from the end of March to June.

The working area's production outputs shown in Figure 40 indicate a reduction in production in April, May and June. However, the total meters developed increased during April and May. The compressed air consumption reduced and supply pressure increased from June to July while production increased. Further analysis will be done to determine if improved compressed air service delivery influenced production performance.

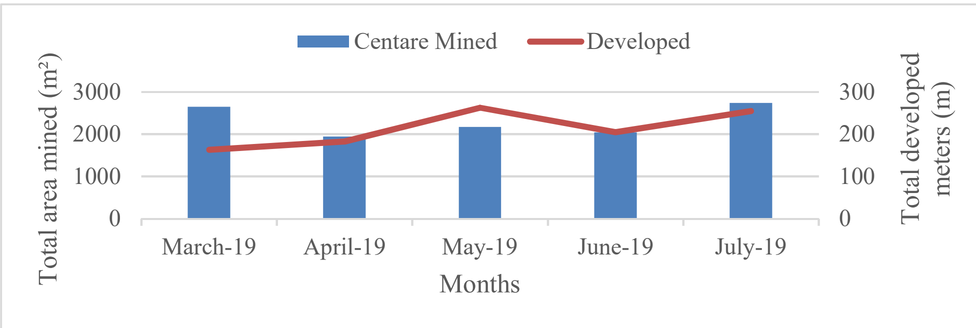

Figure 40: Work area "31WUG2" production outputs

In Section 3.2.3 the overall performance of the working area "31WUG2" shown in Figure 38 was mostly affected by the area mined and development per crew allocated to the working area. The production KPIs shown in Figure 41 compare the area mined per crew worked and per crew allocated.

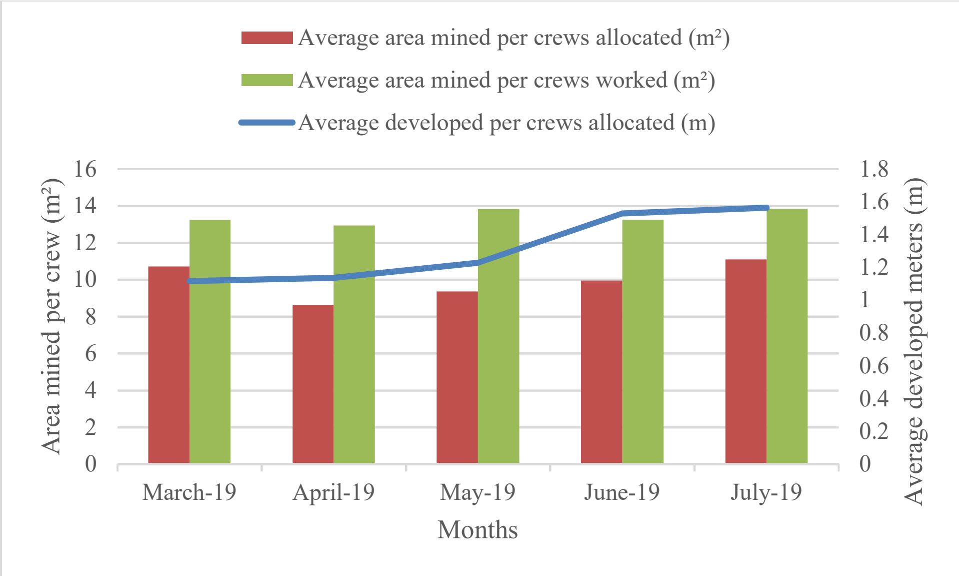

Figure 41: Production per crew worked or allocated

The productivity of the crews worked and the area mined per crew allocated increased from March to July. The decrease in production achieved per crew allocated seen from March to April indicates more production crews were not realising production in these months.

The development per crew allocated increased over the monitored period also showed in Figure 41. The increase in productivity for both production and development can be the effect of increased compressed air pressure.

The performance analysis showed that compressed air service delivery might have affected productivity lost from the end of March to April for the following reasons:

- Production decreased
- Air demand increased
- Supply pressure decreased
- Percentage crews worked decreased

From the performance analysis of the working area "31WUG2", further analysis will be done to confirm and quantify the production loss due to insufficient compressed air supply.

3.3.2. Analyse common drilling performance inefficiencies

The performance analysis of working area "31WUG2" indicated a decrease from April to March in productivity and compressed air service delivery. Further evaluation of drilling performance at each active panel is required.

To determining if compressed air service delivery affected the production outputs, individual panel production outputs per working crew were compared to the expected pressure at those panels. Figure 42 compares the averaged drilling performance of all the active panels per month. The size of the dots on the graph indicate the number of crews who worked on a specific day.

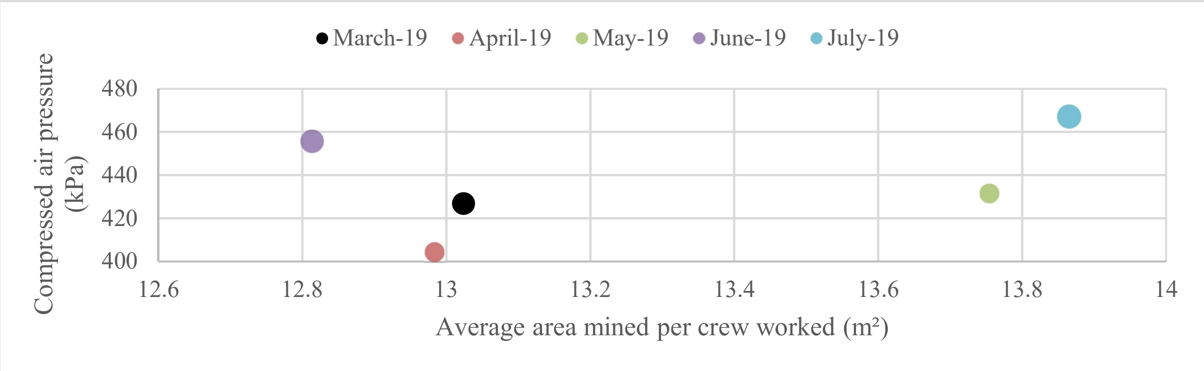

Figure 42: Monthly averaged drilling performance

The averaged drilling performance for April and March is lower as the production achieved per working crew and the compressed air pressure is less than July. May realised a higher average area mined per crew worked even though pressure was low. This does not indicate improved drilling performance as fewer crews worked.

When determining whether a panel's performance has been affected by compressed air service delivery, every panel's production outputs must be benchmarked to its own common drilling performance.

Figure 43 shows panel 33's pneumatic drilling performance, comparing the production achieved per working crew to the expected compressed air supply of this individual panel. The common drilling performance was determined, as shown in the green block in Figure 43. The common drilling performance is the average area mined mostly achieved by production crews. This is the physically maximum area that can be achieved in one shift. The minimum supply pressure of the common drilling performance is the lowest pressure where full production still could have been achieved. Days with insufficient compressed air service delivery were identified below the common drilling performance, shown in the red block.

Days circled in red indicate days when production was underachieved compared to the common drilling performance and the pressure was below the minimum common drilling pressure in that specific month. This proves insufficient compressed air pressure affected production on these days.

Days circled in black indicate when the area mined per crew is the same as the common drilling performance but with lower compressed air pressure than the minimum. However fewer crews worked indicating insufficient compressed air supply also affected production.

Underperforming production with good service delivery indicated in the yellow block can be due to various other reasons than insufficient compressed air supply.

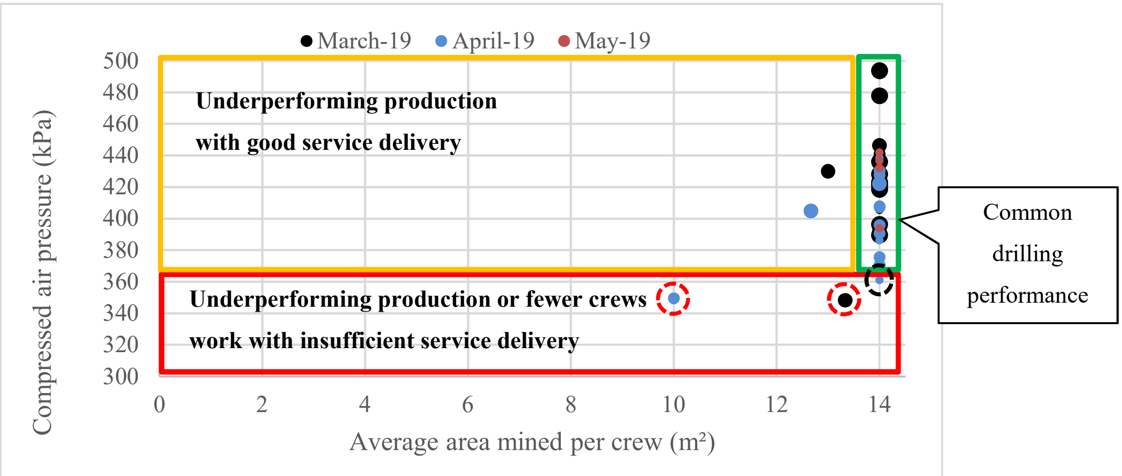

Figure 43: Panel 33 pneumatic drilling performance

The production loss identified due to insufficient compressed air pressure was 2 m² during March and 36 m² during April. The total production loss due to insufficient compressed air pressure at Panel 33 during April is 9.5% of the total production achieved.

