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

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

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November 2017

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ACKNOWLEDGEMENTS

As the author of this study I would like to express my sincere gratitude to the following parties for their assistance and support during the completion of this study:

- First and foremost, I would like to give thanks to my Father, Lord and Saviour. I am truly grateful for the opportunity You have given me, Father, to complete this study and for Your continuous love and mercy. Without Your guidance, this would surely not have been possible.
- I would like to thank prof. Eddie Matthews and prof. Marius Kleingeld for the unique opportunity of completing my post-graduate studies, while continuously developing as an engineer and person. Thank you to Enermanage (Pty) Ltd and its sister companies for financial support to complete this study.
- I would like to thank my study leader, Dr Johann van Rensburg, for his guidance and advice. I truly value your open-door policy and willingness to listen.
- A thank you to my study mentor, Dr Johan Bredenkamp, for his absolute diligence with regards to advising and assisting me throughout this study. Your inputs were highly valued and it was an absolute privilege to work under your guidance throughout the course of this study.
- I would like to thank my parents, Dirk and Marié Nell, for supporting me throughout this study. I am truly grateful for all the love and support in assisting me to reach my goals in life.
- Thank you to my sister and brother-in-law, Madri and Hilco Henning, for keeping me positive and focused and knowing when to completely distract me for my own benefit. Your love and support is much appreciated.
- I would like to thank my friends for their patience and understanding. I would not have been able to complete this study without your continuous support and motivation.
- To all the mining personnel who have helped me countlessly. I cannot thank you enough for investing in me as a person and as an engineer. Thank you for always being willing to teach me and develop my engineering capabilities, despite your busy work schedules.
- I would also like to thank my co-workers for their valued inputs and time, especially Mr Pieter Peach and Dr Philip Maré for their guidance and sacrifice of personal time to assist me in this study. I am truly grateful.
- Finally, I would like to give a special thanks to my wife, Kristy Nell. Your support throughout this study was of immeasurable value. Thank you for always making time to listen and being willing to assist in whatever way you can. I hope I can be of such assistance in your future ventures.

ABSTRACT

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

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Degree: Master of Engineering (Mechanical)

Keywords: Deep-level gold mining, compressed air network inefficiencies, drill rock penetration rate, production optimisation, limited infrastructure

The global gold mining industry is currently on a growing trend, while the local gold mining industry in South Africa has been experiencing a decline in gold production. This is due to a unique set of production challenges faced by this industry of which production cost increases are one of the major concerns. This encourages deep-level mines to implement cost saving initiatives in the form of effectively using existing infrastructure.

One such area offering large potential for optimisation is addressing deep-level gold mine compressed air network inefficiencies. These inefficiencies include low service delivery pressure supplied to pneumatically operated drill rigs in the working areas. Lower service delivery results in an increase in drilling time and an increase in compressed air usage which contributes to operational costs. Through addressing these inefficiencies an increase in rock penetration rate can be achieved on the pneumatically operated drill rigs, leading to reduced drilling times.

A need was evident to optimise these compressed air networks with the aim of improving the total amount of drilling time. A methodology was developed with the aim to identify, evaluate and address these compressed air network inefficiencies. This methodology incorporated root cause analysis as well as guidelines for effective boundary selection procedures.

An investigation performed on Mine A indicated that a specific compressed air network inefficiency contributed to a pressure drop of approximately 87 kPa during peak drilling periods. The pressure drop was measured from the compressed air supply to the working areas of the main production levels. The developed methodology was applied and a solution was developed to address this inefficiency. It was simulated that replacing specific undersized pipe sections with the correct sized pipes would reduce the pressure drop by at least 45 kPa during daily operation.

The solution was implemented on the compressed air network of Mine A. Nearly 400 m of incorrectly sized pipe sections and line restrictions were replaced with correctly sized pipe sections. This resulted in a minimum measured pressure drop of 14 kPa during off-peak drilling periods and decreased the peak drilling pressure drop to approximately 25 kPa. Validating these results with the predictions through simulation yielded an error of less than 2%.

The improved service delivery pressure was used to calculate the improvement in the drilling rate of rock penetration. The selected model indicated a 20% increase in drilling rate because of the increase in supply pressure. This improved penetration rate was translated into a production increase of approximately R 11-million per annum. This resulted in a potential financial benefit of 3% increase in terms of production profit for the presented case study.

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LIST OF ABBREVIATIONS

Abbreviation	Description
GDP	Gross Domestic Product
KPI	Key Performance Indicator
PTB	Process Flow Toolbox
RAW	Return Air Way
RCA	Root Cause Analysis
RPM	Revolutions Per Minute
RPR	Rock Penetration Rate
SA	South Africa
SCADA	Supervisory Control And Data Acquisition
STP	Standard Temperature and Pressure
UCS	Unconfined Compressive Strength
WBS	Work Breakdown Structures

LIST OF SYMBOLS

Symbol	Description	Units
A	Minimum cross-sectional area	m^2
C	Plant capacity	cfm
$C_{discharge}$	Discharge coefficient	-
C_p	Specific heat capacity of the compressed air	$kJ/kg{\cdot}K$
D	Hydraulic pipe diameter	m
d	Pipe inside diameter	m
$\mathcal{E}$	Surface roughness	mm
f	Friction coefficient	-
g	Gravitational Acceleration (9.81)	m/s^2
hf	Friction head loss	m
Δh_{ls}	Hydraulic loss	m
h_m	Minor head loss	m
k	Specific heat ratio of the compressed air (1.4)	$kJ/kg{\cdot}K$
K_m	Minor loss coefficient	-
L	Pipe length	m
$\dot{m}_{air}$	Mass flow rate of the air	kg/s
n	Polytropic compression exponent	-
η_{comp}	Compressor efficiency	-
η_{motor}	Motor efficiency	-
p_1	Initial pressure	kPa
p_2	Final pressure	kPa
p_a	Atmospheric pressure	kPa
p_c	Compressed air pressure	kPa
P_{line}	Pressure in the compressed air line	kPa
Q	Flow through pipe	m^3/s
Q_{Leak}	Amount of air lost through leaks	m^3/s
R	Gas constant for air (0.287)	$kJ/kg{\cdot}K$
ROP	Rate of penetration	mm/s
Re	Reynolds number	-
RPM	Revolutions per minute	rev/min
Tonnes	Short tonnes of ore mined daily	*tonnes*
t	Time	s
T	Atmospheric temperature of air	K
T_{line}	Temperature in the compressed air line	K

V	Cross sectional fluid velocity	m/s
v	Kinematic viscosity	m^2/s
v_1	Initial fluid velocity	m/s
V_a	Free air volume	m^3
V_c	Compressed air volume	m^3
$w_{comp,in}$	Work required compressing fluid	kJ/kg
Z_1	Initial altitude	m
Z_2	Final altitude	m
μ	Dynamic viscosity	Ns/m^2
ρ	Fluid density	kg/m^3

GLOSSARY

"Air wolf"	Employee dedicated for leak detection in a compressed air network
"Apples with apples"	Ensuring that comparable parameters are evaluated with one another
"Baseline"	Data reference point used for future comparison
"Blasting"	Process of using explosives to break large rock bodies into smaller pieces for excavation
"Centralised blasting"	System ensuring blasting commences in a safe and controlled manner through initiating blasts from a central source simultaneously
"Centre gully"	Place where all the blasted rock is transported to from the stope face
"Cleaning/Sweeping"	Process of collecting all the blasted rock from the stopes and loading it into the hoppers
"Compressor house"	Building containing all the compressors and compressor auxiliaries
"Cross -cut"	Travel way connecting stope areas with haulages
"Energy intensive"	Process requiring a significant amount of energy
"Gold standard"	Previous standard used to quantify a currency's value
"Mine life cycle"	Period extending from initial exploration to rehabilitation of a mine
"Mechanised mining"	Use of specific machinery for mining activities
"Mining modernisation"	Process of implementing technological advancements in the mining industry

"Narrow reef"	Ore deposit with a narrow distribution range, usually mined through conventional mining techniques
"Off-peak drilling period"	Periods excluding mine drilling periods
"Operational costs"	Cost inquired for production purposes
"Ore pass"	Transporting tunnel for material from one level to another
"Ore Reserve"	Ore deposits which can economically and legally be extracted from the earth
"Peak drilling period"	Periods pertaining to mine drilling time
"Raise"	Incline development at the stope
"Rock face"	Furthest point of development/mining which is drilled and blasted
"Rock penetration rate"	Tempo at which drills penetrate the rock face
"Root cause analysis"	Analysis techniques used to identify the root problem
"Service delivery"	Refers to principles and standards supplied for production purposes
"Skip"	Large container used to hoist the blasted rock to surface
"Slinging"	Process of lowering equipment/ materials down the mine
"Stope"	Mining site containing the rock face
"Synergy"	Process of combining different process to yield a larger combined benefit than could be obtained separately
"Tramming"	Process of transporting the blasted ore from the mining site to the central ore passes
"Validation"	Process used to ensure the obtained results accurately address the problem statement

"Verification"	Process of ensuring the developed solution strategy is accurate and can be used
"Winze"	Decline development in the stopes

1. INTRODUCTION

1.1. South African gold mining

1.1.1 Value and importance of gold

Gold mining is an important part of the global mining sector due to the immense value it contributes. Historically, gold played a significant role in defining the value of a country's currency, which is known as the "gold standard". Nowadays, gold is not directly coupled to a country's currency, but still influences it greatly, especially that of active gold exporting countries. [1]

In times of financial uncertainty, gold is used to protect a country's currency due to its value and the fact that it cannot be diminished as in the case of currency. Countries typically invest in gold during tough economic times due to its increasing value despite economic challenges. This is known as hedging and serves as an excellent method to secure funds for national as well as private investment portfolios [1].

Gold was first discovered in South Africa in 1886 on the Langlaagte farm, presently known as Johannesburg, Gauteng [2]. For the financial year of 2016, the gold mining industry in SA contributed 4.4% to the total global gold production, resulting in R28 billion in employee earnings [3]. Since its discovery it has led to the development of a vast mining industry [4].

1.1.2 Production trends

For more than the last four decades the South African gold mining sector faced numerous challenges in terms of its production output. Figure 1-1 illustrates the declining gold mining production trend for the past 13 years.

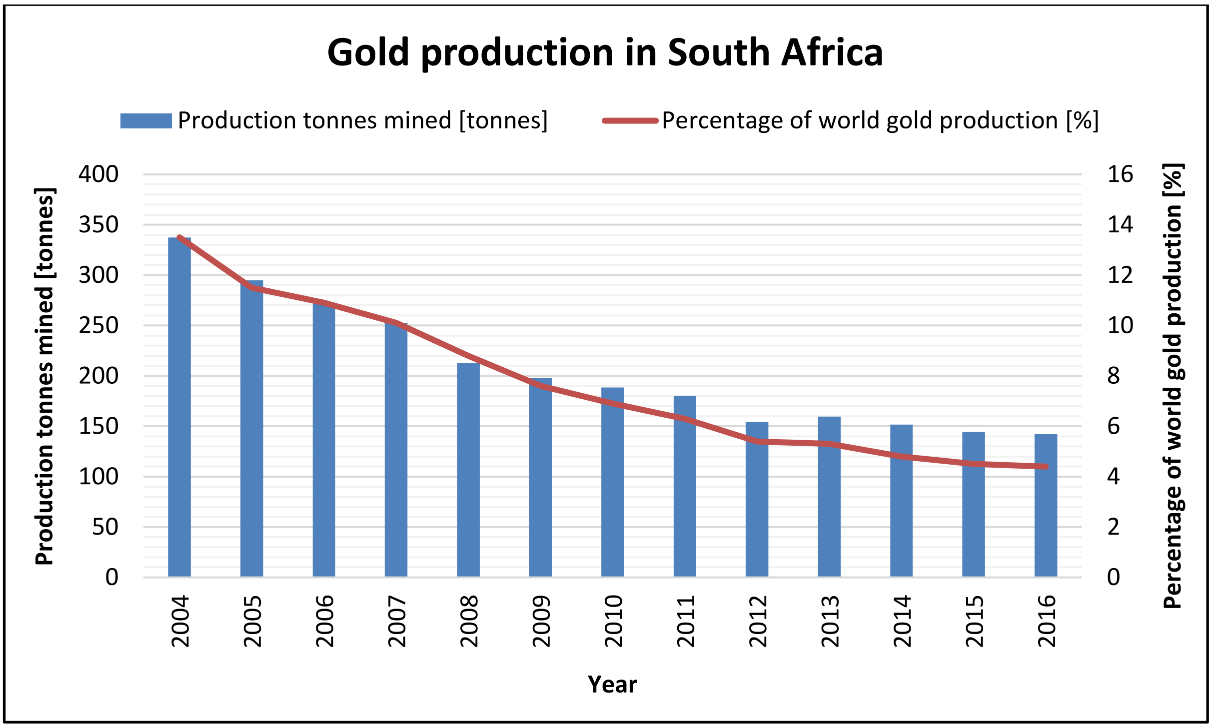

Figure 1-1: Gold production in South Africa [3]

The South African gold mining, which was once the leading global gold producer from as early as 1970 (1000 tonnes a year) to 2007, has dropped significantly to sixth place in 2016 , as shown in Figure 1-2 [5], [6], [7].

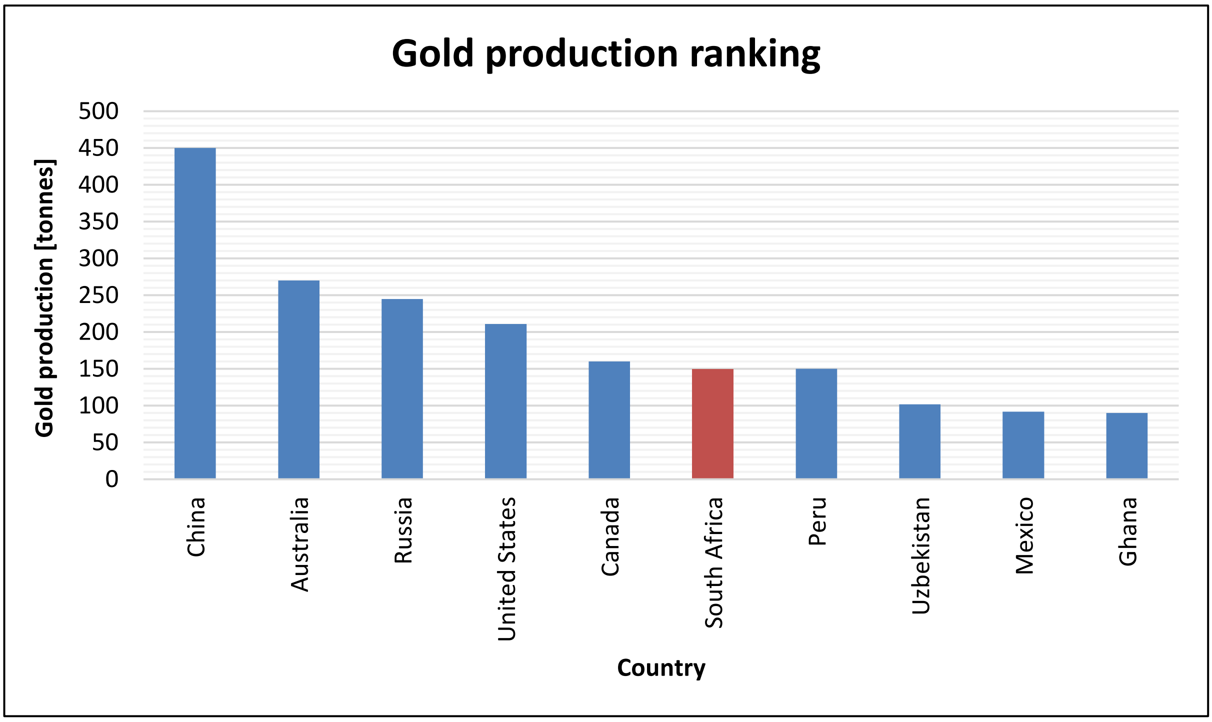

Figure 1-2: Gold production ranking by country [7]

This decreased ranking highlights the fact that the South African gold mining industry is under severe pressure. On the contrary, Figure 1-3 illustrates the production growth in the global gold mining sector from 2004 to 2016 along with the rise and fall in gold price. It is clear that a positive growth in the global gold mining industry exists with the exemption of the financial crisis in 2008. [8]

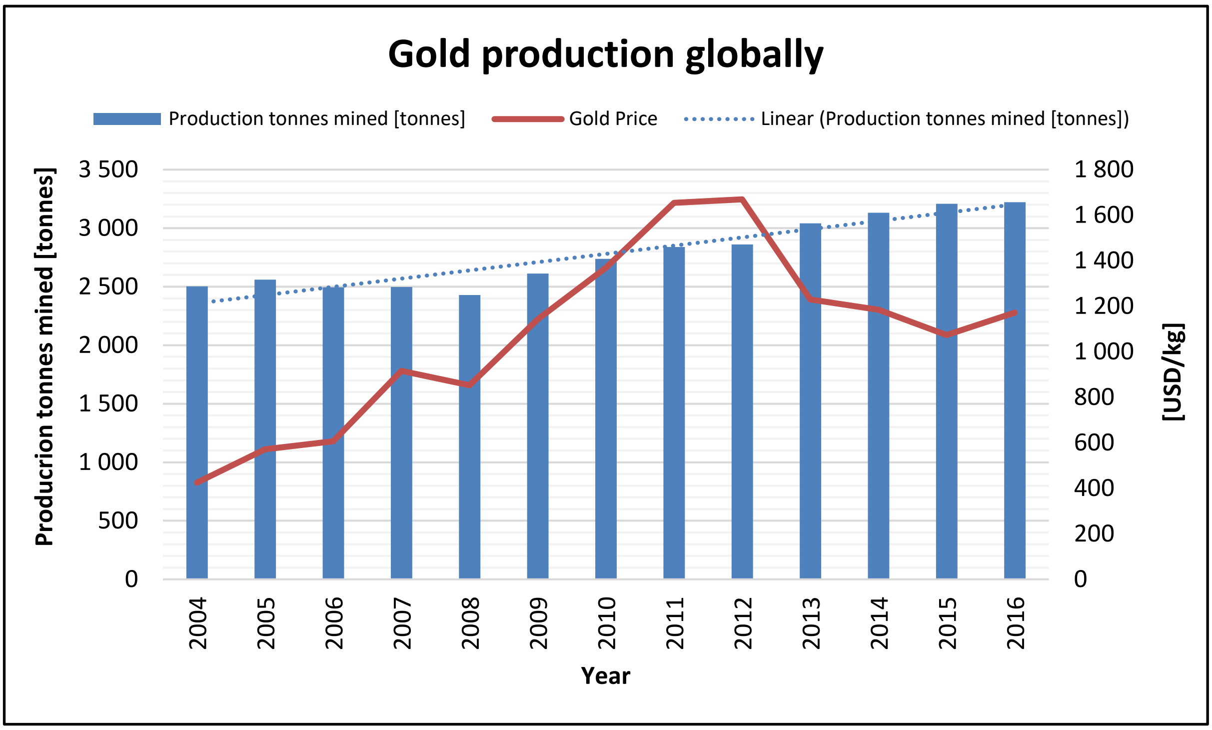

Figure 1-3: Gold production globally [8]

With the global gold production trends increasing while the SA gold production trends are decreasing, one might draw the conclusion that gold ore deposits in SA are nearing exhaustion. The next section elaborated on SA's current gold reserves.

1.1.3 Gold reserves

Gold ore reserves refer to ore deposits which can both economically and legally be extracted from the earth. The global gold reserve ranking for the top ten countries are shown in Figure 1-4.

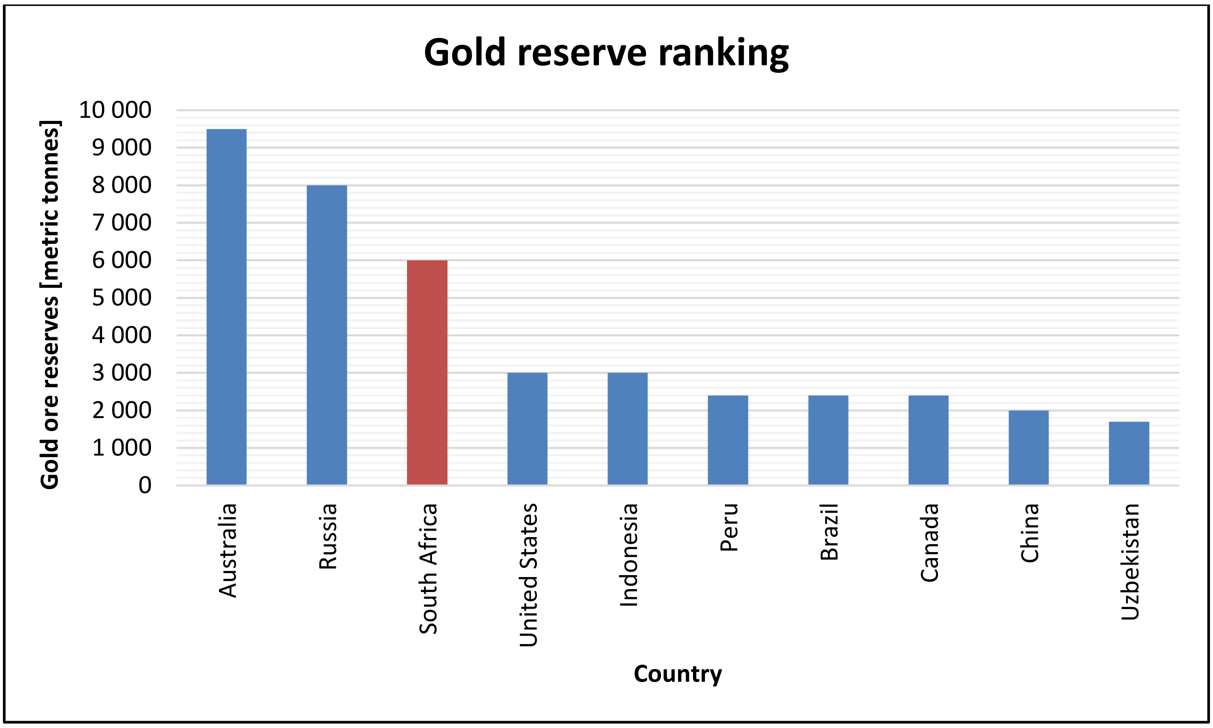

Figure 1-4: Gold reserve ranking by country [9]

When taking into account that SA still holds the number three spot in gold reserves (as shown in Figure 1-4), the potential for SA's gold mining industry to reclaim the top gold production spot becomes evident. Countries such as Australia and Russia support this theory due to both ranking within the top 3 countries for gold production tonnes as well as gold reserves.

From the previously discussed sections, it is strange to find the South African gold mining industry on a downwards production trend when the country holds the third highest ranking in gold reserves. This indicates that other challenges must be present. The next section will focus on the current gold mining climate in SA and highlight the main challenges that the mining companies, which are actively involved, must face.

1.1.4 Challenges faced in the South African gold mining industry

The decline in production tonnes as shown in the previous section is primarily ascribed to the ever-increasing production costs faced by South African gold mining companies [10]. These production cost increases can be mainly divided into the following categories [10], [11]:

- Electricity costs
- Labour costs
- Infrastructure limitations

Gold mining companies in SA have been directed to a more aggressive approach to reducing production costs while retaining maximum profit margins. The above-mentioned challenges are discussed in more detail in the following sections.

Electrical costs

When comparing the electricity usage of various mining industries, it was found that the gold mining sector is responsible for 47% of the total electricity usage by the mining industry. Platinum mining accounts for 33% and the residue of all other mining sectors are responsible for the remaining 20% [12]. It is clear that the gold mining sector is the more energy intensive when compared with other mining sectors.

Deep-level gold mining is an electrical energy intensive industry due to large amounts of ground that needs to be excavated, blasted, transported and processed from depths of up to 4 kilometres [13]. Effective use of electrical energy is therefore crucial. Figure 1-5 depicts the various systems on gold mines and their contribution to the total electrical energy consumption.

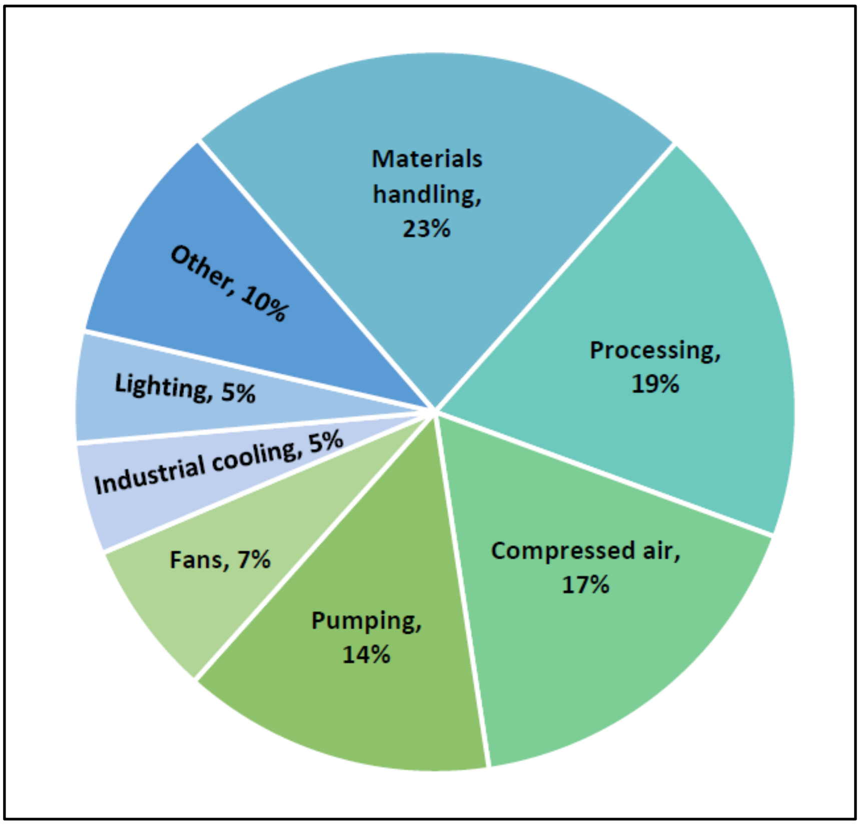

Figure 1-5: Electrical energy consumption breakdown of deep-level gold mines [12]

Figure 1-5 indicates that one of the largest electricity consumers on a gold mine is compressed air. Although this system is outranked by processing and material handling, it should be noted that the latter both include numerous processes.

The mining sector is currently experiencing steep electricity price increases. Due to the energy-intensive processes of the gold mining industry, this electricity price increase greatly impacts the production costs involved. Figure 1-6 illustrates what percentage of the contributed gross domestic product (GDP) from the mining sector is spent on electricity purchases.

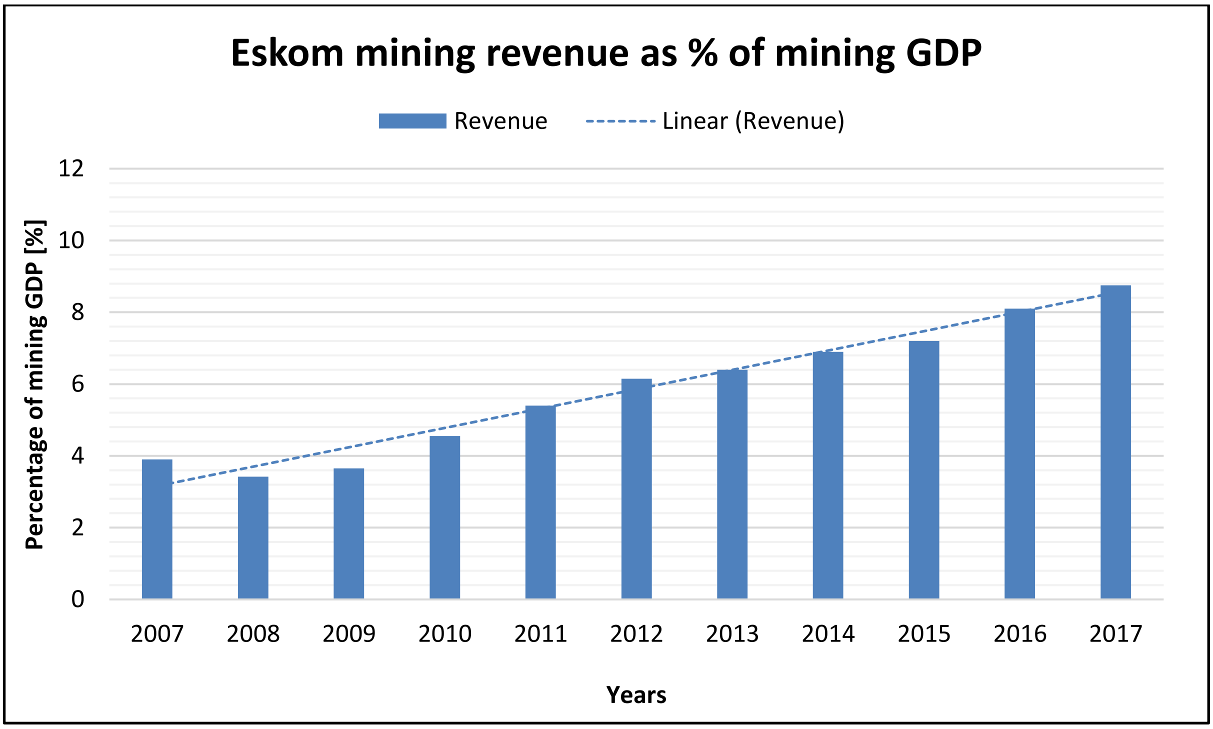

Figure 1-6: Eskom mining revenue as % of mining GDP [14]

The drive behind implementing energy efficiency initiatives have increased for the gold mining industry in SA. Focus has been placed on reducing the energy input through optimising current infrastructure and processes. These initiatives should be further developed through ensuring that electrical energy optimisation strategies primarily focus on the larger electricity consumers such as compressed air systems. [15]

Increase in electricity cost directly influences mining productivity due to the increase in operational costs [15]. Increased productivity strategies will need to be investigated to counter the effect of ever-increasing electricity costs.

Labour costs

The political drive for social and racial equality had, and still has, a significant impact on the South African gold mining industry Frequent union strikes drastically influence the overall productivity of the mining sector and consequently lead to increases in wages [10] [16]. Figure 1-7 illustrates this graphically through the indexed[1] graph shown.

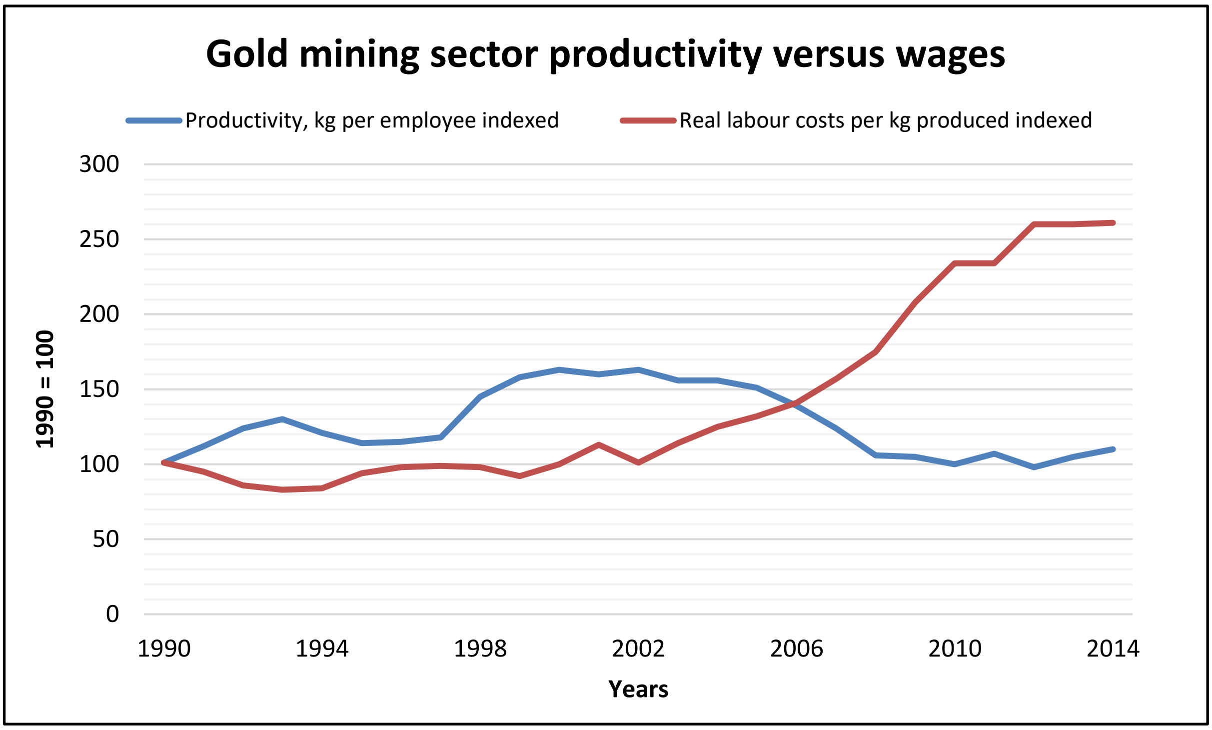

Figure 1-7: Gold mining sector productivity versus wages [10]

As labour costs increase while productivity decreases, the economic stress intensifies on gold mines, resulting in retrenchments and downscaling. SA has therefore seen a sharp decline in employment numbers as a result of the ever-increasing financial strain. This directly impacts the GDP contribution as illustrated by Figure 1-8.

[1] Graphs indexed to 100 in year 1990. Graphs represent the margin of change compared to one another and do not reflect actual values.

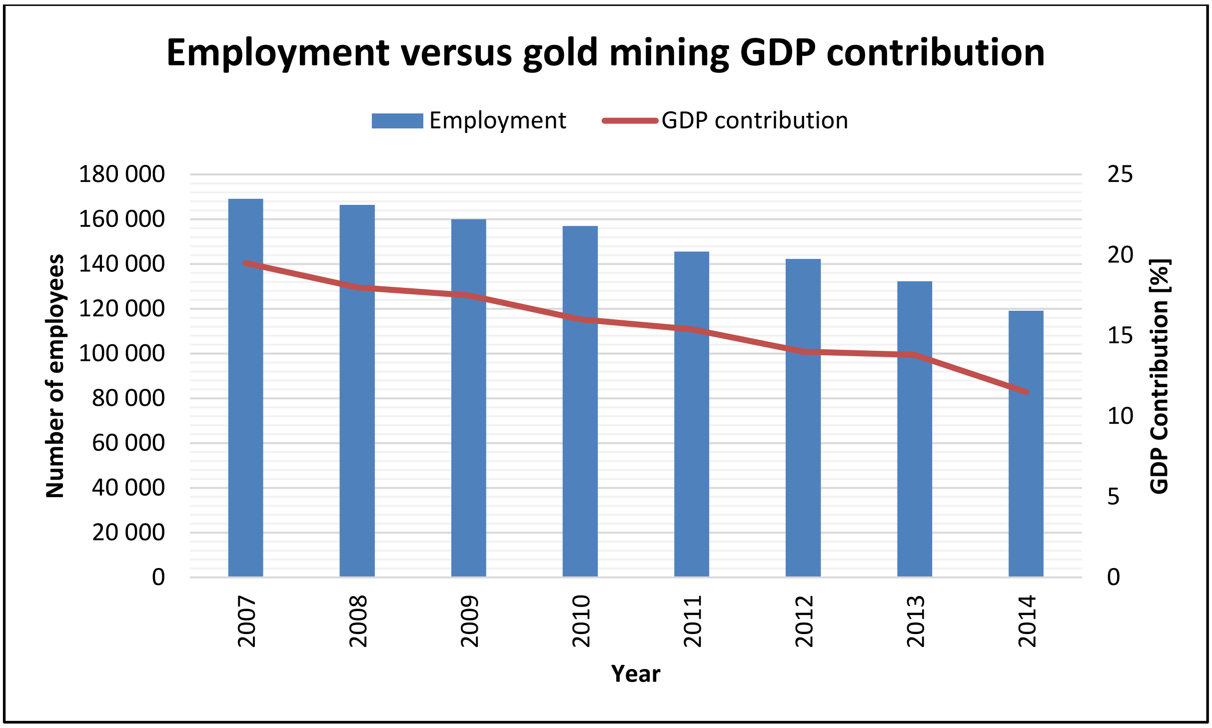

Figure 1-8: Gold mining GDP contribution in South Africa versus employment [10]

Figure 1-8 shows how the economic strain has led to a reduction in employed mine personnel. In turn this directly influences the GDP and leads to the weakening of the national economy.

Limited infrastructure

The term infrastructure can range from machinery, instrumentation, pipe networks, storage equipment etc. The infrastructure should be used effectively to ensure the execution of an optimised mining cycle. Some mines are challenged with outdated infrastructure and optimisation of mining processes is therefore limited.

The future of deep-level gold mines and the mining sector in general rely on modernised equipment and process. Modernisation entails making use of technological advances and ensuring various processes work in synergy such as the implementation of mechanised mining equipment. This will ensure access is obtained to additional ore reserves [17].

Modernising the gold mines of SA will extend the life of mines to approximately 2045 [18]. It can be further extended through successfully implementing a 24/7 mining cycle [18]. Figure 1-9 illustrates the potential benefit of modernising gold mines.

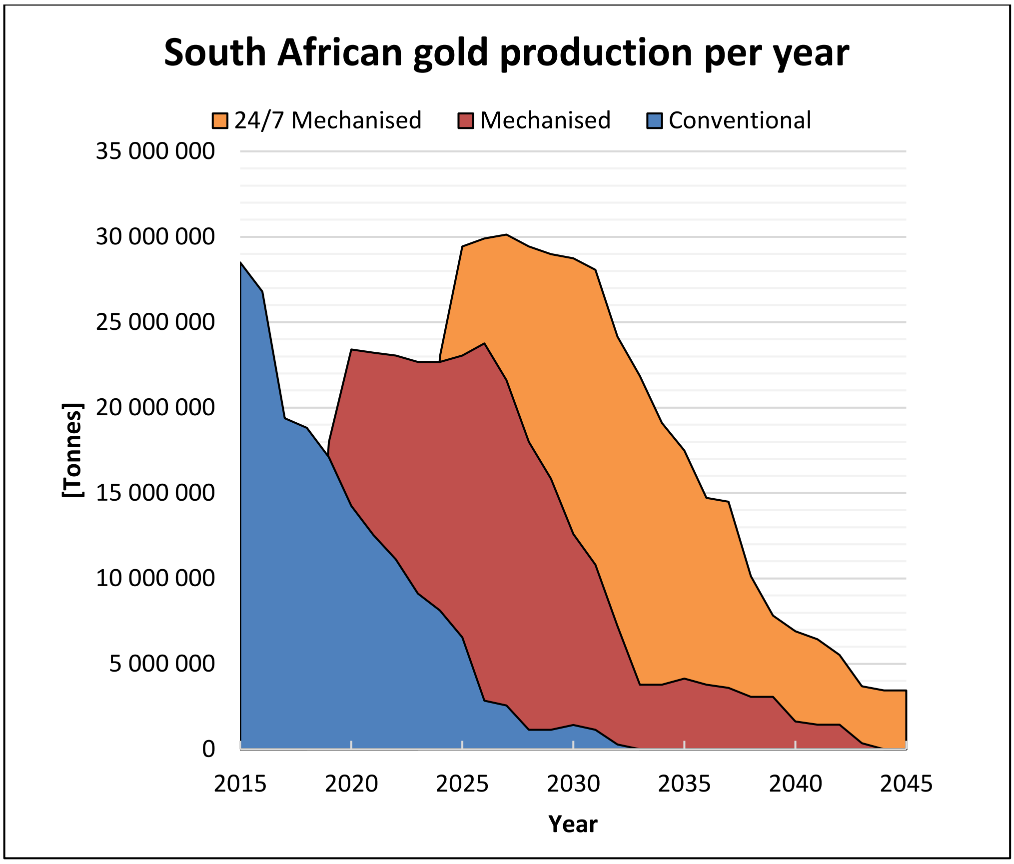

Figure 1-9: Potential gold tonnes increase through mine modernisation [18]

If gold mines in SA are not modernised they will face a sharp production decline by the year 2019-2020 and could potentially result in the closure of gold mines by the year 2033 [18]. However, modernising a gold mine is no easy or quick task and will not be implementable on all gold mines [18]. These processes take years to completely implement up to the point where the full benefit is realised [18].

Interpreting gold mine challenges

These previously discussed challenges, namely increasing electrical costs, labour wage increases and limited infrastructure all contribute to an increase in overall production costs in the gold mining industry of SA. It is therefore crucial that, for the interim, the focus be placed on how the current method of mining can be optimised to ensure that the life of mine is extended to its full capacity while other technologies such as modernisation are being implemented. This will mean using the current infrastructure in a more efficient manner to ensure that optimised production is achieved.

One method of doing this is improving the efficiency of current production systems through specifically looking at inefficient systems such as compressed air networks. These networks are full of wastage and inefficiencies which all contribute to a decrease in production efficiency.

1.2. Compressed air network inefficiencies

In literature gold mine compressed air systems are strongly related to production due to the fact that they are mainly used during drilling processes [19], [20], [21]. On the other hand, it is also regarded as one of the most inefficient and energy intensive systems on deep-level mines [21]. The inefficiency again provides large opportunities for improvement and optimisation [19]. The challenge is, however, to optimise these systems without affecting production activity as it remains a gold mine's main priority [22].

The inefficiency of deep-level gold mine compressed air systems can be mainly ascribed to the fact that these systems are very complex, with piping networks extending over several kilometres [23]. In some instances these systems may even have overall efficiencies of nearly 2% when taking into account the compressor efficiency, drill efficiency, reticulation network losses as well as possible leaks [24]. Figure 1-10 illustrates a typical layout of a deep-level mine where each tunnel is normally equipped with compressed air pipes.

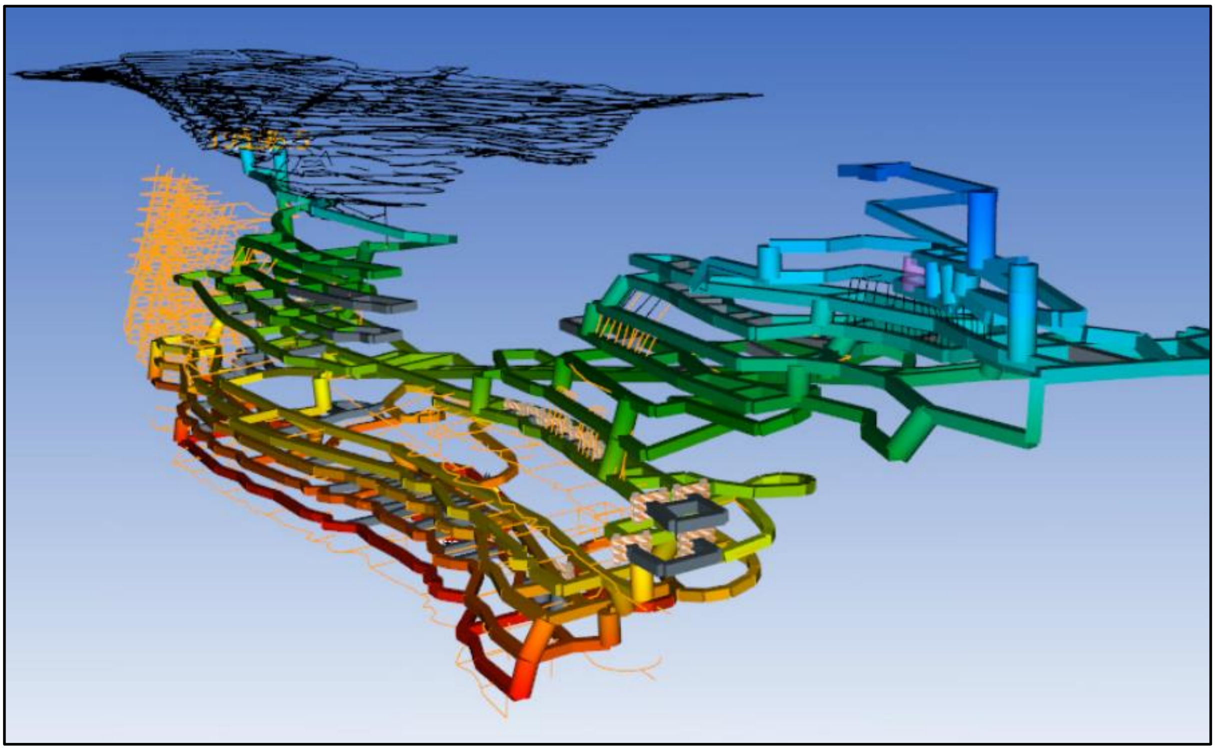

Figure 1-10: Typical deep-level mine layout [25]

From Figure 1-10 the complexity of these systems becomes evident. These systems are furthermore plagued by deterioration as the life of mine progresses due to network inefficiencies [21]. Such inefficiencies are difficult to identify due to limited monitoring infrastructure being available and in many instances it is even more difficult to quantify for financial motivation to repair [21]. These inefficiencies include:

- Incorrect pipe sizes being used
- Pressure losses due to pipe valves/restrictions
- Sharp pipe bends
- Pipe scaling
- Incorrect pipe installation and development strategies
- Leaks

The mentioned inefficiencies directly influence production through affecting the service delivery conditions supplied to active mining areas in deep-level gold mines. As a result of poor service delivery, production trends decrease when drilling targets are not met. Addressing these inefficiencies is crucial in optimising the mining process.

Due to financial and social constraints, mines cannot issue capital expenditure on replacing these systems with more efficient systems such as electrically or hydraulically powered drills. It is therefore important for current compressed air networks to be optimised as far as possible. Optimising these networks is a difficult task with the limited infrastructure available, but once identified, can be addressed to improve compressed air network efficiency and in turn optimise production.

1.3. Problem statement and need of the study

South Africa has been on a declining gold production trend for more than the past decade. This decline can be ascribed to a variety of social and economic challenges straining the growth of its gold mining industry. The impact of these challenges might worsen with time and it is essential that effective and feasible solutions be developed for gold mines to remain competitive within global markets.

With the current South African gold mining companies under severe financial pressure, it is essential to ensure that current infrastructure is used in a more efficient manner. By optimising current infrastructure, larger profit margins can be secured.

One of the most inefficient systems in the gold mining industry is that of compressed air networks. These networks are plagued by leaks, pipe restrictions, incorrect pipe sizes etc. Identifying these inefficiencies is a difficult task because of the limited monitoring capabilities present in most mines.

As mentioned, these networks play a vital role during production because of the poor service delivery conditions directly influencing drilling targets not being met. It is therefore essential to ensure these networks are optimised to the maximum extent to improve and sustain production targets. Optimisation of these compressed air networks will include the identification and addressing of these network inefficiencies to ensure maximum service delivery is achieved. With optimal service delivery conditions supplied, drilling targets can be met or even increased, which in turn will increase production.

1.4. Study objectives

To ensure the compressed air network inefficiencies are reduced on gold mines that consist of limited infrastructure, this study will aim to accomplish the following objectives:

- Identify, evaluate and address compressed air network inefficiencies such as incorrect pipe sizes, pipe restrictions, leaks, incorrect development/installation strategies etc. Addressing such inefficiencies will improve compressed air network performance on deep-level gold mines through improving the quality of service delivery conditions.
- Develop a procedure for optimising compressed air networks with the use of limited infrastructure.
- Quantify the impact of compressed air network optimisation in terms of production increase.

1.5. Study outline

A summary of each chapter in this study is provided as follows**:**

Chapter 1

This chapter serves as an introduction to the study and provides an overview of the state of gold mining in South Africa. This sector's growth, reserves and challenges are discussed. From the challenges a problem statement and need for the study are formulated. Finally, the study objectives are provided.

Chapter 2

In this chapter, an overview of the mining process is presented. All relevant compressed air network components are discussed and specific focus is placed on the fundamental principles to evaluate these networks. The chapter concludes with an overview of previously implemented studies in this field. Each study is scrutinised to identify applicable information and possible shortcomings that can be used to benefit the outcomes of this study

Chapter 3

Chapter 3 presents the development of a research methodology. The methodology mainly focuses on identifying, evaluating and addressing compressed air network inefficiencies with the aim to improve production output.

Chapter 4

In Chapter 4, the developed research methodology was applied to an actual case study. A solution strategy was developed, verified, implemented and validated to ensure that all the objectives of the study are clearly met. The results of the implemented solution strategy are also presented and explained in this chapter.

Chapter 5

This chapter concludes the results of the study and compares the outcome with the objectives stated in Chapter 1. During this chapter, the problem statement is addressed and the main conclusions are presented. Finally, recommendations for further studies are discussed.

2. LITERATURE STUDY

2.1 Introduction

The literature review focuses on theory and supporting information required to effectively address the problem statement, discussed in Chapter 1. The first part of this chapter focuses on mining in general and provides more detail on each component related to the study.

The latter half of this chapter focuses on evaluating a compressed air network, with specific focus on the fundamentals and what previous studies have concluded. Although relevant findings from these studies will be used, it will be clearly indicated why there is a need for this specific study. The chapter breakdown is illustrated in Figure 2-1.

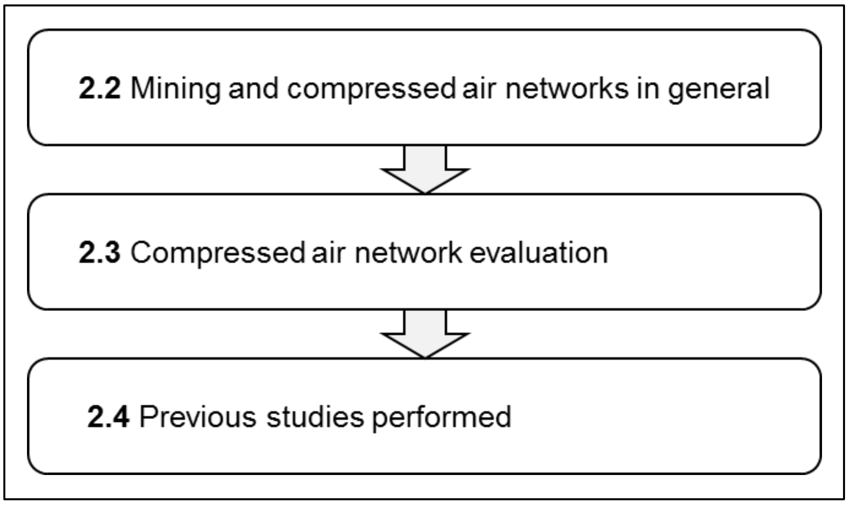

Figure 2-1: Literature study chapter overview

2.2 Mining and compressed air networks

2.2.1 Preamble

Understanding the mining process is the first essential step to investigate the correlation between production and the compressed air network itself. This section will therefore focus on providing a broad overview of the mining process and the various components of a deep-level mine compressed air network.

2.2.2 Mining procedure overview

The mining process as a whole can be described through a simplified life cycle. This life cycle includes all the various components involved in the mining process and indicates the order of events. Figure 2-2 illustrates a typical mining life cycle.

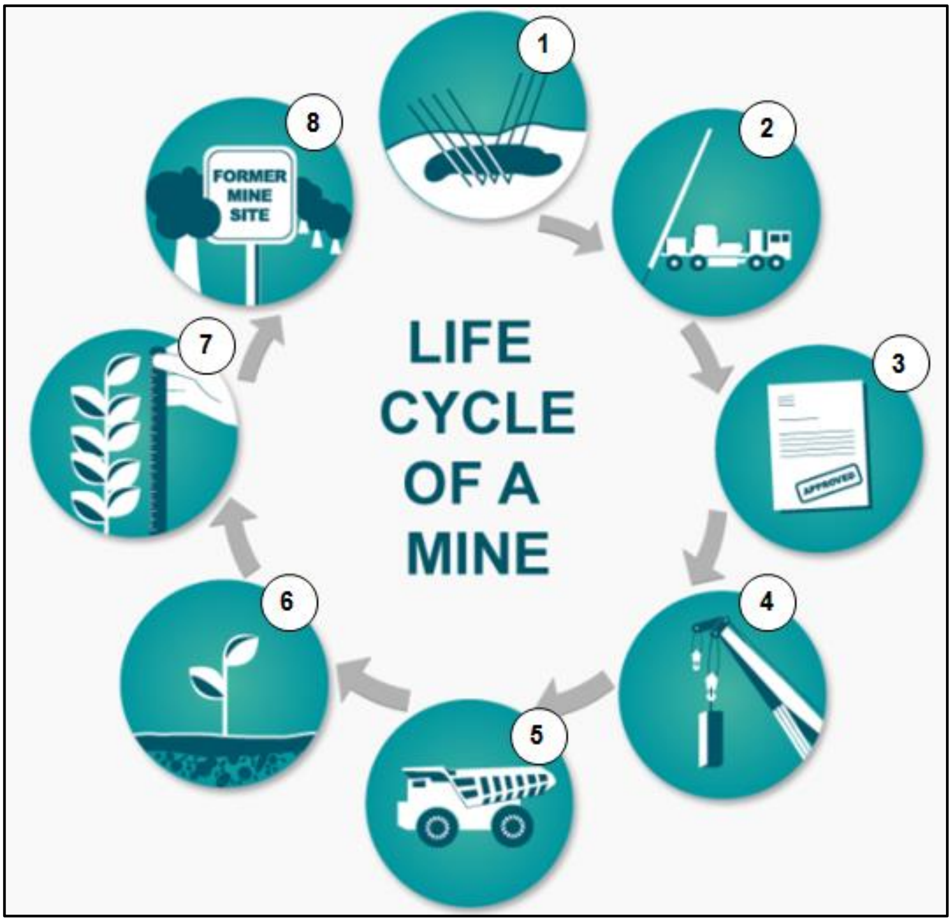

Figure 2-2: Life cycle of a gold mine [26]

The explanation for each stage in a mine life cycle is as follow [26]:

1. Exploration: Generative stage
2. Exploration: Primary exploration stage
3. Exploration: Evaluation stage
4. Development stage: Mine construction
5. Production phase
6. Mine closure and rehabilitation
7. Monitoring and evaluation
8. Lease relinquishment

Mining can be either categorised in surface mining (open pit mining) or underground mining. This is determined by the type of resource being mined as well as its geological location [27]. Gold mining in South Africa mainly entails deep-level mining, which involves sinking a shaft to reach the ore body deep underground [28] [29] [30] [31].

Depending on the layout of the ore body, underground mines normally make use of conventional narrow stope mining where, in some cases, a more sophisticated mechanised approach is followed [17]. Figure 2-3 illustrates the basic structure of an underground mine as well as an open pit mine.

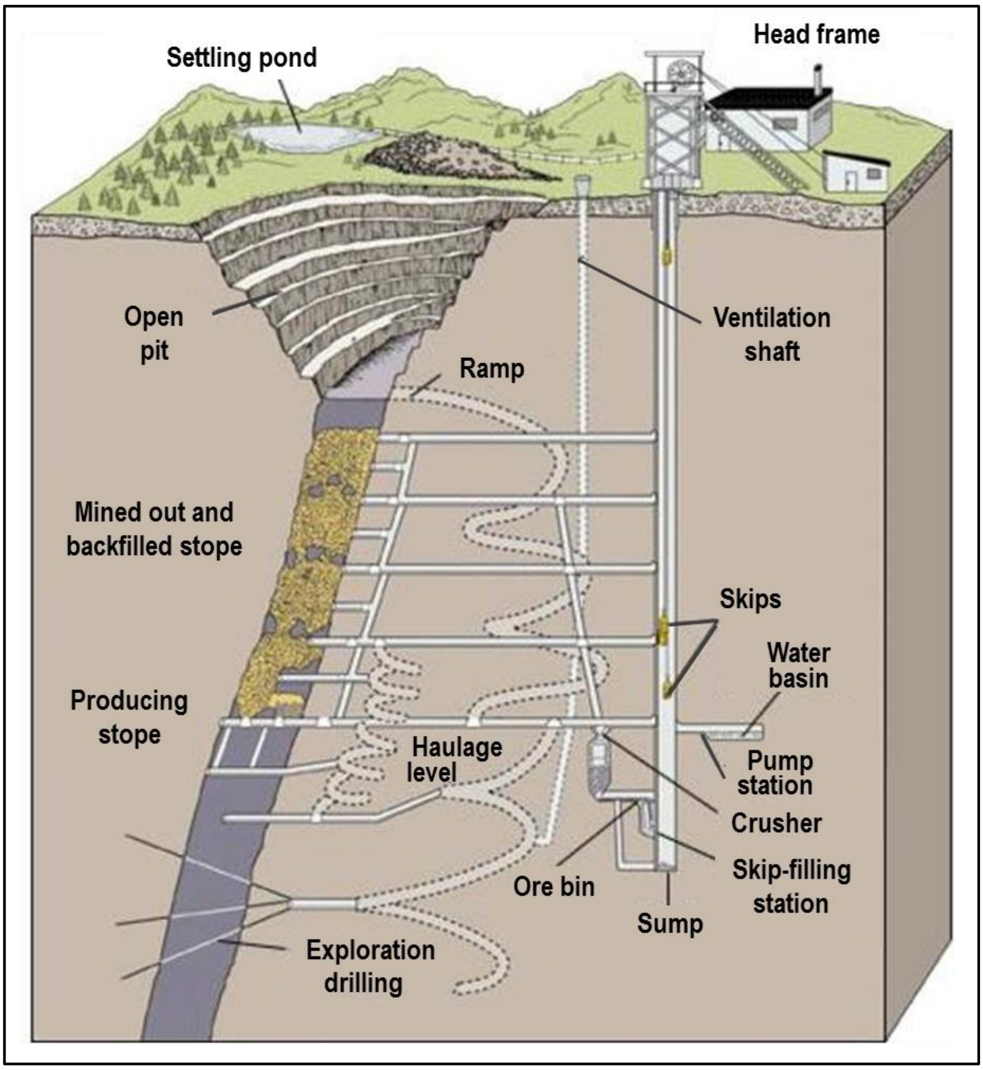

Figure 2-3: Underground and open pit mines - Basic infrastructure [32]

From Figure 2-3 a shaft, which is used by workers to travel to the working areas, is sunk near a gold reef. As mining progresses, the distances to these working places increase as the deposits become deeper to reach. Travelling to these working areas presents an overall challenge for typical underground gold mines.

Travelling and access

One unique challenge of deep-level gold mining is accessibility. Most of these mines only have one access point. Many mines, however, have a service shaft or alternative escape routes, but these are normally far from the working areas and only used in case of emergencies. This means that thousands of workers, equipment and ore are transported on a daily basis through the exact same entry point.

As mining progresses to reach deeper ore bodies, travelling time becomes more extensive, with workers using multiple modes of travel before reaching the working areas. In some cases travelling distances to work places exceed 4 km [13]. Through personal experience it has been found that these travelling times sometimes exceed 2 hours in one direction. This is due to the availability of transportation mediums, routine maintenance strategies and a vast amount of people requiring transport.

When transporting workers to the various working areas, it is essential that the transportation be as quick as possible to ensure optimal working time without jeopardizing the safety of the workers. Worker transportation mediums typically include [21]:

- Lifts, known as cages
- Train carts
- Chairlifts
- Conveyor belts

These transportation mediums form a vital part of the mining process and directly influence production if not managed effectively. Workers only have a predetermined timeframe to work in which is called a shift. When travelling times consume the majority of the shift, limited time is left to complete actual work. The next section focuses on the different shifts.

Mining shifts

Gold mining is a continuous process with large workforce numbers. Shift allocation and effective use of all workers is an important aspect of mining to consider. There are mainly three consecutive activities during a mine working weekday. These activities are divided into 3 shifts and are discussed as follow:

- Drilling shift:	During this shift all the blasting holes are drilled on the rock face.
- Blasting shift:	This shift entails charging all the drilled holes with explosives, detonating the explosives and supporting key blasted areas.
- Cleaning/Sweeping shift:	During this shift all the blasted rock is excavated and transported to loading areas. Blasted areas are also further supported.

According to South African legislation, normal work hours may not exceed 45 hours per week [33]. This led to a three work-shift allocation according to the following times:

- Morning shift: 06:00 – 14:00 (Drilling)
- Afternoon shift: 14:00 – 22:00 (Blasting)
- Evening shift: 22:00 – 06:00 (Cleaning/Sweeping)

The challenge is to ensure each shift is effectively used, taking into consideration that travelling times can consume as much as half of a work-shift. Limited work time means that project planning and tracking become vital to ensure all moving parts are goal orientated. The nature of the work conducted during each shift will now be explained in more detail to gain a better understanding as to how they integrate and influence each other.

Drilling

"Drilling" in the gold mining industry refers to the process of drilling holes in the rock face with the use of rock drills [34]. Pneumatically driven drills are mostly used, which are normally supplied from the compressed air network. [24] These drills are used to drill holes in a specific pattern on the rock face, which will be used during the blasting to load the rock face with explosives.

A variety of drilling patterns exists, which depends on the type of rock, area to be drilled and application. Due to seismic activity and structural integrity, smaller blast areas are the preferred choice [35]. Figure 2-4 shows a typical example of a drilling pattern on a rock face.

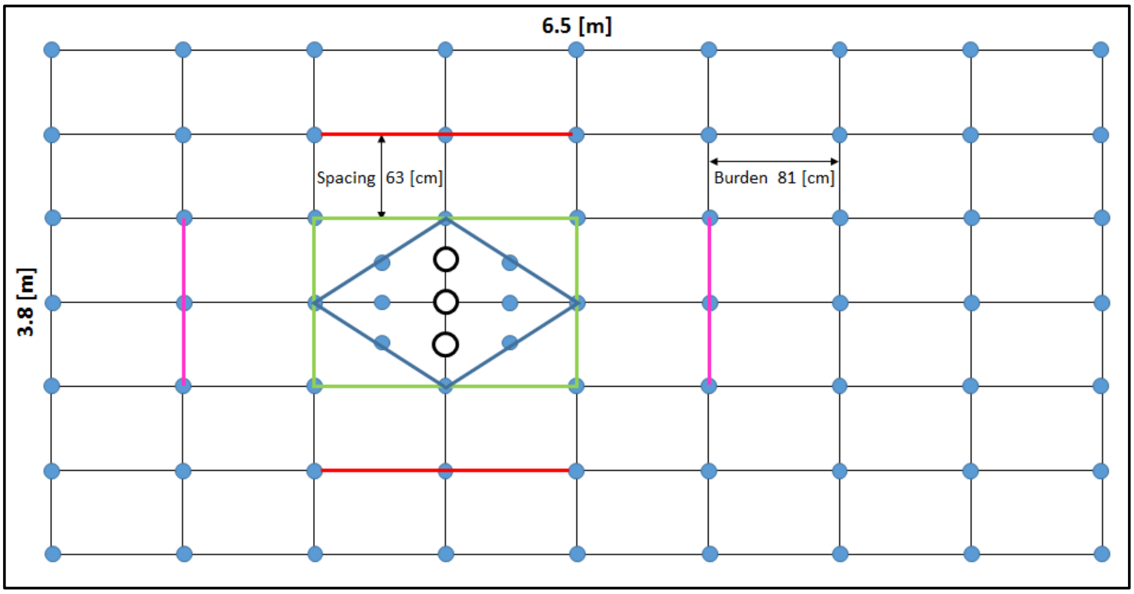

Figure 2-4: Typical burn cut drilling pattern [21]

The pattern shown in Figure 2-4 consists of three large breakaway holes (indicated by black circles) in the centre of the drill pattern. These holes serve as a breaking point during detonation to ensure the rock breaks in a controlled manner, de-stressing the sidewalls [36]. The coloured lines connecting various dots indicate a typical detonation sequence where holes with the same colour will be detonated simultaneously. An estimate for the number of holes to be drilled can be calculated from Equation 2-1.

Equation 2-1: Estimating the number of holes to be drilled per area [21]

$$Number\ of\ holes\ to\ be\ drilled = 2.2 * Area\ [m^2] + 16$$

The nominal stope face width is approximately 1 m, with blast hole depths between 1 m and 1.5 m normally drilled. These holes are drilled at angles in the range of 70°. This yields a typical forward advancement of between 0.9 m and 1.4 m. [37]. Once the drilling is complete, the panel is ready to be charged for blasting.

Blasting

During the blasting process, all the drilled holes are charged up with an explosive emulsion and accompanying detonator. The blasting sequence is timed from the holes nearest to the breaking point outwards. This ensures that the blasted rock breaks inwards and does not damage the outer walls. Damaging the outer walls would result in additional supporting to retain structural integrity[2,3].

Today the South African mining industry uses an electronic centralised blasting system. This system improves the overall health and safety environment during the blasting process by ensuring all personnel are well away from the blasting zones. Centralised blasting also improves the seismic activity due to a more controlled blasting environment [36].

In narrow reef mining, stope developing is normally performed at an angle called a raise (incline) or a winze (decline), which closely follows the ore grade line [38]. This incline also assists in ensuring blasted rock can be gravity fed to the centre gullies for collection [38]. After this blasting process has been completed, all the blasted rock needs to be collected and transported from the stope face to the surface. This process is referred to as cleaning and sweeping.

[2] Colin Howard, Senior Shaft Engineer Mine A, 2017/07/03
[3] Stoping standards – Harmony Gold, 2014

Cleaning and sweeping

As soon as blasting has been completed, the majority of the ore is spread out in front of the stope panels. The blasted ore is kept from spreading throughout the stoping area during blasting by erecting a protective blasting barrier [39]. The cleaning process entails collecting all the blasted ore and transporting it to ore passes with loading bins in the specific stoping area.

The first step involves collecting the blasted ore from the stope face. This is done through large scrapers, powered by winches, running down the stope face and centre gullies. These scrapers transfer the ore into smaller ore passes supplying the loading bins at a lower level. Figure 2-5 graphically explains this concept [37], [39].

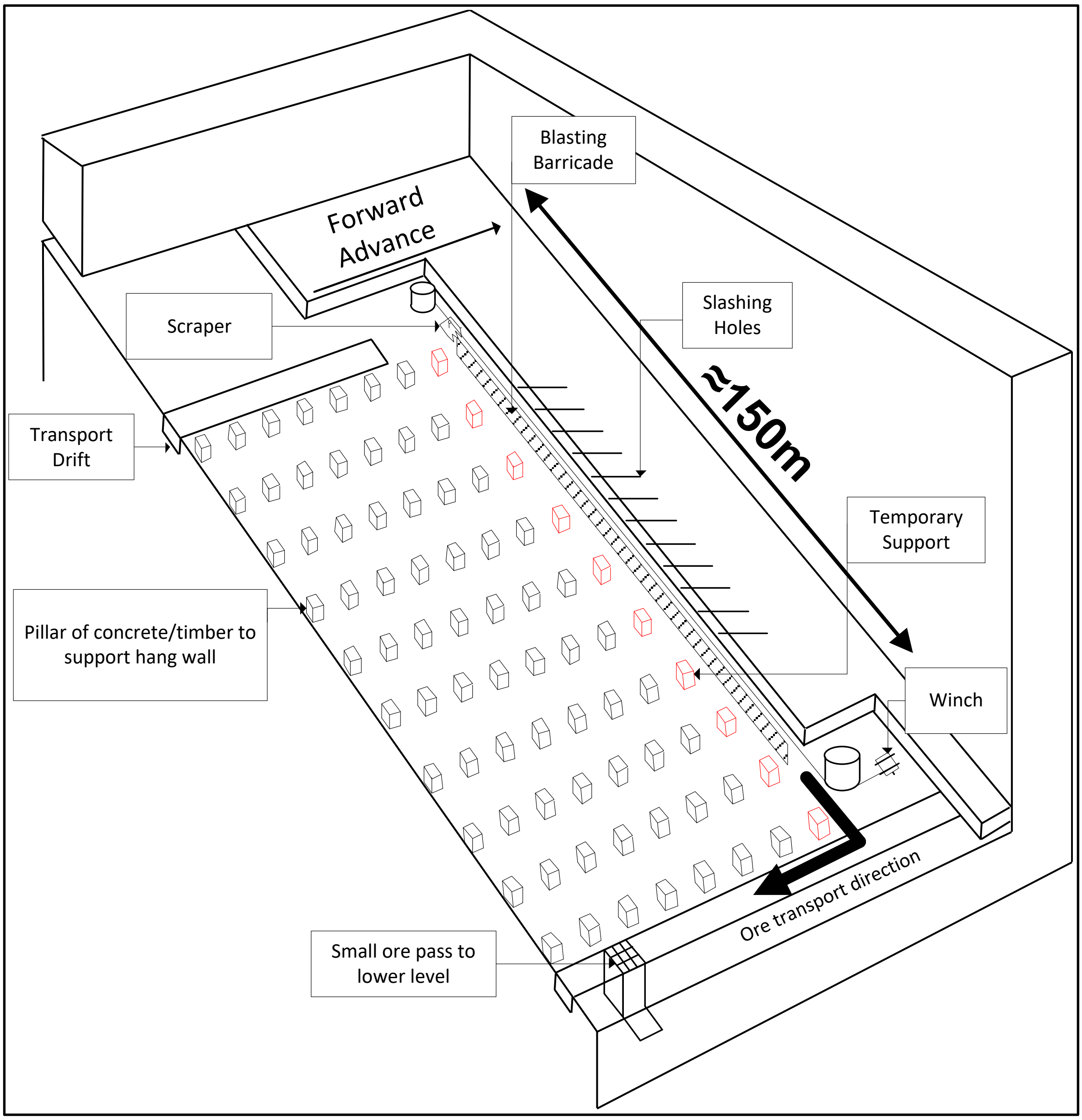

Figure 2-5: Schematic of cleaning process [39]

After the blasted ore has been collected by the scrapers, fines[4] remain within the blasted rock, which is collected through a process known as sweeping. Sweeping is normally done through the use of equipment such as brooms or water hoses on the stope face to ensure all the fines are washed from the blasted area [40].

Another method of sweeping is by using compressed air to blow all the fines from the stope face. This method is very expensive (usually referred to as wastage) and not permitted due to the danger of workers getting injured when blowing the fines at high pressures. Applying this high pressure compressed air to the stope face also exposes workers to high noise levels, which can be damaging to their ears [21].

After all the ore and fines have been collected, all of it needs to be transported all the way from underground to the surface processing plants.

Transportation and loading of ore

Deep-level gold mines make use of diverse transportation systems. These systems include hoppers (train carts) that are used to collect the ore from the loading boxes at each stoping site and transporting it (process known as tramming) to the central ore passes [34]. In many instances, especially trackless mining, ore is transported through vehicles and conveyor systems to the ore passes. Figure 2-6 illustrates this process.

[4] Small pieces of rocks/dust left over after blasting

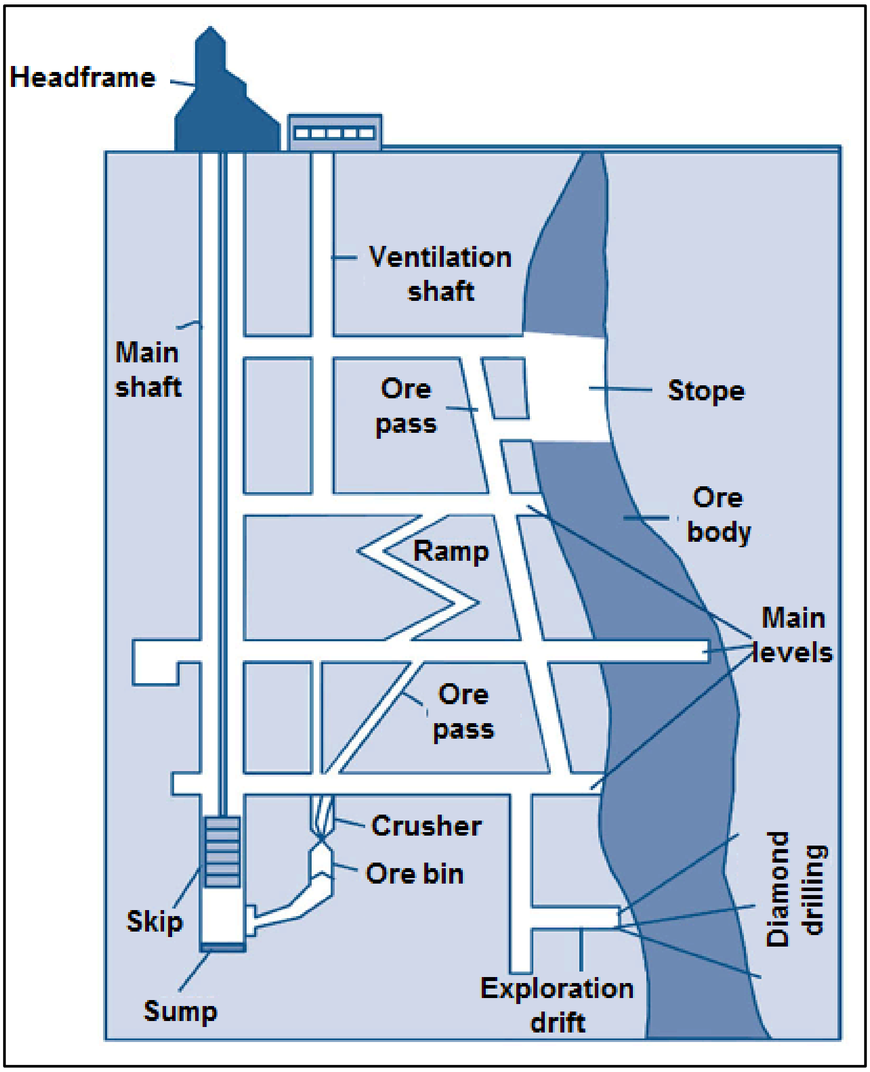

Figure 2-6: Basic ore transportation layout of a deep-level mine [41]

From the central ore passes the ore is gravity fed to the bottom of the shaft where the loading skips transport it to surface through a process called hoisting. The hoisted ore is transported via rail or conveyor to a gold processing plant where it is taken through various processes to finally produce pure gold [41].

With a background on mining procedures, the following section will focus on how these procedures are reliant on compressed air for effective operation.

2.2.3 Compressed air as an important driver in the mining industry

Compressed air networks form the backbone of several mining processes and it is imperative to thoroughly understand the networks from generation to the point of use. Deep-level mine compressed air networks can be divided into three main categories, namely:

- Supply side
- Reticulation network
- Demand side

Each category consists of various components ranging in size, application and function. These categories are discussed in more detail throughout the succeeding sections. Figure 2-7 illustrates a simplified overview of components of a compressed air network on a deep-level gold mine.

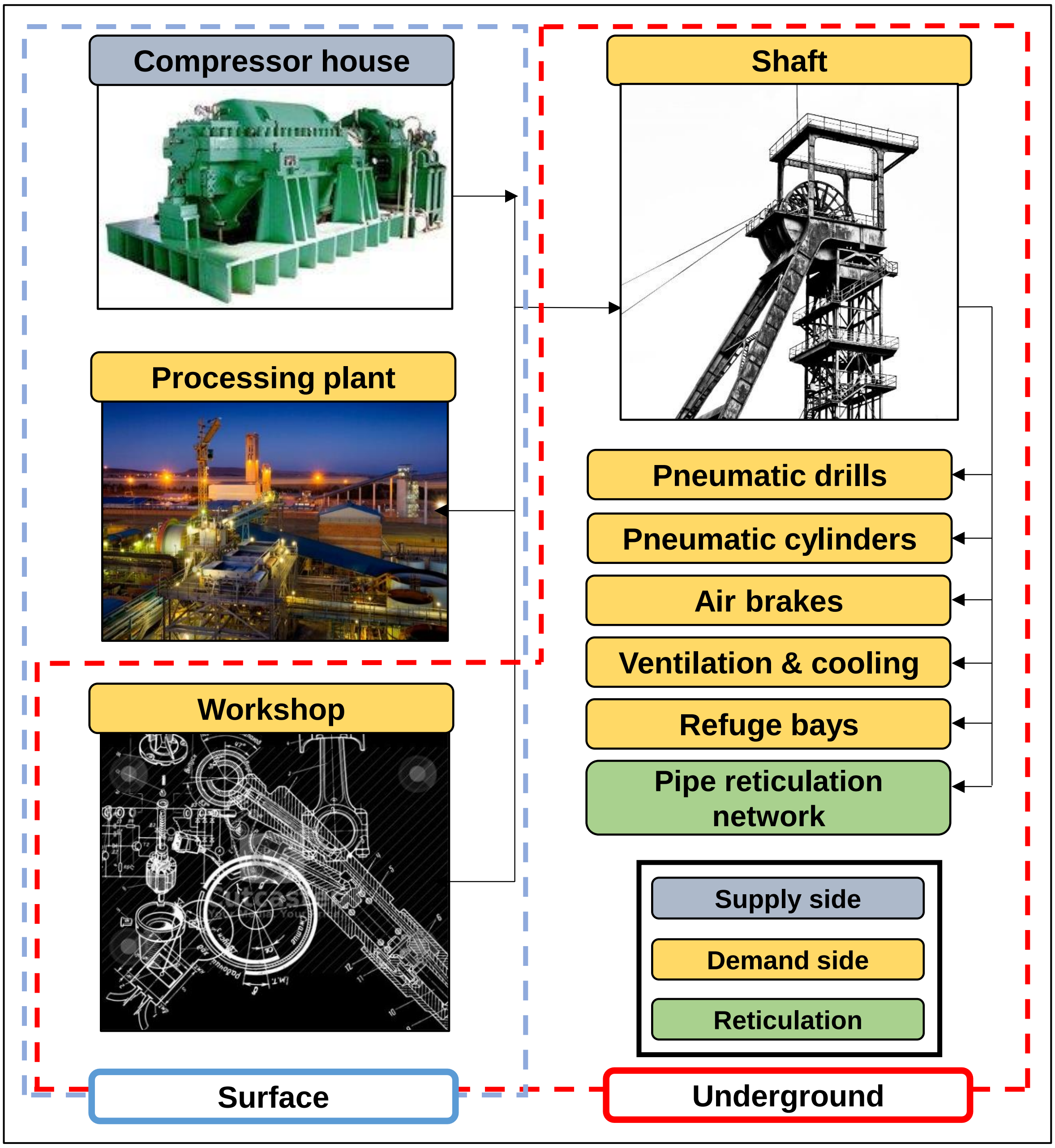

Figure 2-7: Basic overview of compressed air network components on a typical gold mine

Supply side

The supply side of a compressed air network acts as the heart of the network and includes all equipment responsible for producing compressed air pressure to the network. The supply side is usually referred to as the compressor house, which contains all the compressors used for compressed air generation.

A wide range of different compressors exist on the market, but they are mostly divided into 2 main categories, namely positive displacement machines and continuous flow machines [42]. The first changes the volume of the working fluid to increase the pressure, whereas the latter increases the velocity of the working fluid to increase the pressure. [42]. Figure 2-8 illustrates the main compressor types by the main categories.

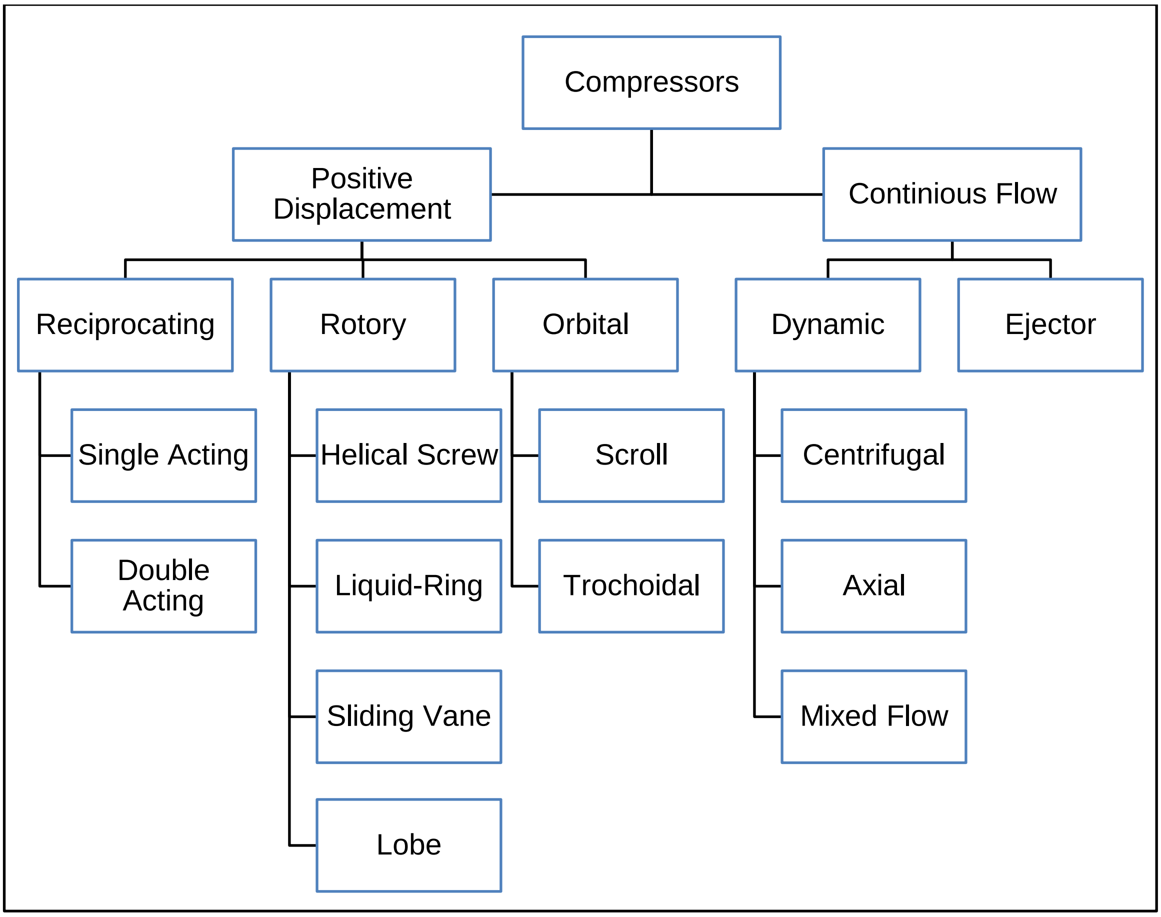

Figure 2-8: Compressor types by category [42]

The type of compressor required for a specific purpose depends on the application at hand. Figure 2-9 illustrates the different operating ranges for the various compressor types illustrated in Figure 2-8 [42].

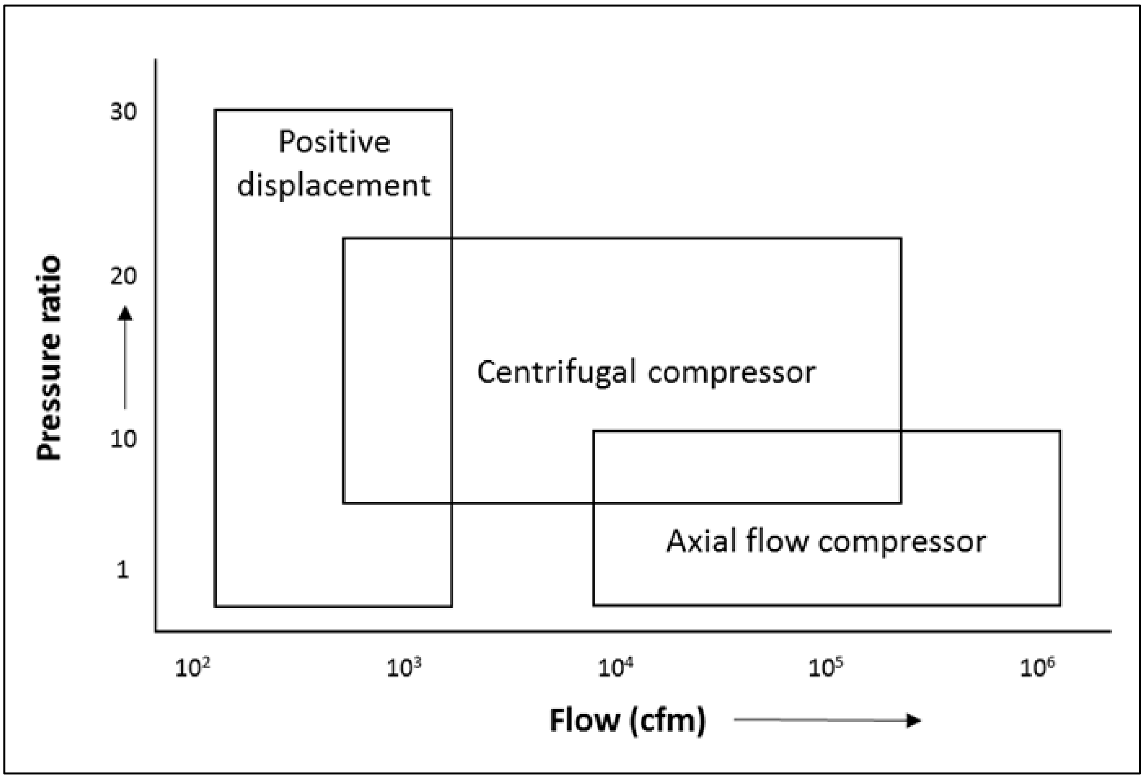

Figure 2-9: Typical compressor operating zone [43]

The South African deep-level gold mining industry mostly uses multi-stage centrifugal compressors due to their large operating range and compact size [23], [43], [44]. This large operating range best suits the dynamic compressed air usage of the mining industry, which ensures that unnecessary compressed air is not being generated. Figure 2-10 illustrates a typical multi-stage centrifugal compressor used on deep-level gold mines.

Figure 2-10: Multi-stage centrifugal compressor [44]

Despite their large operating range these compressors are fairly efficient. Figure 2-11 illustrates the advancements with regards to the efficiency of centrifugal compressors over the past 50 years.

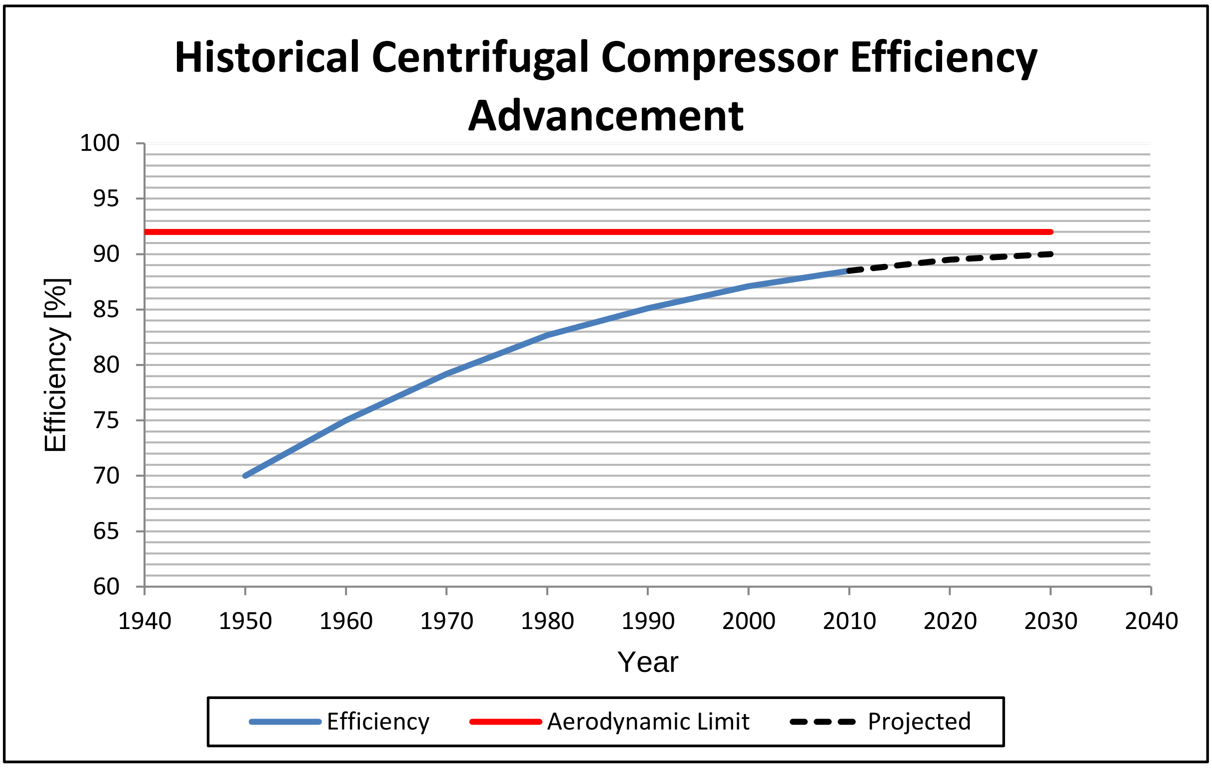

Figure 2-11: Historical centrifugal compressor efficiency advancements [45]

It is common in the deep-level gold mining industry to find a number of centrifugal compressors running in parallel to meet the required flow demand [21]. These compressors are safely located inside a compressor house where each compressor is connected to a common supply manifold.

Centrifugal compressors consist of various control mechanisms, which are used to effectively meet the supply with the demand. One such mechanism is that of guide vane control which allows the compressor to vary its delivery flow output depending on the demand requirements. However, guide vane control can only induce compressor cut back to a set limit, after which the additional compressed air is released through a blow-off valve into the atmosphere to prevent compressor surge.

The generated compressed air from the compressors is supplied to a variety of end-users through a pipe reticulation network. These end-users are referred to as the demand side and will be discussed in the following section.

Demand side

The compressed air network supplies a wide variety of disciplines from engineering, health and safety to the production department in deep-level gold mines. The various uses pertaining to each department is discussed in more detail throughout this section.

- ***Pneumatic drills***

  Pneumatic drills are used to create the blasting holes as discussed earlier in this section. A wide variety of drills are available on the market, each adapted for specific drilling conditions and applications.

  One popular type used in the deep-level mining industry is the handheld, air leg supported, compressed air driven drill used for narrow reef stoping (A complete part assembly description of a typical series, G25 rock drill range, can be viewed in APPENDIX D) [46]. These drills are compact in size compared to other larger types and can be operated by a single person. The added air leg ensures that optimal forward thrust is maintained, which increases drilling times. Figure 2-12 shows the basic operation of such a drill.

Figure 2-12: Pneumatic rock drill in operation [47]

Alternative drilling methods have been investigated in the past to ensure production is successfully optimised. Table 2-1 indicates the efficiency percentage of the various drilling methods which have been investigated.

Table 2-1: Drilling efficiency for different energy sources [24]

Drilling performance by energy source	Efficiency of compressor or pump	Reticulation pressure/ voltage drop	Energy left after leaks	Efficiency of drill	Overall efficiency
Compressed Air	61 %	75 %	31 %	15 %	**2 %**
Oil Electro-Hydraulic	80 %	80 %	100 %	38 %	**24 %**
Hydropower - pumped	85 %	83 %	95 %	34 %	**23 %**
Hydropower - gravity	96 %	78 %	95 %	34 %	**24 %**
Electric drill	100 %	90 %	100 %	34 %	**31 %**

From Table 2-1 it is clear that low efficiency is present throughout the compressed air network up to the pneumatically operated drills [21]. According to research there is large potential in changing from conventional compressed air drilling to electrically powered drills and as of late a lot of research has been completed in this field [24], [46], [48]. Figure 2-13 illustrates a typical electric drill.

Figure 2-13: Electrically powered drill [49]

Converting the mining industry from pneumatic drill rigs to electrical drills is a difficult process. A large amount of capital is required to replace the current compressed air infrastructure with an electric alternative. This replacement has proven to be time-consuming and faces various production constraints [48].

At this stage, alternatives such as electric drills are not financially feasible although it shows great promise for the future of deep-level gold mines. Focus should therefore be placed on reducing compressed air network inefficiencies. Doing this will lead to a production improvement as a result of the increase in rock penetration rate, which reduces the amount of time spent on drilling a hole.