The same pneumatic drilling performance analysis was done for every active panel of working area “31WUG2”. Production loss days due to insufficient compressed air pressure are indicated for each panel shown in Figure 44. Red circles indicate underperforming productivity and black circles indicate fewer crews worked due to compressed air pressure. These circles assume that lower pressure effected production crews.

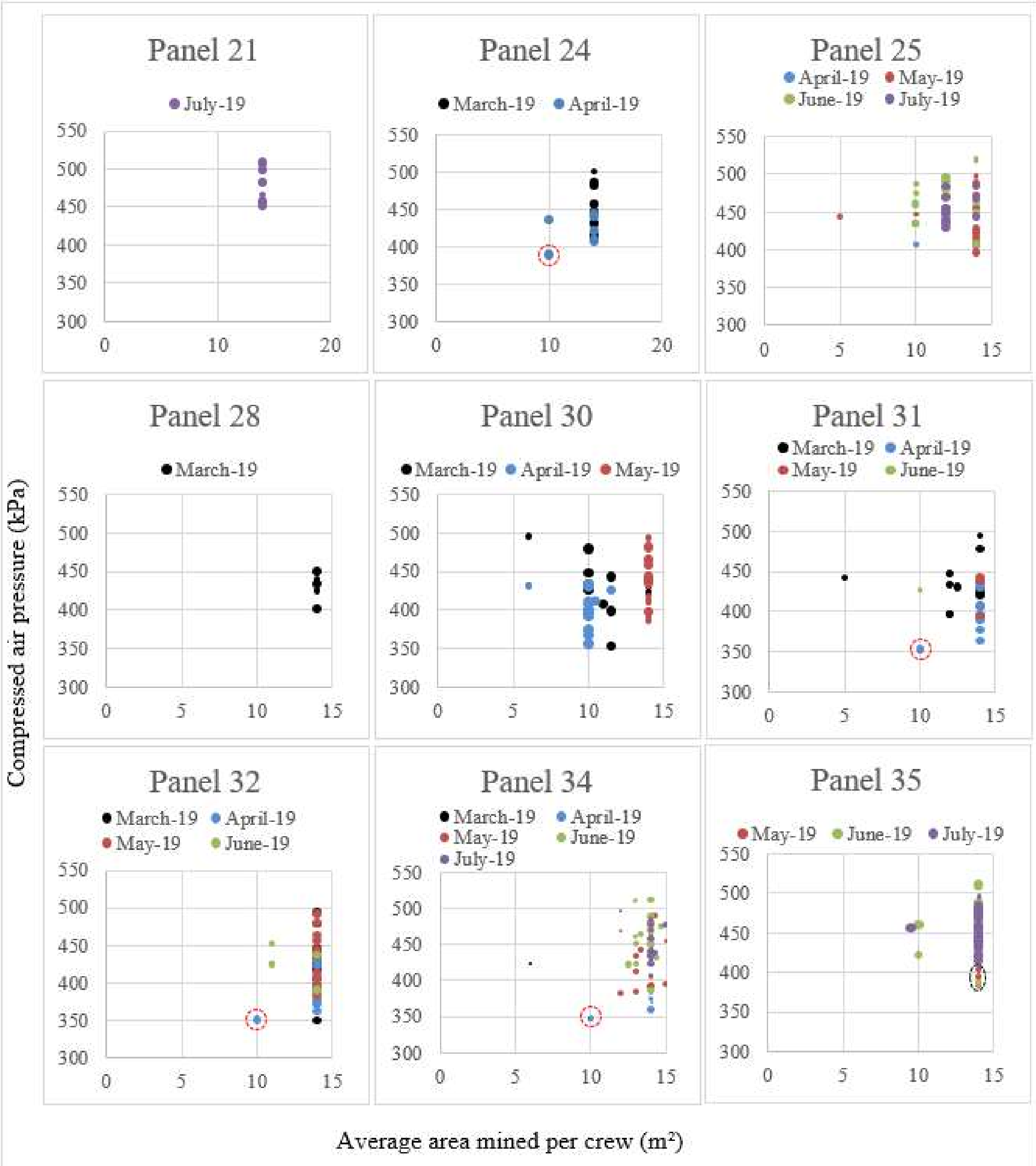

Figure 44: Individual panel pneumatic performance

The days identified in the panel pneumatic performance graphs above are also indicated in Figure 45. In this figure the number of crews worked per day at all active panels is compared to the lowest compressed air pressure supply to the working area. The size of the dots on the graph indicate the number of crews that did not achieve any production. Therefore the larger the dots the more crews did not achieve production. Red circles indicate underperforming productivity due to compressed air pressure and black circles indicate fewer crews worked due to compressed air pressure.

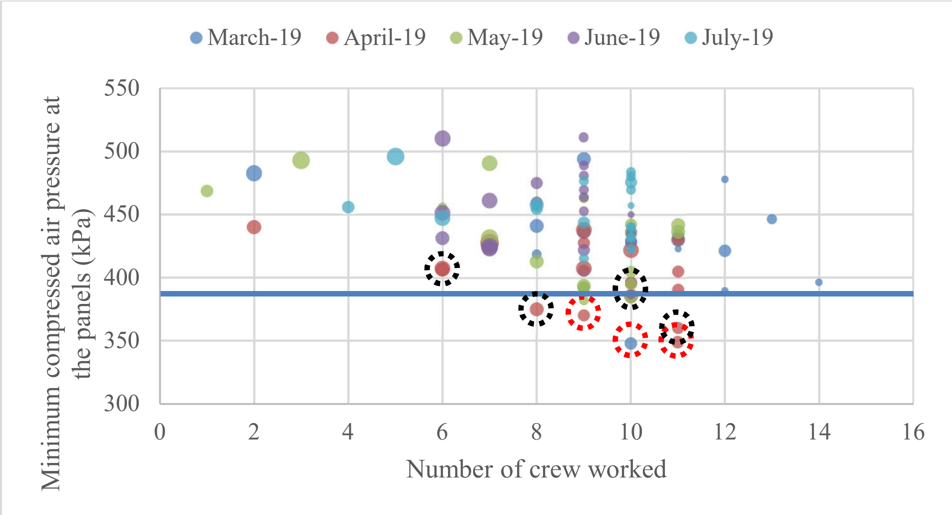

Figure 45: Number of crews worked compared to the compressed air service deliver pressure

The blue line drawn on the graph shows the minimum compressed air pressure required at the panels to minimise the risk of production loss due to compressed air. The minimum required expected compressed air pressure is 50 kPa below the average minimum supplied air pressure.

The maximum identified production loss per day specified due to inefficient compressed air service delivery is summarised in Table 7 below. The production loss in an area mined is the difference between the actual area mined and the common drilling performance target. The target can be achieved when service delivery is optimal. In analysing Figure 44 the area mined was 1.27% less than the target area due to insufficient compressed air service delivery. The working area's production could, therefore, be 1.27% more with improved service delivery.

Table 7: Inefficient service delivery incidents for work area "31WUG2"

Inefficient service delivery incidents	**Production loss in area mined**	**Production loss percentage for the production day**	**Production loss percentage for the monitored time period of five months**
29 March	28 m²	19%	0.25%
9 April	8 m²	7%	0.07%
30 April	36 m²	25%	0.32%
Fewer crews worked	70 m²	N/A	0.63%
	Total missed production due to inefficient service delivery		**1.27%**

3.3.3. Validation of factors influencing drilling performance

The pneumatic drilling performance graphs in the previous section identified three days where most of the panels' production was affected. For the identified days compressed air consumption and supply pressure at the start of the working area was compared to the overall monthly average in Figure 46 and Figure 47.

On 29 March the overall compressed air consumption increased by 43% and the minimum supply pressure was 33 kPa below the average. The sudden increase in compressed air consumption is not due to drilling as the compressed air consumption increased over the whole day not only in the drilling shift.

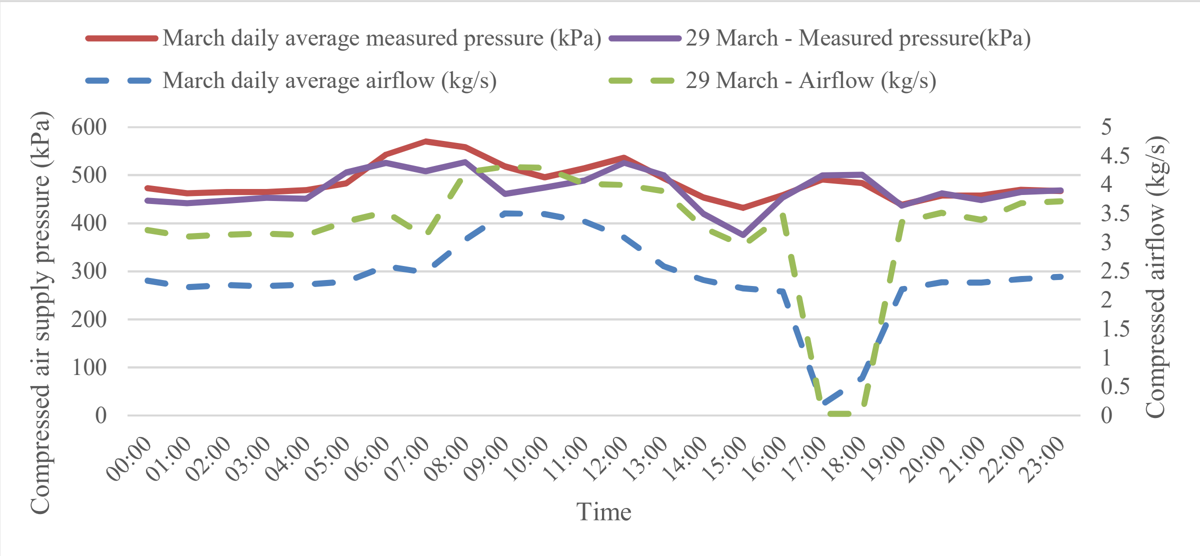

Figure 46: Daily service delivery for March

On 9 and 30 April the peak compressed air consumption increased by 34%; however the supply pressure was close to the average, as shown in Figure 47. The working area's compressed air service delivery was not affected by the consumption of other levels or the undersupply from the surface compressors as the supply pressure was not affected.