Rock penetration rate (RPR) refers to the penetration of the drill bit into the rock within a given amount of time. The parameter is normally measured in millimetres per second mm/s and serves as a measure to evaluate drill performance and correlate this performance with production [50]. The RPR of a pneumatic drill is highly subjected to the supplied pressure and directly influences the drill's efficiency [51].

Comparing the rock penetration rate of different drills gives an indication of how drilling can be optimised to positively influence production. The influence on production is explained as follows:

- If drilling targets are not met, a decrease in drilling time will result in more blasting holes being drilled, which leads to more panels being blasted. This ultimately leads to an increase in ore volumes that need to be excavated [24], [51].

- Where drilling targets are met, decreasing the drilling time will lead to drill operators finishing earlier. This will especially be advantageous when travelling time to work places increases [11].

- During drilling periods more electrical energy is consumed on the compressors due to the larger compressed air demand. Decreasing the drilling times will therefore automatically lead to energy savings [44].

- There is also a health and safety benefit coupled with the decrease in drilling times. Pneumatic drills operate at high noise levels and continuous exposure could be hazardous to drill rig operators. Reducing these exposure times to high noise levels and the inherently dangerous mining environment, specifically encountered closest to the currently mined area, increases overall health and safety of the workforce [52].

➢ *Refuge chambers*

A refuge chamber is a supported chamber which serves as an assembly point for mine workers in case of emergency. Figure 2-14 provides a simplified layout of a typical refuge chamber in a deep-level mine.

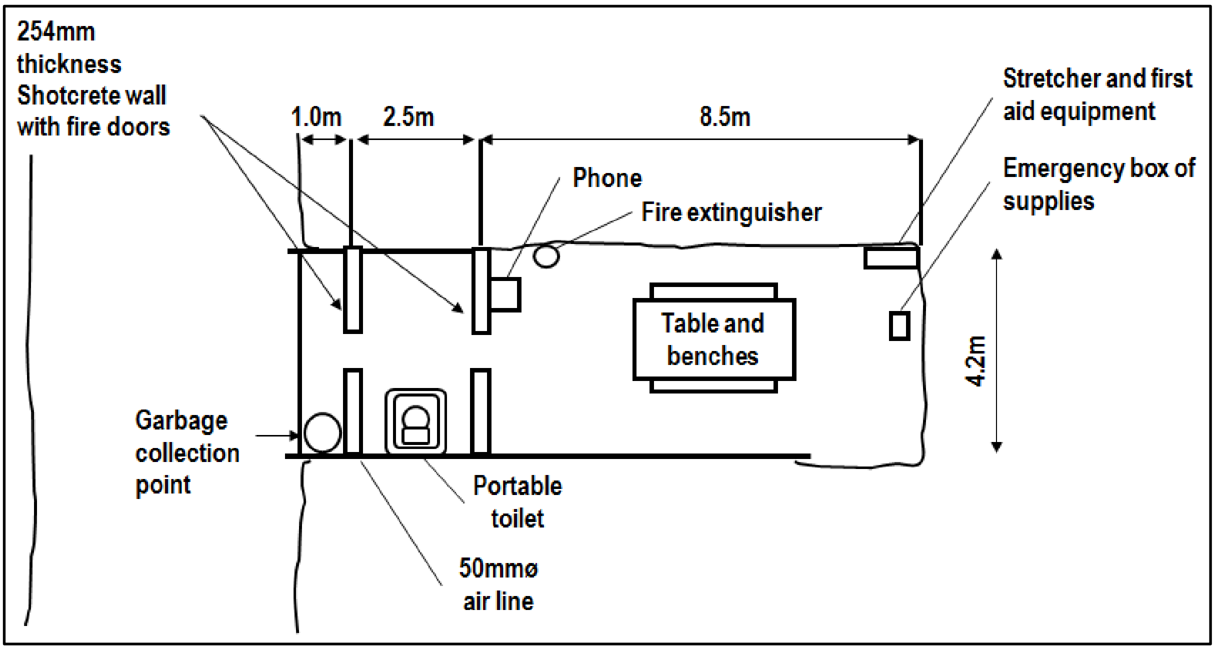

Figure 2-14: Basic refuge chamber layout [53]

To ensure a safe environment during an emergency, the chambers are supplied with compressed air. The compressed air provides fresh air to the occupants and pressurises the chamber to prevent smoke from entering in case of a fire [53].

➢ *Cylinders*

A vast number of processes in the mining environment are controlled through pneumatic cylinders. The operation of loading boxes is a popular example of such a process. Figure 2-15 illustrates a pneumatically operated loading box, commonly found in gold mines [21].

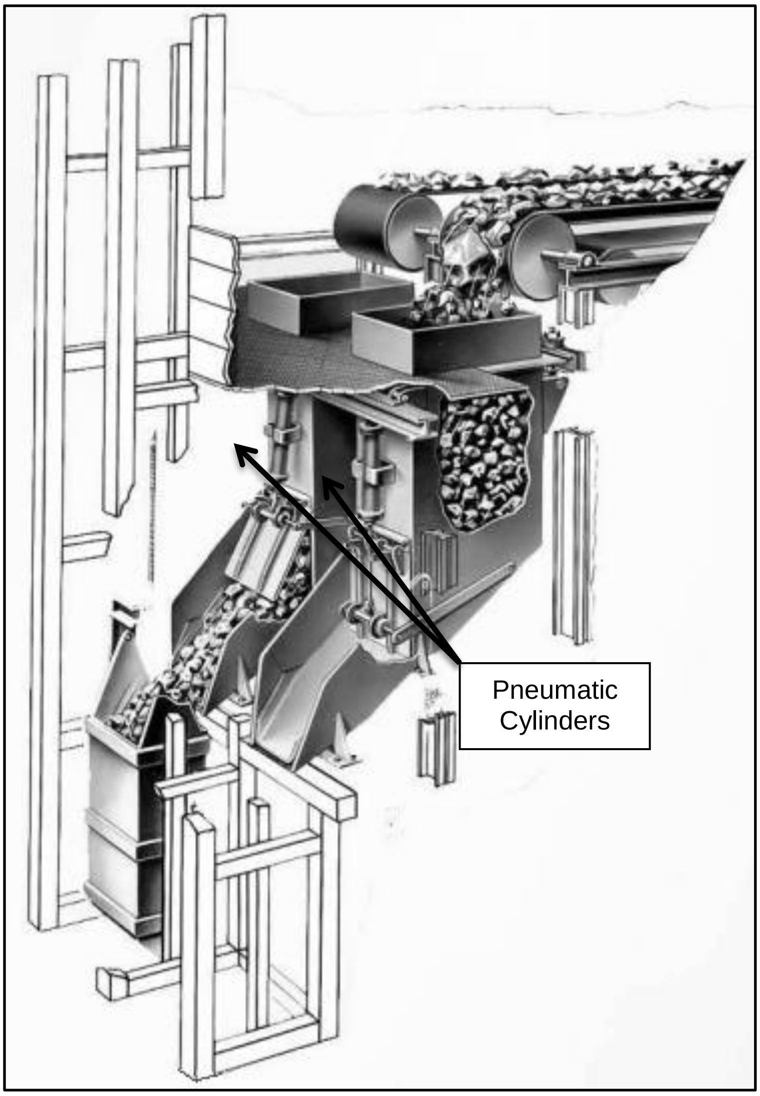

Figure 2-15: Pneumatic loading box illustration [54]

As illustrated by Figure 2-15, large pneumatic cylinders are used to open and close the control buckets [21]. These buckets ensure hoppers are adequately filled with ore during the tramming process. If these cylinders do not receive adequate air pressure, it might not open or close, which influences the amount of ore transported from underground to the surface per shift.

- ***Gold processing plants***

In many gold processing plants compressed air is still being used for agitation purposes [55]. In cases where the processing plant is adjacent to the mine shaft, it is common to find the compressed air network of the mine shaft being extended to the processing plant for supply. This results in a constant supply being required from the mine's compressor house due to the continuous nature of most gold processing plants. Figure 2-16 shows the basic layout of a gold plant and where compressed air is required in the process.

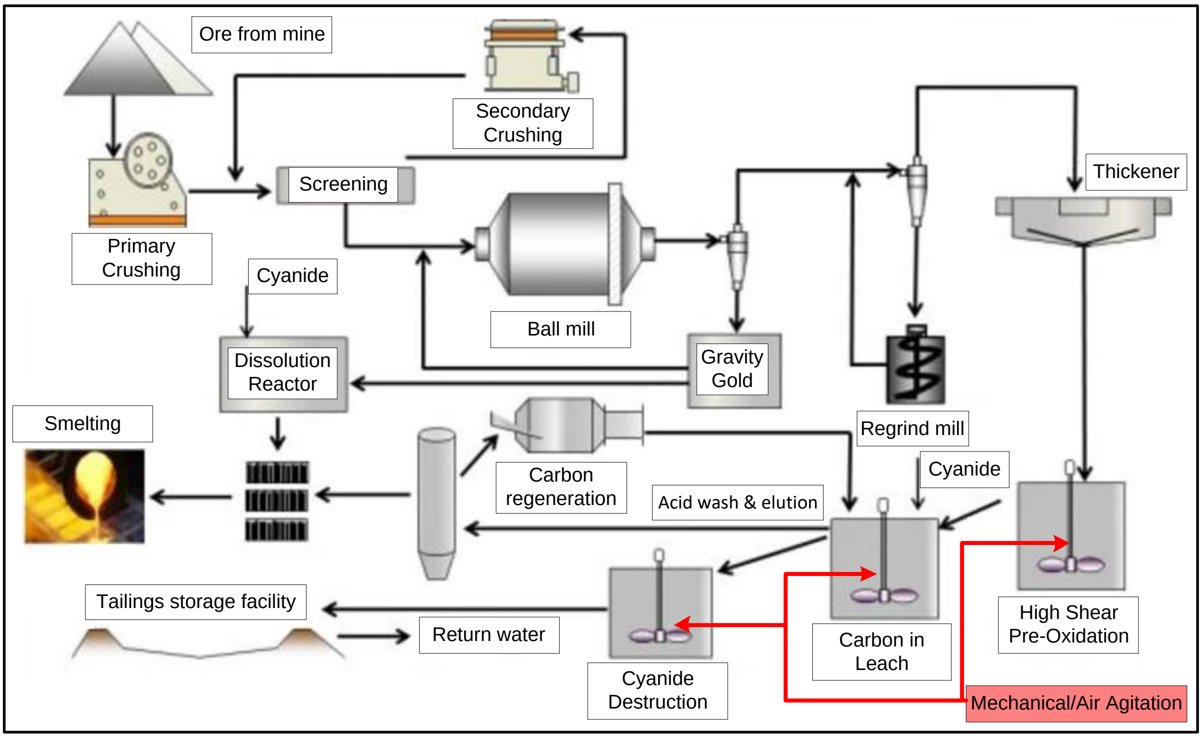

Figure 2-16: Basic gold plant layout [56]

➢ ***Wastage***

Compressed air is often used in new development areas to temporarily cool down workers, although this is a misuse thereof. Compressed air network problems arise with these kinds of practises.

The final category is that of the reticulation network which spans across the whole mine. This category is discussed in the next section.

Reticulation network

The reticulation network consists of all the pipes connecting the supply with the demand side. It is important to ensure that the piping network remains within design specifications to minimise the losses and inefficiencies [21]. The following sections focus on pipe sizes and maintenance of the piping networks to remain within the design specifications.

➢ ***Pipe sections and sizing***

Various types of pipes are installed in deep-level mine compressed air networks, depending on the location and specific demand. Larger incoming pipes consist of a more permanent fixture which are flanged pipe sections that are bolted to one another. These larger pipe sections are normally in the range of 10" and larger [21].

At the developing ends and working areas the compressed air network construction is much more dynamic in nature and quick clamp-on pipes are used. A wide variety of pipe sizes and couplings are available and primarily depend on the application [57]. One such brand is Victaulic® pipes, consisting of either shoulder-grooved or screw pipes. These pipes are joined with couplings as shown in Figure 2-17 [57].

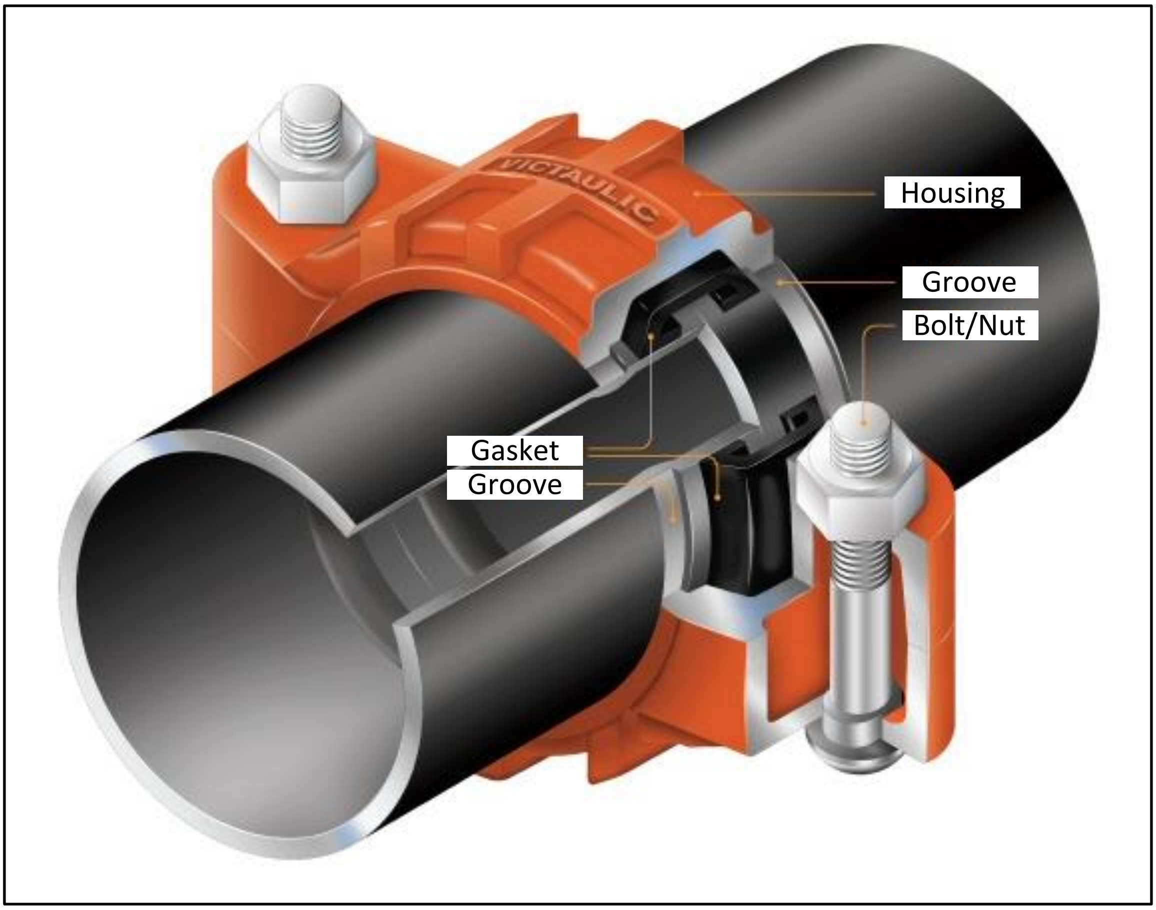

Figure 2-17: Grooved Victaulic® coupling [57]

It is common to find pipe sizes decreasing from the main shaft to the various levels, from levels to haulages, haulages to cross-cuts and cross-cuts to stoping areas. It is therefore essential to remain within design specifications as mining progresses deeper to ensure unwarranted line restrictions are not created [58].

Maintenance and development of compressed air networks

Maintaining a compressed air network in a large mining environment is a complex procedure. Previously, personnel, referred to as 'air wolves'[5], were assigned with the sole responsibility of

[5] Dedicated leak detection team [88]

maintaining the network and ensuring leaks are repaired. Due to financial constraints and job retrenchments in the mining sector, these responsibilities are now shared among workers [10].

At the developing ends, incorrect pipe sizes are often installed because of the mining mind-set of “using what you got” rather than “using what is required”. Without dedicated “air wolves”, these temporary inefficiencies become permanent development strategies which in time leads to large pressure drops within the compressed air network.

Another large concern that plagues compressed air reticulation networks is that of leaks [21]. These leaks, although easy to detect, are difficult to fix due to production downtime required [23]. The challenge is to accurately quantify identified leaks and prioritise them accordingly to enable a feasible maintenance strategy.

A study performed on a 30-year-old mine indicated that as much as 52% of the installed compressor flow capacity was wasted on leaks [21]. Another case study of a 20-year-old mine supported this with 39% of the installed compressed air lost to leaks [21]. This is concerning, considering the overall efficiency of the compressed air driven drills as previously discussed. Figure 2-18 illustrates a percentage leak source breakdown of 867 leaks, identified during a case study [21].

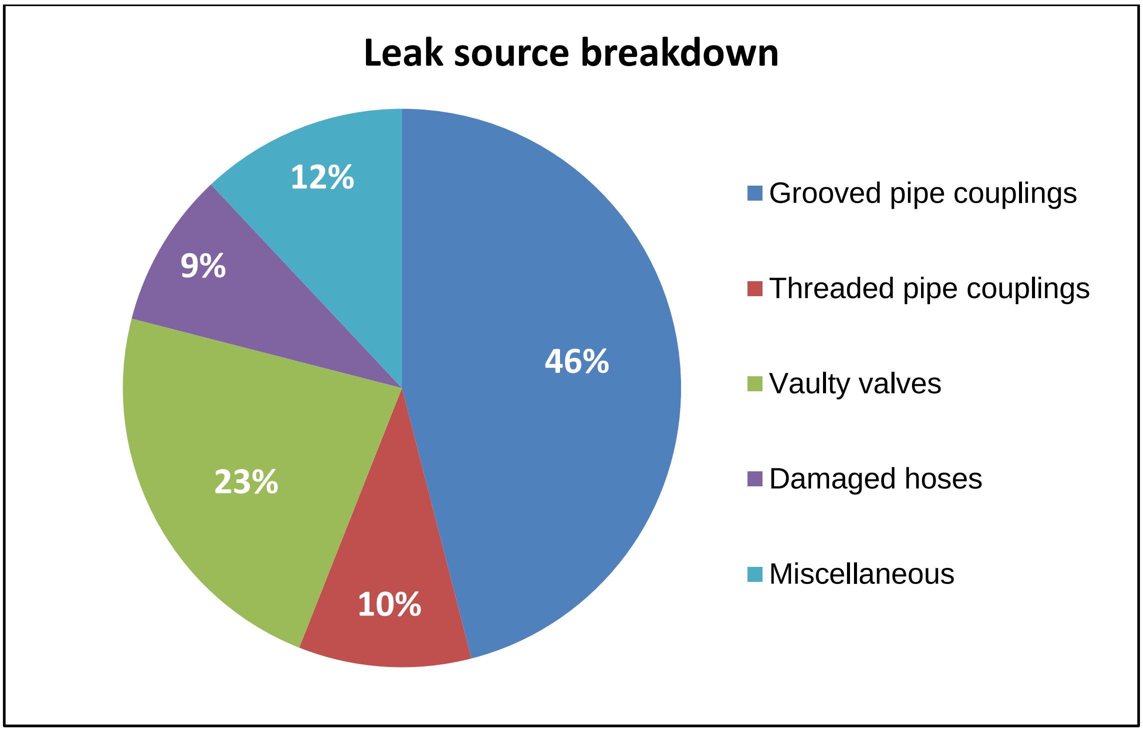

Figure 2-18: Leak source breakdown [21]

Figure 2-18 shows that the majority of leaks are a mere result of maintenance negligence and poor installation practises. This typically results in premature gasket failure on pipe couplings [21].

A basic overview of the mining process has been provided in this section. The various components of a deep-level mine compressed air system have also been discussed, highlighting the typical inefficiencies with these components. The following section focuses on evaluating these integrated systems based on theoretical data, fundamental calculations and analytical techniques.

2.3 Compressed air network evaluation

2.3.1 Preamble

This section addresses the evaluation of a compressed air network through investigating various analysis techniques used to calculate the performance of a compressed air network. Throughout this section, focus will be placed on the theoretical approach of compressed air calculations, especially line losses and their impact on the compressed air network.

The latter part of this section will focus on identifying suitable simulation software for the mentioned calculations. Methods for obtaining required data for such simulation models and how they can be applied to large compressed air networks which have limited infrastructure in terms of monitoring will also be discussed in more detail.

2.3.2 Root cause analysis (RCA)

Root cause analysis (RCA) refers to a technique used to assist with the identification of the root cause for any given problem [59]. In industry one is frequently confronted with the effects of an underlying problem rather than the problem itself. When applying the RCA method it is important to note that the root cause will be defined at a high hierarchy level and will have to be investigated in detail to obtain a detailed problem breakdown.

There are various methods in applying the RCA method with the most common strategy being the “5 whys” [60]. This strategy involves asking the “why” question repeatedly with the aim to eliminate mere repercussions of the problem, while assisting in identifying the root cause of the problem. This is a powerful problem identification tool which ensures that the focus remains on the root cause of the problem rather than addressing the repercussions. Figure 2-19 illustrates a simplified layout of the RCA technique using the “5 whys” approach.

In many instances the root cause might not be something which can be addressed directly due to time constraints or financial feasibility. Focus should then be diverted to the immediate repercussions caused by the root cause and minimise the effect thereof. Although this will not directly address the problem at its source, it will assist in alleviating the affects to a point where operations can commence normally.

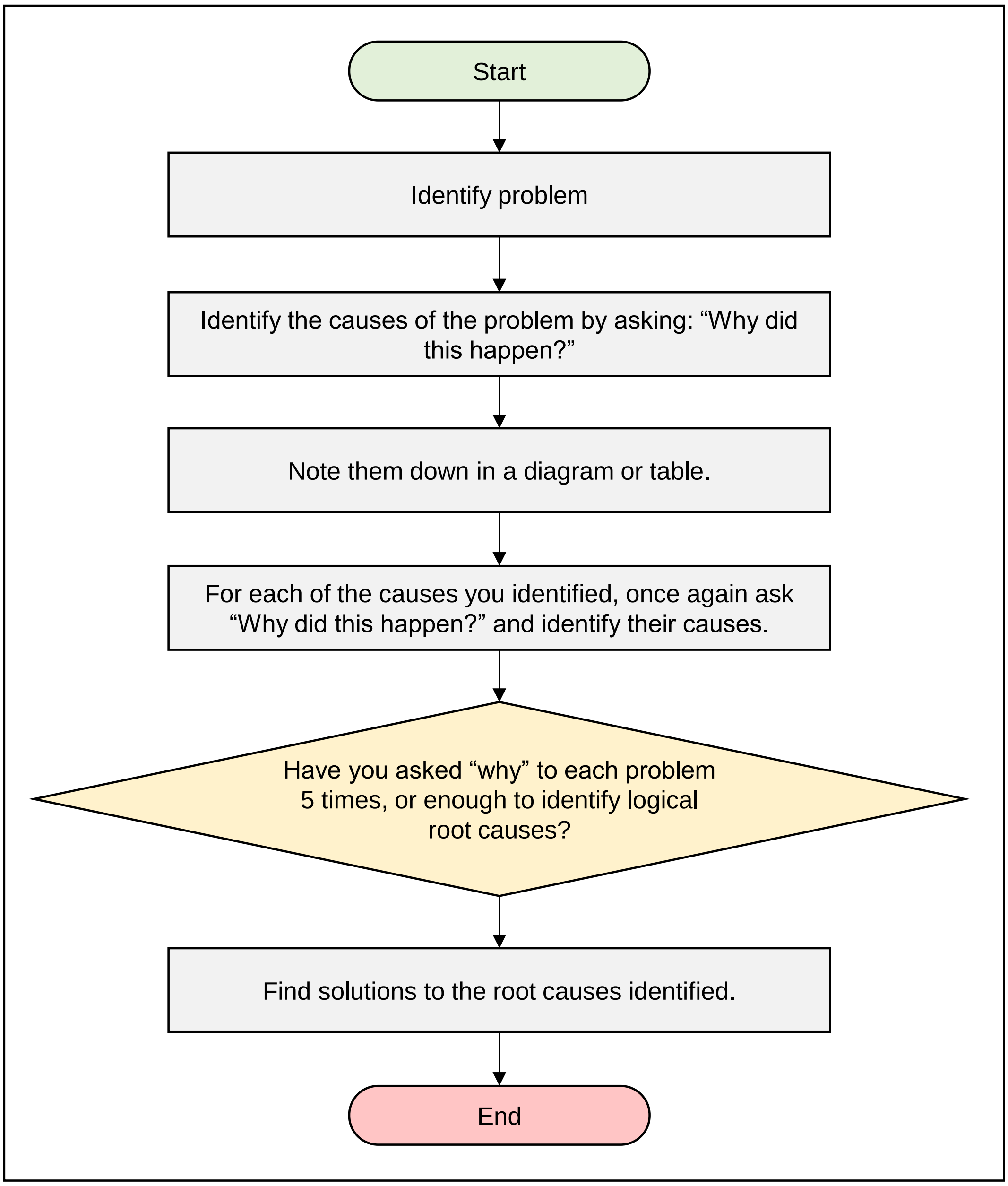

Figure 2-19: 5-Why Process Flowchart [61]

With the problem more clearly defined the next step entails evaluating the compressed air network through performing various calculations to accurately define the problem. These calculations are discussed in the following sections.

2.3.3 Compressed air network requirement

The requirement of a compressed air network can be determined through various ways and primarily depends on the production. It is important to ensure the installed supply capacity meets the compressed air network requirements. There are three basic techniques which can be used to calculate the compressed air network requirement, which are discussed below.

Formula [21]

The first technique involves using a formula to correlate the amount of planned tonnage with the use of compressed air. This formula as shown in Equation 2-2 serves only as a good method of approximating the compressed air requirement.

Equation 2-2: Correlation between daily tonnes mined and compressed air usage

$$C = 140T^{0.5}$$

Where

C	=	Plant capacity	cfm
$Tonnes$	=	Short tonnes of ore mined daily	tonnes

Comparison [21]

Another technique involves comparing effectively operating compressed air networks with one another to establish an average between the quantities of compressed air required for the number of tonnes mined per day. Table 2-2 illustrates an example.

Table 2-2: Determining the compressed air demand average per daily tonnes mined

Mine	Tonne per day	Air requirement	Air/tonne
Mine A	2 300	7 000	3.04
Mine B	3 310	16 000	4.83
Mine C	2 500	9 000	3.60
Mine D	1 200	4 400	3.67
Average	**2 328**	**9 100**	**3.79**

Detailed analysis [21]

This technique involves computing the total compressed air requirement through adding the requirement of each individual compressed air consuming piece of equipment. To perform such an analysis is essential to have a good understanding of all the compressed air dependent equipment in the mine.

2.3.4 Auto compression

Auto compression refers to an increase in air pressure due to the force of its own weight [21]. In theory this effect is always present, but in practise it is only noted in cases of great depths/height. The pressure increase due to auto compression can be calculated using Equation 2-3.

Equation 2-3: Pressure gain due to auto compression (Constant adiabatic flow) [21]

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

Where

p_2	=	Final pressure	kPa
p_1	=	Initial pressure	kPa
g	=	Gravitational Acceleration – 9.81	m/s^2
Z_1	=	Initial altitude	m
Z_2	=	Final altitude	m
T_1	=	Temperature of the compressed air	K
C_p	=	Specific heat capacity of the compressed air	$kJ/kg.K$
k	=	Specific heat ratio of the compressed air – 1.4	$kJ/kg.K$

Figure 2-20 illustrates the effect of auto compression at various depths for different surface delivery pressures. It is important that this effect be anticipated to prevent pipe bursts down the shaft.

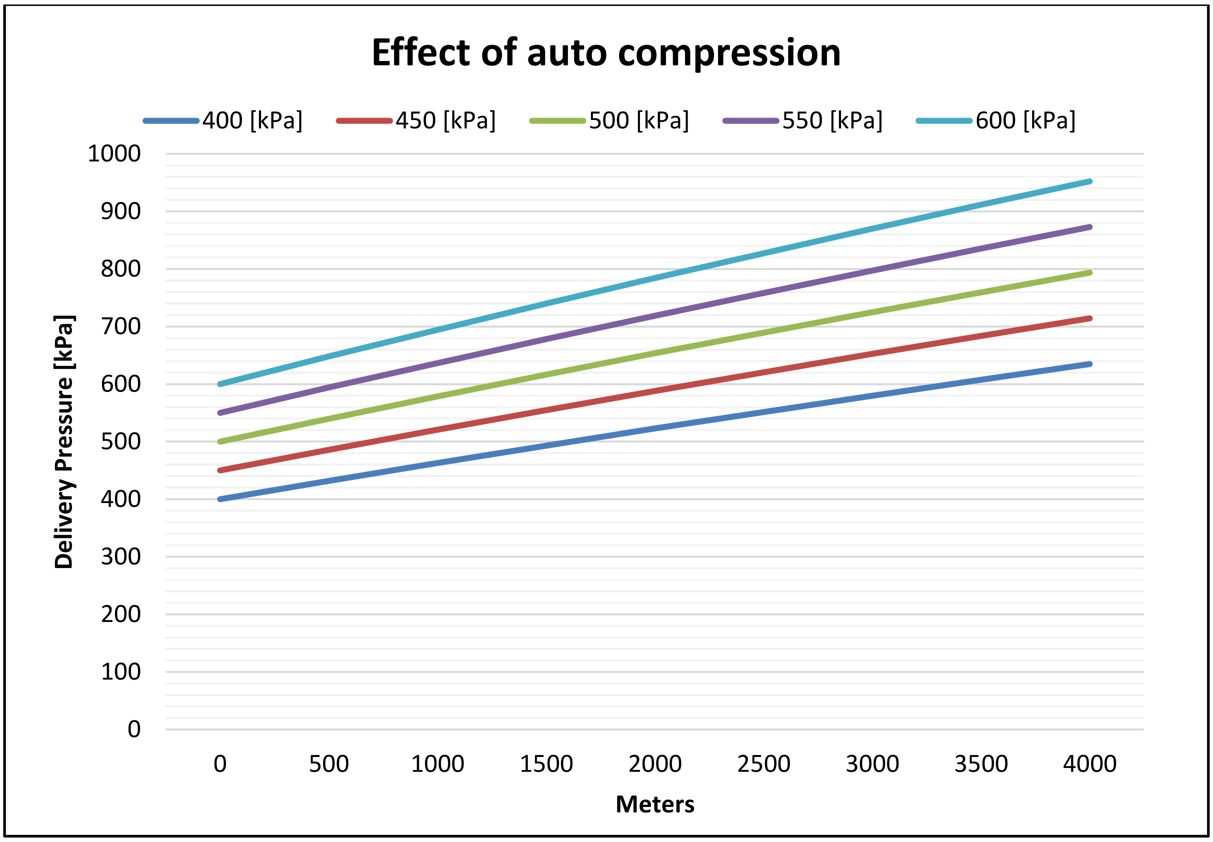

Figure 2-20: Effect of auto compression for various surface delivery pressures [21]

It is very important to account for auto compression when investigating a compressed air network, especially when taking pressure measurements at different elevations. In cases where similar pressure readings are measured at different elevations, the conclusion should not be made that no pressure loss is present. The auto compression for the elevation difference should rather be calculated and subtracted from the lower level's pressure measurement to ensure the two pressure points are accurately compared.

2.3.5 Compressed air line losses

In deep-level gold mines, the compressed air networks tend to be extensive and intricate. This brings compressed air line inefficiencies, such as pressure losses, to the equation and need to be identified and addressed when evaluating these networks [21].

Compressed air network inefficiencies can primarily be divided into two categories, namely major (linear) head losses and minor head losses. Major head losses are dependent on the pipe length whereas minor head losses refer to flow disturbances caused by various components within the pipe network. The classification of major and minor losses is not necessarily indicative of the loss proportion. Short pipe networks featuring an intricate set of components such as valves, bends and instruments can be faced with greater substantial minor losses than major losses. The opposite again will hold true for large extensive networks. [62]

These head losses, resulting in pressure losses, are inherent to any system where a fluid is involved [62]. Focus should be placed on ensuring these losses are within acceptable ranges and not to accomplish complete prevention thereof. The theoretical calculations for the two different categories are discussed as follows:

- ***Major head losses (frictional losses)***

These losses are present mainly due to the flow regime of the fluid as well as its viscosity [62]. Major losses associated with specific pipe characteristics can be calculated by using the Darcy-Weisbach equation provided by Equation 2-4.

Equation 2-4: Darcy-Weisbach equation [63]

$$h_f = f\frac{LV^2}{D2g}$$

Where

h_f	=	Friction head loss	m
f	=	Friction coefficient	$-$
L	=	Pipe length	m
V	=	Flow velocity	m/s
D	=	Pipe diameter	m
g	=	Gravitational acceleration – 9.81	m/s^2

The friction coefficient (f) is a function of both the Reynolds number and the corresponding pipe roughness [62]. Depending on the flow characteristic, which is determined by the Reynolds number, an approach can be selected to calculate the friction coefficient. For laminar flow conditions, the friction factor can be calculated using Equation 2-5.

Equation 2-5: Friction factor - Laminar flow [64]

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

There is still a lot of uncertainty regarding friction factors within the transient flow regime. Although many equations serve as a good approximation, there remains a substantial error involved [64].

Equation 2-6 gives the Colebrook-White equation to determine the Darcy friction coefficient for turbulent flow. This equation serves as the basis for the Moody Diagram, which is found in APPENDIX E.

Equation 2-6: Colebrook-White equation [65] – Turbulent flow

$$\frac{1}{\sqrt{f}} = -2.0log\left[\left(\frac{\varepsilon}{3.7D}\right) + \left(\frac{2.51}{Re\sqrt{f}}\right)\right]$$

Where

f	=	Friction coefficient	$-$
ε	=	Surface roughness	m
D	=	Hydraulic pipe diameter	m
Re	=	Reynolds number	$-$

One clear limitation of the Colebrook-White equation is that it is an implicit equation requiring iterative solving as well as an initial guess value. Alternatively, various explicit equations have been developed such as the Swamee–Jain equation [66]. This equation is provided by Equation 2-7.

Equation 2-7: Swamee–Jain equation – Turbulent flow [66]

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

Where

f	=	Friction coefficient	$-$
ε	=	Surface roughness	m
D	=	Hydraulic pipe diameter	m
Re	=	Reynolds number	$-$

The Swamee-Jain equation serves as a good approximation for the Darcy-Weisbach friction coefficient in most applications, while presenting an explicit means of solving the friction coefficient. The Swamee-Jain equation is also dependant on the Reynolds number and relative surface roughness of the relevant pipe.

The Reynolds number is a non-dimensional parameter, indicating the state of fluid flow through a pipe. This parameter is a function of the pipe dimensional characteristics and dynamic flow properties. A fluid is either in the laminar-, transient- (transition between laminar and turbulent) or turbulent flow regime [64]. The Reynolds number can be determined from Equation 2-8.

Equation 2-8: Calculating the Reynolds Number [67]

$$Re = \frac{\rho V D}{\mu} = \frac{VD}{\nu}$$

Where

Re	=	Reynolds number	m
ρ	=	Fluid density	kg/m^3
V	=	Cross sectional fluid velocity	m/s
D	=	Pipe diameter	m
μ	=	Dynamic viscosity	Ns/m^2
ν	=	Kinematic viscosity	m^2/s

The Reynolds number characterises the type of flow present inside the pipe. Table 2-3 indicates the three different characterisation regions.

Table 2-3: Reynolds number flow characterisation [64]

Reynolds number (Re)	Re < 2300	2300 < Re < 4000	Re > 4000
Flow regime	Laminar Flow	Transient Flow	Turbulent Flow

To complete the calculation of the friction coefficient, the surface roughness is also required. Table 2-4 lists typical surface roughness factors for various pipe materials commonly found in the industry.

Table 2-4: Typical surface roughness (ε) values for different pipe materials [62]

Type of Material	Roughness (mm)
Concrete	1.2
Cast iron	0.26
Galvanised iron	0.15
Wrought iron	0.045
Commercial steel	0.045
Rubber	0.01
Fiberglass	0.005
Stainless steel	0.002
Copper, brass, PVC	0.0015
Glass	0.0

With the friction coefficient known, the major head losses associated with the specific pipe sections can be calculated.

- ***Minor head losses***

Minor head losses play an important role in shorter pipe sections. These losses can be calculated by using Equation 2-9.

Equation 2-9: Minor head loss [62]

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

Where

h_m	=	Minor head loss	m
K_m	=	Minor loss coefficient	$-$
V	=	Flow velocity	m/s
g	=	Gravitational acceleration	m/s^2

The K_m value is related to the various components in the compressed air network that contribute to line losses. Refer to APPENDIX F for a list of minor loss coefficients related to various pipe network components. Once the major and minor losses have been calculated, the total head loss can be calculated by summing all the losses. The total head loss can be translated into a pressure drop by using the Bernoulli equation provided by Equation 2-10:

Equation 2-10: Bernoulli equation with hydraulic loss

$$\frac{v_1^2}{2g} + \frac{p_1}{\rho g} + z_1 = \frac{v_2^2}{2g} + \frac{p_2}{\rho g} + z_2 + \Delta h_{ls}$$

Where

v_1	=	Initial fluid velocity m/s	
p_1	=	Initial fluid pressure	Pa
g	=	Gravitational acceleration	m/s^2
ρ	=	Fluid density	kg/m^3
z_1	=	Fluid elevation	m
Δh_{ls}	=	Hydraulic loss	m (sum of the major and minor head losses)

It is important to note that this equation only holds true under the following conditions:

- points 1 and 2 lie on a streamline,
- the fluid has constant density,
- the flow is steady and
- there is no friction.

2.3.6 Compressed air wastage

Compressed air wastage is a common occurrence in deep-level mine compressed air networks [21]. The term wastage specifically refers to leaks and intentional misuse of compressed air. Wastage of compressed air is often overlooked and do not receive the attention it deserves [21]. Creating awareness of the impact of these wastages is very important as it largely influences the efficiency of the compressed air networks.

In a well-performing compressed air network, wastages comprises of approximately 10 % - 15 % of the total compressed air consumption through production [21] [68]. Compressed air network drop tests are usually conducted to determine the current status of wastages and quantify the impact thereof. The drop test procedure is explained as follow:

Step 1:

Determine the total amount of compressed air in the system. This will require knowledge of the total pipe network length and corresponding pipe diameters.

Step 2:

The above-calculated pressurised volume should be converted to free air volume at standard temperature and pressure (STP). This can be achieved by using Equation 2-11.

Equation 2-11: Calculating free air volume [21]

$$V_a = \frac{p_c V_c}{p_a}$$

Where

V_a	=	Free air volume	m^3
V_C	=	Compressed air volume	m^3
p_a	=	Atmospheric pressure	kPa
p_c	=	Compressed air pressure	kPa

Step 3:

During this step, all the compressed air lines should be pressurised to normal operating pressure.

Step 4:

All the lines are then closed at every end of each level as well as from the supply side (compressed air network must form an isolated "vessel"). It is therefore important that as much open ends as possible are closed to ensure accurate test results are obtained.

Step 5:

After the network has been isolated, the time is measured for the system pressure (gauge pressure) to reach zero.

Step 6:

The Briggs formula is then used to calculate the compressed air wastage. This formula is illustrated by Equation 2-12.

Equation 2-12: Briggs formula [21]

$$Q = \frac{5V}{2t}$$

Where

Q_{Leak}	=	Amount of air lost through leaks	m^3/s
V	=	Volume of free air lost in the system	m^3
t	=	The time it takes for the gauge pressure to reach zero	s

Reducing these wastages by, for example, repairing leaks, results in a cost benefit, considering the electrical energy required to supply the leaks with compressed air. Figure 2-21 illustrates this energy wastage graphically.

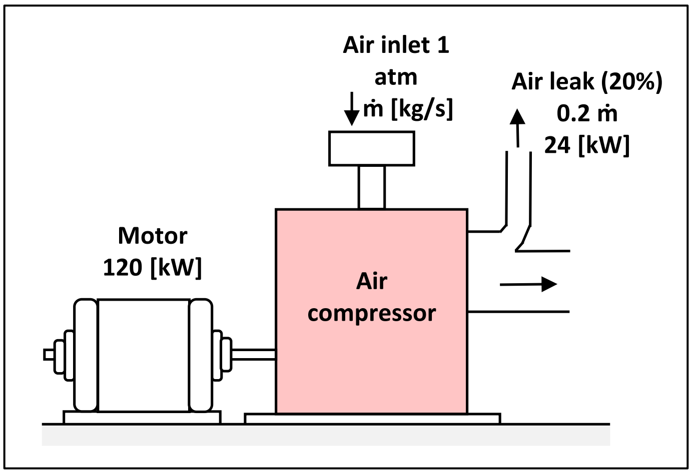

Figure 2-21: Energy wasted through leaks [68]

Quantifying the electrical power wasted through leaks can be used as cost motivation to repair such leaks. The first step in calculating the wasted power is to determine the mass flow rate through the identified leak. Leaks occurring at pressures exceeding 2 atm were proven to have an air velocity equal to that of the local speed of sound [68]. In deep-level gold mines, which normally operate between 300 kPa – 700 kPa, Equation 2-13 can be used to determine the mass flow rate of the compressed air escaping through the identified leak.

Equation 2-13: Mass flow rate through an air leak [68]

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

Where

$\dot{m}_{air}$	=	Mass flow rate of the air	kg/s
k	=	Specific heat ratio (1.4 for air)	$-$
P_{line}	=	Pressure in the compressed air line	kPa
T_{line}	=	Temperature in the compressed air line	K
R	=	Gas constant for air 0.287	$kJ/kg \cdot K$
A	=	Minimum cross-sectional area	m^2
$C_{discharge}$	=	Discharge coefficient (ranges between 0.6 for a sharp-edged orifice to 0.97 for well-rounded circular holes)	

The mass flow can now be used to calculate the mechanical energy required by the compressors to supply the leak. This can be achieved by using Equation 2-14.

Equation 2-14: Work required to compress a for supplying a leak [68]

$$w_{comp,in} = \frac{nRT}{\eta_{comp}(n-1)}\left[\left(\frac{P_2}{P_1}\right)^{(n-1)/n} - 1\right]$$

Where

$w_{comp,in}$	=	Work required compressing fluid	kJ/kg
η_{comp}	=	Compressor efficiency [normally between 70 - 90]	%
R	=	Gas constant for air (0.287)	$kJ/kg \cdot K$
T	=	Atmospheric temperature of air	K
P_2	=	Absolute pressure of compressed air line	kPa
P_1	=	Atmospheric pressure	kPa
n	=	Polytropic compression exponent [n=1.4 for isentropic compression; 1<n <1.4 for intercooling]	

The final step is to calculate the electrical power wasted through the leak. This calculation can be performed through multiplying the result of Equation 2-13 with the result of Equation 2-14. Equation 2-15 illustrates this calculation [68].

Equation 2-15: Electrical power wasted through leak

$$Power\ wasted = \dot{m}_{air} \times w_{comp,in}$$

The power wasted can also be interpreted in terms of potential power savings that could be realised through repairing the identified leak. This potential power saving can be translated to a cost saving through considering the cost of energy as shown in Equation 2-16.

Equation 2-16: Energy cost savings

$$Cost\ savings = \left(\frac{Power\ wasted\ \times Operating\ hours}{\eta_{motor}}\right) \times Unit\ cost\ of\ energy$$

Where

$Operating\ hours$	=	Operating hours over the relevant period	
η_{motor}	=	Motor efficiency	
$Unit\ cost\ of\ energy$	=	Unit rate of energy	R/kWh

Equation 2-13 to Equation 2-16 were used to calculate the annual financial wastage through different leak sizes at different operating pressures. The inputs for the calculations discussed throughout this section are provided by Table 2-5. These inputs are for illustrative purposes to enable the development of the graph shown in Figure 2-22.

Table 2-5: Annual leak cost input table

Parameter	Value	Parameter	Value
Ambient pressure	101.1 kPa	Average electricity price	0.532 R/kWh
Ambient temperature	20 °C	Compressor efficiency	80 %
System temperature	25 °C	Motor efficiency	90 %
Operating hours	24 hours	Discharge coefficient	0.65
Operating days per week	7 days	Specific heat ratio	1.4
Work weeks per year	52 weeks	Polytropic compression exponent	1.4

Figure 2-22 shows the output of the leak cost calculations. It is evident that the financial cost of a leak increases with the leak size and operating pressure.