The sudden increase in compressed air consumption from the working area is mostly due to an increase in drilling as the compressed air consumption increased more during the peak drilling shift than during the rest of the day.

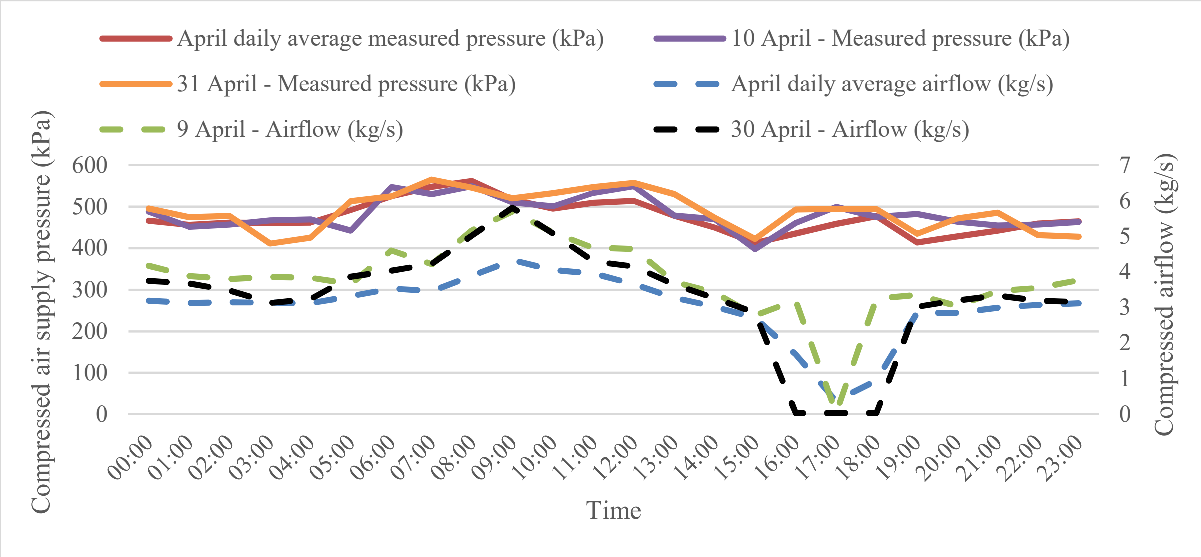

Figure 47: Daily service delivery for April

The analysis of the compressed air consumption and pressure at the start of the working area validated that a change in service delivery caused production loss. Insuring compressed air supply pressure stays the same and crews' air demand remains constant will ensure less production loss due to compressed air.

Production panels with the necessary compressed air service delivery without achieving common drilling performance targets can be due to various reasons. Mining crews might need to attend to other problems before drilling can start. The summary of the reasons for missed blasts is shown in Figure 48. The production loss due to missed blasts is 26% of the total possible blasting opportunities.

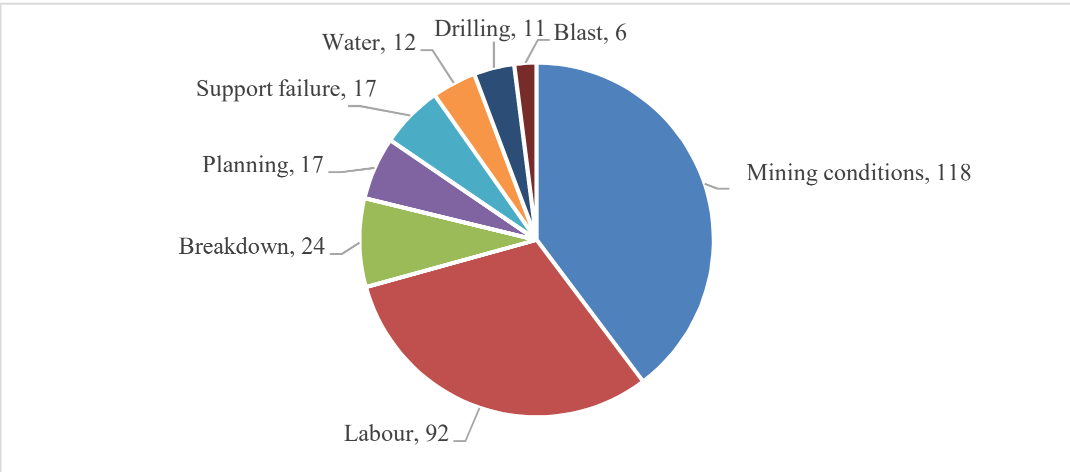

Figure 48: Number of missed blasts in the work area

3.3.4. Determine the cost of lost production

The total identified production loss due to insufficient compressed air supply at the drills of working area “31WUG2” was 142 m². The production loss is calculated as a Rand value to indicate the potential of improved compressed air service delivery.

The basket price and ore grade are available in any mine’s mineral resource and mineral reserve statement. The Rand basket price per ounce for this particular mine is R15 389. Ore is extracted at 4.24 grams per ton. The missed production as a result of poor compressed air service delivery is estimated at a value of R1 million for this work area.

3.4. Case Study B: Level 30 UG2 West

The working area “30WUG2” was identified as a potential working area with production loss due to insufficient compressed air service delivery. The mining crews reported lost production due to inadequate compressed air pressure and further analysis was needed.

The pneumatic drilling performance analysis was used to verify the compressed air complaints and to identify possible production loss due to insufficient compressed air supply. The total production loss due to compressed air service delivery was valued at R1.8 million.

3.4.1. Working area performance analysis

Working area “30WUG2” performed second lowest in the overall weighted performance analysis in Section 3.2.4 from March to July. The working area had three missed blasts due to compressed air complaints on 29 April. This day is indicated with a red vertical line in Figure 49. This graph shows the peak compressed air consumption and the expected compressed air pressures at the start and end of the working area.

The compressed air performance analysis does not show a trend in increased compressed air consumption or a drop in expected compressed air pressure at the end of the working area. The increased compressed air consumption on a number of days caused the expected pressure at the end of the working area to decrease significantly. This could cause production loss. However compressed air complaints occurred only at the end of April.

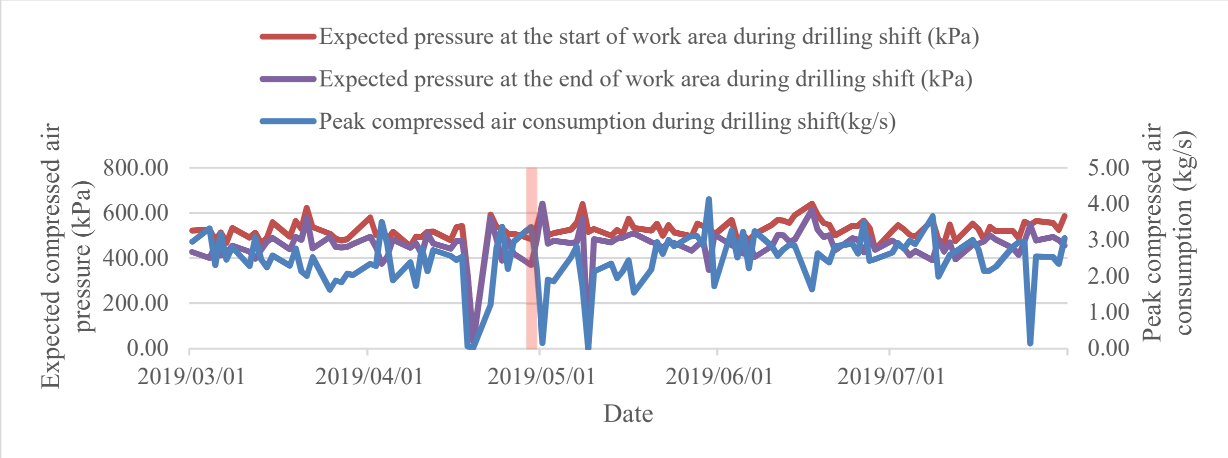

Figure 49: Work area "30WUG2" peak compressed airflow and pressure

The other reason for underachieving in the weighted performance analysis is the high number of unproductive crews allocated to a working area.

Figure 50 shows how the average area mined per working crew and per allocated crew increased. An analysis is needed to determine if production loss per crew at the beginning of the period is due to insufficient compressed air delivery. Figure 51 shows how production outputs improve during this period. More production requires more compressed air service delivery.

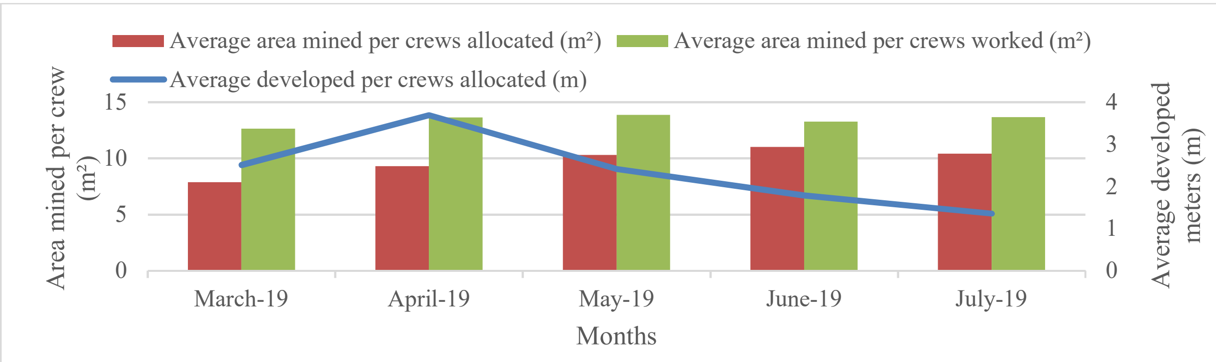

Figure 50: Production per crew worked or allocated

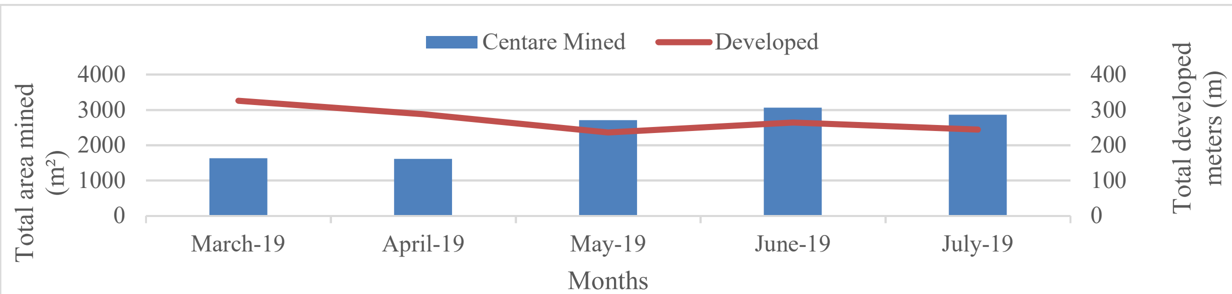

Figure 51: Work area “30WUG2” production outputs

The performance analysis showed that compressed air service delivery could have affected productivity on a number of days for the following reasons:

- Air demand increased
- Expected pressure at the end work area decreased
- Production improved and more compressed air demand is expected
- Mining crews reported missed blasts due to compressed air pressure

From the performance analysis of the working area “30WUG2”, further analysis is required to confirm and quantify the production loss due to insufficient compressed air supply.

3.4.2. Analyse common drilling performance inefficiencies

The monthly averaged pneumatic drilling performance graph, Figure 52, compares the area mined per working crew with the average peak compressed air supply pressure. The size of the dot on the graph represents the percentage of crews worked based on crews allocated.

From Figure 52 it is clear that the higher the average expected compressed air supply pressure, the more crews worked and the better the production per crew. June was the only exception therefore further analysis is required. However, detailed analysis is required to determine if compressed air pressure caused fewer crews to work.

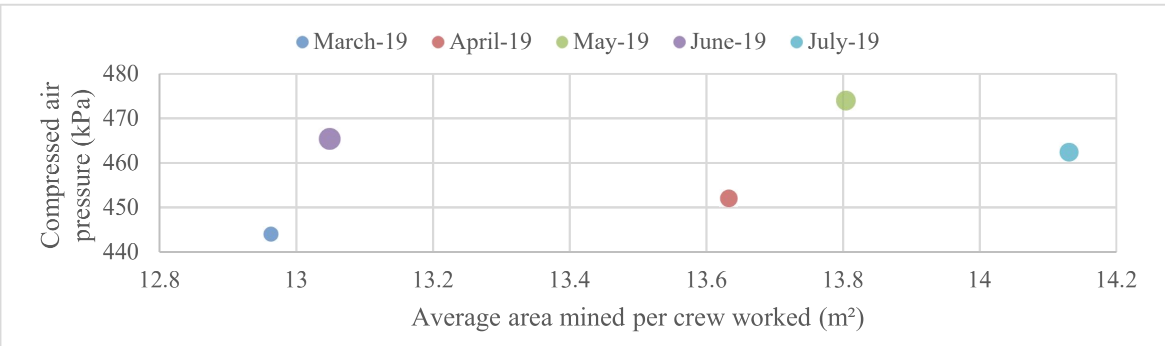

Figure 52: Monthly averaged pneumatic drilling performance

Detailed pneumatic drilling performance graphs in Figure 53 identify possible days production was lost due to insufficient compressed air service delivery per panel. The expected compressed air service delivery is compared to the area mined per working crews. The size of the dot indicates the number of working crews.

The common drilling performance is the most achieved production per crew with service delivery pressure more than the lowest full production day.

Days that possibly could be affected by service delivery are circled in red. The pneumatic drilling performance and compressed air service delivery is lower than the common drilling performance on these days.

Days were also identified where the area mined per crew was the same as the common drilling performance. However, fewer crews worked due to lower compressed air pressure. These days are circled in black.

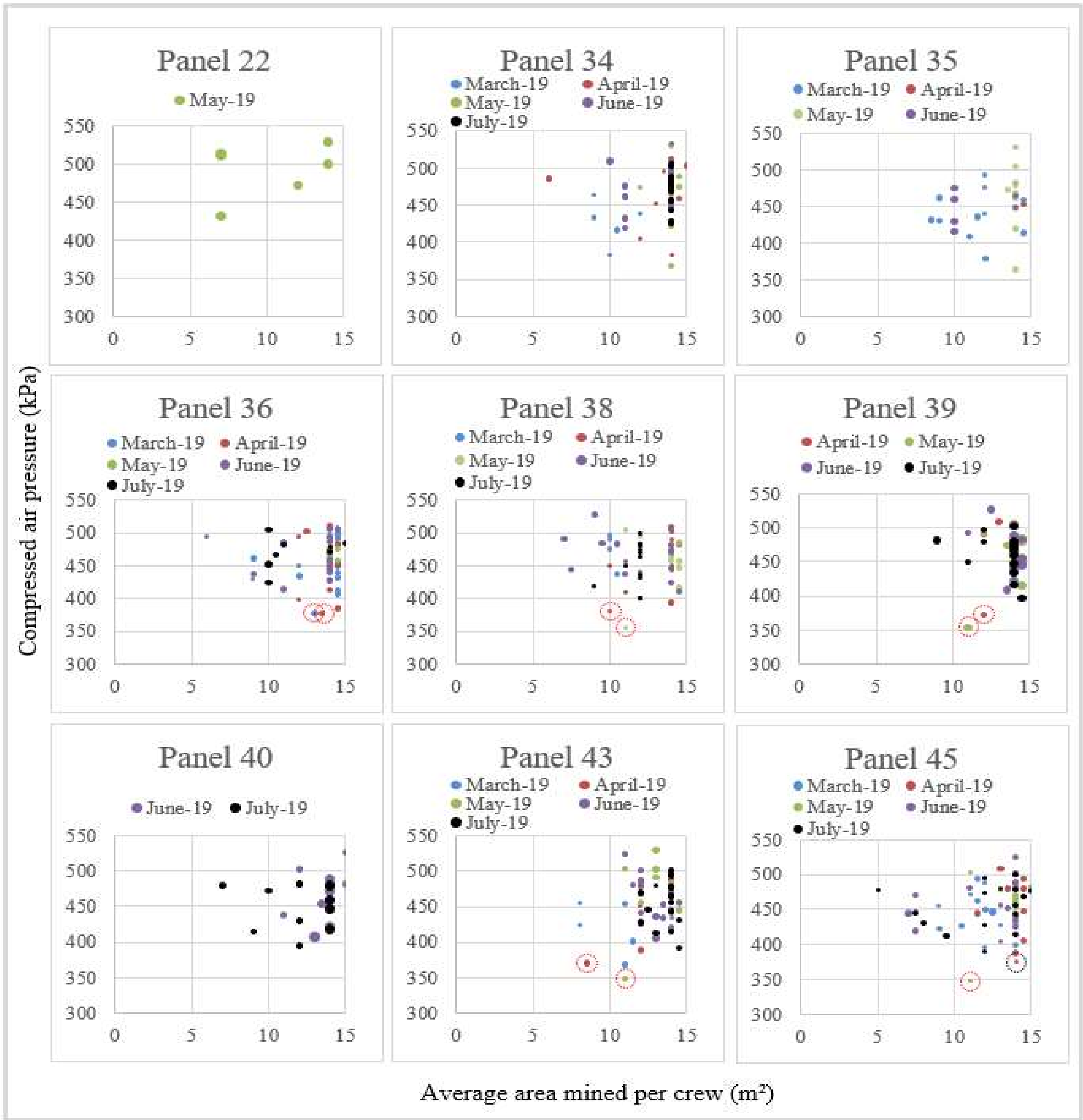

Figure 53: Individual panel pneumatic performance

The days identified in the pneumatic drilling analysis are also shown in Figure 54 where the minimum service delivery pressure at the panels is compared to the number of working crews. Red circles indicate underperforming productivity due to compressed air pressure and black circles indicate fewer crews worked due to compressed air pressure. The size of the dots indicates the number of crews that did not realise any production.