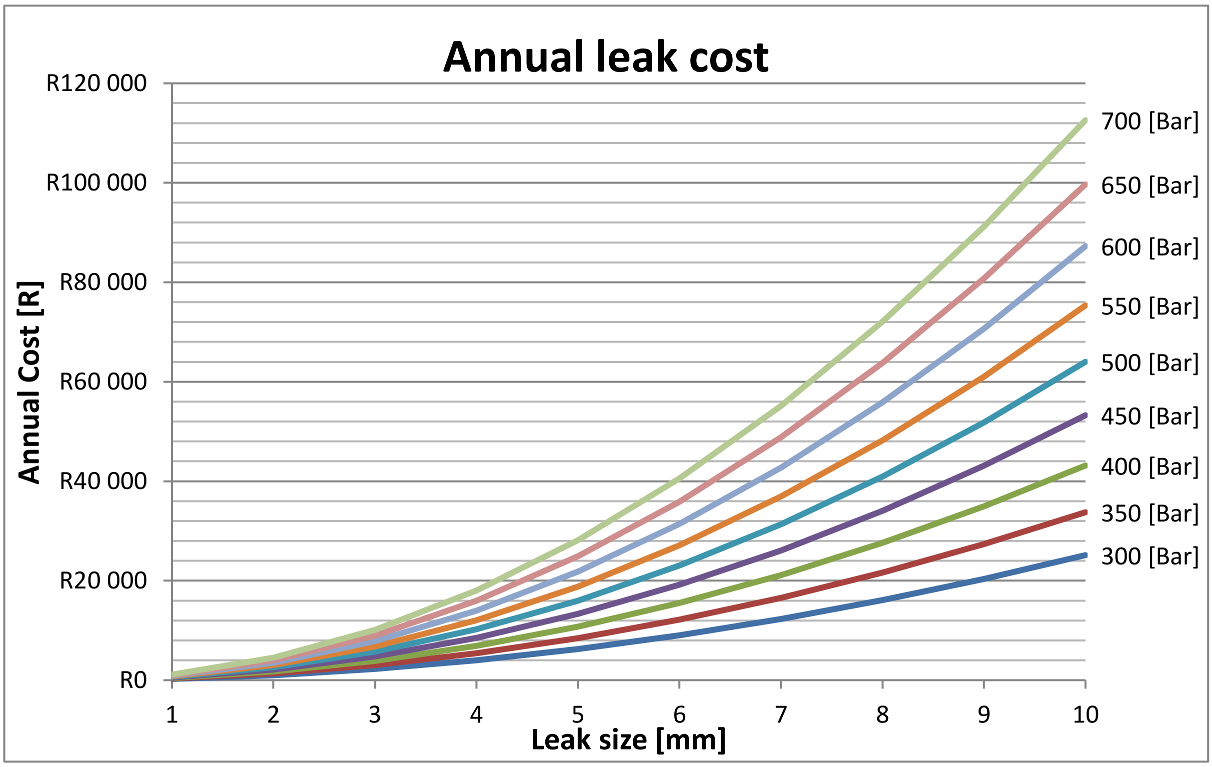

Figure 2-22: Annual leak cost

As mentioned during Chapter 1 of this study, many mines are faced with the challenge of compressed air leaks. The above-mentioned equation can therefore be used to more accurately quantify these leaks and determine the financial benefit of repairing such leaks.

The majority of the evaluation techniques discussed up to this point require certain input data for the discussed parameters. Collecting data on the mine is therefore essential. The next section focuses on how these data sets can be collected.

2.3.7 Data availability on mines

Most mines use Supervisory Control and Data Acquisition (SCADA) systems, which actively monitor various processes and parameters in real time. In some instances these SCADA systems have the capability of saving data to an historian for future analysis purposes.

Many South African gold mines lack the capability of adequately monitoring their compressed air network infrastructure. This leads to some of these networks being operated without a clear measure of performance. In such cases data need to be obtained manually by taking measurements.

Various manual measurement methods for collecting data on compressed air networks are available and largely dependent on the type and size of boundary being investigated. The main parameters required to characterise a compressed air network are pressure, flow and the amount of electrical energy required for compressed air generation. Table 2-6 provides a summary on portable equipment that can be used to obtain the data on these parameters when not available for a specific required point.

Table 2-6: General information on portable measurement equipment [69], [70] , [71]

	Flow	**Pressure**	**Power**
Power Source	Battery or external (plug in)	Battery	Battery
Battery Life	6 - 8 Hours (2 min interval)	±200 Days (2 min interval)	160 days (2 min interval)
Max	224 m/s	2000 kPa	5 A
Min	0 m/s	0 kPa	0 A
Accuracy (Decimal)	0.00001	0.01	0.01

The equipment discussed in Table 2-6 is visually depicted by Figure 2-23 to Figure 2-25.

Figure 2-23: Portable pressure logger [72]

Figure 2-24: Portable compressed air mass flow meter [73]

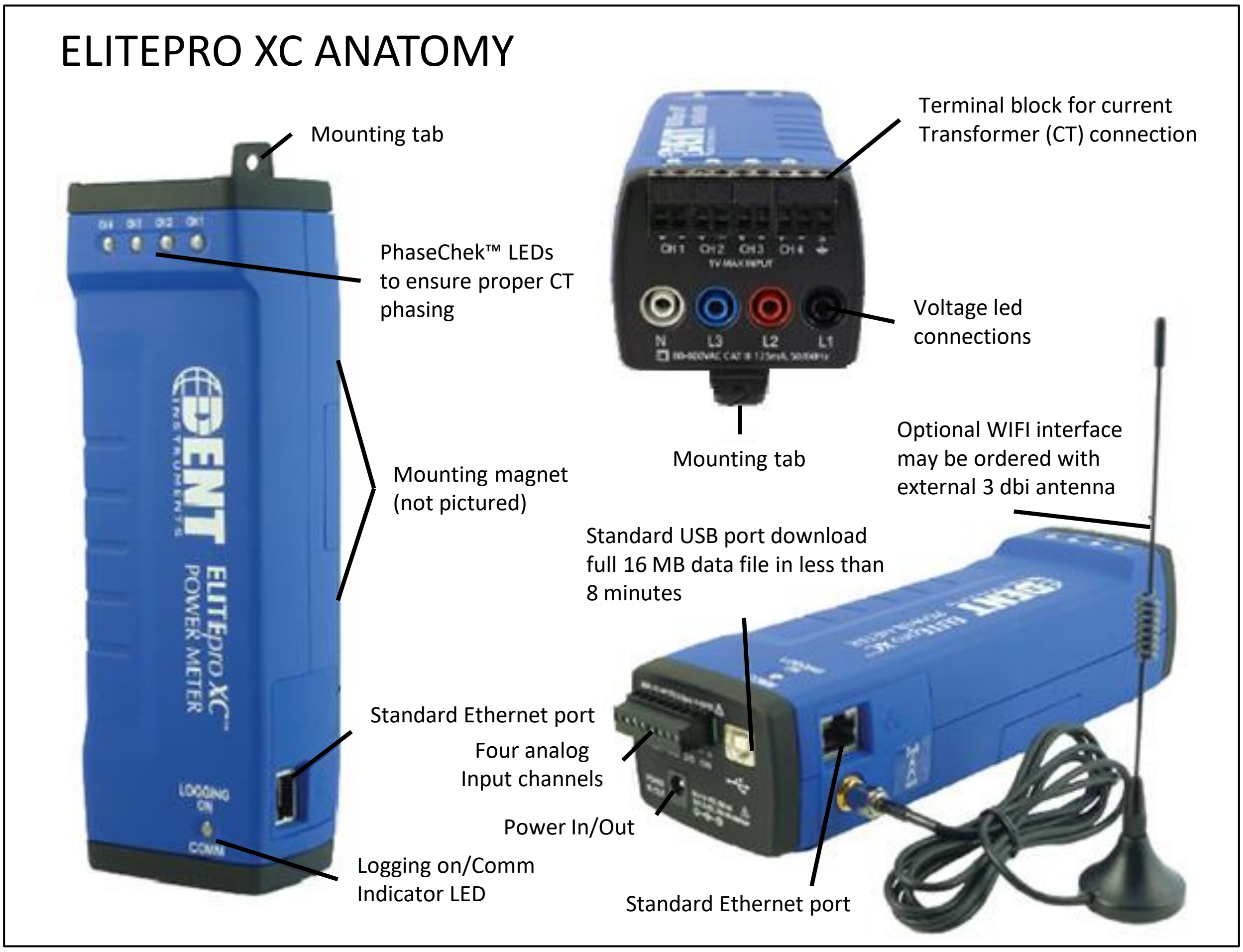

Figure 2-25: Portable power logger [74]

With data now readily available, simulation software can be used to analyse the compressed air network and investigate possible alteration scenarios.

2.3.8 Simulation Packages

A wide variety of flow simulation packages exist. The aims of these packages are, however, to accurately and quickly simulate various flow scenarios. This allows the user to perform a number of analyses as accurately as possible. Some of these packages are discussed in more detail below.

SolidWorks flow simulator [75]

This simulation package uses the Navier-Stokes equation for computing the flow characteristic for a specific scenario. It requires part modelling before a flow simulation can be constructed. The simulation can be categorised as external (ex. airfoils) or internal (ex. pipe flow) flow scenarios depending on the user's requirements. This flow simulation package is, however, only available as an add-in to SolidWorks. Figure 2-26 illustrates a typical flow simulation example performed with SolidWorks flow simulation package.

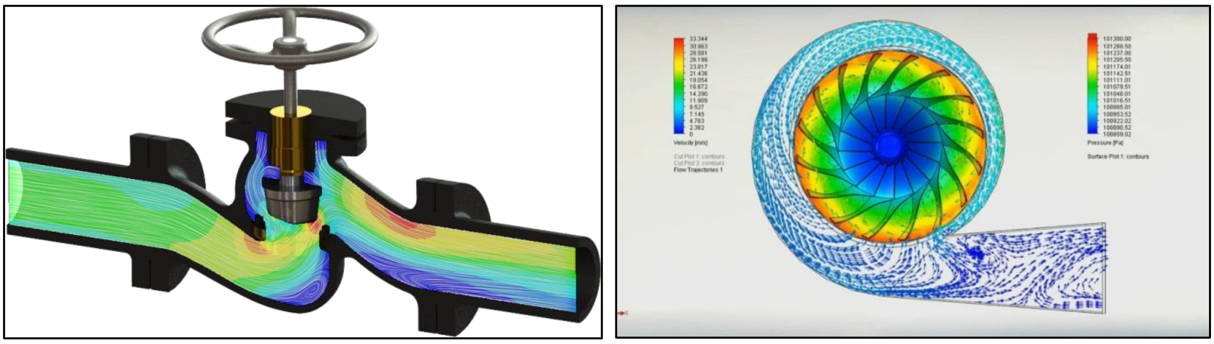

Figure 2-26: Typical illustration of SolidWorks flow simulation [76]

From Figure 2-26 it is evident that complex problems can be solved at an extremely detailed level although this will be dependent on the level of the part modelling detail.

KYPipe [77]

KYPipe simulation software aims to solve steady-state flows and pressure for pipe network systems. This software, however, is subjected to liquid flow and can only be applied to gas applications which adhere to constant density. The software package uses mass continuity and energy equations to solve for various parameters.

KYPIPE therefore serves as a better approach for hydraulic application where liquid density can be taken as a constant.

Flonex [78]

This simulation package offers the flexibility of evaluating both compressible gasses as well as incompressible liquids. The demo version, however, only allows a maximum of ten pipe sections to be added with a maximum of ten nodes.

This simulation software offers a wide variety of mining applications, unfortunately coming at a costly price.

Process Toolbox (PTB) [79]

Process Toolbox (PTB) is a thermal hydraulic simulation flow solver used to simulate various mine systems such as water reticulation systems, refrigeration systems or compressed air networks. This simulation package can accurately simulate and incorporate all the components of a compressed air network into a single simulation model. It can be used to easily identify network inefficiencies and evaluate the impact of proposed solution strategies. The compressed air pipe calculations are approached in a similar way to that discussed under the line friction losses section.

Simulation package selection

The previous simulation packages were evaluated to discuss the advantages and disadvantages of each as shown in Table 2-7 .

Table 2-7: Simulation packages evaluation

	Advantages	Disadvantages
SolidWorks flow simulator	• Accurate software • Detailed solution for specific components • Evaluates many additional parameters.	• Expensive and requires full SolidWorks simulation package • Time-consuming to model individual components
KYPipe	• Easy to use • Fairly accurate	• Not suitable for compressible fluids
Flownex	• Accurate • Has been used in mining applications	• Expensive • Only limited features in demo account
Process Toolbox (PTB)	• User friendly • Accurate for mining applications • Easily accessible	• 2- Dimensional • Fairly new to the market

From Table 2-7, Process Toolbox was selected as the simulation package for the specified study, mainly due to the accessibility thereof. This simulation package has also been used and proven accurate in various mining-related studies and is based on the fundamental principles discussed throughout this chapter [79], [80], [81].

2.4 Previous studies performed on compressed air networks

This section provides an overview on studies conducted regarding the optimisation of mine compressed air networks. To ensure the research is accurately compared and falls within the boundaries of this study, the research was evaluated on the basis of the following criteria:

- Research performed on addressing compressed air line inefficiencies
- Research performed on correlating compressed air network improvements with production increases.

Each study that falls within the boundary of the above-mentioned criteria was divided into the following discussion points:

- Title of study
- Brief overview
- Shortcomings and recommendations
- Model accuracy (where applicable)
- Experimental procedure followed (where applicable)
- Results (where applicable)

2.4.1 Addressing compressed air inefficiencies

The first research criterion of interest is that of compressed air line inefficiencies. As discussed throughout this chapter, these inefficiencies need to be identified, evaluated and addressed to ensure compressed air systems are effectively used. Numerous studies were found in literature regarding compressed air network inefficiencies and the most relevant are provided as follows:

Study 1 (2012) [23]

Title	:	An integrated approach to optimise energy consumption of mine compressed air systems
Author	:	J.H. Marius
Overview	:	The study mainly focused on identifying various methods to reduce compressed air energy consumption on deep-level mines. One such method was to reduce the leaks on the network. A substantial financial benefit was proven.
Shortcomings & Recommendations	:	Line friction losses were not investigated as part of the study and the focus was primarily placed on high level initiatives. These initiatives also solely focused on the energy saving benefit. A recommendation was made by the author to investigate the additional savings that could be realised through addressing the line losses.

Study 2 (2007) [82]

Title	:	Investigating the effects of different DSM strategies on a compressed air ring
Author	:	J.W. Lodewyckx
Overview	:	The study focused on demand side management techniques, which can be implemented to reduce the compressed air energy consumption load and in turn realise energy cost savings.
Shortcomings & Recommendations	:	The study solely focuses on energy savings and not quantifying the impact on production. It was recommended that future work be done on the control and wastage of compressed air in the underground mining environment.

Study 3 (2014) [19]

Title	:	Reconfiguring mining compressed air networks for cost savings
Author	:	J.I.G. Bredenkamp
Overview	:	The study proposed strategies to reconfigure surface compressed air networks for cost savings, which was proven to be viable when evaluating the obtained results. The author also mentions the importance of considering line pressure losses and incorporating the impact during the solution development phase of the study.
Shortcomings & Recommendations	:	The study did not quantify the effect of addressing compressed air line losses on production. It was recommended that the reconfiguration strategies be applied to the underground compressed air networks to ensure inactive mining areas are not being supplied with compressed air.

These studies primarily focused on the energy saving benefit that can be realised through optimising deep-level mine compressed air networks. Although some of these energy saving benefits are significant, it does not compare with the financial benefit of improving production through optimising these networks.

From the mentioned shortcomings there is therefore a clear need to identify, evaluate and address compressed air line losses and investigating the impact such changes has on production.

2.4.2 Correlating compressed air network performance with production

As discussed in section 2.2.3, rock penetration rate serves as the correlation between the compressed air network and production in deep-level gold mines [24], [51]. Through evaluating the effect on drill rates when compressed air networks are altered, the impact on production can be determined.

Although rate of penetration (ROP) can be experimentally measured, as done by some drill suppliers, research was conducted to determine the practical viability of underground compressed air changes on the ROP. Numerous studies were identified and evaluated according to the following criteria:

- Experimental procedure followed
- Modelling accuracy
- Final results

The aim of these studies was to evaluate rate of rock penetration under various circumstances to enable the calculation of drilling tempo. These studies are discussed below in more detail.

Study 4 (2015) [51]

Title	:	Experimental investigations on penetration rate of percussive drill
Author	:	S. B. Kivade, Ch. S. N. Murthy and H. Vardhan
Overview	:	This study focuses on experiments with the purpose of constructing an explicit equation which can be used to predict the rate of rock penetration on sedimentary rock types typically found in the mining environment.
Experimental Procedure Followed	:	The experimental procedure conducted was covered by the International Society of Rock Mechanics (ISRM). The outline of the study consisted of a pneumatically driven drill rig which was subjected to various forward thrusts, supply pressures and drill bit sizes. The rock penetration rate was measured on ten different standardised rock samples and a model was constructed.
Modelling Accuracy	:	The standard model error was found to be 0.3384 %.

Results

Equation 2-17: Predictive rate of rock penetration

$$\begin{aligned} PR \quad &= 0.0879242 + 0.0111569 \times A - 0.246978 \times B \\ &+ 0.0070986 \times C - .0000100938 \times A^2 \\ &+ 0.003057 \times B^2 - 0.00000760976 \times C^2 \\ &+ 0.0000103687 \times A \times C - 0.0000546415 \times B \times C \end{aligned}$$

Where

PR = Poisson ratio

A = Drill bit size	mm
B = Air pressure	kPa
C = Thrust	N

Study 5 (2010) [24]

Title : The energy and water required to drill a hole

Author : P. Fraser

Overview : The aim of the study focused on determining the amount of energy required for various drilling methods. The study also confirmed that compressed air operated drills are more energy intensive than other drilling methods, emphasizing the need to optimise current compressed air driven drill network.

Results : Verified rock penetration rates for a variety of drills as determined by the drill suppliers. These rates can be used as verification for other explicit rock penetration predictive models.

Study 6 (2003) [83]

Title	:	Performance analysis of drilling machines using rock modulus ratio
Author	:	S. Kahraman
Overview	:	The study correlated the modulus ratio (MR) with the rate of penetration for rotary-, diamond- and percussive drills. It was found that a strong linear correlation exists between the rock modulus ratio[6] and penetration rate for percussive drills.
Experimental Procedure Followed	:	The data of three independent drill rig investigations were evaluated, which were performed in 1970, 1972 and 1987, respectively. Rate of penetration was correlated with the rock porosity for each investigation and evaluated for accuracy.
Modelling Accuracy	:	Strong model accuracy was obtained for rock samples having a porosity value lower than 1.23%, whereas higher porosity values were excluded from the data. Additional investigation was recommended for higher porosity values and variances in drilling.
Results	:	For the discussed conditions relating to model accuracy, the three studies yielded the following equations:

Equation 2-18: Selim and Bruce (1970) - RRP vs. MR

$$PR = 0.14MR + 3.25$$

Equation 2-19: Schmidt (1972) - RRP vs. MR

$$PR = 0.014MR + 11.97$$

Equation 2-20: Howarth (1987) - RRP vs. MR

$$PR = 0.0084MR + 14.4$$

[6] Modulus ratio refers to the ratio between elasticity modulus and compressive strength of a material [83]

Study 7 (2011) [84]

Title	:	Rock drillability prediction from *in situ* determined unconfined compressive strength of rock
Author	:	V.C. Kelessidis
Overview	:	The study investigated the correlation between the rate of rock penetration and the unconfined compressive strength (UCS) of the rock. Various methods for determining the USC values were evaluated.
Modelling Accuracy	:	The model is dependent on accurate UCS data and greatly relies on the specific mining area.
Experimental Procedure Followed	:	Various indirect methods to determine the UCS values were evaluated and compared with actual tedious destructive sample tests.
Results	:	The study uses R. Teale's equation to form a rough penetration rate model illustrated by Equation 2-21.

Equation 2-21: Rock penetration rate - Based on Teale's equation

$$R = \frac{(\pi/30)(RPM)(\mu D/3)(W/A)}{\frac{UCS}{eff} - \frac{W}{A}}$$

Where

R	=	Rate of penetration	mm/s
RPM	=	Revolutions per minute	rev/min
μ	=	Friction coefficient	-
D	=	Bit diameter	m
W	=	Weight on bit	N
A	=	Bit face area	m^2
UCS	=	Unconfined compressive strength	MPa
eff	=	Efficiency of transferring	-

Table 2-8 evaluates studies 4 – 7 with regard to rock drilling penetration rates. Each study is compared with the others according to the criteria supplied in Table 2-8 to ensure an accurate model is used for correlating compressed air network performance with mining production.

Table 2-8: Study evaluation of rock penetration rate

	Study 4	**Study 5**	**Study 6**	**Study 7**
Equation/Table	Equation	Table	Equation	Equation
Number of variables	3	-	1	7
Ease of use	Easy	Easy	Easy	Complex
Model Accuracy	91% R^2 value	-	79% R^2 value	UCS dependent
Limitation	Approximate rock properties	Does not consist of variable pressure data	Only suitable for porosity below 1.23%	Does not cater for variable pressure

From Table 2-8, the model developed during study 4 was selected due to the flexibility of using this model at various pressures with the smallest number of input parameters required.

2.4.3 Critical analysis of previous studies

The previously discussed studies are summarised in Table 2-9. The aim of this summary is to highlight the focus of each specific study.

Table 2-9: Analysis of previous studies

	Study 1	**Study 2**	**Study 3**	**Study 4**	**Study 5**	**Study 6**	**Study 7**
Compressed air alteration as energy saving initiative	✓	✓	✓				
Quantifying parameters influencing drill penetration rate				✓	✓	✓	✓
Correlating compressed air network modifications to production	✗	✗	✗	✗	✗	✗	✗

From this summary table it is clear that little to no focus has been placed on the impact compressed air network modifications have on production. Limited literature was available regarding this exact topic and therefore this study aims to address this shortcoming.

2.5 Conclusion

This chapter presented an overview on mining processes, its operation and the various deep-level mine compressed air network components. Fundamental principles regarding compressed air networks were researched to enable accurate evaluation of such networks. The network evaluation specifically focused on mines with limited infrastructure.

Various simulation packages were identified and evaluated according to determined criteria. Process Toolbox was selected as an accurate simulation software package which comprises all the fundamental principles to calculate various compressed air characteristics.

The latter part of this chapter presented the findings of previous studies, focusing on compressed air network inefficiencies and the correlation of network performance against production. The rate of drill penetration, which serves as a correlation between production and drilling, was also discussed in more depth. The findings of these studies were evaluated and the models required to quantify the impact on production through compressed air network efficiency improvements were identified.

The succeeding chapters will use the information gathered through the literature review to develop a solution methodology.

3. METHODOLOGY

3.1 Introduction

This chapter focuses on developing an accurate solution methodology. Figure 3-1 illustrates a simplified layout of the developed methodology.

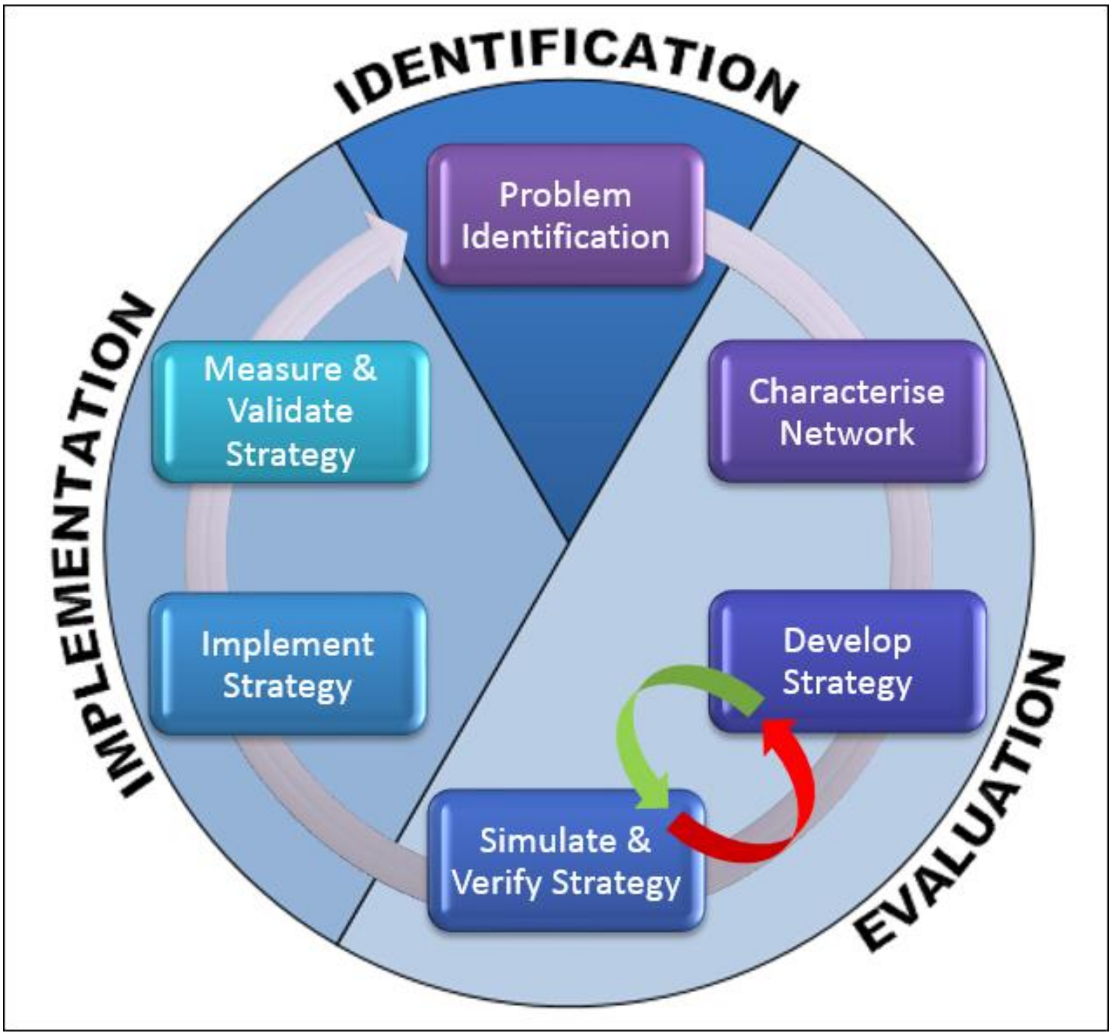

Figure 3-1: Simplified layout of the research methodology

The first step of the methodology entails identifying the problem at hand. The evaluation phase follows and focuses on characterising the compressed air system, leading to the development of a feasible solution strategy. The proposed solution strategy is then simulated and optimised to obtain theoretical results prior to implementation on a practical system. The inner detail of each step in the methodology is discussed in the following sections.

3.2 Identifying compressed air network inefficiencies

3.2.1 Preamble

Compressed air networks in the deep-level gold mining industry are intricate and difficult to investigate. Identifying an inefficiency or problem in such a dynamic environment can be extremely complicated. However, ensuring that the problem is identified correctly will ease the process of developing a solution strategy to such a problem. It is also important to define a boundary around the identified problem to ensure scope creep is kept to a minimum.

3.2.2 Root cause analysis (RCA)

The first essential step is to identify the problem at a high level to ensure focus is placed on the correct area of concern. This is done through applying the RCA technique discussed in section 2.3.2 . Answering the 5 why's successfully will give more definition to the problem at hand as well as ensure that an accurate boundary can be defined for the investigation.

3.2.3 Defining the boundary

Boundaries may range from the entire network to a specific workplace within the network. For the purposes of this study the term "network" refers to a compressed air network. Accurately defining the boundary and key performance indicators (KPIs) will enable accurate tracking of the improvements made to the compressed air network.

Figure 3-2 illustrates the three main types of boundaries when referring to deep-level mine compressed air networks. It is, however, important to note that these boundaries are interconnected with each other. Although it might be more simplified to investigate each boundary individually, the interconnecting nature should always be taken into account.

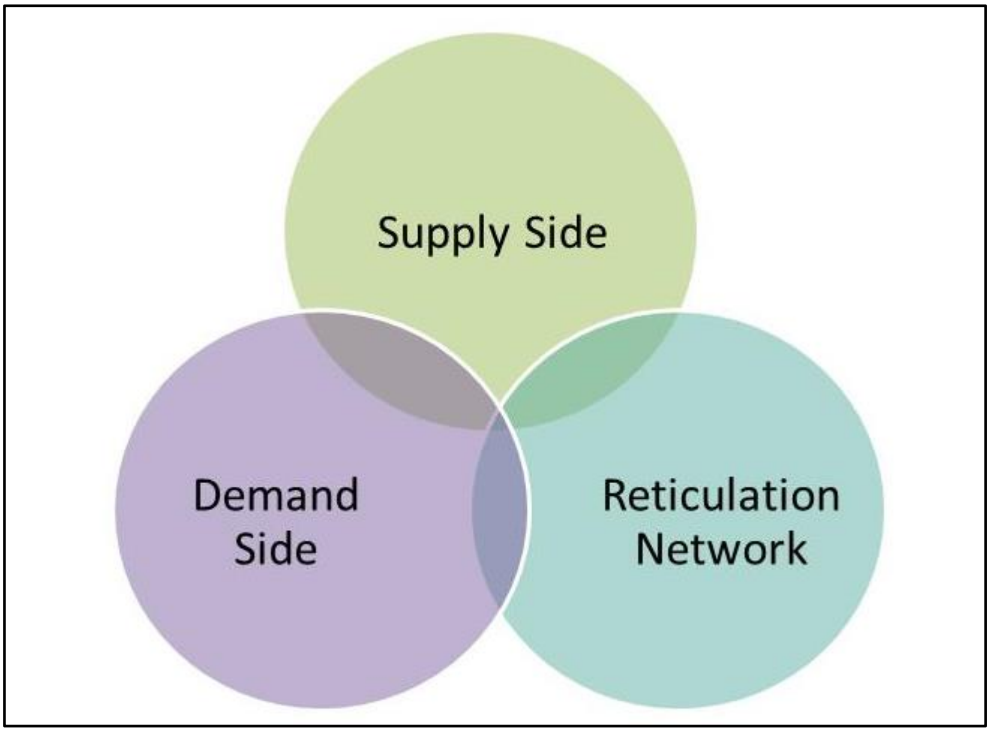

Figure 3-2: Main boundaries of a deep-level mine compressed air network

Compressed air supply side

This boundary consists mainly of the machinery used for compressed air generation. The supply side can be seen as the "heart" of the compressed air network and should be in a good working condition.

When evaluating the compressed air network, it is important that all the basic relevant information pertaining to the supply side is firstly gathered to ensure that, as will be discussed during a later stage, the required information is readily available for use. The information that is required is summarised as follows:

- number of compressor houses and their locations,
- number and type of compressors in each compressor house,
- installed capacity of each compressor (power, flow and pressure ratings),
- availability of historical data and monitoring infrastructure,
- pressure set point of each compressor,
- control capabilities of each compressor, and
- compressor availability and reliability.

This information will enable accurate evaluation of the supply side of the compressed air network. The supply side of a compressed air network tends to be static and predictable. The dynamic boundaries are the demand side and compressed air reticulation network, which are discussed in the following sections.

Compressed air demand side

The demand side of a compressed air network mainly comprises of processing plants, drill rigs, loading equipment, refuge bays and dam agitation. The following information is required when defining the demand side boundary of the compressed air network:

- number of shafts and processing plants reliant on the compressed air supply,
- point of delivery in reference with the compressor houses,
- compressed air requirements of each shaft and plant (pressure and flow),
- nature of the compressed air demand (constant or shift orientated), and
- general compressed air consumption, discipline and control measures.

The final boundary serves as a link between the supply and demand side and is discussed in the following section.

Compressed air reticulation network

This boundary can be defined as the transportation medium between the supply and demand side. In other words, it refers to the pipe reticulation network from the supply side to the demand side.

Deep-level mine reticulation networks are very large and complex and for this reason it should be approached systematically. It is important to obtain the following information:

- entire reticulation network layout (surface and underground),
- overall length and various pipe sizes of the reticulation network,
- operating limits and design specifications,
- effect of auto compression on the reticulation network,
- pipe material used and installation methods,
- ease of access to the network for flow and pressure data acquisition,
- scope to upgrade the network, and
- overall condition of the network (leaks, maintenance strategies used and development strategies.

It is important to note that a compressed air reticulation network is very dynamic in terms of network size and configuration. This means that an apparent risk is ever present for a network to gradually progress and develop outside the initial design specifications. Establishing the margin between the current state and original design specifications is crucial to enable network characterisation as will be discussed at a later stage. The next section will focus on evaluating a compressed air reticulation network of which characterisation forms an integral part.

3.3 Evaluating the compressed air network

3.3.1 Preamble

Evaluating the compressed air network entails characterising the network, developing a solution strategy for the identified problems, verifying and simulating the impact of the proposed solution strategies and optimising the strategies to be implemented. Each phase of the evaluation process is explained in more detail throughout this section.

3.3.2 Characterising the network

Measurement point identification

Identification of measurement points should follow a holistic approach. This can be accomplished through focusing on the incoming supply columns at various levels to help identify problematic levels more easily. Once the problematic levels have been identified, additional measurement points should be located prior to splits and directly after split ends to identify which side should take priority. Finally, measurement points should be placed at the start of cross-cuts (X/C) and at the far ends of each cross-cut at the point of delivery. Figure 3-3 illustrates a simplified layout of this procedure.

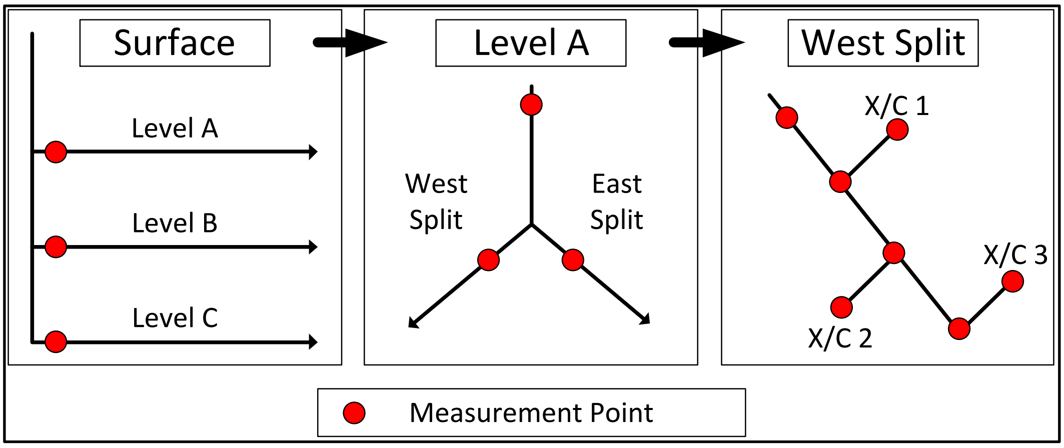

Figure 3-3: Simplified layout of measurement point identification

It is also important to take into consideration that some instruments are highly sensitive to line disturbances, for example flow meters installed downstream of a valve. Understanding the limitations of each instrument will ensure accurate data collection.

Data collection

Network characterisation includes data acquisition and effective data interpretation. The first step for collecting data on a compressed air network is to establish the existing data sources. This will indicate whether the desired identified measurement points are being monitored through an active control system (SCADA), or whether manual measurements will have to be taken (Refer to section 2.3.7). Figure 3-4 shows a process flowchart on how the data collection strategy should be approached to assist in investigating and understanding the problem.

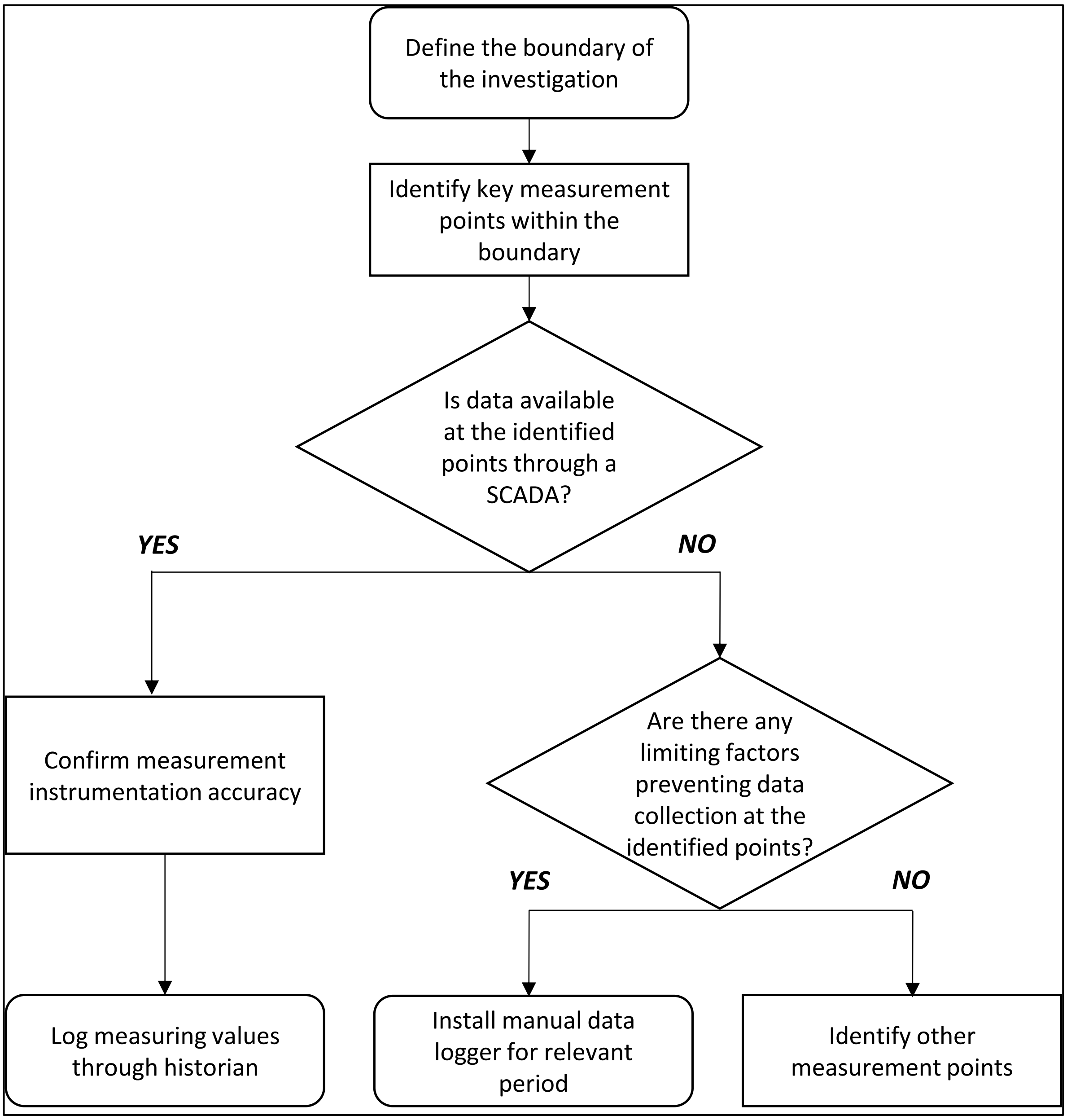

Figure 3-4: Basic data collection flowchart

Once all the measurement points have been identified and data collected, appropriate baselines can be constructed to accurately quantify the impact after a solution strategy has been implemented.

Baseline development

Baselines should be developed for each identified boundary has been investigated and will typically include baselines for power, flow and pressure, where applicable. Each baseline should represent all the key parameters within each boundary. Baselines can be divided into operational- and electrical baselines and may be explained as follow:

Operational baselines:

- Pressure (taken at each compressor outlet, common manifold or identified measurement point on the reticulation network)
- Flow (taken at each compressor outlet, common manifold or identified measurement point on the reticulation network)

Electrical power baselines:

- Power usage (Individual compressor power)

Figure 3-5 illustrates a typical 24-hour average operational pressure baseline.

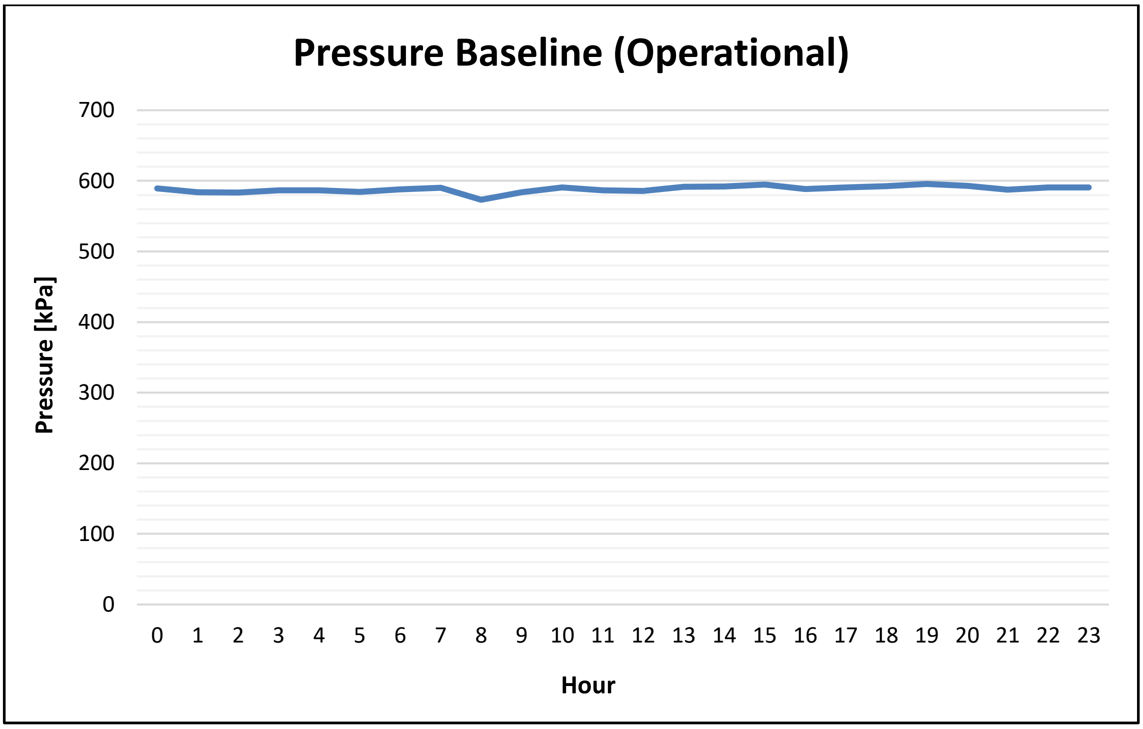

Figure 3-5: Baseline development example

Baselines for flow and power will be developed in the exact same fashion as indicated in the example of the pressure baseline shown Figure 3-5.

Baseline scaling

Baseline periods and implementation periods usually do not share the same timestamps. Numerous compressed air network changes occur between the constructed baseline period and the actual implementation date. It is, however, crucial to compare apples with apples to determine the actual impact of implemented changes. Baseline scaling is used to achieve this by using the compressor outlet flow and pressure conditions as a reference point.

Figure 3-6 illustrates this concept graphically by comparing scaled and un-scaled pressure measurements for a theoretically determined baseline.

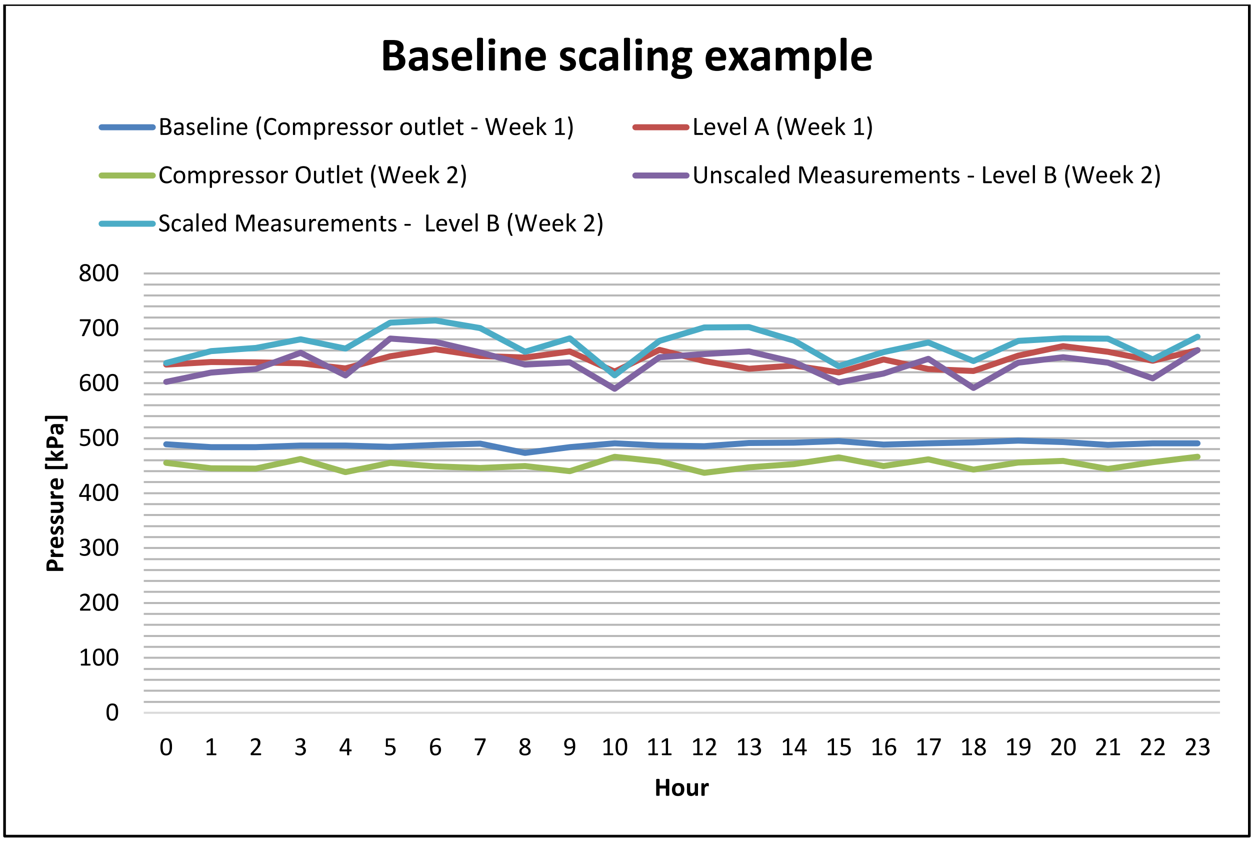

Figure 3-6: Baseline scaling example

In Figure 3-6 we see a baseline (compressor outlet conditions – discharge pressure) measured during the first week of investigations along with a pressure measurement taken at level A on the reticulation network. The investigation progresses to level B during the second week, where pressure measurements are taken on the reticulation network at level B as well as the pressure discharge end of the surface compressors. It is clear that the discharge pressure measurement of the surface compressors during week 2 differs from that of the baseline which was constructed during week 1.

The un-scaled measurements taken on level B during week 2 seem to be similar and in some cases lower than the previous measurements taken at level A. However, the measured pressure values at Level B should be scaled accordingly to account for the decrease measured at the discharge end of the surface compressors during week 2. This is done by calculating the factor by which the discharge values during week 2 differ from the discharge values measured during week 1, and adjusting the measured pressure values on level B with these factors. New scaled values are obtained for the measurements taken on level B and can now be compared to the pressure values measured of level A.