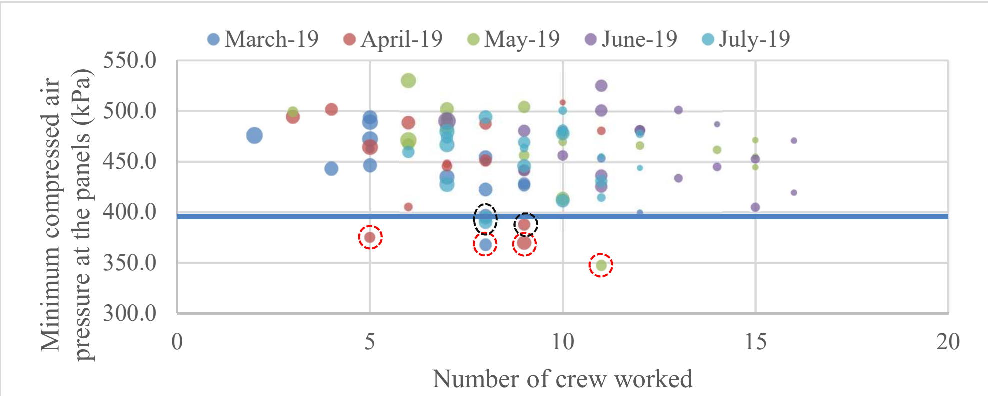

Figure 54: Number of crews worked compared to the compressed air service delivery pressure

The blue line drawn on the graph shows the minimum compressed air pressure required at the panels to minimise the risk of production loss due to compressed air. The minimum required expected compressed air pressure is 50 kPa below the average minimum supplied air pressure.

Production days affected by insufficient compressed air supply for working area "30WUG2" are listed in Table 8 below. On average 30% of production is lost per day due to insufficient compressed air pressure. The working area's production could be improved by 3.33% with better service delivery.

Table 8: Inefficient service delivery incidents for work area "30WUG2"

Inefficient service delivery incidents	Production loss in area mined	Production loss percentage for the production day	Production loss percentage for the monitored time period of five months
6 March	48 m²	30%	0.41%
3 April	28 m²	28%	0.24%
29 April	63 m²	35%	0.54%
30 May	46 m²	26%	0.40%
Fewer crews worked	70 m²	N/A	1.74%
	Total missed production due to inefficient service delivery		**3.33%**

3.4.3. Validation of factors influencing drilling performance

The pneumatic drilling performance graphs in the previous section identified four production days where drilling performance could have been influenced due to insufficient compressed air supply. The days are highlighted in red in Figure 55. The insufficient compressed air service delivery for all four days is due to an over demand in compressed air.

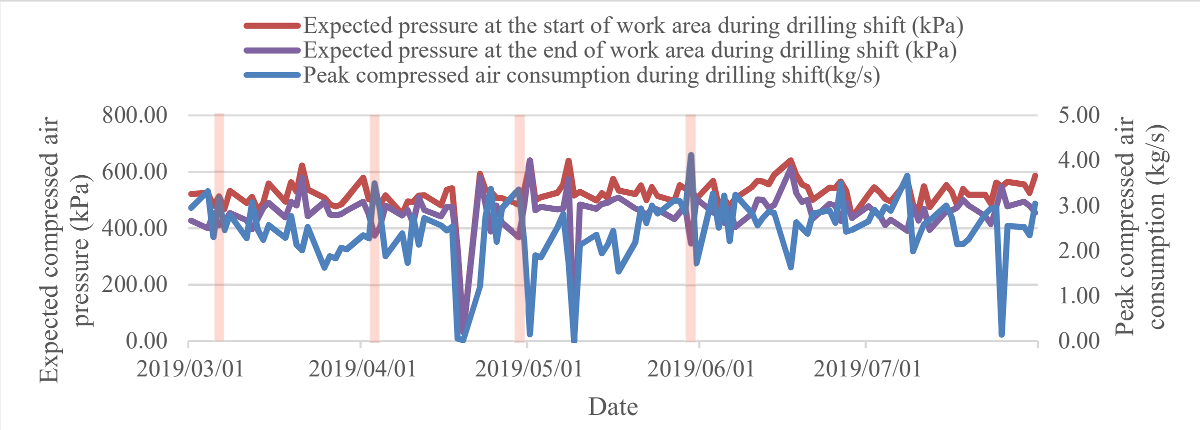

Figure 55: Work area "30WUG2" peak compressed airflow and pressure

Only on 29 April poor compressed air pressure complaints were noted. The reasons for missed blasts on this day identified above as an insufficient service delivery day were inspected to verify if the complaints were valid. It is more convenient for the mining crews to give reasons for not producing than investigating actual causes for production losses.

Improving compressed air service delivery at the working areas will ensure an increase in compressed air demand but will not cause the compressed air pressure to decrease below the minimum required pressure. This will prevent future production loss due to compressed air service delivery.

3.4.4. Determine the cost of lost production

The total identified production loss due to insufficient compressed air supply of working area "30WUG2" was 255 m². The production loss is calculated as a Rand value to show the potential of improved compressed air service delivery.

The basket price and ore grade are available in any mine's mineral resource and mineral reserve statement. The Rand basket price per ounce for the undisclosed mine is R15 389 per ounce at

4.24 grams per ton of ore extracted. The missed production is estimated at a value of R1.8 million for this working area.

3.5. *Case Study C: Level 29 UG2 West*

The identified working area's performance in production and compressed air service delivery was analysed on a selected panel. The effect of compressed air wastage on the drilling performance was also further analysed.

3.5.1. Working area performance analysis

The overall weighted performance analysis rated working area "29WUG2 as the third most likely working area to be affected by an undersupply of compressed air service delivery. The KPI measure that reduced the performance score was the "area mined per working crew" although a large number of crews worked.

Figure 56 compares the production per allocated crews and per working crews. The average area mined per working crew was below 12.6 m² from April to June and only increased in July.

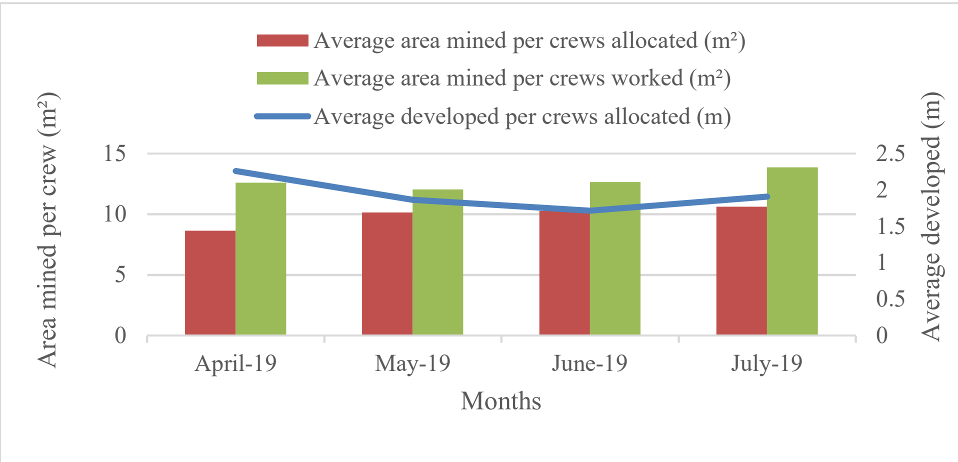

Figure 56: Production per crew worked or allocated

The peak production- and wastage-compressed air usage is plotted together with the total area mined per day in Figure 57. The compressed air wastage reduced from middle May and more production was achieved. The peak production compressed air consumption is more on some production days than others. The peak production compressed air does not correlate directly to production achieved; therefore, further investigation is required.

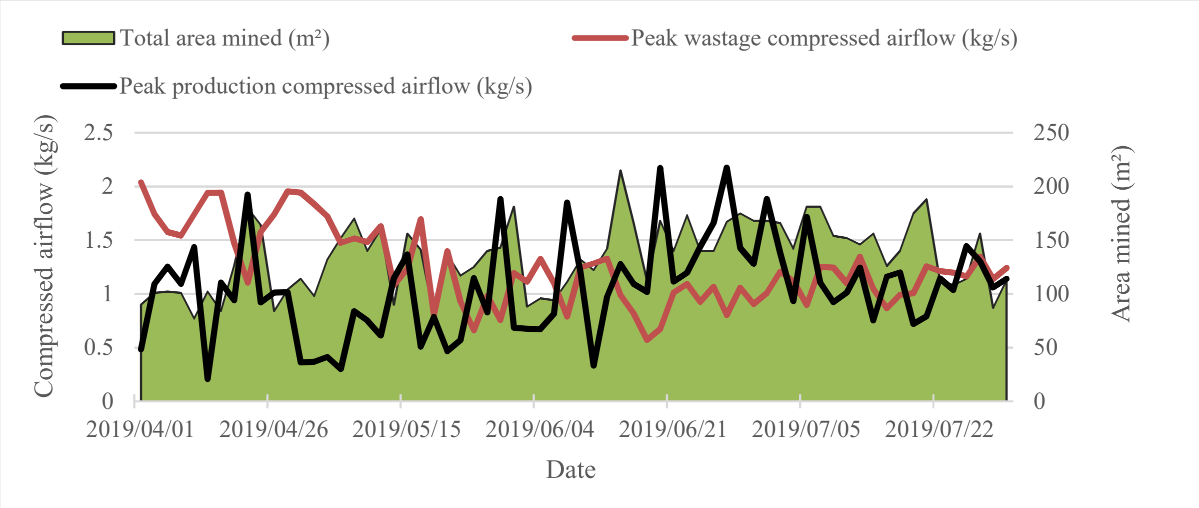

Figure 57: Peak production & wastage compressed airflow compared to production

To determine if the number of crews had an effect on the overall peak compressed air consumption per day, the peak compressed air is plotted against the number of crews that are allocated to a working area in Figure 58. The peak compressed air consumption was the highest during the time that the least number of crews were assigned to the working area.