Baseline scaling therefore enables the accurate comparison between measurements taken at different time periods while accounting for system changes that might have occurred during these different time periods. From the accurately scaled baselines, solution strategies can be constructed, as will be discussed during the next section.

3.3.3 Developing a solution strategy

Evaluating baselines

The compiled baselines for each identified measurement point should be evaluated to determine where the largest impact can be made to improve the compressed air network. A baseline should therefore be present for each previously identified measurement point. These baselines are evaluated according to the specific boundaries (reference to section 3.2.3) and explained as follows.

Compressed air supply side

The baselines constructed for measurement points within the supply side boundary will indicate whether the supply is adequate for the required demand. This will be evident from the power, delivery pressure and delivery flow baselines. The delivery pressure profile will flat line in cases of sufficient compressed air supply. In case of an undersupply, an upside-down bell curve will be visible on the delivery pressure profile, especially during the peak drilling periods.

This can also be detected from the power usage of the compressors, which will show the compressors running close to the installed electrical capacity. This typical scenario is illustrated by Figure 3-7 for a compressor with the installed capacity of 5 MW.

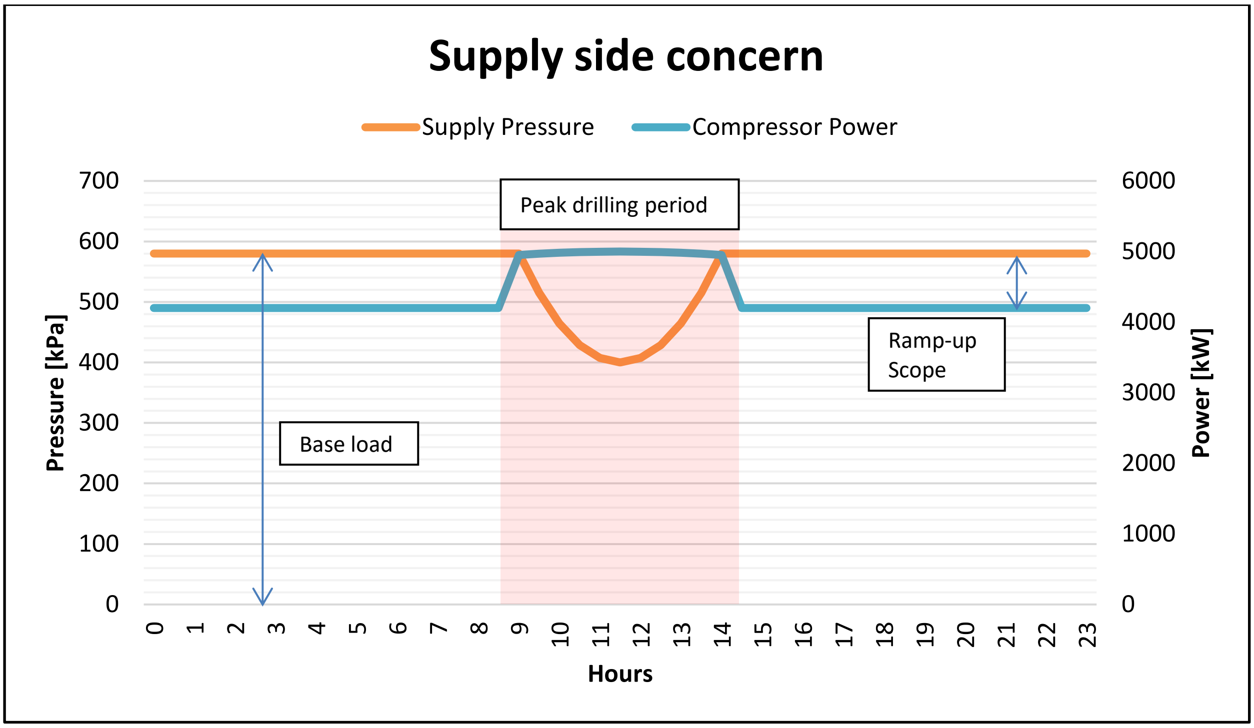

Figure 3-7: Inadequate supply of compressed air

On the supply side there are a few possible alterations which can be investigated in an attempt to match the supply with the demand. These alterations typically include

- starting up/shutting down compressors to match demand profiles,
- implementing automatic control for energy saving,
- running different compressor combinations for energy savings (manual dynamic control), or
- adjust compressor discharge pressure set points (dynamic set points).

Most of these alterations are site specific and only those available can be investigated for possible implementation.

Compressed air demand side

The demand side boundary should be evaluated by determining whether the total compressed air demand requirement exceeds the supply capacity, as was discussed in section 2.3.3. It is important to take a realistic line loss coefficient into account to determine whether the demand is exceeding the installed capacity. This can be determined by comparing the base load to the calculated compressed air requirement. If the base load is too high, compressed air abuse might be present.

Potential adjustments to reduce the demand can be summarised as follows:

- replace compressed air consuming equipment with alternatives such as hydraulic cylinders,
- ensure refuge bays are effectively pressurised and regulated,
- investigate efficiency of drill rigs,
- educate workers on the financial cost of wasting compressed air,
- revise repair and maintenance strategies, and
- employ a dedicated team to constantly monitor the compressed air network.

Compressed air reticulation network

From the daily average pressure profiles, constructed from the measurement points located on the reticulation network, it will be evident where the largest pressure drops occur. These pressure drops will be fairly constant between two measurement points on the same pipeline, indicating compressed air network inefficiencies such as leaks. Figure 3-8 illustrated a typical reticulation network baseline.

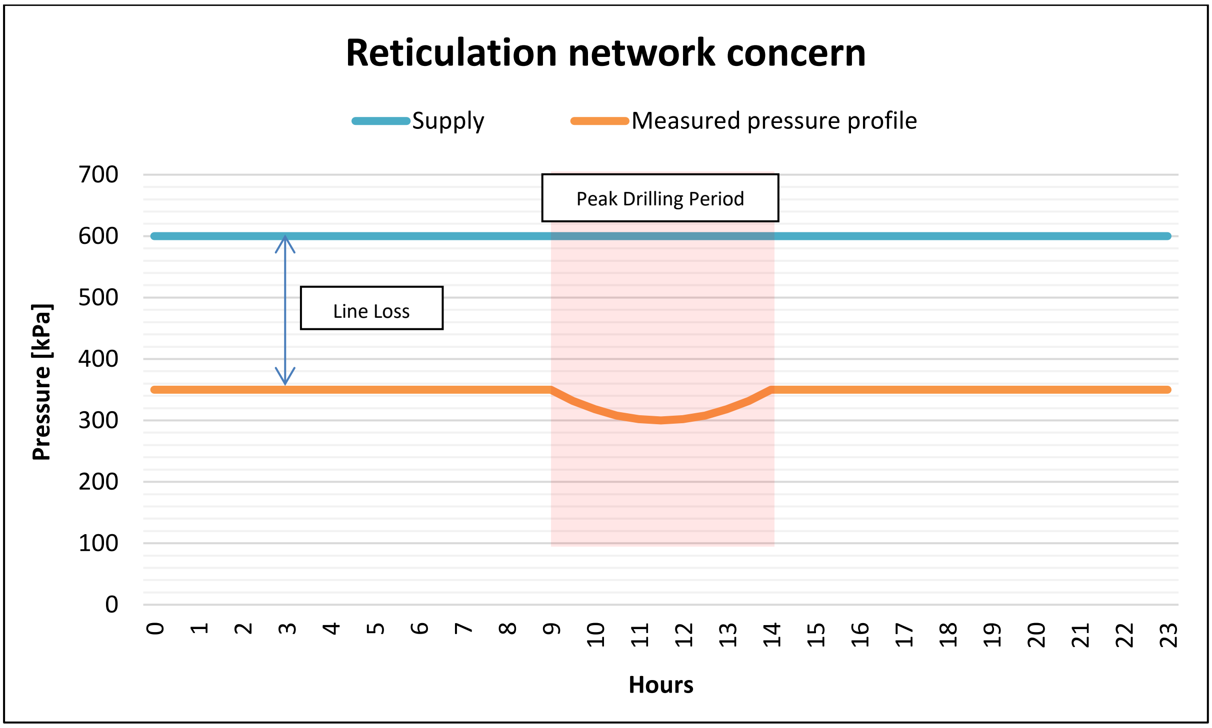

Figure 3-8: Compressed air reticulation side problem

Identified inefficiencies will be prioritised using a scoring system with reference to specific criteria as shown in Table 3-1. The highest total score will indicate where the largest potential is to optimise. The score will be assigned on a scale of 0 (minimum) to 10 (maximum) using

Equation 3-1.

Equation 3-1: Baseline score calculation

$$Score = \left[\frac{(Measured\ Value - Minimum\ Measured\ Value)}{(Maximum\ Measured\ Value - Minimum\ Measured\ Value)}\right] * 10$$

Table 3-1 will be populated for each measured pipe section within the reticulation network according to the criteria discussed below.

Table 3-1: Criteria description of prioritising inefficiencies

Criteria	Description
Pressure difference (Low – 0; High – 10)	Refers to the difference in pressure between the measured starting point of the pipe section and the measured end point.
Pipe length (Long – 0; Short – 10)	Refers to the total pipe length between the two measured points. The shorter the pipe, the larger the concern for a given pressure drop.
Nominal pipe size (Large – 0; Small – 10)	Refers to the nominal pipe size of the measured pipe section. The smaller the pipe diameter, the larger the concern for a given pressure difference.
Ease of alteration (Difficult – 0; Easy – 10)	Refers to how easily the pipe can be replaced. This accounts for accessibility, production influence and general repair.
Repair time frame (Time-consuming – 0; Quick – 10)	Refers to how long it will take to repair an identified concern. The faster the repair, the more appealing to address the problem.
Implementation/ Repair Cost (Expensive – 0; Cheap – 10)	Refers to the costs involved with repairing the identified pipe section/sections. The cheaper the repair, the more appealing to address the problem.
Total Score	Summation of the previous assigned scores.

Example

Figure 3-9 illustrates four different pipe sections. Each has a unique length, nominal pipe size as well as a different measured pressure drop.

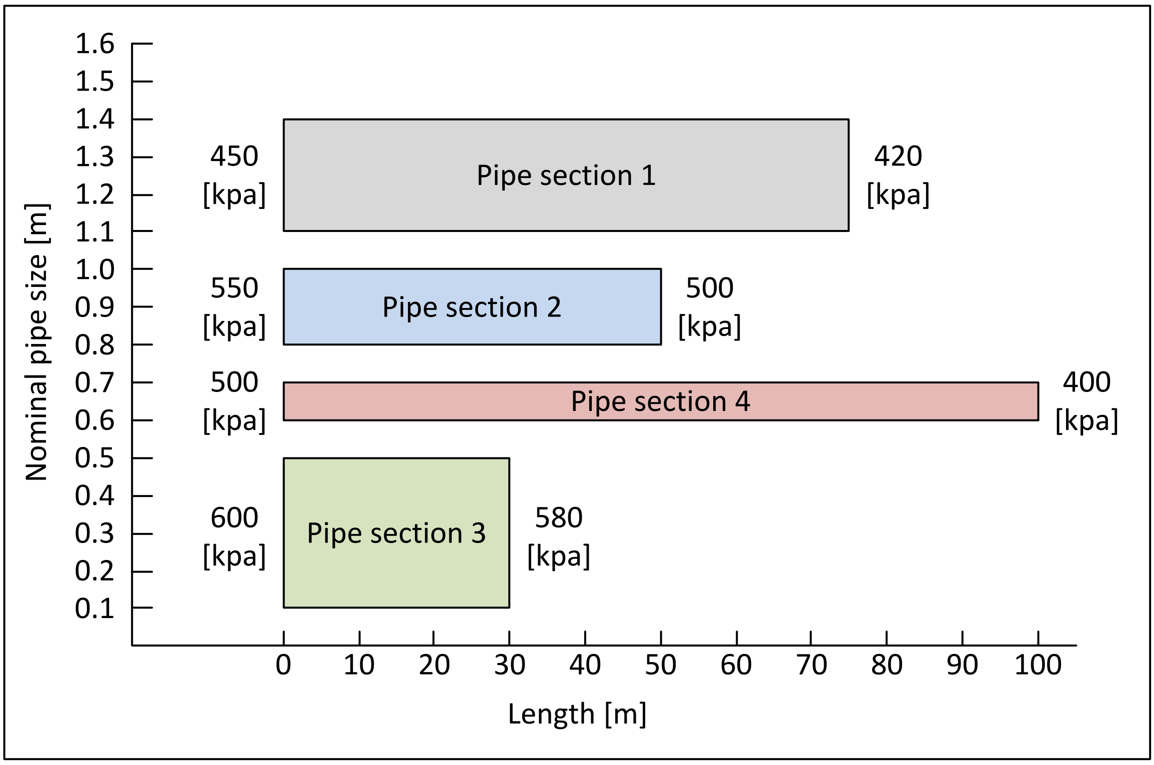

Figure 3-9: Example of various pipe sections

Table 3-1 can now be populated with the given values indicated in Figure 3-9 by using

Equation 3-1. For each criterion, the maximum and minimum values will be supplied. For pipe section 1, the pressure difference score is calculated as follows:

$$Score = \left[\frac{(\,Pressure\ Difference\ (Pipe\ section\ 1) - Minimum\ \ Pressure\ Difference)}{(Maximum\ \ Presssure\ Difference - Minimum\ Pressure\ Difference)}\right] * 10$$

$$= \left[\frac{30\ [kPa] - 20\ [kPa]}{100\ [kPa] - 20\ [kPa]}\right] * 10 = 1.25 = 1\ (rounded)$$

However, for the criteria pipe length and nominal pipe size, the score calculated using

Equation 3-1 should be subtracted from the number 10 to obtain the final score. This is done due to the smallest values in these two criteria indicating larger impact potential if repaired.

Table 3-2: Example of prioritising inefficiencies

Criteria	Minimum Measured	Maximum Measured	Pipe 1	Pipe 2	Pipe 3	Pipe 4
Pressure difference (Low – 0; High – 10)	20 kPa	100 kPa	1	6	10	0
Pipe length (Long – 0; Short – 10)	30 m	100 kPa	4	7	0	10
Nominal pipe size (Large – 0; Small – 10)	2 "	16 "	3	6	10	0
Ease of alteration (Difficult – 0; Easy – 10)	-	-	3	5	6	1
Repair time frame (Time-consuming – 0; Quick – 10)	1 Month	1 Year	2	7	4	0
Implementation/ Repair Cost (Expensive – 0; Cheap – 10)	R 100 000	R 1 000 000	3	5	7	1
Total Score	-	-	16	36	**37**	12

Table 3-2 shows that it will yield the highest impact to first repair pipe section 3 when considering each criterion

Strategy selection

Developing an effective solution strategy for the identified inefficiencies will to start with the "low hanging fruit" first. Figure 3-10 illustrates this concept with relation to the various identified boundaries.

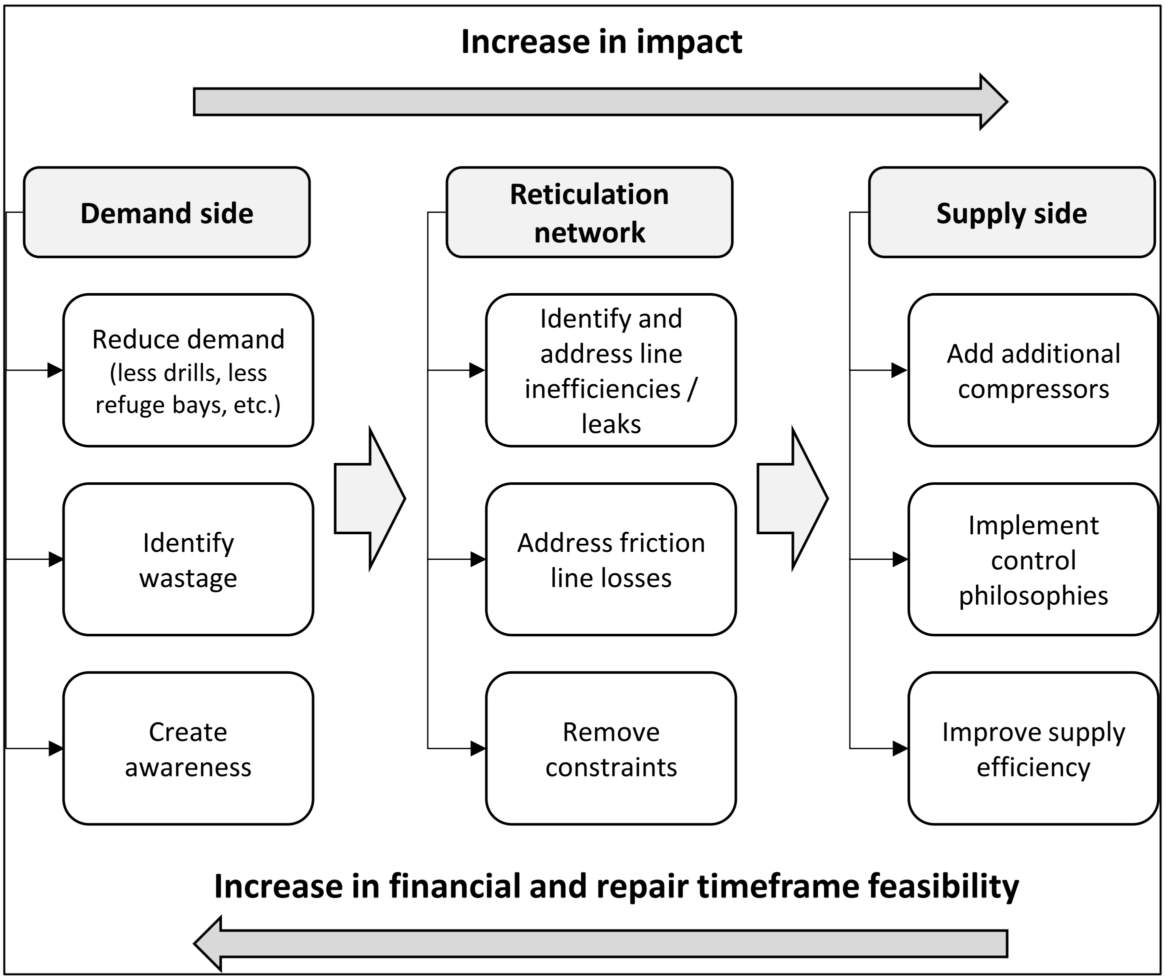

Figure 3-10: Development solution strategy overview

From Figure 3-10 it is evident that there exists an optimum solution point for financial and schedule feasibility and the potential impact of proposed solutions. This solution will typically have the largest performance impact potential at a low implementation cost and time. The developed strategy needs to be simulated and verified prior to recommending an ultimate solution as discussed in the following section.

3.3.4 Simulating and verifying the solution strategies

The aim of the simulation is to ensure the proposed changes actually result in the anticipated impact. Not all solution strategies can be simulated, such as creating awareness under mining personnel. The impact of these strategies needs to be monitored over time to establish historical trend lines, which can be used for analysis.

Simulation software

Process flow Toolbox (PTB) will be used to simulate the impact of the various proposed compressed air network alterations to assist with prioritising each accordingly. For the purposes of this study the main objectives of the simulation are:

- investigating the effect of increasing/decreasing compressed air being supplied,
- determining the effect of demand side load adjustments such as adding/removing drill rigs or reducing compressed air wastage, and
- determining the possible pressure drop decrease when replacing identified pipe sections with new pipe sizes as well as removing restrictions within the compressed air reticulation network.

The above-mentioned objectives will be dependent on the specific boundary which was selected for the investigation. The specific boundary will therefore be simulated and therefore might exclude other boundaries in the simulation.

Simulation verification

PTB will be verified through a controlled data set where all the required parameters can be measured and verified against the outputs of the simulation model. Verification is essential to ensure simulation accuracy.

3.3.5 Optimising the solution strategy

During this step, the objective will be to revise the preceding sections of the research methodology and ensure each step is diligently executed. This takes new information into account which might have been added during the execution of the methodology process.

The solution is optimised by investigating whether the implementation of the solution strategy addresses the problem identified during the root cause analysis. Should this not be the case, the simulation model will be used to investigate the requirements to successfully address the identified problem. The process shown in Figure 3-11 will be used to ensure an optimised solution is presented for implementation.

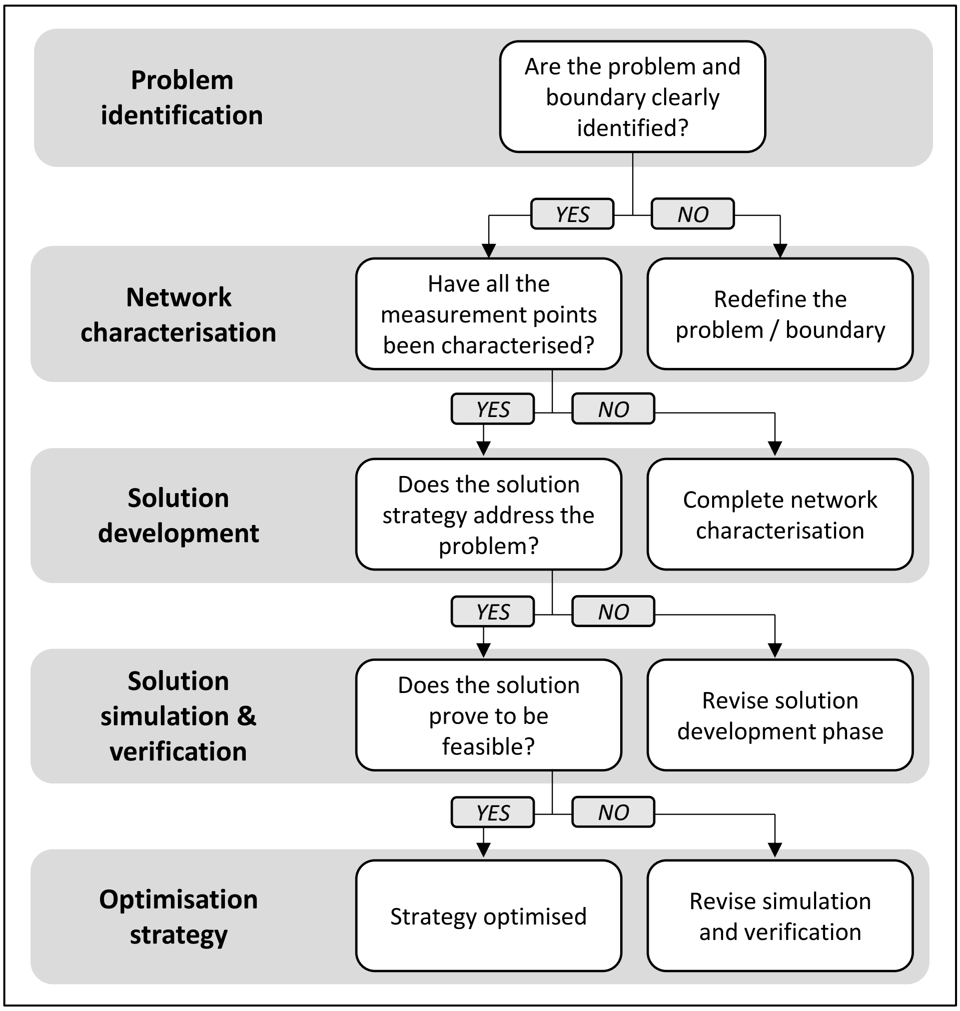

Figure 3-11: Solution optimisation process

Once the proposed solution strategy has been optimised, it can be implemented. The next section focuses on the implementation phase of such a strategy.

3.4 Implementing a developed strategy

3.4.1 Implementation

Implementation of the proposed solution strategy is subjected to several steps. Taking into account that the implementation is focused on the specific problem identified, these steps are summarised as follows.

Procurement

Procurement of required infrastructure, parts and skilled resources should be done in advance to prevent project delays. The lead time on some parts could be several months and could result in costly delays. The sourcing of required infrastructure and parts should be done timeously, approaching local markets first.

Resource allocation

Ensuring workers are planned and informed of work during allocated downtime for repairs is crucial to ensure the required personnel are available during key project times. In most cases, the resource allocation of people results in project delays due to poor planning and communication from project managers.

A detailed project plan, which clearly indicates each person’s role and expected deliverables, should be constructed. Deliverables should be divided into smaller work breakdown structures (WBS) to ensure planning occurs at a detailed level. This plan should be strategically scheduled and updated with the project progress.

Installation procedures

Installation procedures should be in place and accompanied by adequate inspection procedures to ensure high quality of completed work. Ineffective installation procedures will lead to poor performance and deterioration/failure of implemented optimisation strategies.

Logistical constraints

One of the largest challenges in the deep-level mining industry is the logistical factor of transporting the parts and equipment to the required locations for installation. This requires shaft slinging, which directly conflicts with shaft schedules. It is vital to ensure that production remains unaffected to minimise financial losses. Thorough planning in advance is therefore required for the transportation of parts and equipment.

3.4.2 Validating and quantifying the improvements

The next step is to validate and quantify the impact of the implemented solution strategy. Figure 3-12 illustrates the procedure which will be followed.

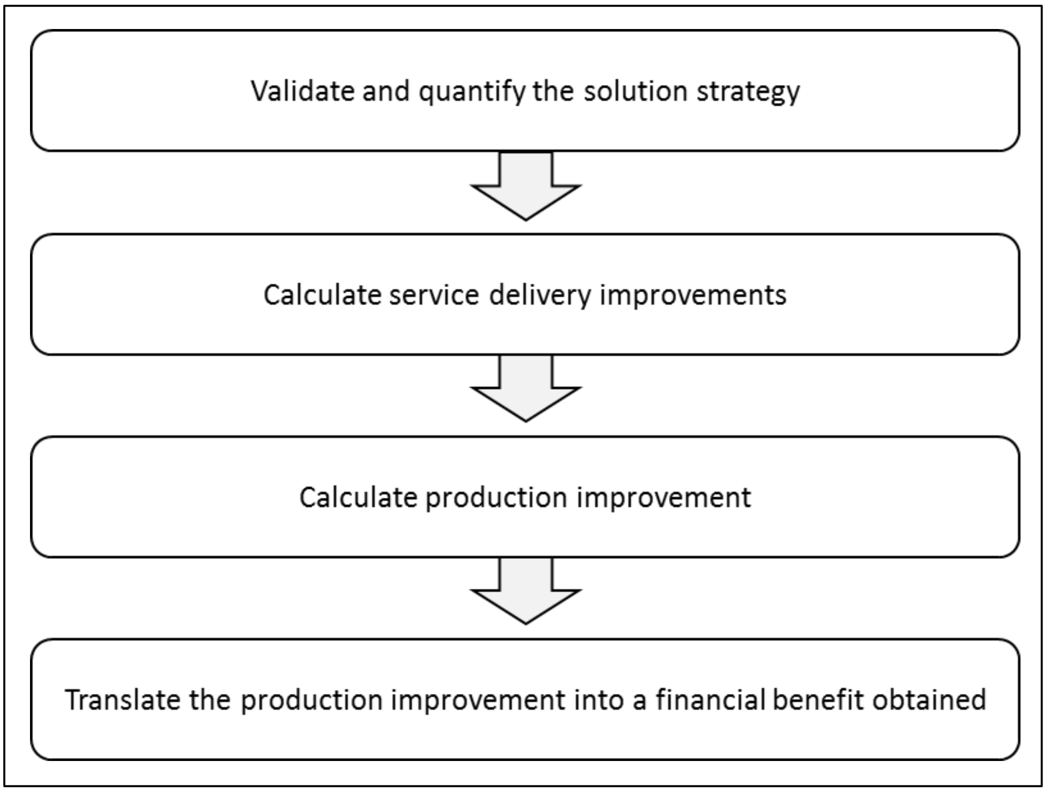

Figure 3-12: Validation and quantification procedure

Quantifying improvements

The measured data after implementation should be evaluated in the same fashion as the baseline data. The data are then compared to the baselines to quantify the compressed air network improvements. Quantification includes calculating the average improvement over a daily profile as well as during peak drilling periods.

To validate the impact of the proposed solution, the above-mentioned improvements will be compared to the simulated improvements. It is, however, important to normalise the simulated impact to the current compressed air network conditions during the comparison. This adjustment is explained for each boundary in more detail below.

Supply side

Validating the impact made on the supply side should account for compressed air demand increase/decreases. It is therefore important to monitor the demand side through pressure and flow measurements to indicate these changes.

Demand side

Validating the impact on the demand side should account for any changes on the supply side. The impact of demand side improvements should not be confused with supply side adjustments such as additional compressors running since the baseline development phase.

Reticulation network

Validating the impact on the reticulation network should account for changes on both the supply- and demand side, before and after implementation. Changes should also be considered when validating the simulated impact with the measured impact. Taking these changes into account can be done through updating the simulation model with the recent compressed air network conditions and consequently compare "apples with apples".

After the compressed air network improvements have been validated, the next step is to translate the improvements into production benefits. This basically comes down to proving the correlation between an efficient compressed air network and improved production figures on a mine. Figure 3-13 illustrates the correlation graphically.

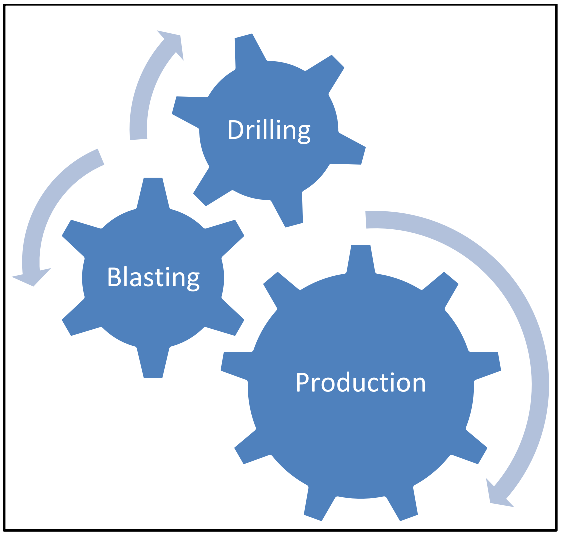

Figure 3-13: Compressed air network and production correlation

The compressed air flow and pressure supplied to the drill rigs directly influences the performance of the drills in terms of rock penetration rate. When considering a fixed drill time (shift bound), a decrease in rock penetration rate translates to a decrease in the number of holes that can be drilled during this period.

A given number of blast holes are required before blasting can commence. It is therefore evident that production will be affected if these blast hole targets are not met. An increase in drill performance will also lead to more blast holes being drilled during a shift, which directly means more tonnes get mined. There are four different scenarios to quantify the production improvement:

- amount of drilling time saved per panel,
- additional ore to be mined when saving time on drilling,
- increase of drilling targets due to saved drilling time,
- mitigating the increase in travelling time as mining progresses.

The first step, however, will be to calculate the improved rock penetration rate. This can be done by using Equation 2-17, discussed in Chapter 2. For reference purposes it is provided as follows:

$$RPR = 0.0879242 + 0.0111569 * A - 0.246978 * B + 0.0070986 * C - 0.0000100938 * A^2 + 0.003057 * B^2 - 0.00000760976 * C^2 + 0.0000103687 * A * C - 0.0000546415 * B * C$$

Table 3-3 summarises the inputs which will be required to calculate the amount of time saved, as well as the additional ore which can be mined. The production improvement should be calculated for each improved work area to determine the total impact on the mine's production.

Table 3-3: Production impact analysis inputs

Workplace Parameter	Index	Unit
Panel height	*A*	m
Panel width	*B*	m
Number of holes per panel	*C*	-
Hole depth/ drill length	*D*	m
Number of drills per panel/manifold	*E*	-
Forward advancement during blasting	*F*	m
Average drill shift	*G*	hr
Previous rock penetration rate	*H*	m/s
New rock penetration rate	*I*	m/s
Travelling times	*J*	hr
Gram gold per tonne	*K*	g/tonne
Rock density	*L*	kg/m^3
Gold price	*M*	R/g

Table 3-4 shows the calculation performed from the input values in Table 3-3. Each input and calculated value has been assigned with an index letter. These index letters represent the specific value of the input parameter or the calculated parameter used throughout the calculation process.

Table 3-4: Production impact analysis – Calculations

Workplace Parameter	Index	Calculations	Unit
Square meters	N	= A * B	m²
Total drill distance	O	= C * D	m
Total drill distance per square meter	P	= O / N	m/m²
Rock volume blasted per panel	Q	= F * N	m2
Rock weight per panel	R	= Q * L / 1000	tonne
Gold per panel	S	= R * K	g
Previous drill time per square	T	= P / H	s/m²
Previous drill time per square	U	= T / 60	min/m²
Previous drill time per square	V	= U / 60	hr/m²
Total previous drill time required	W	= U * N / 60	hr
Previous drill time per shift	X	= X / E	hr
New drill time per square	Y	= P / I	s/m²
New drill time per square	Z	= Y / 60	min/m²
New drill time per square	AA	= Z / 60	hr/m²
Total new drill time required per panel	AB	= Z * N / 60	hr
New drill time per shift	AC	= AB / E	hr
Rock penetration rate improvement	AD	= (1-(Y/T)) * 100	%
Total time saved per panel	AE	= X - AC	hr
Additional squares that could be drilled	AF	= (AE * 3600) / Y	m²
Additional holes that could be drilled	AG	= (P * AF) / D	-
Additional rock blasted	AH	= AF * F	m³
Additional rock blasted weight	AI	= AH * L / 1000	tonne
Additional gold extracted	AJ	= AI * K	g
Financial benefit of additional gold	AK	= M * AJ	R

From Table 3-4, the impact on the production output and financial benefits through implementation of the improvements can be determined. These figures will ultimately highlight the feasibility of the study.

Production data will be required to validate the calculated results, but will only serve as a guideline and should not be evaluated in isolation. Numerous factors complicate tracking the impact made on production, which include labour issues, decrease in ore deposits, new mining sites, increasing travel distances and accurately documented production tonnes.

3.5 Conclusion

A methodology was developed to optimise production through improved efficiency of compressed air networks. The developed methodology contains key components, specifically designed for mines containing limited infrastructure.

The first steps entailed a root cause analysis and clearly defining the boundaries. The next step was to characterise the compressed air network and focused on identifying key measurement points and collecting data to enable accurate baseline development. These baselines were evaluated and prioritised in terms of potential impact to ensure focus is placed on largest compressed air network inefficiencies. The potential impact of addressing these inefficiencies was simulated and a solution strategy was selected.

The final step of the methodology is to implement the developed solution and quantify the impact on the mine's production trends. Specific focus is placed on the significant financial benefits that can be realised through improving the efficiency of deep-level mine compressed air networks. Chapter 4 presents the detail on the feasibility of the developed methodology.

4. IMPLEMENTATION AND RESULTS

4.1. Introduction

This chapter focuses on the implementation of the developed methodology on a practical case study. The main aim of the case study is to prove that improving the efficiency of deep-level mine compressed air networks, comprising limited infrastructure, may result in improved service delivery and consequently improved production. The results of the implementation are presented and interpreted in detail throughout this chapter.

4.2. Case study background

4.2.1 General information

The methodology was implemented on the compressed air system of a gold mine in the Free State province of South Africa. The mine is located on the southern parts of the Witwatersrand Basin and further referred to as Mine A due to confidentiality. It has an estimate workforce of 1900 employees, including permanent contractors [85].

Mine A exercises narrow reef mining, which is a typical property of gold mines in SA. For the past three years, Mine A has had an average gold ore grade of 4.2 gram per tonne gold g/t Au [85]. This low ore grade is expected to rise to 5.26 g/t Au with the addition of the new decline, which is slightly below the average grade of 5.69 g/t Au achieved by similar operations in the nearby vicinity [85]. This current low ore grade means high volumes of ore need to be extracted and processed to secure a safe profit margin. This increased production rate highlights the drive for increase in production efficiency for Mine A.

Mine A experienced drilling problems at their active mining levels due to inadequate pressure supply from the compressed air network. This study was therefore initialised to assist in identifying the case and possible solution[7].

4.2.2 Mine A compressed air network

The compressed air reticulation network of Mine A is intricate and supplies compressed air from either compressor house 1# or 2# to the underground mining sections and a gold plant located on surface. Figure 4-1 shows a simplified surface layout of the compressed air network at Mine A.

[7] Colin Howard, Senior Shaft Engineer Mine A

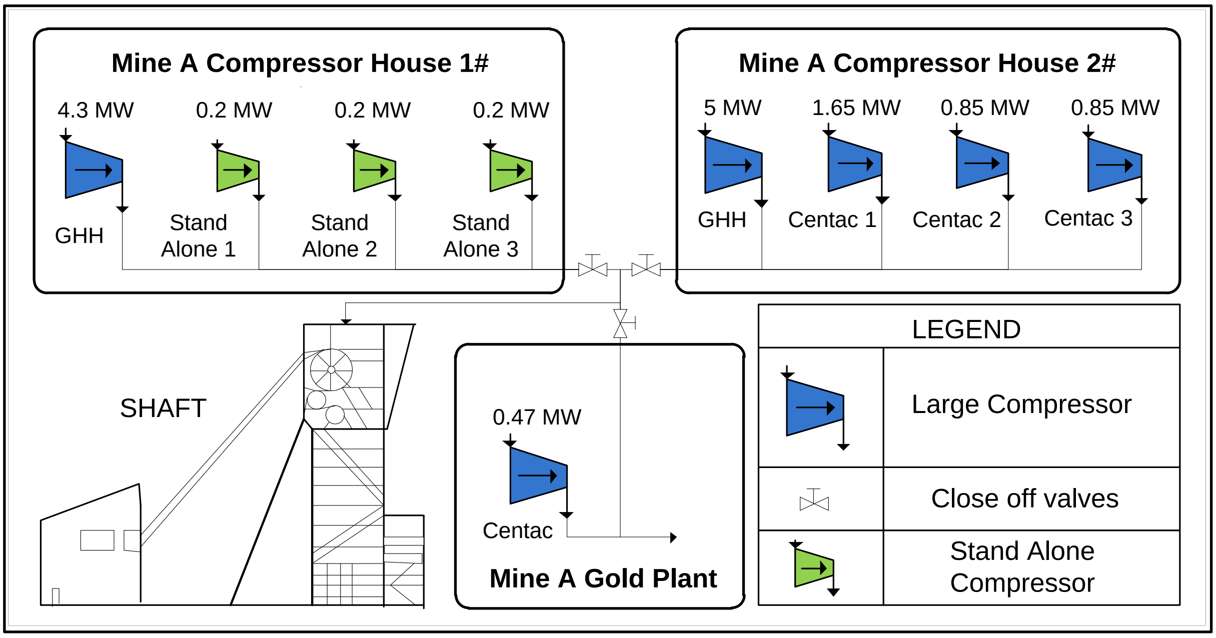

Figure 4-1: Surface compressed air network layout at Mine A

Table 4-1 to Table 4-3 summarise the installed capacities of all the compressors and their current operational status.

Table 4-1: Compressor information - Mine A 1#

Compressor	Installed capacity (kW)	Installed capacity m^3/h (cfm)	Current status
GHH	4300	50970 (30000)	Online (Ready)
Stand Alone 1	200	2039 (1200)	Online (Ready)
Stand Alone 2	200	2039 (1200)	Online (Ready)
Stand Alone 3	200	2039 (1200)	Online (Ready)

Only two of the stand-alone compressors can run simultaneously. This is due to the capacity constraints of the transformer not being able to support all three stand-alone compressors running simultaneously.

Table 4-2: Compressor information - Mine A 2#

Compressor	Installed capacity (kW)	Installed capacity (cfm)	Current status
GHH	5000	50970 (30000)	Running
Centac – 1	1650	16990 (10000)	Offline
Centac – 2	850	7646 (4500)	Offline
Centac – 3	850	7646 (4500)	Offline

The motors of Centac – 1 and Centac – 3 have been refurbished and both await final alignment and commissioning. Centac – 2 was offline at the time of the study due to problems on the compressor.

Table 4-3: Compressor information - Mine A Gold Plant

Compressor	Installed capacity (kW)	Installed capacity (cfm)	Current status
Centac – 1	470	3834 (2260)	Offline

This compressor has not been used for a while and will require maintenance to be commissioned for operation again. All of the above-mentioned compressors supply the same compressed air pipe network, forming a large supply loop.

From Figure 4-2 it can be seen that compressed air is either supplied from 1# or 2#, depending on compressor availability and maintenance schedules. A basic side view of the compressed air pipe layout is shown in Figure 4-2.

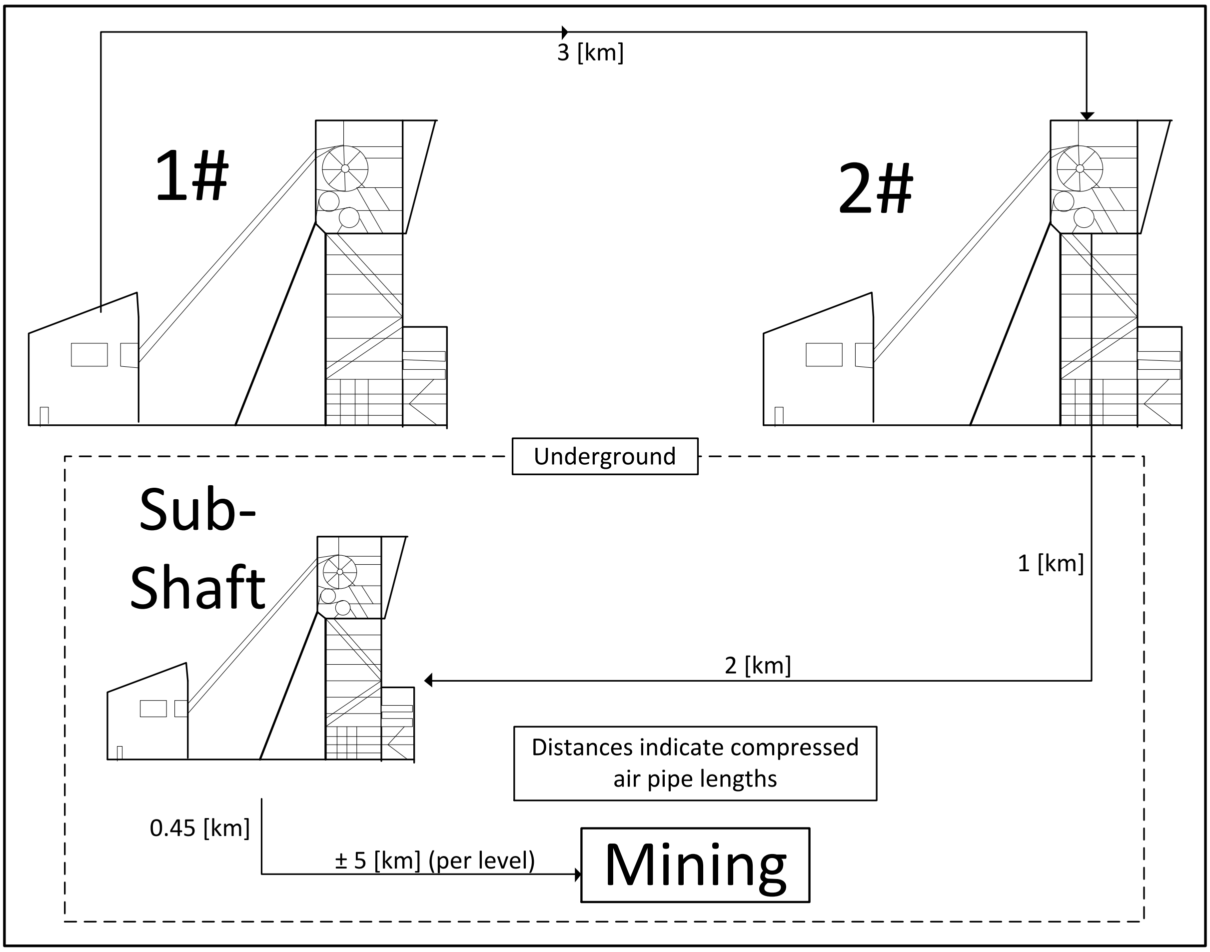

Figure 4-2: Side view of the pipe reticulation network at Mine A

Only 2# at Mine A is equipped with the required infrastructure to accommodate large compressed air columns. Therefore, all compressed air used underground is supplied by means of 2#. This leads to the compressed air network being inefficient, especially when the compressors at 1# are used. The compressed air needs to travel a long distance (from Figure 4-2) to the working places since the mining activity occurs closer to the sub-shaft of 1#.[8] [9]

Mining currently reaches depths of up to 1450 m at Mine A, and will increase in the future with the added decline project [85]. This contributes to the complexity of the underground compressed air reticulation network. Figure 4-3 illustrates a simplified layout of the various underground mining levels at Mine A, which form part of the compressed air reticulation network.