As the number of crews increased the peak compressed air consumption decreased. From the graph in Figure 58, it is shown that the decrease in wastage compressed air consumption is the reason for the reduction in overall compressed air consumption.

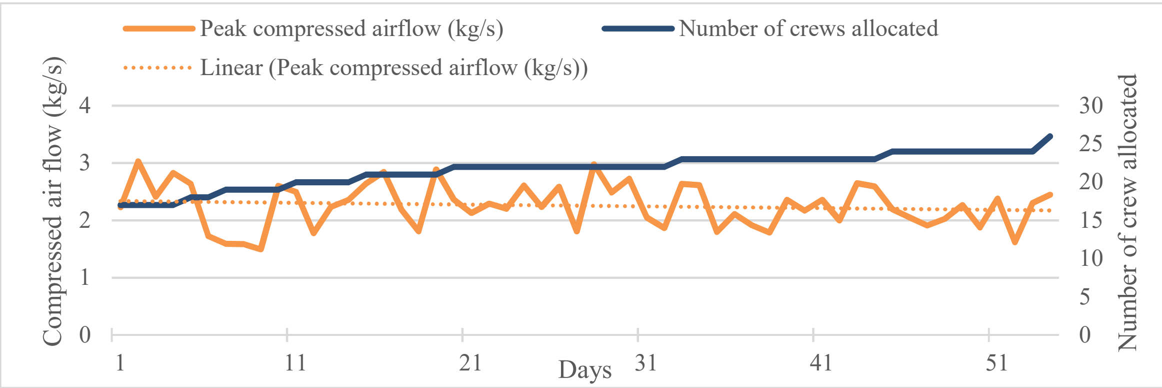

Figure 58: Work area "29WUG2" peak compressed airflow and number of crews allocated (Number of crews sorted from low to high)

With the overall peak compressed air consumption being unstable, it is expected that compressed air service delivery pressure will also be unstable.

The effect of service delivery pressure on the area mined is analysed in Figure 59. This is done by ranking the minimum expected compressed air pressure calculated per active panel from highest to lowest with the corresponding area mined for each day.

As the minimum pressure decreases, there is no correlation in production changes. However, as indicated in the red block on the graph, the production is consistently low as the expected minimum pressure is less than 392 kPa.

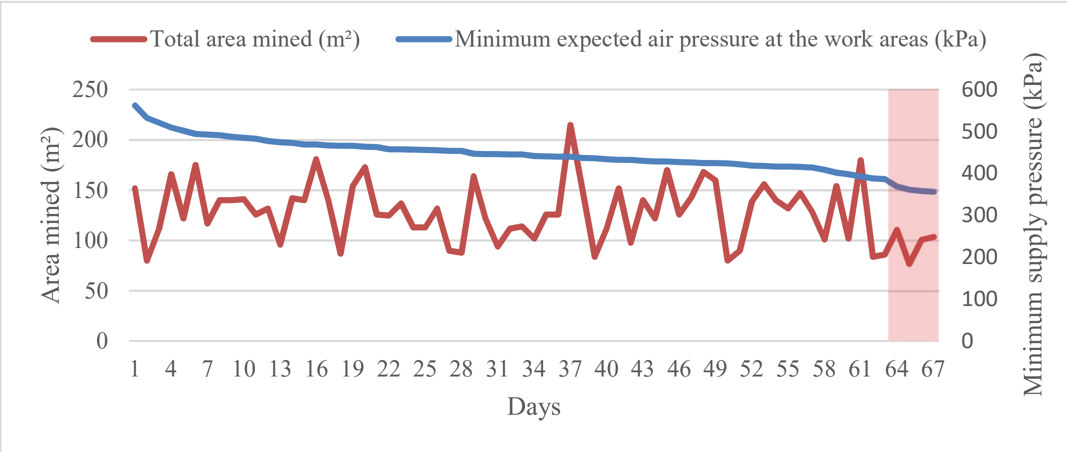

Figure 59: Area mined compared to the expected pressure (Expected pressure sorted from high to low)

From days indicated in the red block, four out of the six days occurred during April, when the compressed air wastage was above average. The pneumatic drilling performance analysis must be done to further investigate the effect of compressed air wastage on production.

3.5.2. Analyse common drilling performance inefficiencies

The average pneumatic drilling performance graph per month is shown in Figure 60 below. The size of the dot indicates the number of crews that worked during the month. The average area mined per working crew was the weakest in May. However, the average supply compressed air pressure to the active panels was higher compared to other months. This could have been due to more crews allocated that affected productivity. The higher the average compressed air pressure the more production crews worked during the month.

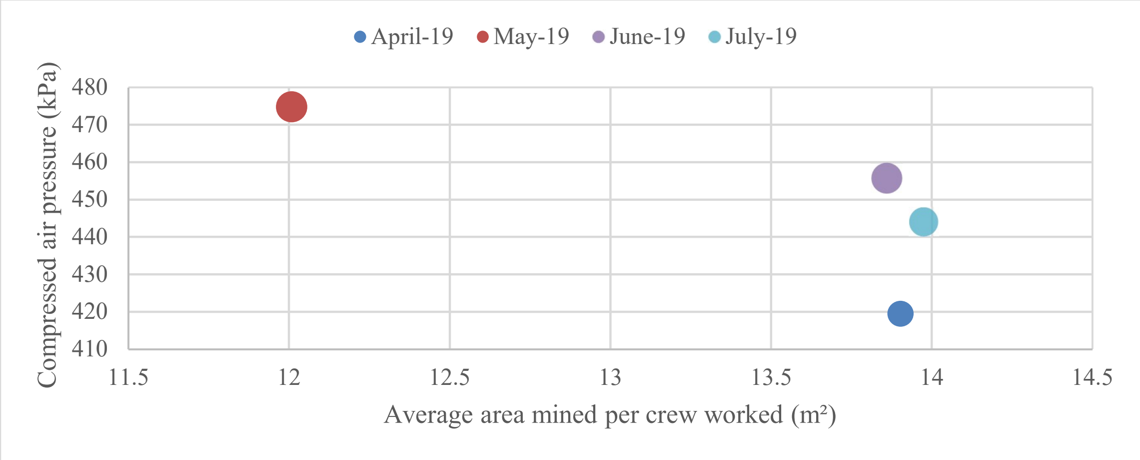

Figure 60:Monthly averaged pneumatic drilling performance

Panel 56 is the panel furthest away from the compressed air supply and is active for the entire investigation period from April to July. The panel furthest away from the compressed air supply is most likely to be affected by insufficient compressed air pressure. The pneumatic drilling performance analysis was done on panel 56.

The average area mined per working crew is compared to the peak supply pressure, shown in Figure 61. The size of the dots on the graph indicates the number of missed blasts. The common drilling performance is the average area mined mostly achieved by production crews. The minimum supply pressure of the common drilling performance is the lowest pressure where full production still could have been achieved. Days with insufficient compressed air service delivery were identified below the common drilling performance, shown in the red block.

Insufficient drilling performance within the same supply pressure range as the common drilling performance is indicated in the orange block. These unproductive days are not due to insufficient compressed air pressure as the expected pressure is the same as the common drilling performance. The underperforming days below the common drilling performance will be investigated separately to determine the reason for low compressed air service delivery.

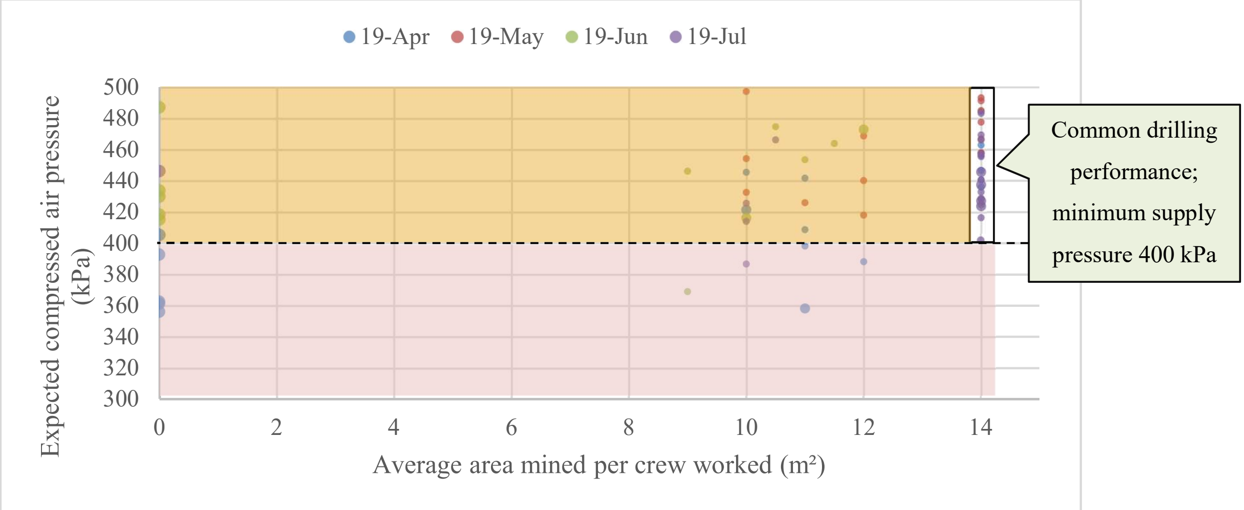

Figure 61: Pneumatic drilling performance for panel 56

Nine unproductive days with insufficient compressed air supply were identified in the pneumatic drilling performance analysis. The reasons for not achieving production are investigated to determine if the reported reason relates to poor compressed air service delivery. If the reason recorded by personnel for not drilling was due to rock drills or airlegs, unproductiveness can be due to insufficient compressed air pressure at the drills. Table 9 shows the reasons for not blasting and the area not mined due to compressed air service delivery.

Table 9: Panel 56's area not mined due to service delivery

Date	Total area mined (m²)	Reported reason for missed blast	Area not mined due to service delivery (m²)
24-Apr	0	Winch cable	0 - Valid reason for not mining
5-Apr	0	Misfire	0 - Valid reason for not mining
10-Apr	0	Rock drill problem	28
29-Apr	0	Winch cable	0 - Valid reason for not mining
6-June	18	-	10
26-July	20	-	8
2-Apr	11	Rock drill problem	17
3-Apr	22	-	6
11-Apr	24	-	0 - Valid reason for not mining
		Total area not mined due to service delivery (m²)	**69**

The panel most affected by compressed air pressure was panel 56. This panel was analysed and the total production due to inadequate compressed air pressure was identified as 69 m². The production for panel 56 could have increased by 4.7% if the compressed air service delivery was adequate.

3.5.3. Validation of drilling performance influencing factors

The identified production loss due to insufficient compressed air pressure was validated. Underperforming days were analysed and compared to other panels' performance. Table 10 below shows the reasons for low service delivery pressure at the drills and the production achieved by the other panels.

Table 10: Inefficient service delivery incidents for panel 56 of work area "29WUG2"

Date	Total area mined (m²)	Expected compressed air pressure (kPa)	Reported reason for missed blast	Reason for insufficient compressed air pressure	Area mined by other panels (m²)	Area not mined due to service delivery (m²)
10-Apr	0	362	Rock drill problem	Supply pressure below 500 kPa	110 - 8/9 crews worked	28
6-June	18	369	-	Supply pressure below 462 kPa	93 – 9/10 crews worked	10
26-July	20	386	-	Supply pressure below 475 kPa	94– 7/11 crews worked	8
2-Apr	11	358	Rock drill problem	Supply pressure below 500 kPa	90 – 8/9 crews worked	17
3-Apr	22	398	-	Increased air demand	80 – 7/9 crews worked	6
			Total area not mined due to service delivery (m²)			**69**

The supply pressure at the start of the level was the main reason for insufficient compressed supply at Panel 56. The total area not mined due to inadequate compressed air delivery for Panel 56 was 69 m² in a four-month period. April was identified as the month with the highest compressed air consumption, and the total area not mined due to compressed air was 51 m² in April alone. June and July missed an area of 10 m² and 8 m² respectively.

3.5.4. Determine the cost of lost production

Panel 56 was analysed to identify and validate production loss due to insufficient compressed air pressure at the panel. The area not mined due to compressed air service delivery is 69 m² in a period of four months.

The basket price and ore grade is available in any mine's mineral resource and mineral reserve statement. The Rand basket price per ounce for the undisclosed mine is R15 389 per ounce at 4.24 grams per ton of ore extracted.

The missed production is thus estimated at a value of R0.5 million for Panel 56 during April. An additional R164 000 is lost in achieved production during June and July.

3.6. Results and improvements

This chapter focused on applying the developed methodology to an actual mine. The developed methodology was used to identify compressed air inefficiencies and to analyse the pneumatic drilling performance of production areas. The pneumatic drilling performance was used to determine the effect of insufficient compressed air service delivery on production outputs.

The literature discussed in Section 1.4.3 showed that there is a direct correlation between compressed air supply pressure and a pneumatic rock drill's rate of penetration. However, all these studies were lab experiments and not measured in an actual mining environment. The human factor and external factors involved need to be taken into consideration when analysing the effect of insufficient compressed air service delivery pressure at the drills.

The working areas to be analysed were scored according to KPIs developed to determine the compressed air efficiency, the drilling performance and the reported missed blasts due to compressed air. The three working areas most likely to be affected by insufficient compressed air service delivery were further analysed.

The pneumatic drilling performance analysis compared the expected pressure at the working area with productivity and the number of crews worked. The common drilling performance of every panel was determined and used to identify underperforming production outputs due to insufficient compressed air.

The results proved the following:

- Case study A, B and C identified production loss due to inadequate compressed air pressure at the working areas. Inadequate compressed air pressure is due to an over-demand in the working area or of a decrease in supply pressure.

- Developed KPIs can be used to holistically monitor work areas and determine potential production loss due to insufficient compressed air service delivery.
- Production crews can only mine the full face length of a working area. Increased compressed air pressure in working areas with sufficient service delivery will only decrease the time spent drilling and will not increase production.
- Compressed air service delivery of a working area is dependent on the performance of production crews in different working areas. A compressed air network is put under pressure when the demand for air is above average. Typically a high demand will occur when mining crews start late or try to finish before shift end or month end when production targets need to be met.
- As more production crew are assigned to a working area the compressed air wastage reduces. Miners manage compressed air wastage in this instance as higher demands and lower pressures are experienced in working areas. Thus, more compressed air is used for production.

From the three case studies evaluated, it is clear that compressed air and the management thereof correlates to the area mined. This is only true if compressed air pressure drops below the common drilling performance of the working area. Less production was lost due to insufficient compressed air service delivery when compressed air wastage was decreased. Compressed air is mostly managed by miners and efficiency of the compressed air service delivery will only be increased if this benefits them, e.g. production targets for bonuses or extended working hours.

The percentage production loss caused by inadequate compressed air supply to the working areas analysed in case study A, B and C is 1.27%, 3.33% and 4.7% respectively.

All the production loss due to insufficient compressed air pressure was validated. The total production lost was calculated as R3.5 million in a five-month period for the three most inefficient production areas.

3.7. Limitations and constraints

Limitations and constraints discovered during the implementation of the developed methodology are the following:

Limited knowledge of crews' actions

Mining personnel record reasons for not blasting. However, tasks during the shift while no blasting is taking place are not recorded. The crews may be drilling but do not complete the drilling face. Therefore they do not blast and no production is recorded. The calculated expected compressed air pressure at every panel will thus not correlate with the production recorded. The crews may also have done other necessary work during these unproductive shifts that are not recorded, e.g. ensuring safety, repairing infrastructure.

A more detailed record of activities during unproductive shifts needs to be maintained in order for compressed air service delivery to be adequately evaluated.

Compressed airflow assumptions

The compressed air pipe network divides to multiple working areas after being measured by the installed flow meters. Thus, the compressed airflow dedicated to a working area is not measured due to the flow measured before the split in the pipe network.

The methodology assumes that compressed airflow is dedicated to a working area depending on the number of crews allocated to that working area. As the measurement of the flow is not done in each working area, the assumption cannot be confirmed.

Calculated expected pressure at the working areas

The compressed air pressure drop from the pressure transmitter to the working areas is calculated with various variables based on assumptions and measurements. The change in the expected pressure at the working area can indicate insufficient compressed air as it is compared to production. A more accurate conclusion can be reached by this study if actual pressure is measured in every working area.

3.8. Conclusion

The objectives of this study were addressed by identifying inefficient working areas, analysing the common drilling performance of every working area and determining the production loss caused by insufficient compressed air supply. The total production lost was calculated to be R3.5 million in a five-month period for the three most inefficient production areas.

CHAPTER 4. CONCLUSION & RECOMMENDATIONS

4.1. Summary

South African deep-level mines were under financial pressure in the last years. Problem areas previously mentioned are that deep-level mining's production trends declined, the commodity price decreased, labour costs rose and operational cost increased. South African mines are also limited by underdeveloped infrastructure in comparison with available technologies. One such outdated technology in use in most of the South African mines are pneumatic hand-held rock drills. Optimising outdated infrastructure is necessary for South African mines to remain profitable and competitive.

The pneumatic rock drilling is critical infrastructure as it can affect the overall production performance of a mine. Studies determined the effect of rock characteristics, drill bits and operational variables on the rate of rock drills' penetration used in the mining industry. Previous studies were analysed to identify possible work performed on the optimisation of drilling performance; compressed air insufficiencies were identified in these studies.

The need for the study to develop a practical method to locate inefficient compressed air supply that affects production output for every drilling area was identified. The study's objectives were:

- Develop daily KPIs to monitor working areas' production outputs and compressed air service delivery.
- Develop a methodology to analyse pneumatic drilling performance, to identify possible compressed air service delivery inefficiencies that affect production.
- Verify the methodology by validating the results in a case study.
- Determine the percentage production lost due to insufficient compressed air service delivery.

The methodology developed focused on holistically overviewing the mine's compressed air service delivery and production performance. Ineffective production areas affected by insufficient compressed air service delivery were identified and further analysed to determine the effect on production.