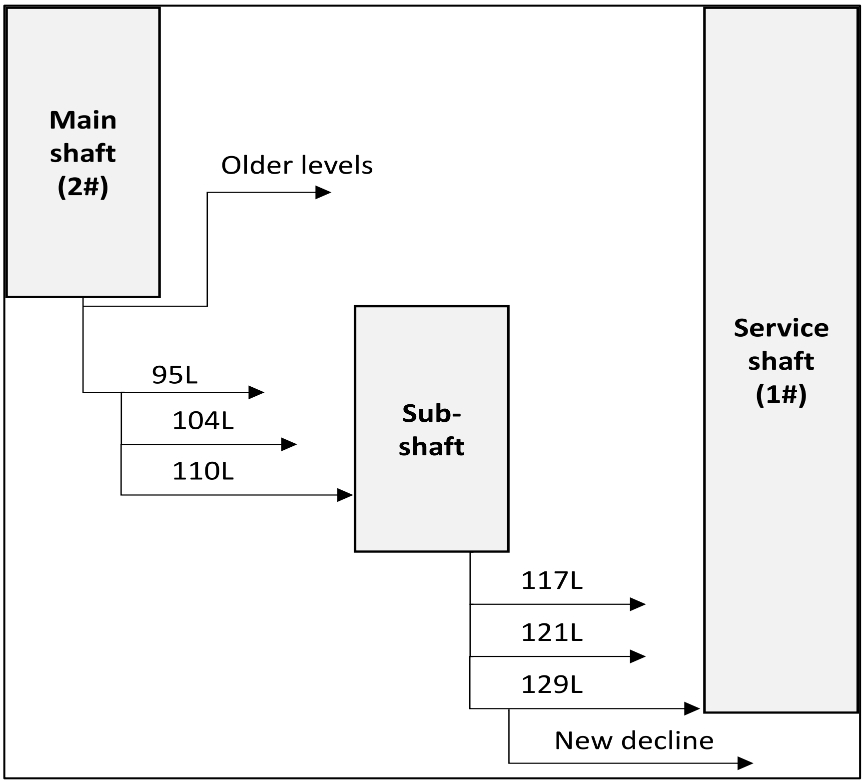

Figure 4-3: Underground level layout at Mine A

The active mining levels are 121 level (L) and, more dominantly, 129L. The latter also contains the newly developed decline. The levels from 95L to 117L are known as the older levels and have already been mined to their full capacity. Compressed air pipe sections supply compressed air to each level. Compressed air is supplied down the shaft and through 95L and 110L to the sub-shaft. From the sub-shaft, compressed air is supplied to 117L, 121L and 129L.

[8] Colin Howard, Senior Shaft Engineer Mine A, 2017/07/03
[9] Robert Holmwood, Senior Consulting Engineer Mine A, 2017/07/03

4.3. Identifying compressed air network inefficiencies

4.3.1 Root Cause Analysis

The first step was to identify the inefficiencies and root cause. Mine A experienced compressed air pressure supply challenges at their active mining levels. This directly influenced production targets due to inadequate pressure being supplied to the drill rigs. As stated during the literature study, these rigs operate ideally on a pressure supply of 500 kPa. An investigation was initiated to identify the root cause of the pressure supply shortfall and prevent Mine A from starting another compressor without knowing whether it will solve the problem.

Figure 4-4 indicates how the root cause analysis method was applied through asking the "why" question consecutively.

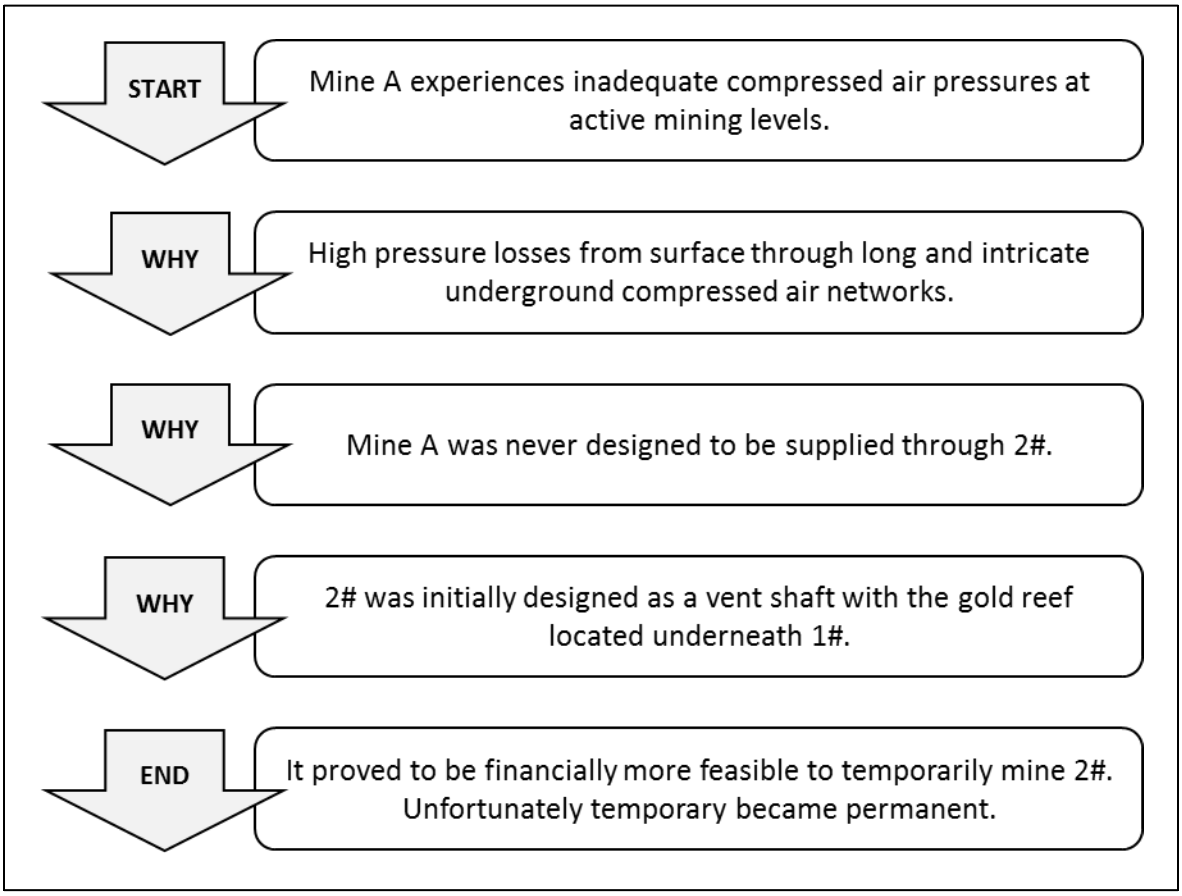

Figure 4-4: Root Cause Analysis - Mine A[10][11]

[10] Colin Howard, Senior Shaft Engineer Mine A, 2017/07/03
[11] Robert Holmwood, Senior Consulting Engineer Mine A, 2017/07/03

The root cause analysis delivered an interesting discovery through indicating that the low-pressure levels at the drill rigs are a mere result of the extensive compressed air network. This extensive network resulted from the fact that 1# was the intended main shaft and led to the compressed air network at Mine A becoming extensive and under designed as shown in Figure 4-2.

The root cause of this inefficiency cannot be directly addressed in the near future. Large capital investment will be required to fully equip 1# with a compressed air supply line, making this a long-term project. To assist in identifying short-term solutions to the inefficiency, boundary selection was performed to ensure focus is placed in the correct area. These boundaries are discussed in the following section.

4.3.2 Defining the boundary

Figure 4-5 represents the constructed surface baseline for flow and power for a week of the GHH compressor (refer to Table 4-2) located at 2#. Note that the primary and secondary y-axes represent the installed capacity in terms of flow and electrical power, respectively.

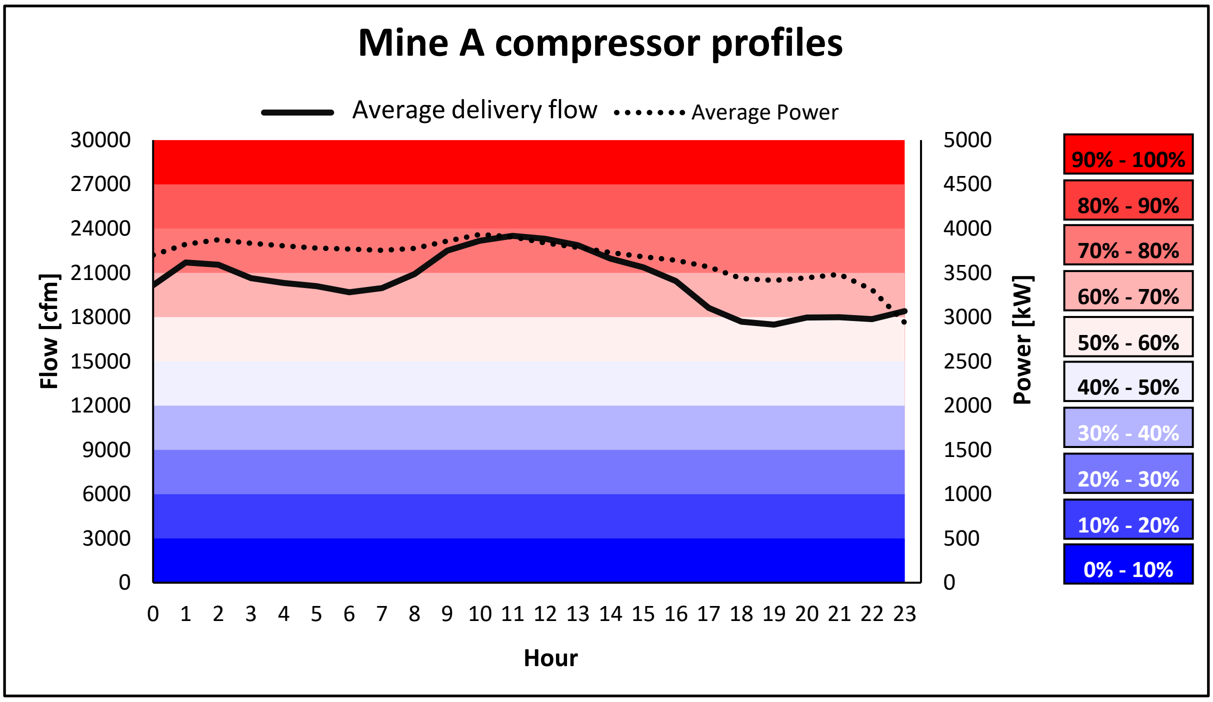

Figure 4-5: Mine A compressor flow and power profiles

Figure 4-5 shows that the compressor rarely runs above 80% of its installed flow/power capacity. This is an indication that sufficient compressed air flow is supplied to the demand side of Mine A. The surface pressure baseline is indicated by Figure 4-6 which was constructed during the same week as Figure 4-5.

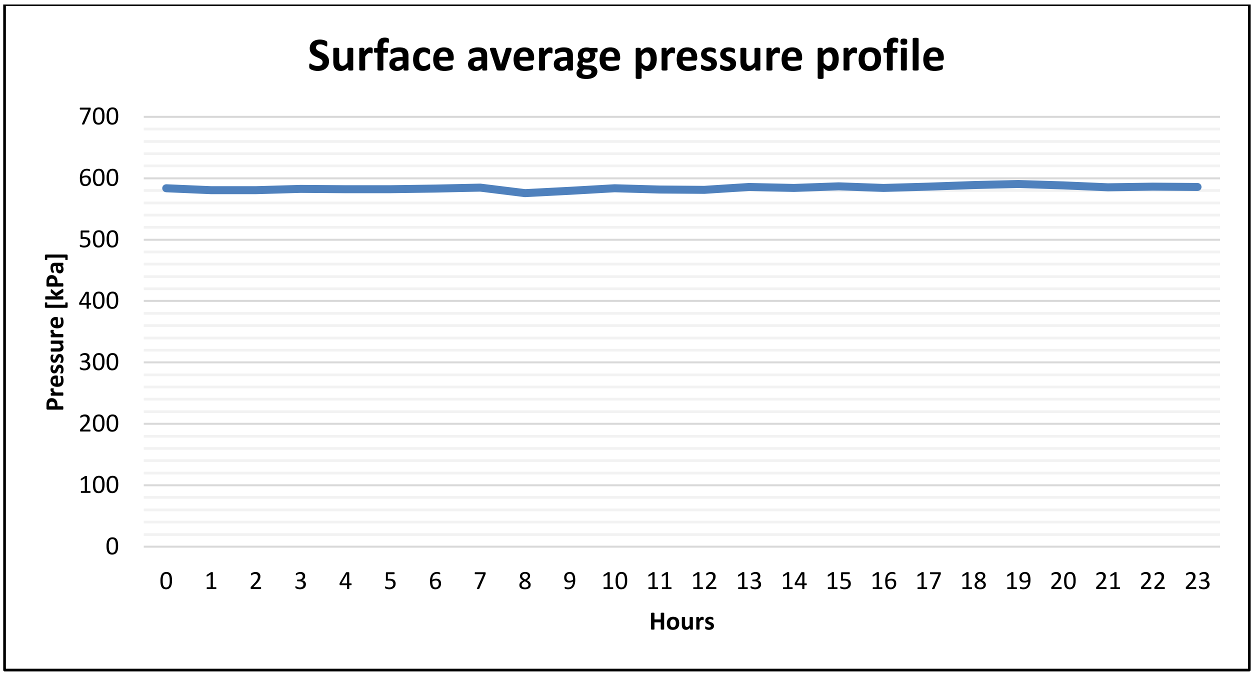

Figure 4-6: Mine A average compressor discharge pressure profile

Figure 4-6 further supports this theory of adequate supply when looking at the flat compressor discharge pressure profile. In cases where the supply is a problem, the discharge pressure profile will consist of larger pressure drops, specifically during peak drilling periods. The supply side boundary was therefore excluded from the boundary of investigation.

Demand side

The next boundary to be defined is that of the demand side. Mine A consists of a wide variety of compressed air users. These various users and their specific compressed air requirements are summarised in Table 4-4.

Table 4-4: Mine A compressed air demand side summary[12]

	Shaft	Gold plant
Quantity	1	1
Average pressure supply @ Compressor house delivery	560 kPa	560 kPa
Consumers	Drills, Refuge Bays, Workshops, Loading Boxes, Tips etc.	Agitation, Workshops
Delivery depth (current maximum below surface)	1450 m	0 m
Required pressure	500 kPa	500 kPa

[12] Frans Saunder, Mine A Optimisations Manager, 2017/07/17

	Shaft	Gold plant
Required Flow	28 000 m³/h – 40 000 m³/h Shift orientated	1600 m³/h
Discipline Issues	Used occasionally for cooling	Good
Number of drills	± 155	0
Number of refuge bays	8	0
Number of loading boxes	± 15	0
Number of tips	3	0

With the information listed above, a detailed analysis can be performed to investigate whether the demand exceeds the maximum possible supply. This detailed analysis can be seen in APPENDIX J. This analysis showed that the demand should reach a maximum compressed air requirement of approximately 38 000 m^3/h. This indicates that demand does not exceed the possible supply, which is 51 000 m^3/h.

Mine A is a fairly cool mine, due to the current low depths at which mining starts in comparison to other, much deeper mines. However, the mine does not consist of a dedicated return air way (RAW), which means old workplaces are used as a return for hot air. It is normal to suspect compressed air wastage will be present in these cases, however, workers aim to hide this during inspection. Although such cases might exist, it is only temporary and was not noticed during the compressed air audit. It can therefore be concluded that the demand side boundary at first glance does not seem to be the problematic area.

With the demand side boundary now clearly defined, the final boundary, namely reticulation network, can be investigated. This is an extensive boundary which should be approached systematically. This final boundary is discussed in the following section.

Compressed air reticulation network

As mentioned previously, the compressed air reticulation network is a complex network of pipes, stretching over several kilometres and varying in size. Table 4-5 summarises all the relevant information regarding this network.

Table 4-5: Mine A reticulation network summary

	Reticulation network		
Total Length	±12 000 m		
Pipe sizes	14", 12", 10", 8", 6", 4", 2"		
Pipe material	Steel pipe (10" >)	Victaulic grooved (4" to 8"),	Plastic hose (2")

	Reticulation network		
Installation methods	Flanges with gasket	Grooved Coupling	Quick Coupling
Auto compression	Applicable to underground levels		
Operating pressure	300 kPa – 700 kPa		
Upgradability	Easier on lower levels due to smaller pipe diameters and section isolation capability. On larger incomers, it is very difficult and costly.		
Monitoring infrastructure	None		
Maintenance strategies	Replaced on failure. Clamps used for leaks.		
Development strategies	Incoming pipe sizes at levels and main haulages – 8" Pipe sizes used in cross-cuts – 6" Pipe sizes used from crosscuts to stope – 4" Pipe sizes used to supply from stope manifold to drills – 2 "		
Leak quantification strategy	No active leak identification or quantification strategy implemented.		

The detailed reticulation network layout of Mine A, including all the relevant levels, is found in APPENDIX I. The layouts were separated to improve the visibility. This will entail taking measurements to accurately classify specific problematic areas for the selected boundaries.

4.4. Evaluating the compressed air network

4.4.1 Network Characterisation

One of the biggest challenges at Mine A is limited infrastructure in terms of instrumentation and communication to equipment. No active SCADA system is in place, which results in poor to no historical data. Alternative means of data collection had to be used to ensure that the compressed air network inefficiencies within the selected boundaries are identified.

Measurement Point Identification

Figure 4-7 illustrates the measurement points (A-G) that were identified to establish the pressure losses from the supply to the point of use. These points served as an initial indication of where the largest pressure losses occurred. It is important to note that the whole compressed air network was still investigated to confirm whether large leaks or tap-off points existed at non-active mining areas. Points F and G where chosen while these areas represent the majority of the mining activity.

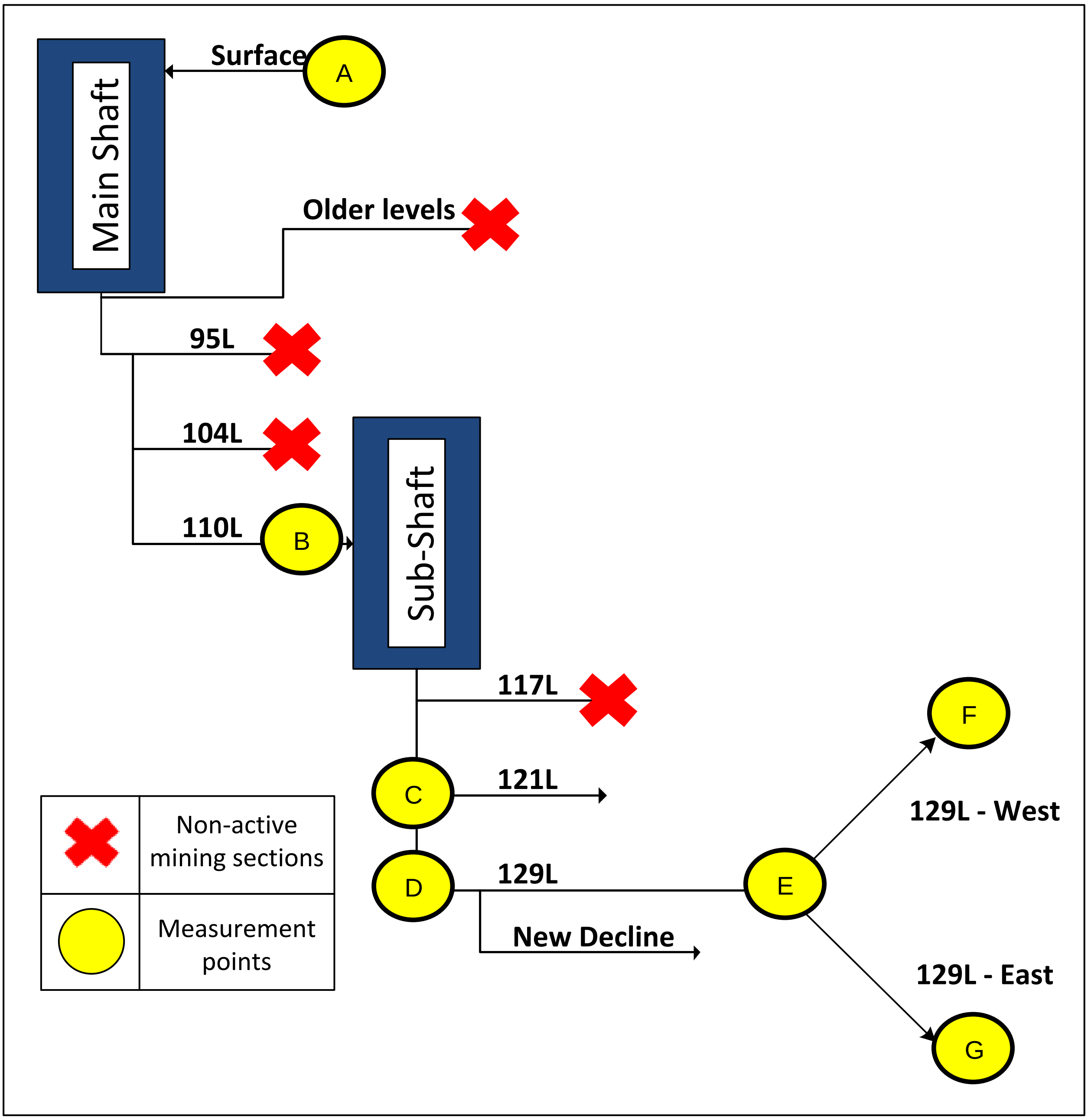

Figure 4-7: Simplified layout of measurement points

The problematic areas were identified by evaluating the pressure drops between points (A - G). Measurements were taken at the level incoming pipes, main split between the east and west haulages as well as at the end points of individual haulages. The detailed layouts of the various levels can be found in APPENDIX I.

The identified measurement points ensured that the investigation could be performed in the shortest time, while also using the minimum amount of measurement instrumentation. Implementing this approach ensured that focus was placed firstly on the most critically affected areas in terms of service delivery to ensure the solution strategy results in maximum impact.

Data collection

The investigation process was conducted over a period of time due to the limited monitoring infrastructure at Mine A. Historical data could not be analysed for compressed air pressure or flow and data were collected through measurements that were taken at strategic locations with the help of portable measurement instrumentation. However, Mine A had historic power data available on their compressors. These data were captured by a third-party metering company and could be accessed through a web-based platform.

Unfortunately, flow measurements could not be obtained for all the identified points where data are required. This is due to the lack of measurement points, instrumentation availability and power supply. For these cases only pressure was measured, which was used to evaluate pressure differences between measurement points.

Constructing a baseline

Baselines were constructed from the measured values and processed into daily average pressure profiles. The identified measurement points could not all be measured simultaneously. This was due to the absence of physical measurement points, which needed to be installed during pre-allocated shutdown periods.

Table 4-6 summarises the dates of the measurements that were taken. These dates were dependant on accessibility, installation of measurement points and portable instrumentation availability.

Table 4-6: Summary of measurements

Location	Start Date	End Date	Total Days Measured	Full Days Measured
Surface	2016/05/13	2017/02/15	42	33
110L	2016/05/13	2016/05/20	8	6
121L (Station)	2016/05/11	2016/05/20	10	8
129L (Station)	2016/05/25	2016/06/02	9	7
129L (Split)	2016/05/25	2016/06/02	9	7
129L (W6)	2016/06/08	2016/06/15	8	6
129L (E8)	2016/06/08	2016/06/15	8	6
129 (Split) - Old	2016/07/29	2016/08/04	7	5
129 (E8) - Old	2016/07/29	2016/08/04	7	5
129 (Split) - New	2017/03/29	2017/04/05	8	6
129 (E8) - New	2017/03/29	2017/04/05	8	6

The absence of measurement points greatly affected the time-frame of the investigation and meant all measured data had to be translated to a common reference point to ensure accurate comparisons. The reference point was chosen to be the surface conditions due to the ease of obtaining data.

The data of the running compressor were used to compile a “reference” baseline. The baseline was developed for two main reasons:

- Compiling a historian to better characterise the surface compressors.
- Enabling accurate comparisons of measured values taken underground at different times, intervals and places.

Figure 4-8 illustrates the measured delivery pressure of the surface compressors which were measured during the investigation periods as shown in Table 4-6.

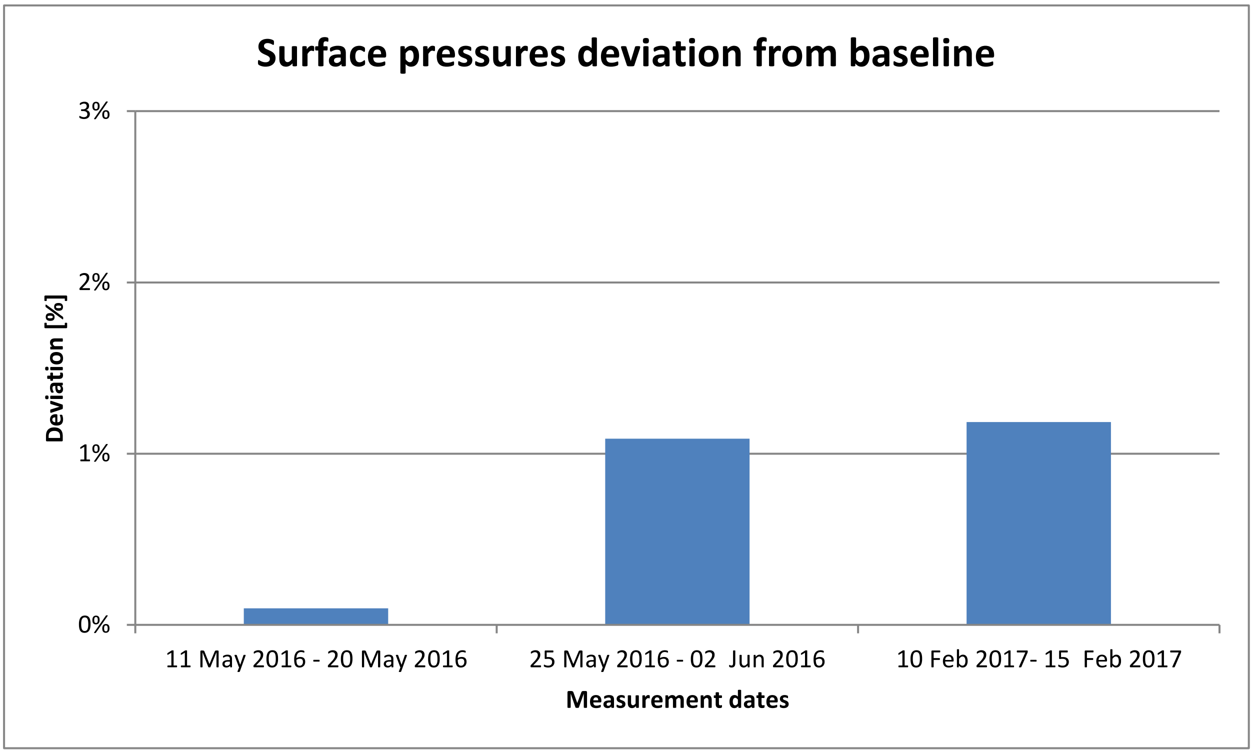

Figure 4-8: Surface average pressure deviation from baseline profile

It is evident when evaluating Figure 4-8 that the pressure profile was fairly constant on surface throughout the investigation. This enables the comparison between levels without the need of scaling measured values.

Figure 4-9 shows the average pressure profiles of all the measured data summarised in Table 4-6. The baselines for each identified measurement point can be found in APPENDIX G.

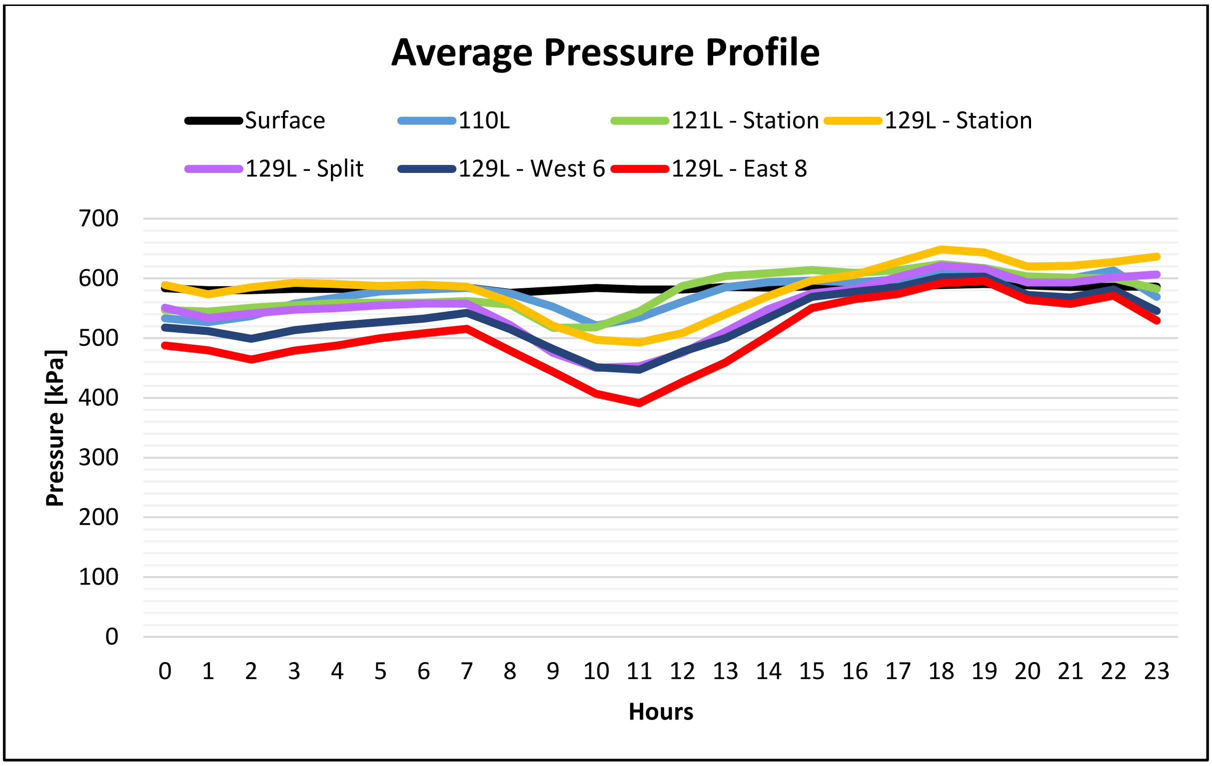

Figure 4-9: Combined Average Pressure Profiles

In Figure 4-9, the large pressure drops during peak drilling periods (09:00 to 14:00) are clearly visible. From the baselines, the largest pressure drops could be evaluated and quantified and led to the development of a solution strategy.

4.4.2 Solution Strategy

The aim was to develop a feasible solution strategy which will have the highest possible impact for the least amount of money and time. This impact refers to a solution strategy that will yield the maximum potential improvement in terms of service delivery and, in turn, production.

Evaluating Baselines

During evaluation of the baselines it was found that both demand and reticulation inefficiencies exist.

The demand side pressure drop occurs fairly constant during the same periods of the day, namely peak drilling periods. This indicates that the reason for the high demand is production driven and not wastage. The focus was therefore shifted to investigate possible inefficiencies on the reticulation network. Addressing these inefficiencies will result in lower pressure drops which will lead to improved service delivery. Table 4-7 prioritises the obtained scoring value for the baselines constructed.

Table 4-7: Case study A - Baseline scope prioritisation

Criteria	Surface to 110L	110L to 121L Station	121L to 129L Station	129L Station to Split	129L Split to West	129L Split to East
Pressure difference (Low – 0; High – 10)	1	1	0	4	7	10
Pipe length (Long – 0; Short – 10)	0	10	10	10	9	9
Nominal pipe size (Large – 0; Small – 10)	0	8	8	8	8	10
Ease of alteration (Difficult – 0; Easy – 10)	1	1	1	10	9	9
Repair time frame (Time-consuming – 0; Quick – 10)	1	2	3	4	9	10
Implementation/ Repair Cost (Expensive – 0; Cheap – 10)	1	1	1	8	10	10
Total Score	4	22	22	44	51	58

From Table 4-7, the baseline constructed for the far end of the east haulage on 129L proves to have the highest impact potential. This indicates that focus should be placed on this pipe section.

Strategy Selection

From the baselines and prioritisation exercise it was clear that the east haulage on 129L should be investigated in more detail. The East haulage was found to have various compressed air pipe sizes installed. These various pipe sizes contributed to the pressure losses over this section. Figure 4-10 illustrates the pressure baseline profile which was constructed during the investigation.

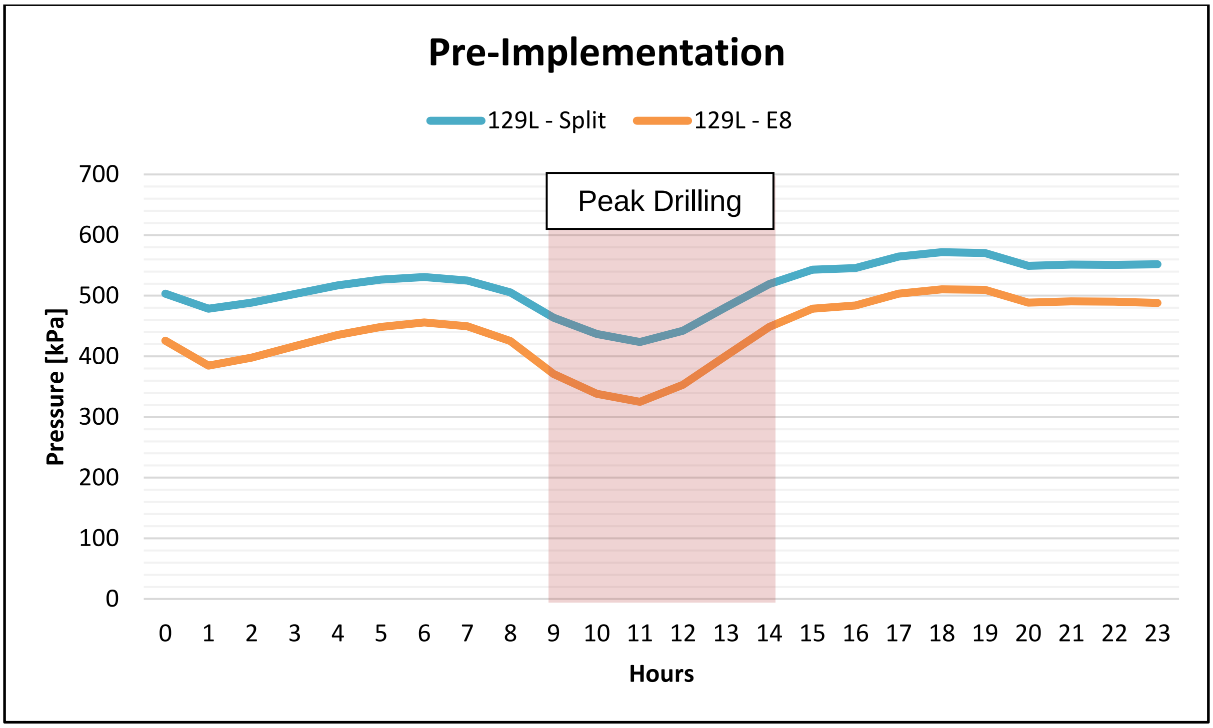

Figure 4-10: 129L - East haulage average pressure profile

Figure 4-10 indicates a large pressure drop between the two measured points. The average pressure at the east 8 haulage was recorded to be 438 kPa. Table 4-8 summarises the pressure drop values measured from the start of the east haulage compressed air pipe split up to the end of the east haulage before any replacements have been made.

Table 4-8: Baseline pressure drop measurements

Baseline	Pressure Drop
Daily average	76 kPa
Average during peak drilling	87 kPa
Daily max	99 kPa
Daily min	60 kPa

It was proposed to replace the 6" pipe sections with 8" pipe sections. This replacement would include leak repair and removal of pipe restrictions such as incorrect air valves and t-pieces. Figure 4-11 illustrates a simplified layout of the east haulage compressed air pipe section that was investigated. Please refer to APPENDIX C for detailed photos pertaining to Figure 4-11.

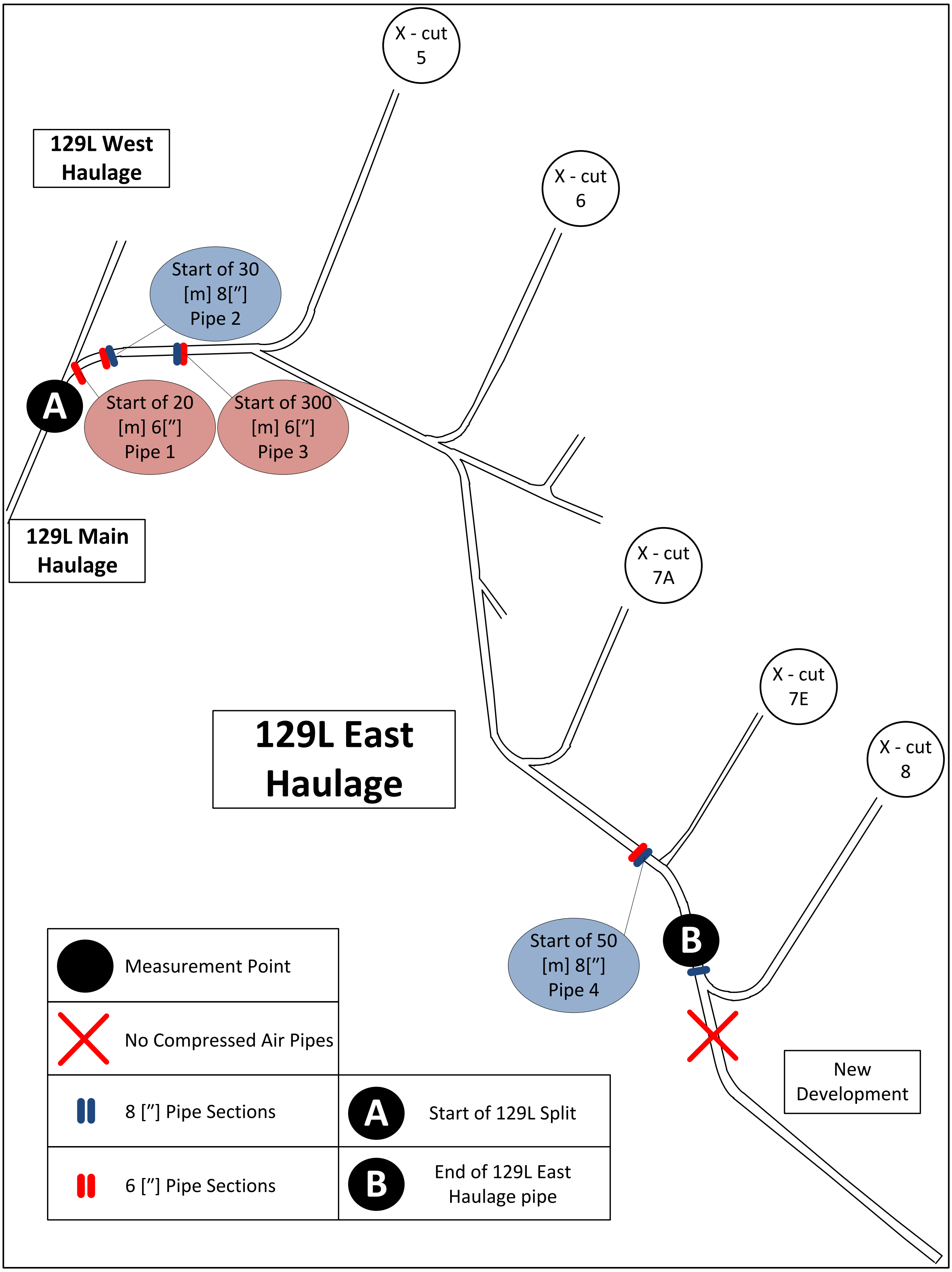

Figure 4-11: 129L East haulage layout

4.4.3 Simulation and verification strategy

The proposed solution strategy was required to be simulated. The purpose of this simulation was to first investigate the potential service delivery improvement that can be expected when replacing the appropriate pipes before recommending it to Mine A's personnel.

The developed PTB simulation model had to be verified to ensure the model is accurate. This verification entailed using existing pressure and flow data to calibrate the model accordingly and ensure the simulated values correlate to actual measured values. For this calibration, Mine B was selected and yielded a calibration accuracy of 92%. The detailed verification procedure and results are provided in APPENDIX H.

The potential impact of changing the 6" pipe sections to 8" pipe sections was simulated with the calibrated PTB simulation model. The basic layout of the simulation model is available in APPENDIX A.

Simulated Solution Strategy

The following steps served as a guideline during the simulation process:

- ***Step 1***

The first step was to simulate the compressed air flow from the constructed pressure baselines. Table 4-9 summarises the input parameters for this simulation step with a surface roughness selected equivalent to a lightly rusted steel pipe.

Table 4-9: PTB simulation inputs - Step 1

	6" Pipe 1	8" Pipe 2	6" Pipe 3	8" Pipe 4
Pipe length	20 m	30 m	300 m	50 m
Pipe flow area	0.018 m^2	0.032 m^2	0.018 m^2	0.032 m^2
Pipe hydraulic diameter	0.152 m	0.203 m	0.152 m	0.203 m
Surface roughness	0.15 ε	0.15 ε	0.15 ε	0.15 ε
Initial pressure (split)	514 kPa			
Final pressure (East 8)	439 kPa			

The compressed air flow could not be measured at the 129L east haulage split point (point A on Figure 4-11) due to the lack of measurement points. The calibrated simulation model was used to determine the compressed air flow required for the supplied inputs, mentioned in Table 4-9. Table 4-10 summarises the outputs of the simulation model.

Table 4-10: PTB simulation outputs - Step 1

	6" Pipe 1	8" Pipe 2	6" Pipe 3	8" Pipe 4
Pressure (start of pipe section)	514 kPa	510 kPa	509 kPa	441 kPa
Pressure (end of pipe section)	510 kPa	509 kPa	441 kPa	439 kPa
Pressure drop per section	4.5 kPa	1.2 kPa	67.5 kPa	1.9 kPa
Total pressure drop	75 kPa			
Simulated flow	7606 m³/h			

- ***Step 2***

The next step was to simulate the effect of replacing the current 6" pipe sections with 8" pipe sections. The flow calculated during step 1 was used as an input with the same inlet pressure at the split (referring to Figure 4-11). Table 4-11 summarises the input values used for the second simulation step. Note that, during this step, the surface roughness was adjusted to match that of a newly installed steel pipe.

Table 4-11: PTB simulation inputs - Step 2

	8" Pipe 1	8" Pipe 2	8" Pipe 3	8" Pipe 4
Pipe length	20 m	30 m	300 m	50 m
Pipe flow area	0.032 m²	0.032 m²	0.032 m²	0.032 m²
Pipe hydraulic diameter	0.203 m	0.203 m	0.203 m	0.203 m
Surface roughness	0.06 ε	0.06 ε	0.06 ε	0.06
Initial pressure (split)	514 kPa			
Constant flow	7606 m³/h			

As can be seen from Table 4-11, all the input values were kept the same with the only difference being the larger pipe diameters. The simulation therefore represents a continuous 8" pipe section with pressure values simulated at the same locations as during step 1. Table 4-12 shows the simulated results.

Table 4-12: PTB simulation outputs - Step 2

	8" Pipe 1	8" Pipe 2	8" Pipe 3	8" Pipe 4
Pressure start	514 kPa	513 kPa	512 kPa	497 kPa
Pressure finish	513 kPa	512 kPa	497 kPa	494 kPa
Pressure drop	1.6 kPa	1.2 kPa	15.3 kPa	2.5 kPa
Constant flow	7606 m³/h			
Simulated pressure drop	18 kPa			

According to Table 4-12 there is large potential to reduce the pressure losses through replacing the 6" pipe sections with 8" pipe sections. The simulation model predicts a theoretical improvement of 57 kPa under the same flow and inlet pressure conditions. The last step is to optimise the developed solution, which is discussed in the following section.

4.4.4 Solution Optimisation

The solution strategy proved to have a large potential improvement on the compressed air pressure supplied to the working areas. The compressed air pressure requirement of 500 kPa in the crosscuts for effective drilling was, however, still not met.

Through using the simulation model, the starting pressure or inlet flow can be theoretically calculated to meet the requirements of the end users. Table 4-13 indicates the service delivery improvements required at the east haulage split (Figure 4-11 – Point A) to ensure a minimum pressure of 500 kPa is delivered to the crosscuts (Figure 4-11 – Point B).

Table 4-13: Simulated results for optimised solution

	Inlet pressure	Inlet flow	East Haulage X - Cut 8 Pressure result
Option 1	**518 kPa**	7606 m^3/h	500 kPa
Option 2	514 kPa	**6724 m^3/h**	500 kPa

Implementing this will require additional investigation and simulation and did not prove to be feasible with the current setup. Increasing the pipe sizes further might prove to be feasible but will have to start at higher levels down due to the 8" pipes supplying compressed air from 110L. It will also be necessary to accurately quantify the pressure losses from the 8" supply column up to the rock drill face.

Increasing the surface compressor delivery pressure set points was also not feasible because of risks of bursting underground pipes seals when exceeding 700 kPa. With the current compressor system already operating at cut-back guide vane angles, it makes no sense to increase pressure set-points. An alternative solution might be to explore the possible benefit and feasibility of installing large accumulator vessels which can be loaded with additional compressed air that will aid during peak drilling periods.

4.5. Implementing a developed strategy

4.5.1 Solution Implementation

It was proposed to implement the developed solution strategy on the compressed air network of Mine A. The implementation would entail replacing all the 6" diameter pipe sections with 8" diameter pipe sections on the East haulage of 129L. These incorrectly sized pipe sections accumulated to a total distance of approximately 400 m.

The initial delay with the implementation was due to the transport of the pipe sections from the surface down to the required level for installation. This required the winders for slinging, which were already allocated for various other tasks. It took approximately 3 months, from placing the order for the new pipe sections up to the point where the first pipes were transported down by slinging to the 129L east haulage.

Due to 129L east haulage being one of the main production sections of Mine A, the pipe installation had to be done during strategic shutdown periods. Victaulic® grooved pipes were also proposed due to their easy connection ability. The pipes were replaced during engineering shutdown periods to reduce production downtime, which normally occurred once a month. The total installation took nearly 8 months to successfully complete.

4.5.2 Solution impact measurement and validation

Impact measurements

Once implementation was completed, the previously identified measurement points were re-measured to determine the impact of the newly installed pipe section (please refer to APPENDIX B). The collected data were then used to construct a new set of pressure profiles to be compared with the previously constructed baselines. Figure 4-12 depicts the new pressure profiles for 129L east haulage.

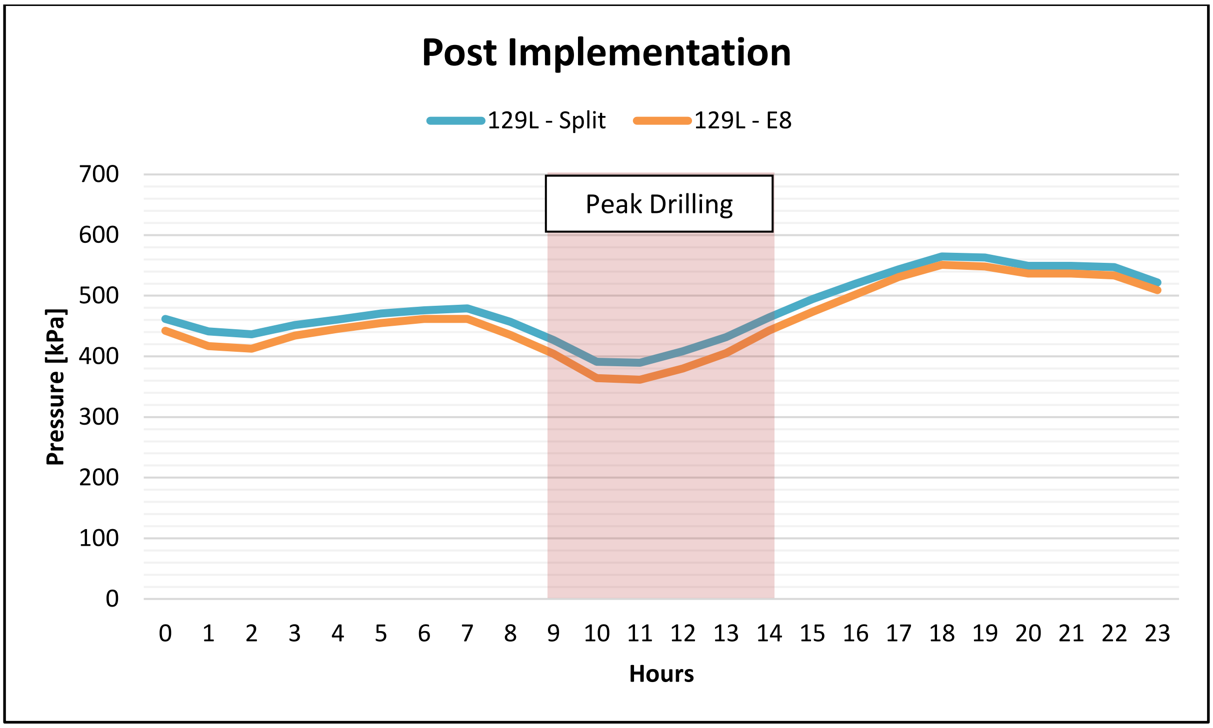

Figure 4-12: 129L - East haulage average pressure profile after implementation

Figure 4-12 shows a significant reduction in pressure losses from the pipe split (Point A –Figure 4-11) to the end point of the level when compared to the previously constructed baseline shown in Figure 4-10 . Table 4-14 summarises the pressure drop measured after all the 6" pipe sections have been successfully replaced with 8" pipe sections.

Table 4-14: Measurements after implementation of solution strategy

	Pre-implementation	Post-implementation	Improvement
Average	76 kPa	19 kPa	**57 kPa**
Average during peak drilling	87 kPa	25 kPa	**62 kPa**
Max	99 kPa	28 kPa	**71 kPa**
Min	60 kPa	13 kPa	**47 kPa**

Table 4-14 indicates a large pressure drop improvement from the measured data. However, when comparing the newly measured pressure drops to the previously measured drops it is essential to account for the inlet condition changes that occurred.

The implementation of the optimisation strategy stretched over an 8-month period. During this time the conditions and requirements of the 129L east haulage changed from the baseline period. This is confirmed by comparing the previously measured values at the east haulage split point (Figure 4-11 – Point A) with the latest measured values.

The changes are mostly related to the dynamic nature of mining activity on the production levels. Figure 4-13 illustrates all the newly developed areas (yellow lines) as well as the additional stope faces (coloured blocks) which were mined during the implementation period of the solution strategy.

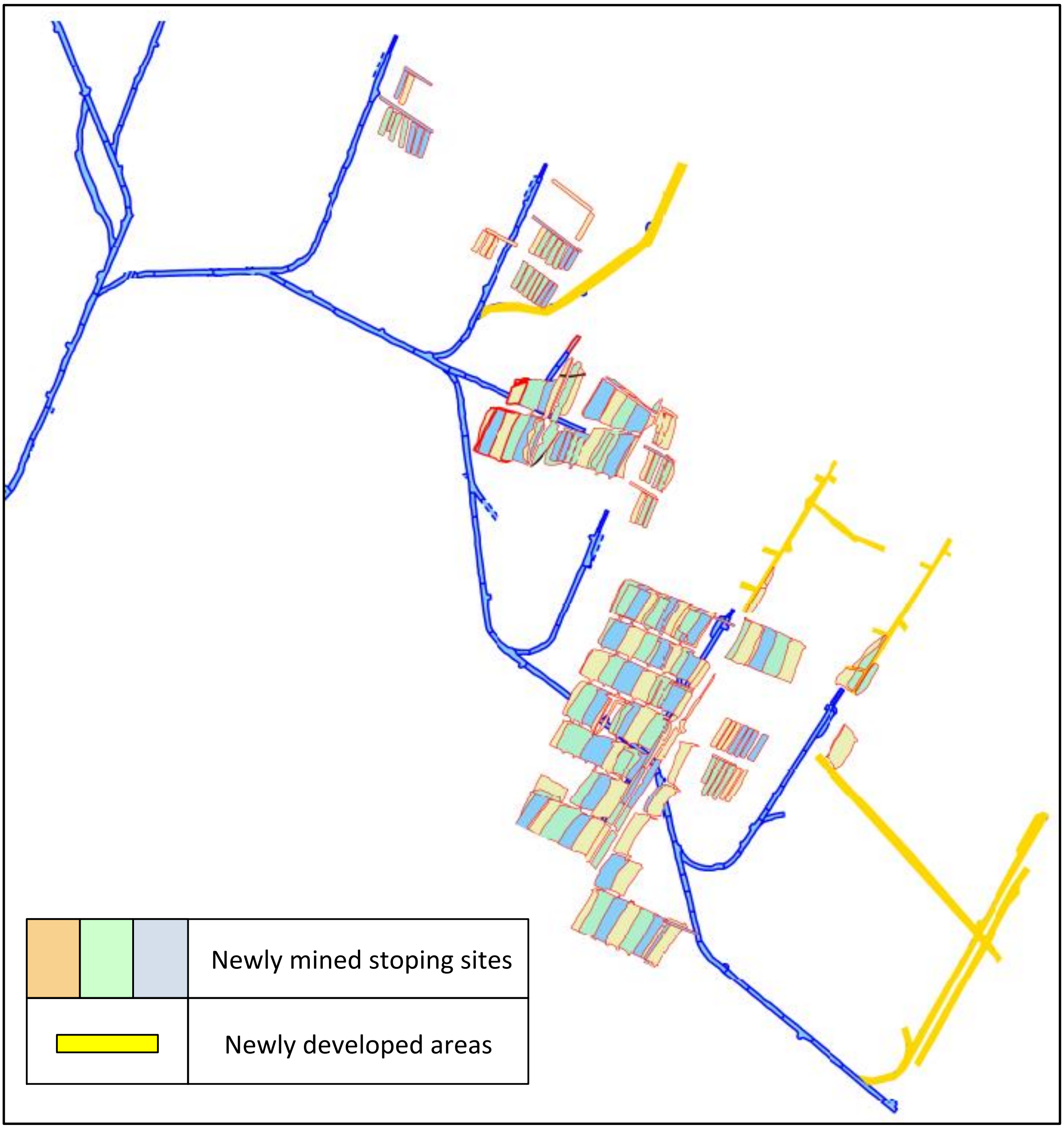

Figure 4-13: Newly developed and mined areas after implementation

These system changes led to an increase in compressed air demand, which directly means higher volumes of compressed air and consequently lower pressures. The compressed air reticulation network also expanded over the implementation period with new pipe sections installed to reach newly developed mining areas. Another large system change was the commissioning of the new decline, which induced increased mining activity and, subsequently, compressed air demand.

Validation

To ensure that system improvements were accurately validated, it was imperative to evaluate the system under the same inlet conditions. The measured data were evaluated for instances where the inlet pressure for the pipe section (point A in Figure 4-11) were identical before and after the new pipe sections were replaced. The pressure most frequently achieved in both instances was determined to be 570 kPa.

The predicted pressure drop was therefore also simulated for the given inlet pressure of 570 kPa. This was done by repeating steps 1 to 2 as was done previously during section 4.4.3. Table 4-15 shows the predicted pressure drop in comparison with the measured pressure drop.

Table 4-15: Validated results

	Predicted Pressure Drop	**Measured Pressure Drop**
Pressure Drop	14.18	13.91 kPa
Simulation error	2%	
Average Pressure drop improvement	**45 kPa**	

From Table 4-15 it is evident that, when simulating the predicted pressure drop for the same inlet pressure conditions, the simulation yields a low error percentage. The average pressure drop improvement of 45 kPa is lower than the theoretically expected 57 kPa due to the logged pressures which were logged at 570 kPa at the pipe split point (Point A - Figure 4-11), primarily occurring outside of peak drilling periods, leading to reduced compressed air flow.

The average pressure improvement as shown in Table 4-15 should therefore rather be compared with the minimum measured average improvement shown in Table 4-14. Doing this results in a 4% error.

4.5.3 Production impact analysis

A theoretical analysis was performed, as discussed in Chapter 3, to determine what the impact would be on production due to the improved compressed air network.

The rock penetration rate increase was calculated for a drill bit size of 34 mm at a design thrust pressure of 700 N. The pre- and post-implementation delivery pressure to East 8 crosscut was used as inputs to calculate the improved rock penetration rate. These pressures were calculated as an average across the 24-hour pressure profile. Table 4-16 shows the improved rock penetration rate resulting from the service delivery improvement.

Table 4-16: Rock penetration rate improvement

	Baseline	Post implementation
Pressure at East 8	438 kPa	483 kPa (@45 kPa improvement)
Rock penetration rate	1.6520 mm/s	2.0623 mm/s
Rock penetration rate improvement	0.4103 mm/s	

Table 4-17 and Table 4-18, respectively, show the inputs used to calculate the impact on production and the outputs as a result of improved service delivery.

Table 4-17: Mine A – Production impact analysis inputs

Inputs	Inputs	Units
Panel height	1.5	*m*
Panel width	28	*m*
No. holes per panel	144	-
Hole depth	1.2	*m*
Number of drills per panel	5	-
Forward advancement	0.98	*m*
Average drill shift	4	*hr*
Previous rock penetration rate	0.0016520	*m/s*
New rock penetration rate	0.0020623	*m/s*
Travelling times	4	*hr*
Gram gold per tonne	4.2	*g/tonne*
Rock density	2600	kg/m^3
Gold price	595 [9]	*R/g*

Table 4-18: Mine A – Production impact analysis outputs

Outputs	Calculation		Units
Square meters	42.0		*m^2*
Total drill distance	172.8		*m*
Total drill distance per square meter	4.1		*m/m^2*
Rock volume blasted per panel	41.2		*m^2*
Rock weight per panel	107.0		*tonne*
Gold per panel	449.5		*g*
	Previous	**New**	
Drill time per square face area	0.69	0.55	*hr/m^2*
Total drill time required	29.1	23.3	*hr*
Drill time per shift	5.8	4.7	*hr*
Rock penetration rate improvement	20		*%*
Total time saved per panel	1.2		*hr*
Additional squares that could be drilled	2.1		*m^2*
Additional holes that could be drilled	7.2		-
Additional rock blasted	2		*m^3*
Additional rock blasted weight	5.3		*tonne*
Additional gold extracted	22		*g*
Financial benefit of additional gold	R 13 300		*daily*
Annual financial benefit[13] per stope	R 3 644 000		*Annually*
Financial benefit of additional gold per square meter	R 6 400		*R/m^2*

Level 129 serves as the main production level and is divided into west and east haulages. The service delivery pressure improvement on 129L – East haulage directly affects three active mining areas.

According to the 2016 financial figures of Mine A, an annual production profit of R 389-million was reported. The theoretical annual financial improvement of this study therefore amounts to an annual saving of R11-million. This is a substantial 3% increase in the mentioned annual production profit of Mine A.

[13] The estimated annual financial benefit was calculated based on 274 work days annually [10]

Production data for 129L east level could only be collected for the period from 9 September 2016 to 28 April 2017 due to the poor record keeping of Mine A. It is recommended that historical production trends be compiled per mining section to more accurately evaluate the financial benefit. Calculations are therefore theoretically based.

4.6. Conclusion

This chapter focused on applying the developed research methodology on a practical case study. The compressed air network of Mine A was investigated to identify the compressed air network inefficiencies. The inefficiencies were evaluated and prioritised according to certain criteria. The prioritisation led to the development of a solution strategy of which the feasibility was evaluated through a verified simulation model.

The solution strategy entailed replacing an incorrectly sized pipe section of nearly 400 m with a larger pipe section. The expected results were simulated to determine the theoretical impact of reducing the pressure losses from the 129L split to the East 8 crosscut. The simulation model predicted that the pressure drop across this pipe section can be reduced to 14 kPa when replacing the pipe section with correctly sized pipes.

The proposed solution was implemented on the compressed air network of Mine A. After implementation, measurements were taken to validate the impact of replacing the pipe sections. Table 4-19 shows a summary of the results realised through the implementation of the solution strategy.

Table 4-19: Results conclusion

Outputs	Calculation		Units
Validation accuracy	2		%
Minimum pressure drop improvement	45		kPa
Predicted minimum pressure drop	14.18		kPa
Measured minimum pressure drop	13.91		kPa
Total time saved per panel	**Previous**	**New**	
Drill penetration rate	0.0016520	0.0020623	m/s
Financial benefit of additional gold	R 13 300		R/daily
Annual financial benefit per stope	R 3 644 000		*Annually*
Financial benefit of additional gold per square	R 6 400		R/m^2

Taking the 2016 financial figures of Mine A, an annual production profit of R 389-million was reported. The theoretical annual financial improvement of this study yielded a R11-million financial benefit when taking into account that three working areas were directly affected by the increase in compressed air service delivery. This is a substantial 3% increase in the mentioned annual production profit of Mine A.

All measurements had to be taken manually due to the lack of instrumentation at Mine A. Although this limitation delayed the investigation of the compressed air network, the inefficiencies could still be identified using the developed compressed air characterisation techniques.

This study proved the feasibility of "Optimising production through improving the efficiency of mine compressed air networks with limited infrastructure". The objectives of this study were addressed through identifying compressed air network inefficiencies, successfully addressing these inefficiencies and quantifying the financial impact in terms of production optimisation.

5. CONCLUSION AND RECOMMENDATIONS

5.1. Preamble

This chapter provides an overview of the study and highlights the main findings. Key points of each chapter will be discussed with the aim of illustrating how the initially identified objectives have been addressed.

5.2. Study summary

Global gold production is on an upwards trend. The South African gold mining industry is, however, under severe pressure due to a variety of unique challenges. These challenges include high operational costs, labour concerns and limited mine infrastructure. To reduce high operational costs and safeguard profit margins, it is essential for the local South African gold mining industry to ensure that current infrastructure is effectively used.

One such area where operational costs can be reduced is on the compressed air networks of deep-level gold mines. These networks are considered to be the least efficient systems in the mining industry. This inefficiency directly influences production targets due to inadequate service delivery supplied to production-related equipment. Equipment such as pneumatic drills operate at a given rock penetration rate, which is dependent on the supplied compressed air pressure. It is therefore important to optimise the efficiency of these networks to alleviate the negative impact on production. To achieve this, the following objectives were formulated:

- Identify, evaluate and address compressed air network inefficiencies with the aim to improve compressed air network performance on deep-level gold mines.
- Develop a procedure for optimising compressed air networks with the use of limited infrastructure.
- Quantify the effect of compressed air network optimisation in terms of production increase.

With the aim of reaching these objectives, Chapter 2 gave a brief overview of deep-level gold mines and focused on the various uses for compressed air. The numerous compressed air components were discussed with special focus on the performance of pneumatically operated drills through the rate of rock penetration during drilling. Fundamental calculations were also presented in conjunction with proposed simulation software using the discussed fundamental.

Previous studies were analysed to ensure recognised work performed in this field of study is applied to the problem at hand. Studies that focused on ways to improve compressed air networks as well as on determining the rate of rock penetration were identified. These studies were reviewed to establish which approach would best suit the given need of this study.

From the information gathered during the literature review, a research methodology was developed to optimise production by improving the efficiency of mine compressed air networks. This methodology specifically focused on identifying, evaluating and addressing these network inefficiencies. Special attention was given to the application of this procedure on mines with limited infrastructure in terms of instrumentation.

During the solution strategy development phase, a root cause analysis was applied along with adequate boundary selections. Each boundary's characterisation was described and led to the development of suitable solution strategies. Optimisation of the solution strategies was accomplished using verified simulation models. This was to ensure credibility of the theoretical impact of the solution strategy and yielded a maximum simulation error of 8%.

The methodology was implemented at Mine A. The largest inefficiency was identified to be an incorrectly sized pipe length of close to 400 m. The verified simulation model predicted that the initial pressure drop of 87 kPa can be reduced to 14 kPa by replacing the incorrectly sized pipe section.

The pipe section was replaced with the correct pipe size and yielded an average pressure drop of 14 kPa. This pressure drop was validated with the predicted pressure drop. The improved service delivery pressure was translated into an improved rock penetration rate of 20%, which could be converted to a potential production increase. Table 5-1 summarises the main results obtained through addressing the specific compressed air network inefficiency.

Table 5-1: Results summary

Outputs	Calculation		Units
Validation accuracy	2		%
Initial minimum pressure drop before implementation	60		kPa
Predicted minimum pressure drop	14.18		kPa
Measured minimum pressure drop	13.91		kPa
Total time saved per panel	**Previous**	**New**	
Drill penetration rate	0.0016520	0.0020623	m/s
Rock penetration rate improvement	20		%
Financial benefit of additional gold	R 13 300		Daily
Annual financial benefit	R 3 644 000		*Annually*
Financial benefit of additional gold per square meter	R 6 400		R/m^2

From Table 5-1 it is evident that a substantial financial benefit can be realised by optimising compressed air networks through addressing inefficiencies. This will not only improve the efficient use of equipment such as the compressors, but also ensure that optimised service delivery pressures are delivered to working areas. This, in turn, will improve production due to the improved rate of rock penetration.

Considering the objectives set out for this study, compressed air network inefficiencies were successfully identified, evaluated and addressed on a mine with limited infrastructure. The impact of addressing these inefficiencies was clearly noted and correlated to a production increase through improving drill penetration rates. An estimated 3% increase in production profit was calculated for Mine A as a result of improved service delivery. This equates to an annual financial benefit of R11-million, which in turn will help Mine A mitigate the high operational costs of modern day gold mining.

5.3. Recommendations for future work

The recommendations for future studies are summarised as follows:

- Rock penetration rate (RPR) improvements were quantified based on models from literature. RPR models should be verified by performing actual tests under actual mining conditions. These models can then be categorised to ensure future case studies know which models are most applicable to their specific study.

- There is a need for developing an accurate leak quantification model. This model should determine the financial impact of repairing leaks. Equipping workers with a method to measure leaks and translate it to financial loss will re-establish focus on maintenance plans and the potential financial benefit of addressing these key issues.

- Due to the dynamic nature of deep-level gold mines, system changes occur on a frequent basis. These system changes influenced the outcomes of the study and should be controlled as best as possible. Investigating alternative methods to mitigate these dynamic fluctuations is recommended.

- More focus should be placed on the trends in production when compressed air networks are altered. Production outputs of specific working areas should be accurately monitored to identify the impact of compressed air network improvements. Selecting mines with enhanced record keeping capabilities and historical trends for various working areas is advised to better understand this phenomenon.

- Despite the obvious impact of improved drilling rates, attention should be placed on the benefit of additional “spare time” in terms of travelling distances. As mines progress, travelling distances directly influence the amount of time spent on drilling the rock face area. Reducing drilling times will serve as a contingency plan to ensure sustained production when travelling time plays an increasing role.

- The feasibility of optimising through addressing network inefficiencies can be investigated on other deep-level mine systems such as the water reticulation system.
- The implementation of the developed solution methodology should be investigated on the compressed air networks of other industries.
- More focus should be placed on the energy saving potential when addressing compressed air network inefficiencies. These savings will only become more substantial when considering sharp electricity price increases.

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APPENDIX A : PTB - Simulation screenshots

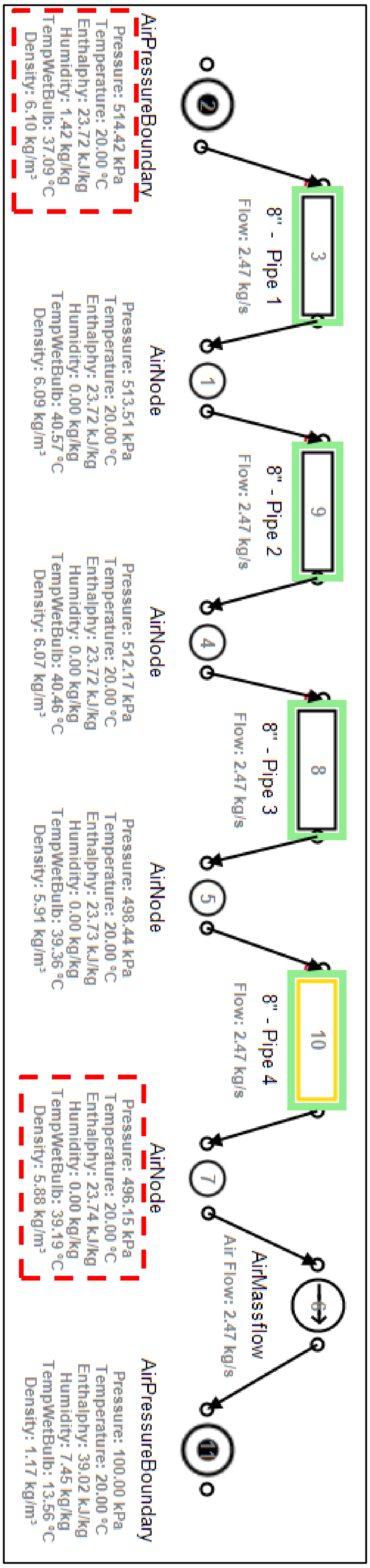


Figure A-2: Predicted pressure drop after implementation – Step 2

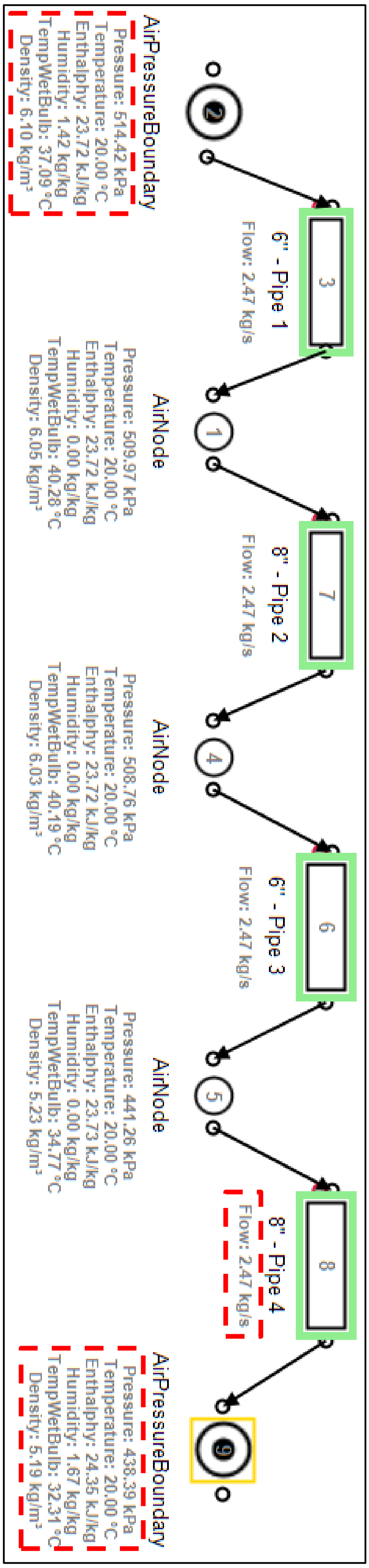


Figure A-1: Simulated flow from pressure drop measurements – Step 1

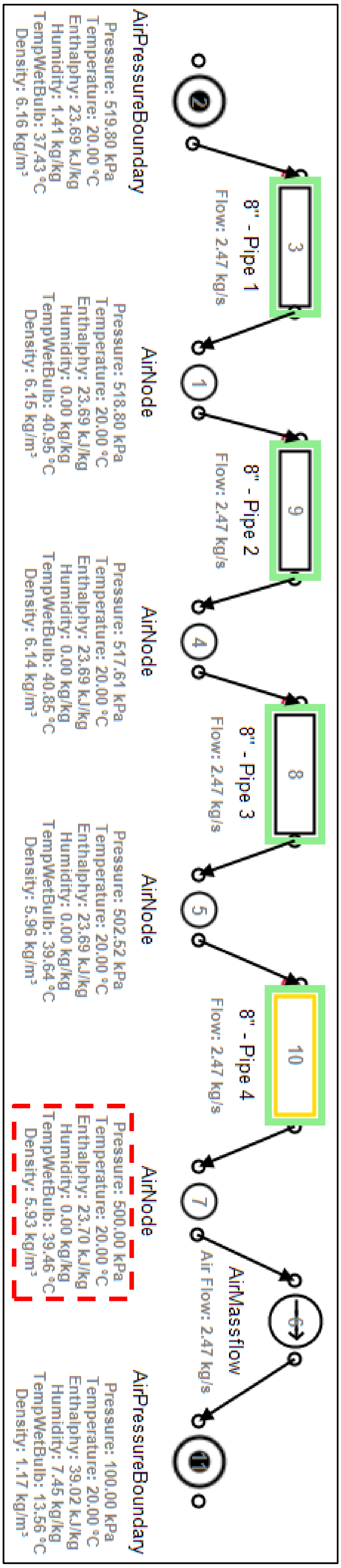


Figure A-4: Optimisation strategy 1 – Alternating pressure

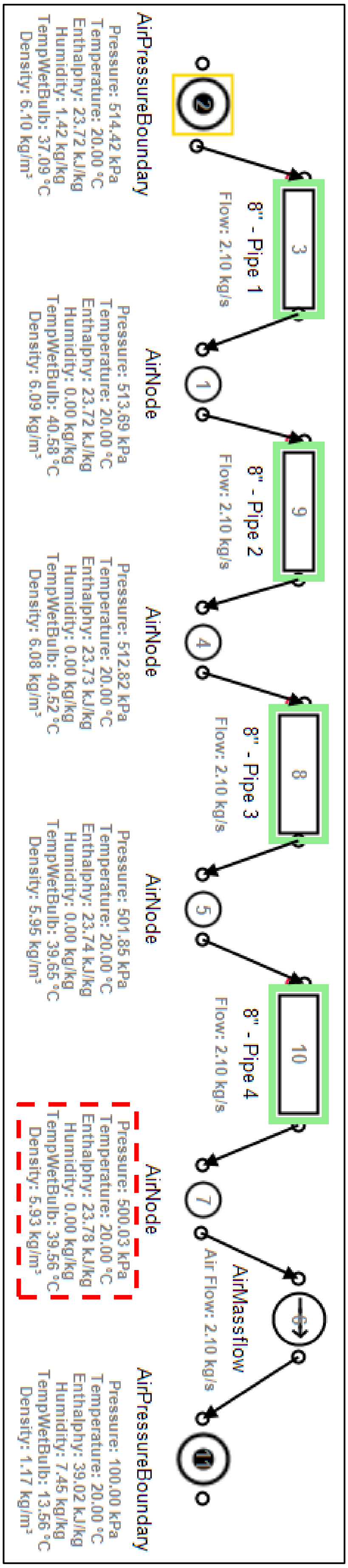


Figure A-3: Optimisation strategy 1 – Alternating flow

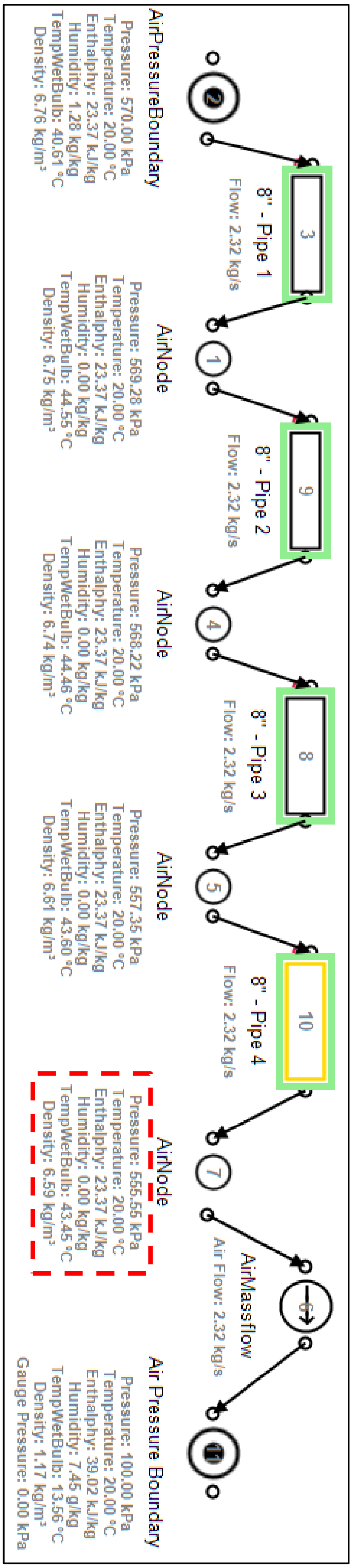


Figure A-6: Validation – Predicted pressure drop after implementation – Step 2

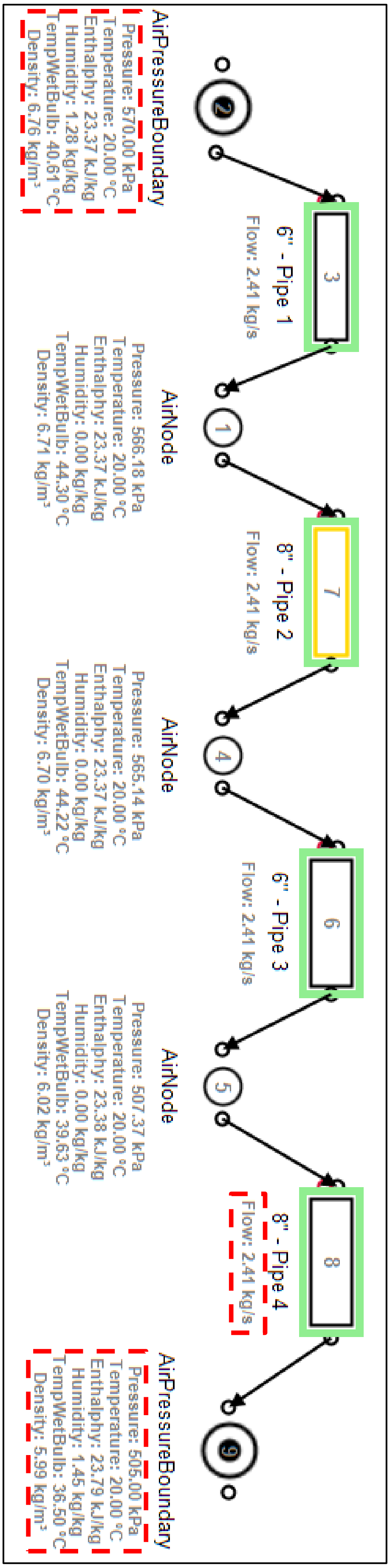


Figure A-5: Validation - Simulated flow from pressure drop measurements – Step 1

APPENDIX B : 129L - Pipe section measured data

Table B-1: Measured data for 129L East haulage pipe section

	Pre-implementation		Post-implementation	
Hour	**129L - Split kPa**	**129L - East 8 kPa**	**129L - Split kPa**	**129L - East 8 kPa**
0	503.54	425.77	461.67	442.44
1	478.66	384.63	441.07	417.00
2	488.69	397.95	436.60	412.78
3	502.71	416.65	451.60	434.39
4	517.18	435.12	460.93	445.22
5	526.87	448.48	470.67	455.00
6	531.01	455.97	475.87	461.78
7	524.77	449.53	479.00	462.00
8	505.44	425.14	456.93	435.44
9	463.68	371.29	427.13	404.00
10	437.11	338.35	391.00	364.39
11	423.68	325.04	389.53	361.56
12	442.45	353.16	408.40	380.11
13	481.50	401.11	431.73	405.22
14	519.42	448.73	464.53	442.67
15	542.83	478.79	494.47	473.22
16	545.50	484.11	519.87	501.56
17	564.69	503.58	543.67	530.89
18	571.83	510.57	564.73	550.94
19	570.47	509.59	562.73	548.28
20	549.27	488.86	549.33	536.78
21	551.57	490.79	549.40	536.78
22	551.01	490.32	547.00	533.39
23	552.11	487.94	521.87	509.06
Average	**514.42**	**438.39**	**479.16**	**460.20**

APPENDIX C : 129L – East Haulage - Pipe section photos

Figure C-1: Figure C 1: Point A – Pipe 1 (8'' to 6'')

Figure C-2: Point B – Pipe 2 (6'' to 8'')

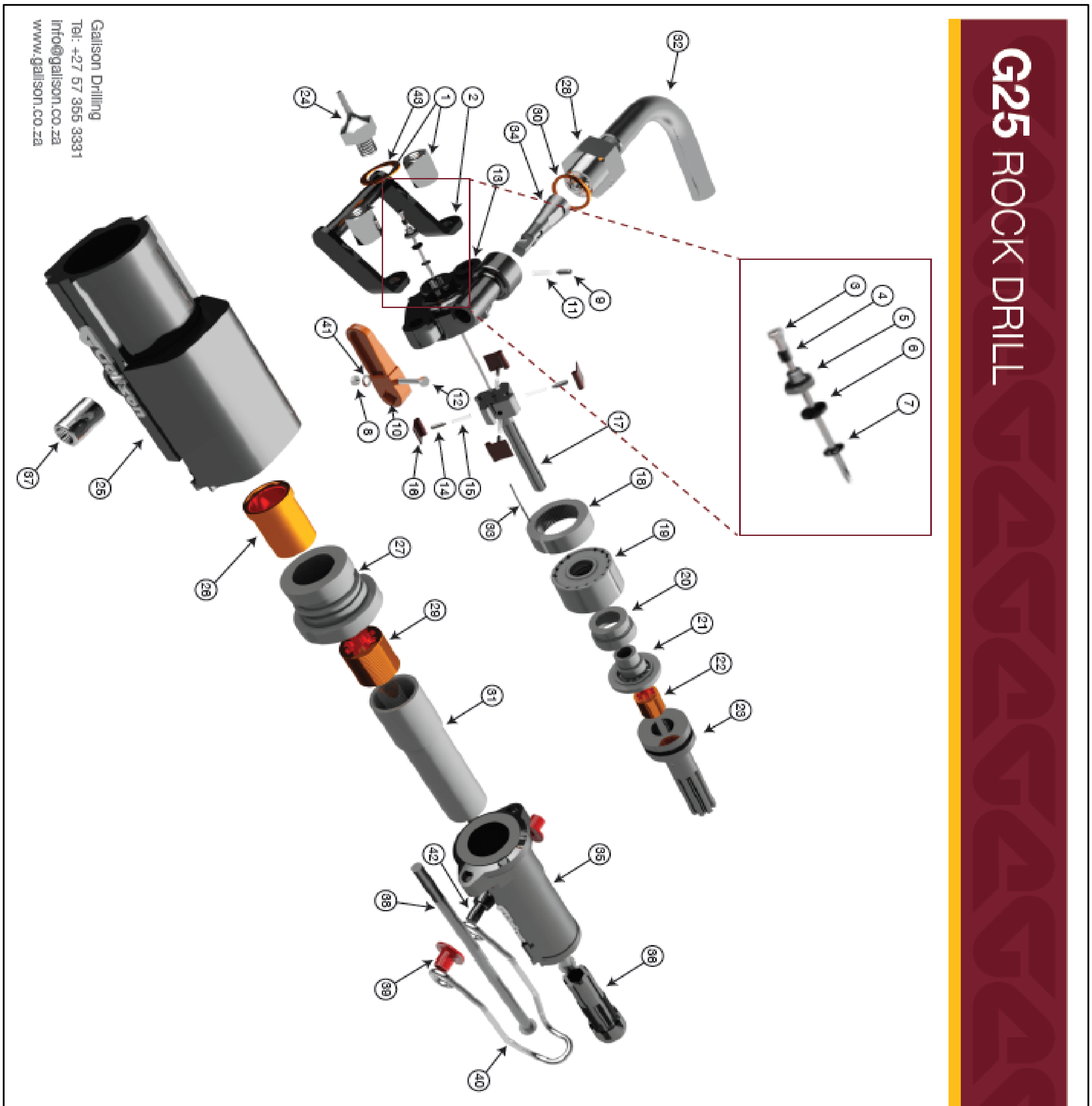
Figure C-3: Point C – Pipe 3 (8" to 6")

Figure C-4: Point D – Pipe 4 (6" to 8")

Figure C-5: Restriction 1 - 129L - 4 '' T- piece

Figure C-6: Restriction 1 - 129L - 6 '' Valve

APPENDIX D : Pneumatic drill component breakdown



ITEM	DESCRIPTION	PART NO.	B/L
1	Siderod nut	S217940	S21-187M
2	Spade handle	S212500	B701
3	Watertube	S215800	S21-229
4	Watertube rubber, small	S213045	S21-45
5	Watertube cap screw	S213042	S21-42
6	Watertube thrust washer	S213049	S24-46
7	Watertube rubber, large	S213044	S21-44
8	Throttle valve handle nut	S153008	121-M10
9	Throttle valve plunger	S151913	S21-29C
10	Throttle valve handle, nylon	S153004	S21-24P
	Throttle valve handle, steel	S153006	S21-24
11	Throttle valve plunger spring	S155712	S21-30
12	Throttle valve handle bolt	S153007	S21-25M
13	Backhead	S254075	S21-21
14	Pawl plunger	S211912	S21-34
15	Pawl plunger spring	S215700	D1611
16	Pawl	S212014	S21-33
17	Rifle bar	S212300	S21-32
18	Ratchet ring	S252100	B3049
19	Valve box	S253800	A2119
20	Valve	S253700	C1648
21	Valve plug	S253900	A2118
22	Rifle nut	S250100	S21-36A
23	Piston	S252200	B3228
24	Backhead spud, 10mm	S213060	
	Backhead spud, 12mm	S213061	
25	Cylinder, muffled	S251101	E752M
26	Cylinder washer liner	S210300	S21-4L
27	Cylinder washer	S253400	B3227
28	Air stem nut	S212800	S21-38
29	Chucknut	S210277	S21-6A
30	Air stem nut copper washer	S212804	S21-91
31	Chuck	S212194	B1500
32	Air stem	S212900	S21-37A
33	Valve box locating pin	S253028	S21-28
34	Throttle valve	S213002	S21-229
35	Fronthead	S251001	A2002
36	Chuck bush, 22mm	S213392	C2009
	Chuck bush, 25mm	S213395	C2010
37	Lug bush	S214700	C1101M
38	Siderod	S217830	C1260M
39	Steel retainer sleeve	S213046	D2146A
40	Steel retainer	S215900	B2869
41	Throttle valve handle washer	S153009	143-M10
42	Steel retainer pin	S213039	D2271
43	Water system nut copper washer	S212704	S21-50

Figure D-1: Typical pneumatic drill rig component breakdown

APPENDIX E : Moody diagram

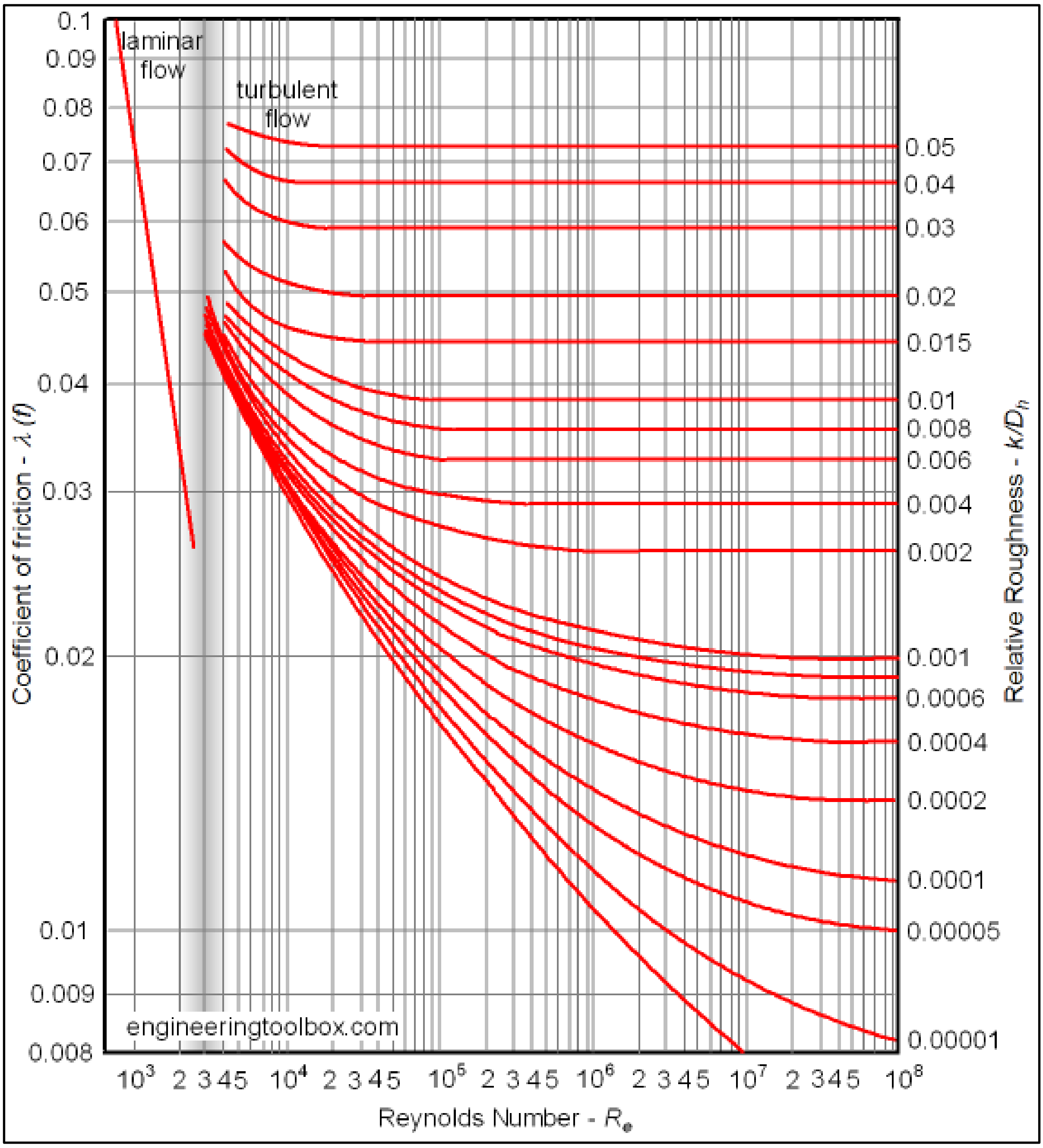


Figure E-1: Moody diagram [86]

APPENDIX F : Minor loss coefficients

Table F-1: Minor loss coefficient in pipes [87]

Type of Component or Fitting	Minor Loss Coefficient ξ	Type of Component or Fitting	Minor Loss Coefficient ξ
Tee, Flanged, Dividing Line Flow	0.2	Angle Valve, Fully Open	2
Tee, Threaded, Dividing Line Flow	0.9	Gate Valve, Fully Open	0.15
Tee, Flanged, Dividing Branched Flow	1	Gate Valve, 1/4 Closed	0.26
Tee, Threaded, Dividing Branch Flow	2	Gate Valve, 1/2 Closed	2.1
Union, Threaded	0.08	Gate Valve, 3/4 Closed	17
Elbow, Flanged Regular 90^o	0.3	Swing Check Valve, Forward Flow	2
Elbow, Threaded Regular 90^o	1.5	Ball Valve, Fully Open	0.05
Elbow, Threaded Regular 45^o	0.4	Ball Valve, 1/3 Closed	5.5
Elbow, Flanged Long Radius 90^o	0.2	Ball Valve, 2/3 Closed	200
Elbow, Threaded Long Radius 90^o	0.7	Diaphragm Valve, Open	2.3
Elbow, Flanged Long Radius 45^o	0.2	Diaphragm Valve, Half Open	4.3
Return Bend, Flanged 180^o	0.2	Diaphragm Valve, 1/4 Open	21
Return Bend, Threaded 180^o	1.5	Water meter	7
Globe Valve, Fully Open	10		

APPENDIX G : Investigation baselines constructed

110 Level

The first investigation point was on 110L where the compressed air pipe splits to 110L and 117L. This point was selected because it is the tap-off point supplying the remaining production levels. The size of the incoming pipe is 14", which is reduced to a 10" at the split. The reduction can be seen in APPENDIX C. The pipe is then further reduced to two 8" pipes. The incoming 14" pipe continues onwards to 117L, only pressurising a refuge bay because no active mining is taking place on this level. The average pressure profile at the incoming pipe on 110L is shown in Figure G-1.