The effect of low compressed air service delivery pressure was analysed by comparing calculated expected pressure at the working area with the production achieved for every active panel per day. If insufficient compressed air service delivery was identified, the compressed air network was analysed to validate whether compressed air service delivery could be influencing the drilling performance.

The methodology was implemented on Mine A over a five-month period, analysing all the production and compressed air service delivery data to identify production lost due to insufficient compressed air service delivery. The production and compressed air KPIs were weighed against each other to identify the three working areas most likely affected by insufficient compressed air service delivery. These three working areas were analysed in case studies A, B and C.

In case studies, the pneumatic drilling performance for every working area was calculated and compared to identify production affected by compressed air. The pneumatic drilling performance is the expected compressed air supply pressure at the drills compared to the production achieved. The common drilling performances were identified for every working area to identify production loss due to compressed air. The reasons for not blasting were also analysed and validated when determining lost production due to insufficient compressed air service delivery.

The production lost identified as a result of insufficient compressed air service delivery at the working areas is summarised in Table 11.

From the results in Table 11 it is evident that a substantial amount of production is lost due to insufficient compressed air supply. Reducing the amount of compressed air wastage will reduce the loss of production due to insufficient compressed air service delivery.

Table 11: Production lost identified as a result of insufficient compressed air service delivery

Case study	Work area	Area not mined (m^2)	Percentage of the total mined (%)	Lost production cost
Case study A	31WUG2	142	1.27	R1 million
Case study B	30WUG2	255	3.33	R1.8 million
Case study C	29WUG2 only Panel 56	69	4.5	R0.66 million

The objectives of this study as previously mentioned were addressed by developing a methodology to holistically overview the production and compressed air performance of a mine and to analyse the individual production areas. The study was thus successful and can be implemented on other mines to determine the effect of insufficient compressed air pressure on production outputs.

4.2. Recommendations

The recommendations for future studies are as follows:

- Modernised drills equipped with sensors to measure supply pressure, thrust force, running times and penetration rate will give a more accurate analysis of the effect of insufficient compressed air service delivery in working areas.
- A more comprehensive compressed air network monitoring system will add value to the study. A feasibility study for installing pressure sensors at the haulage ends or in working areas needs to be conducted. A more accurate representation of the drills' pressure will be achieved.
- A correlation between compressed air consumption, crews and production can be used to determine the optimal number of crews per section/working area.
- The developed study should also be done on water service delivery to drills. The mismanagement of water could affect the drilling performance of mining crews.

- The study showed that labour issues for example sick leave, late arrival or absence from work, are the second largest reason for production loss after mining conditions. Future studies can investigate optimising human resources.
- The feasibility of combining new drilling technologies with pneumatic drilling to ensure better drilling performance should be investigated where compressed air service delivery is insufficient. This will ensure maximum benefit with new drilling technologies.
- Better management of compressed air networks should be implemented. Simulations should be used to determine the effect on service delivery before any crews are moved, added, or working areas' compressed air supply is opened or closed. Continuous analytical studies are needed to improve drilling pressure and decrease production loss due to compressed air.
- The compressors' setpoints should be adjusted according to predicted increases in compressed air demand when more production is expected from mining crews e.g. month-end when production targets need to be met.
- Compressed air delivery for every working area controlled by pressure setpoints should be investigated. This method will ensure the supply pressure at every working area is equal. The pressure will also be constant every day and ensure drilling conditions stay unchanged.

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APPENDIX A: PIPE SURFACE ROUGHNESS

The surface roughness values recommended for different pipe materials are listed in Table 12.

Table 12: Recommended roughness values for commercial ducts [44]

Material	**Condition**	**Surface roughness (mm)**	**Uncertainty (%)**
Steel	Sheet metal, new	0.05	±60
	Stainless, new	0.002	±50
	Commercial, new	0.046	±30
	Riveted	3.0	±70
	Rusted	2.0	±50
Iron	Cast, new	0.26	±50
	Wrought, new	0.046	±20
	Galvanized, new	0.15	±40
	Asphalted cast	0.12	±50
Brass	Drawn, new	0.002	±50
Plastic	Drawn, tubing	0.0015	±60

APPENDIX B: FLOW METER VERIFICATION

The differential pressure flow meters of level 29-31 were verified using method three, developed in section 2.2.2. The results proved that the flow meters were calibrated correctly as the change in flow correlates with the upstream flow meter. The change in flow difference between the upstream flow meter and level 29 to 31 is 19%, 12%, and 10% respectively at maximum flow. Figure 62 to 64 shows the change in flow in the downstream levels and the upstream flow meter as the individual levels are closed.

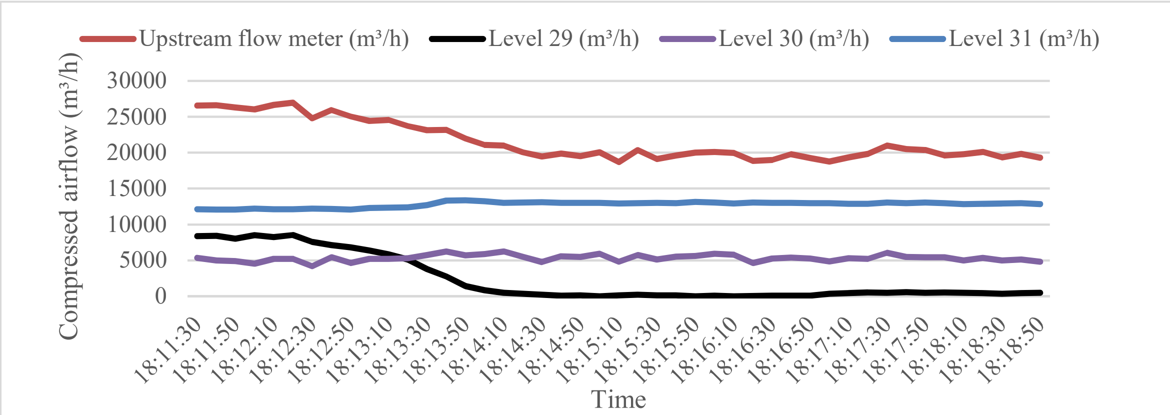

Figure 62: Change in flow verification level 29

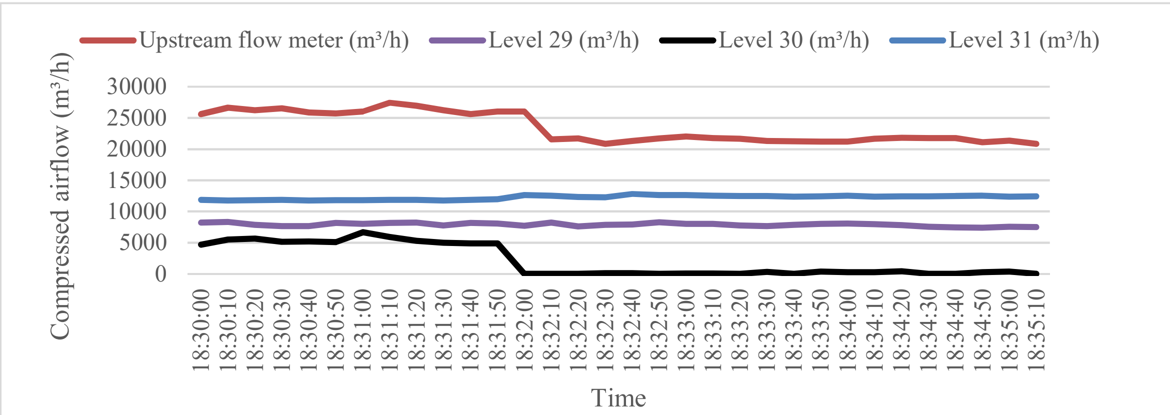

Figure 63: Change in flow verification level 30

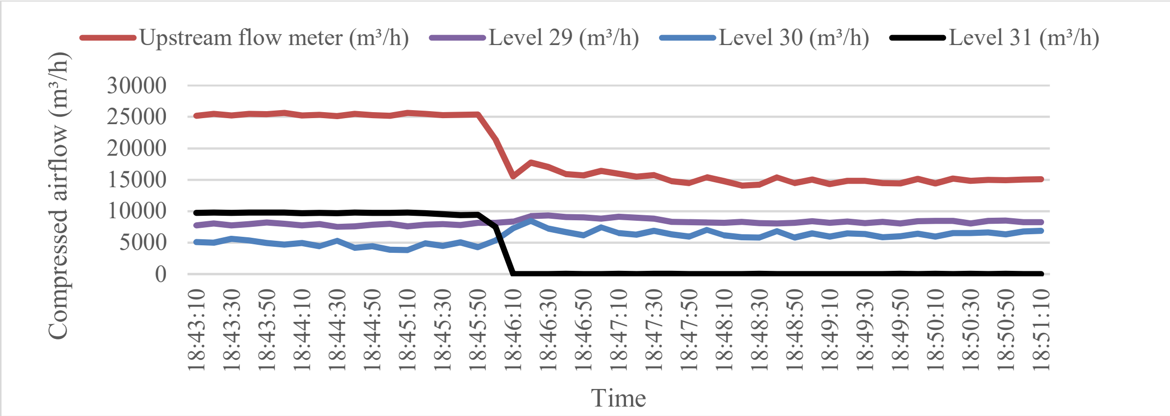

Figure 64: Change in flow verification level 31