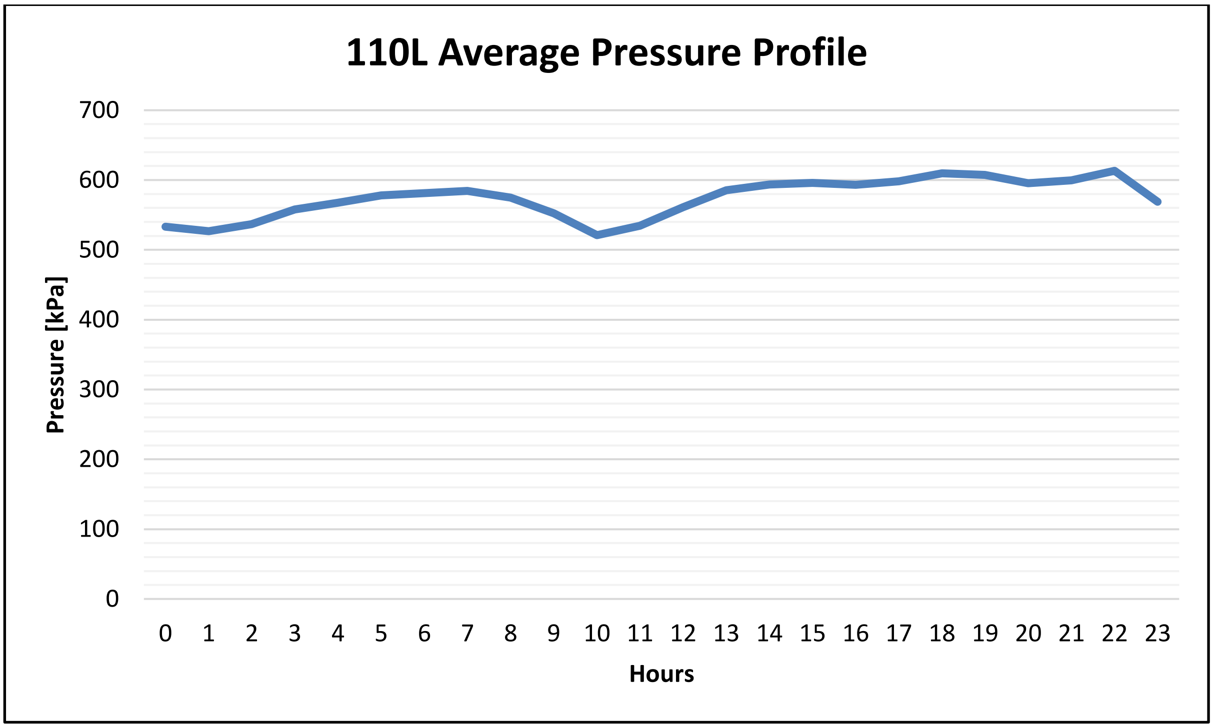


Figure G-1: 110L Average pressure baseline profile

121 Level

The measurement point was selected to be close to the station where the compressed air pipe line first enters the level. There is still minor mining activity on the level. The average pressure profile can be seen in Figure G-2.

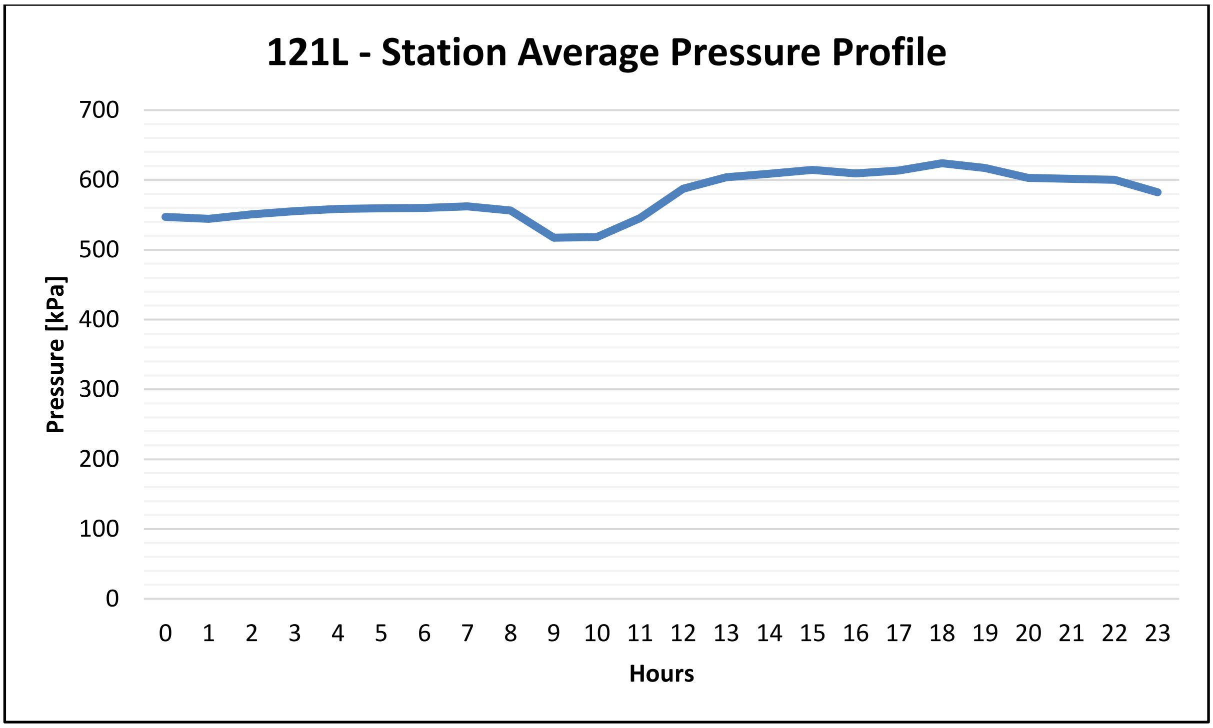


Figure G-2: Average pressure baseline profile 121L – station

129 Level

As mentioned, 129L is the main production level and several pressure measurement points have been identified on this level. The first measurement, as can be seen in Figure G-3 was selected to be near the station in order to compare the pressure at this point to that of 121L at the same location.

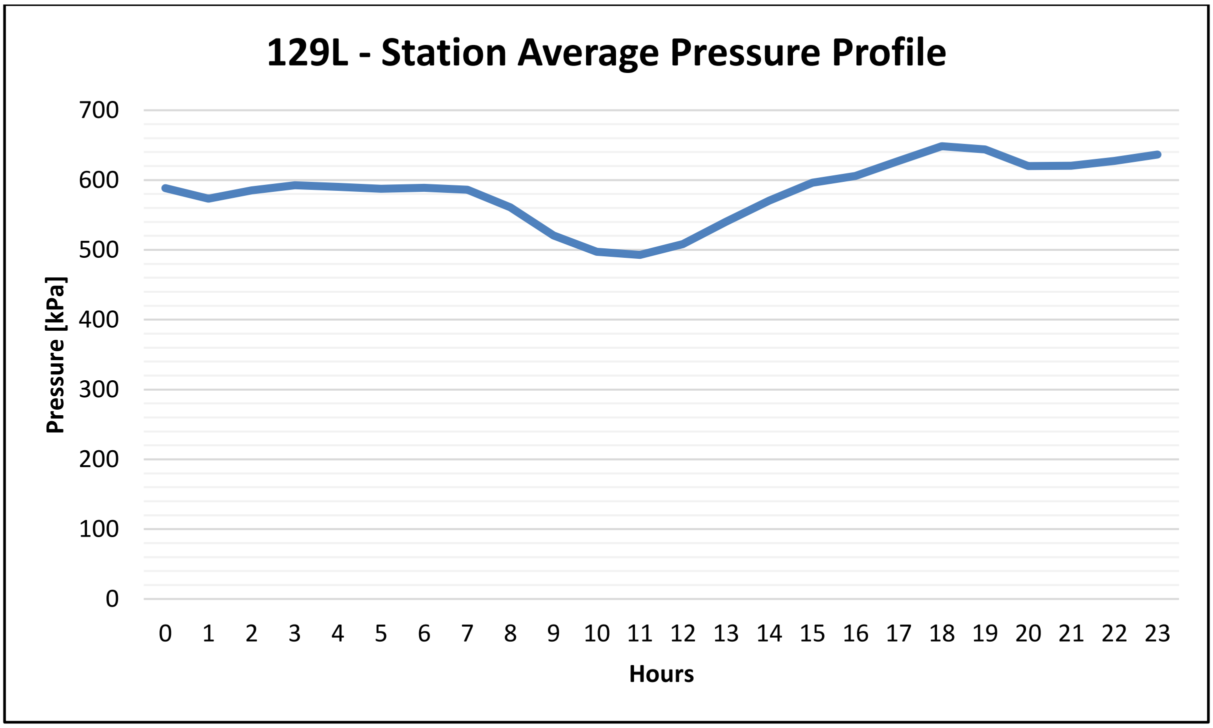


Figure G-3: Average pressure baseline profile 129L – station

The next measurement point was identified before the split between the West and East haulage. The pressure profile can be seen in Figure G-4. When comparing the pressure profile of Figure G-3 and Figure G-4 (Station vs. Split), it is evident that the project tap-off point results in an average pressure drop of 33 kPa on a daily basis. This tap-off point is supplying compressed air to the development of the new decline.

Mine A also has a ring feed which inter-connects levels with one another. The main purpose of these ring feeds was to ensure compressed air is evenly spread to all mining areas due to scattered mining being the norm at Mine A. Closing off the ring feed in this area can be investigated to reduce pressure loss on this production level.

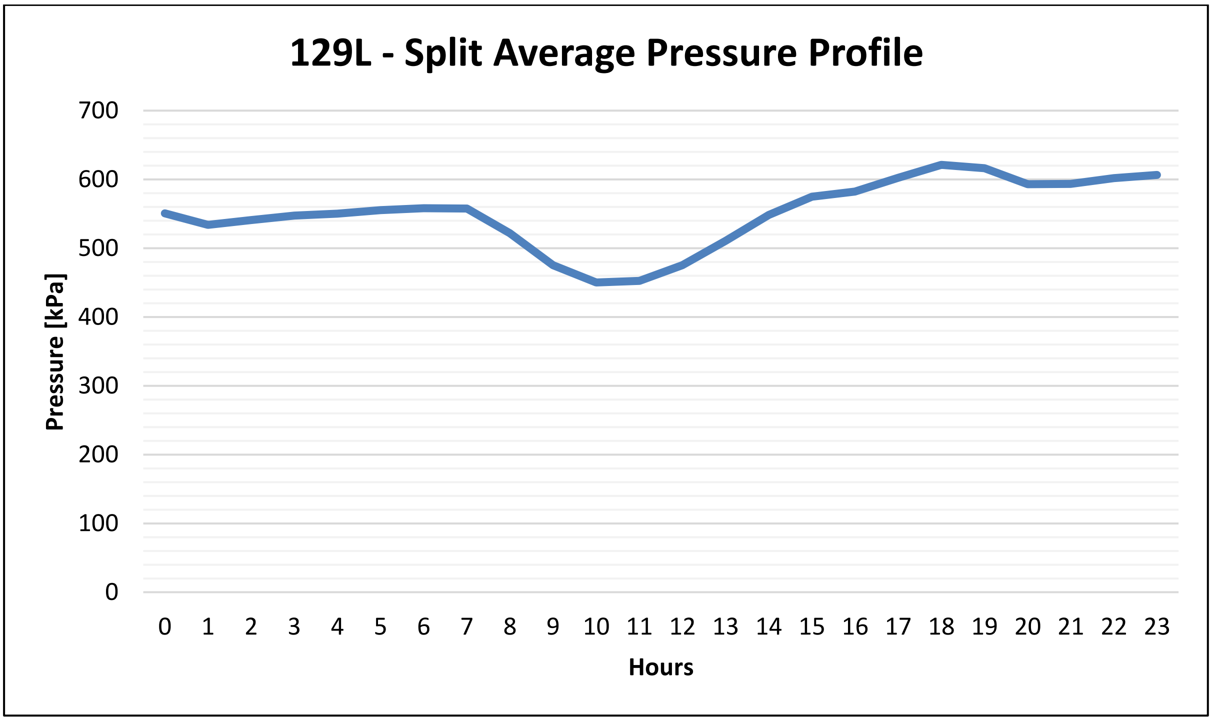


Figure G-4: Average pressure baseline profile 129L – split

The final log positions were identified to be at the furthest possible points on 129L's East and West haulages. These points were selected to analyse the pressure being supplied to the work stations. Figure G-5 and Figure G-6 illustrate the pressure profile that was measured at these respective locations.

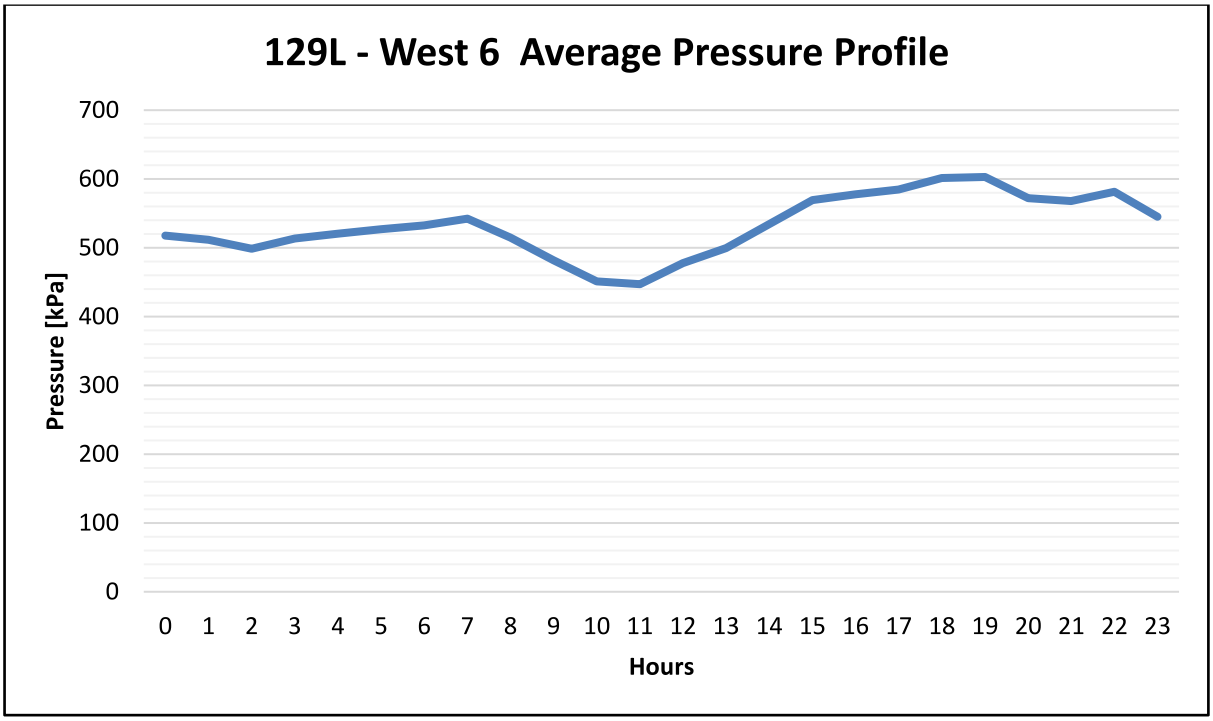


Figure G-5: Average pressure baseline profile 129L - West 6

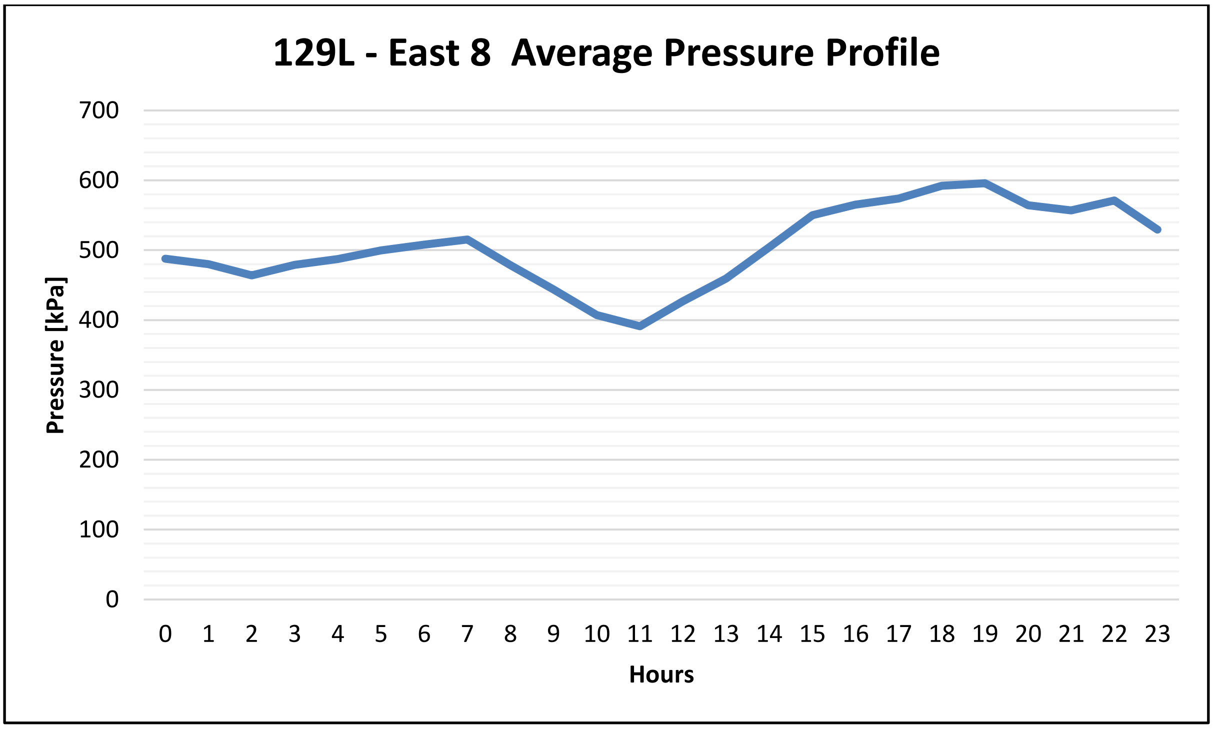


Figure G-6: Average pressure baseline profile 129L - East 8

APPENDIX H : Simulation verification

Figure H-1 indicates the layout for the pipe section used at Mine B, as well as where measurements were taken to verify the simulation model. To verify the simulation model, both flow and pressure measurements were taken.

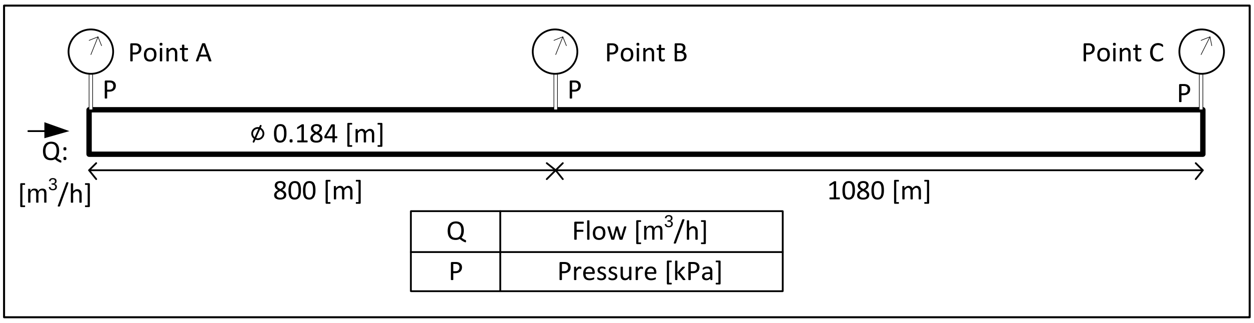


Figure H-1: Simplified layout of the pipe section at Mine B

Pressure was measured at the start of the pipe section (Point A - Figure H-1), after 800 m of pipe length (Point B - Figure H-1) as well as at the end of the pipe section (Point C - Figure H-1). The compressed air flow was measured at the start of the pipe section. Table H-1 indicates the specifications of the pipe section at mine B that was used during the verification process. The surface roughness represents a standard steel pipe.

Table H-1: Pipe specifications used for verification at mine B

	Pipe section 1	**Pipe section 2**
Pipe Length	800 m	1080 m
Pipe Flow Area	0.02660 m^2	0.02660 m^2
Pipe Hydraulic Diameter	0.18400 m	0.18400 m
Surface Roughness	0.06 ε	0.06 ε

The measured pressures at points A and C were used to simulate the pressure at point B. Figure H-2 indicates the measured pressure at point B compared with the simulated pressure at point B over a 24-hour profile.

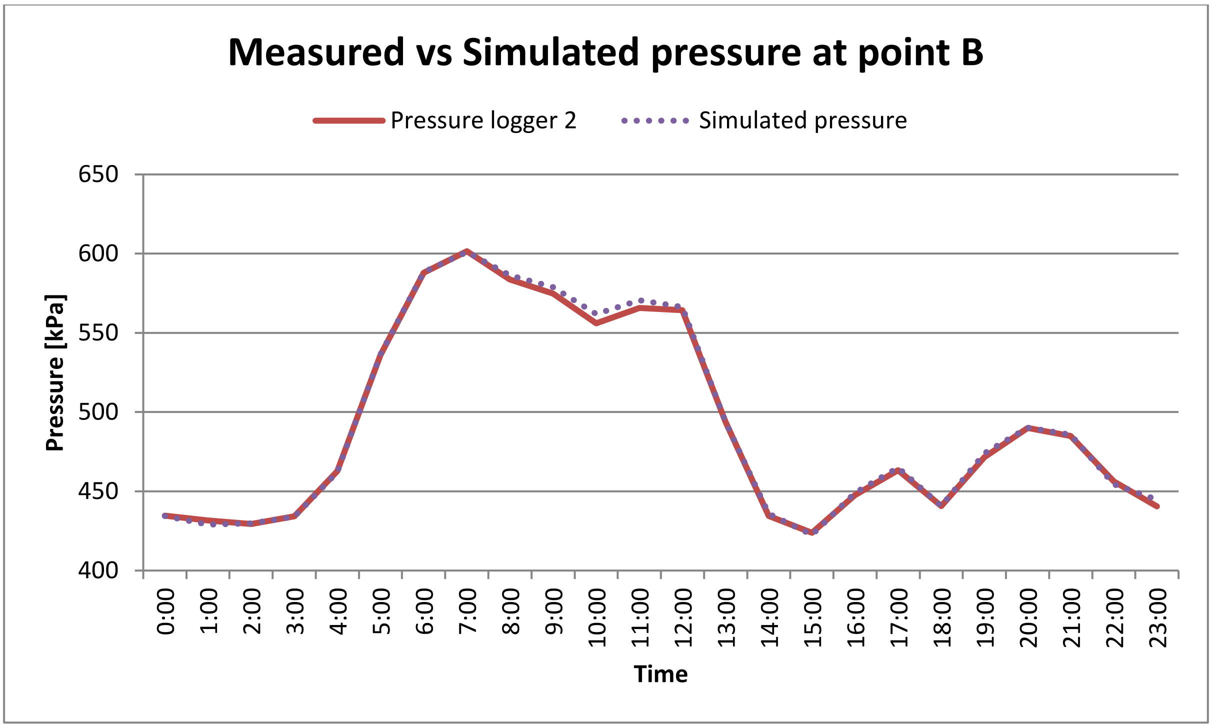


Figure H-2: Measured vs. simulated pressure at point B – Mine B

From Figure H-2 it is evident that the simulated pressure accurately matches the actual measured pressure at point B. The compressed air flow was simulated using the pressures measured at points A and C. Figure H-3 indicates the measured flow when compared with the simulated flow.

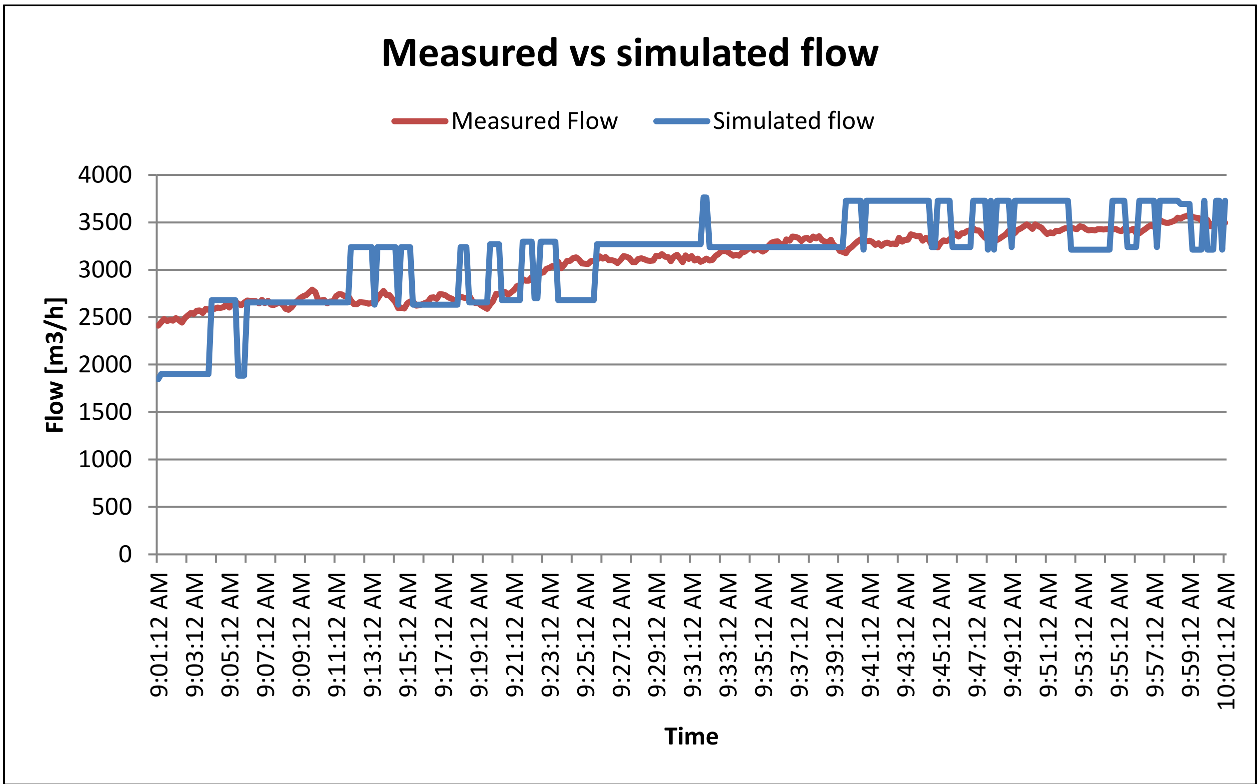


Figure H-3: Measured vs. simulated flow - Mine B

From Figure H-3 it might appear that the simulation does not closely match that of the measured values. The simulated deviation can be attributed to the pressure measurement equipment. The pressure loggers used in this study had a measuring resolution of 10 kPa.

The effect of this pressure logger resolution can easily be indicated by using the measured flow and measured starting pressure (Point A - Figure H-1) of the pipe section and simulating the final pressure (Point C - Figure H-1). Figure H-4 illustrates the simulated pressure at point C.

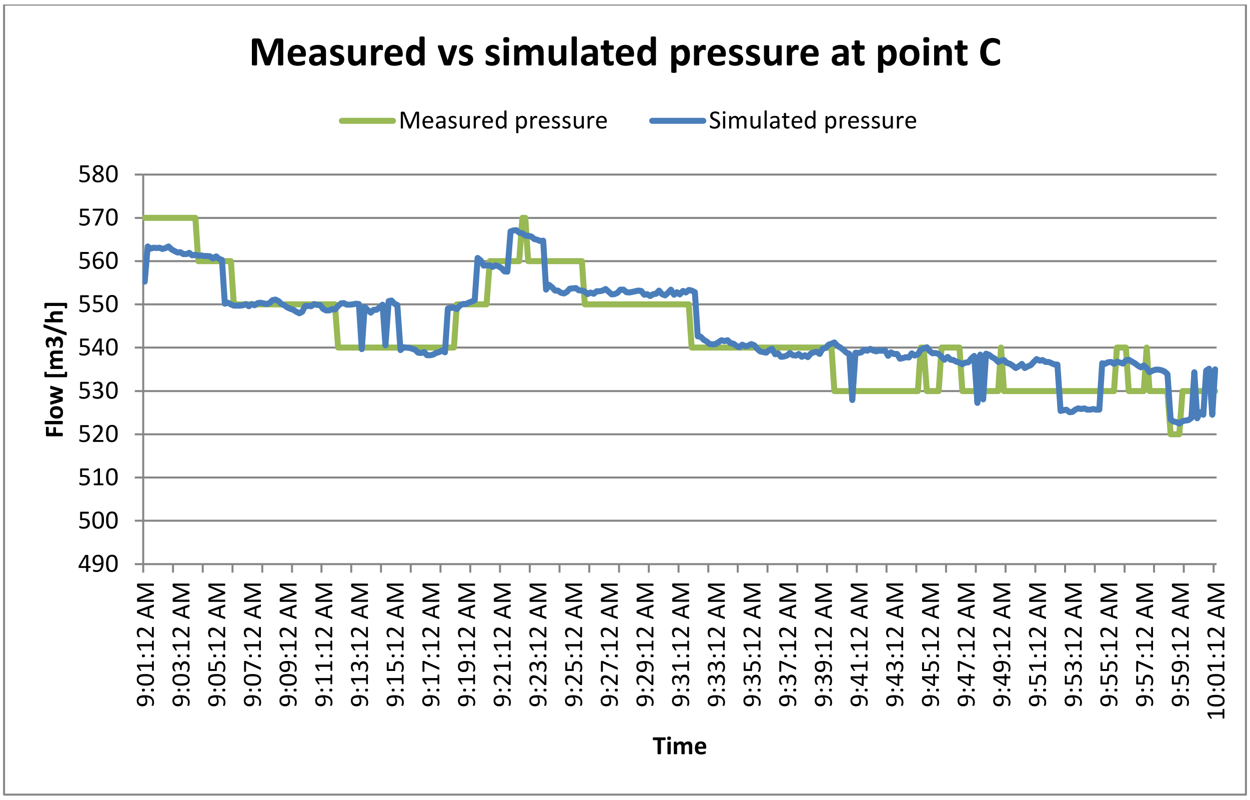


Figure H-4: Measured vs. simulated pressure at point C - Mine B

Figure H-4 indicates that the simulated pressure closely follows the actual measured pressure at point C. The simulation error was determined to be less than 1%. This indicates that the simulated flow, as shown in Figure H-3, is highly sensitive to small changes in pressure.

For example, a pressure of 564.999 kPa will be logged as 560 kPa and a pressure of 565.001 kPa will be logged as 570 kPa. The maximum pressure error is therefore $4.\dot{9}$ kPa. This is more clearly indicated in Figure H-5, which illustrates the effect on simulated flow as a result of change in pressure.

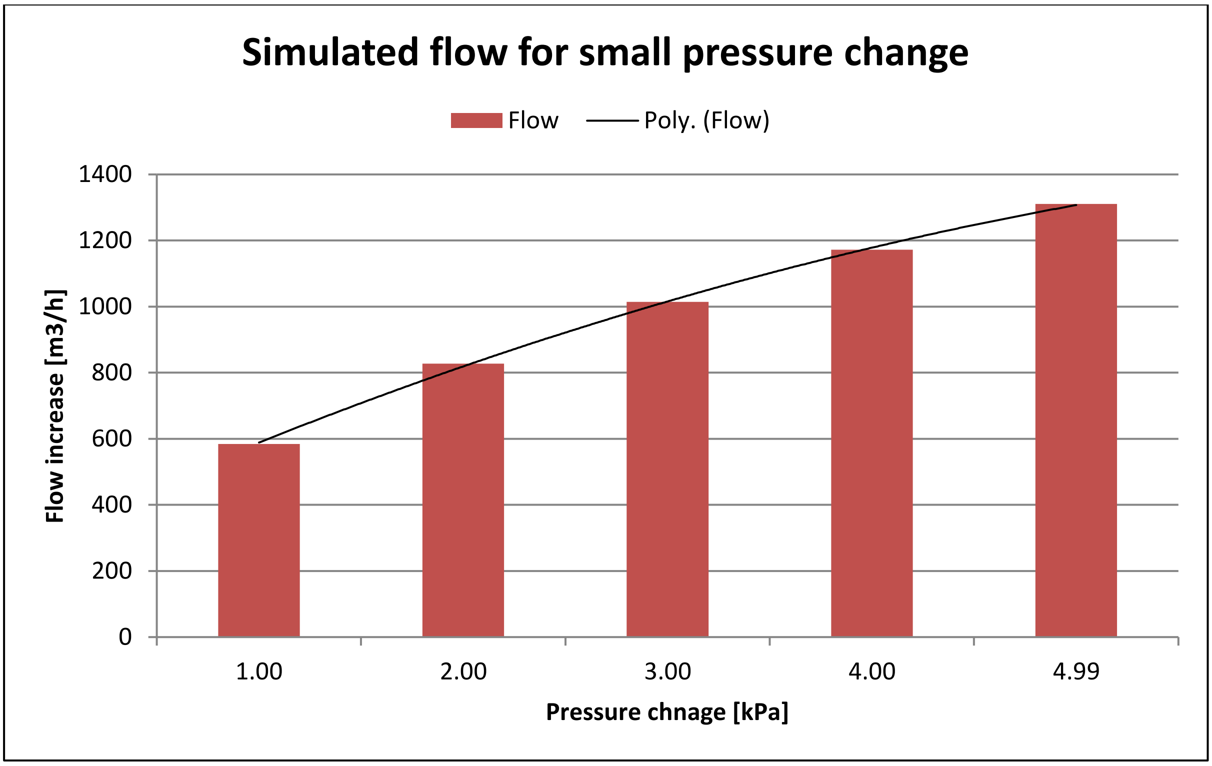


Figure H-5: Simulated flow increase for small pressure changes

From Figure H-5 is can be seen that a pressure change of 1 kPa between the start (Point A - Figure H-1 and end (Point C - Figure H-1) of the pipe section at mine B will have an impact on the compressed air flow of as much as 240 m^3/h. Table H-2 indicates the flow deviation that was measured between the actual flow and simulated flow and shows the approximate correlation to the equivalent change in pressure.

Table H-2: Pressure logger resolution interpretation - Mine B

	Flow	Equivalent pressure change
Minimum deviation	1 m^3/h	0 kPa
Maximum deviation	771 m^3/h	2 kPa
Average deviation	246 m^3/h	0.5 kPa

From Table H-2 it can be seen that the equivalent change in pressure required to induce the flow deviation is well below the pressure logger resolution and will therefore not register on the logged pressure. Table H-3 summarises the simulated errors of the verification process.

Table H-3: Simulation verification error summary

	Pressure at point B	Flow through pipe
Simulation error	1 %	8%

Table H-3shows an acceptable error range for the simulated parameters. The slightly higher error for the simulated flow value can be attributed to the pressure logger resolution of 10 kPa. Figure H-5 indicated the effect on the simulated compressed air flow when small pressure changes occur that are not logged by the pressure logger. The accuracy of the simulation model was therefore confirmed as acceptable.

APPENDIX I: Mine A Relevant level layouts

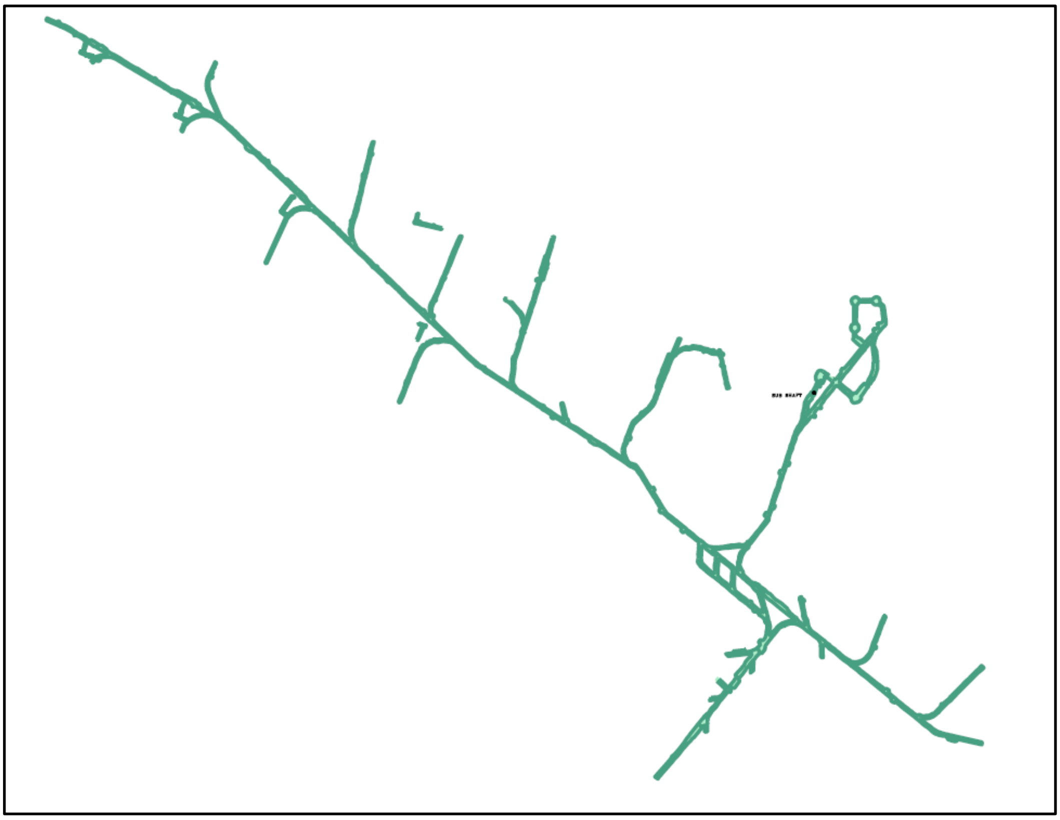


Figure I-1: Mine A 110L layout

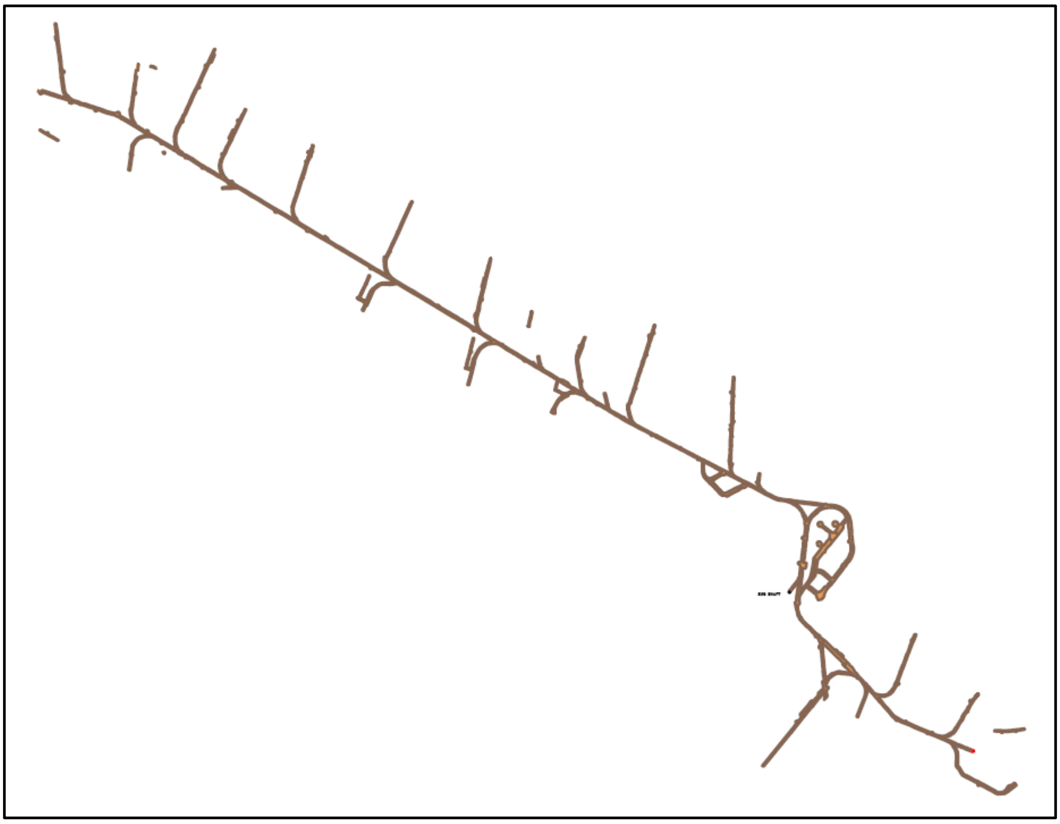


Figure I-2: Mine A 117L layout

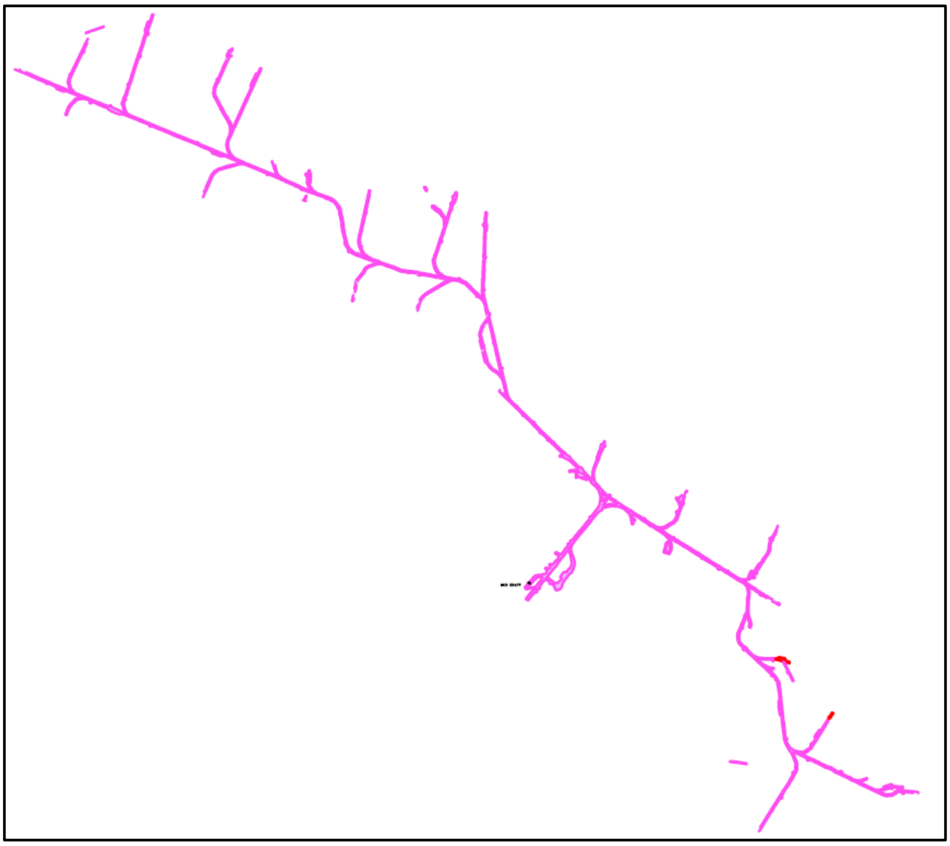


Figure I-3: Mine A 121L layout

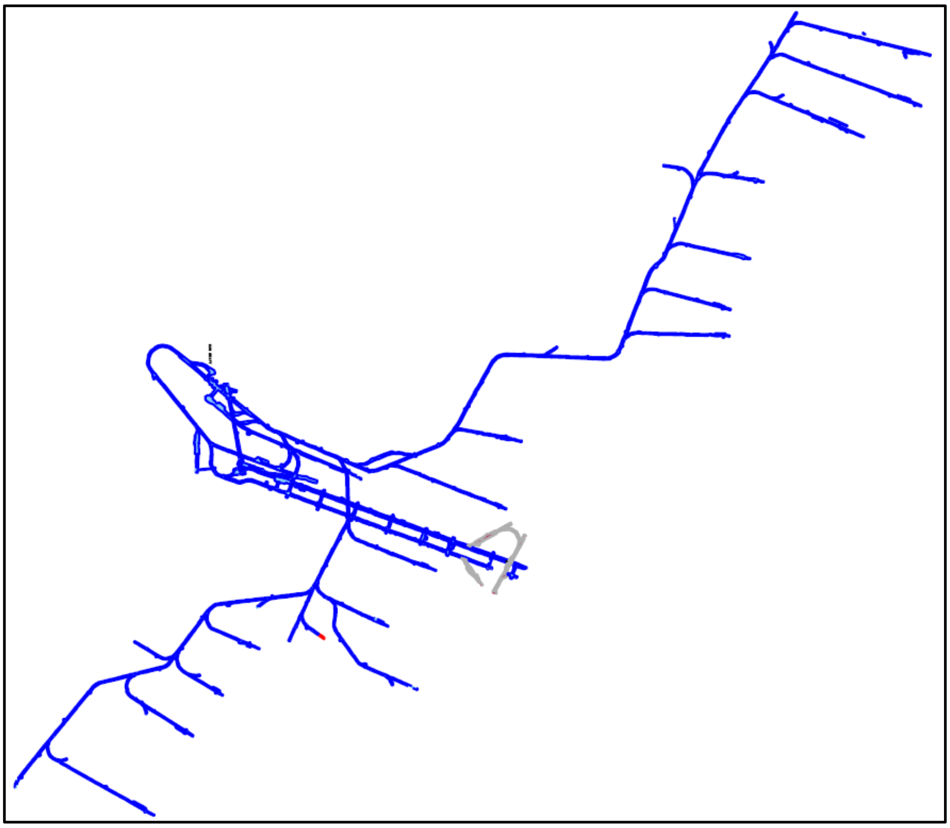


Figure I-4: Mine A 129L layout

APPENDIX J : Detailed analysis of demand requirement

Table J-1: Detailed analysis of demand requirements Mine A

		Operating consumption	% Utilisation	Total air consumption
Number of drills	± 155	316.8 m^3/h	70 %	34 400 m^3/h
Number of refuge bays	8	34 m^3/h	100 %	300 m^3/h
Number of loading boxes	± 15	170 m^3/h	50 %	1300 m^3/h
Number of tips	3	100 m^3/h	50 %	150 m^3/h
Workshops	5	60 m^3/h	50 %	150 m^3/h
Processing plant	1	1700 m^3/h	100 %	1700 m^3/h
Total				38 000 m^3/h (22 400 cfm)