



Identifying and improving inefficient deep-level mine compressed air distribution networks

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ABSTRACT

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The cost of electricity in South Africa is regularly increasing, and the energy availability factor (EAF) is worsened by poorly maintained plants, generation failures, sabotage, and coal and cable theft. This directly impacts the industrial mining sector, not only by reducing profit margins but also through load curtailment, where mining operations are running 20% to 30% below capacity due to electrical constraints.

Platinum-group metals (PGMs) are the leading commodity by sales, with the largest ore deposit in South Africa. Due to the recent decline in basket prices, approximately 25% of the production of primary PGMs is now unprofitable when considering the current spot prices. The long-term sustainability of this sector is greatly at risk, as cost-focused restructuring led to job cuts and postponed investments.

With electricity accounting for 90% of total utility costs, compressed air is the highest electrical consumer next to mining processes. Compressed air is also the key energy source used for pneumatic equipment in conventional mining. Insufficient pressure delivery to consumers may hinder operational performance and subsequently production rates. Shaft personnel often increase compressor supply pressures to accommodate low-delivery pressures and related complaints, increasing operational costs and lowering profitability.

An extensive literature review focused on addressing the issue of low compressed air delivery pressures due to system inefficiencies. This review highlighted the need for a safer and simpler method to address the issue. The proposed solution involved examining the haulage distribution network as a potential option for improving delivery pressures. To achieve this, mathematical

relationships between variables that describe pressure were analysed from first principles to gain a clear understanding of compressed air distribution in distant underground networks.

A methodology was developed to model the compressed air supply at known consumer demands. When applying the developed methodology to a case study mine, a verified baseline model was developed, with each level's pressure profile calibrated to an average mean average percentage error (MAPE) of 4.56%. A weighted MAPE (WMAPE) was introduced to account for high average percentage error (APE) during the blasting shift periods, skewing the MAPE of each level due to low-pressure values. With the weights based on the significance of pressure, a WMAPE of 2.99% for all levels on average was observed.

Furthering the developed method's steps, subsequent strategies were applied to effectively prioritise inefficient levels and identify infrastructural inefficiencies within the haulage distribution network using the developed baseline model. Limitations to identified localised inefficiencies can be addressed using the wastage-depressurisation method, developed to approximate the wastage on the respective level.

The case study mine's compressed air infrastructure does not correctly conform to the dimensional requirements specified in the mine's compressed air engineering standards. The infrastructural requirements are also insufficiently specified, contradictory, and outdated. These standards are, therefore, considered inadequate based on the mine's extensively developed compressed air network at current flow demands.

Solutions to improve inefficiencies were considered and simulated to provide predictive measures of the impact of implementation and the feasibility of implementation to the case study levels. The implementation of Scenario 2 to Case Study A achieved an average pressure improvement of 47.1 kPa (+9.5%), which is strongly correlated with the predicted improvement of 51.6 kPa (+10.4%). A large crosscut wastage was found in Case Study B.

The study is validated through outcomes and accomplishments based on the research objectives.

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NOMENCLATURE

Symbol	Description	Units
A	Area	m^2
C_p	Specific heat capacity	$\text{J/kg}\cdot\text{K}$
D	Diameter	m
D_H	Hydraulic diameter	m
ϵ	Absolute roughness	m
$\mathcal{E}$	Pressure drop per drill user	kPa
f_D	Darcy friction factor	-
g	Gravitational acceleration constant	m/s^2
h	Height	m
k	Specific heat ratio	$\text{J/kg}\cdot\text{K}$
K	Dynamic loss coefficient	-
L	Length	m
m	Mass	kg
P	Pressure	Pa
P_{atm}	Atmospheric pressure	Pa
ρ	Density	kg/m^3
Q	Wastage flow	Nm^3/h
R	Leak rate	Nm^3/min
R_s	Mass specific gas constant	$\text{J/kg}\cdot\text{K}$
Re	Reynold's number	-
Σ	Sum of	-
t	time	s
T	Temperature	K
μ	Dynamic viscosity	$\text{kg/m}\cdot\text{s}$
v	Velocity	m/s
V	Volume	m^3
$\bar{V}$	Average velocity	m/s
η	Efficiency	%
z	Altitude	m
ζ	Pressure loss coefficient	-

LIST OF ABBREVIATIONS

Abs	Absolute
APE	Average Percentage Error
ANN	Artificial Neural Network
Dev	Development End
DN	Diameter Nominal
DSM	Demand-Side Management
DXF	Drawing Exchange Format
CA	Compressed Air
CALDS	Compressed Air Leakage Documentation System
EAF	Energy Availability Factor
FT	Flow Transmitter
GDP	Gross Domestic Product
HDPE	High-Density Polyethylene
IPP	Independent Power Producers
JET	Just Energy Transition
MAPE	Mean Average Percentage Error
MER	Merensky
N/A	Not Applicable
NWU	North-West University
OEM	Original Equipment Manufacturer

PGM	Platinum Group Metals
PLC	Programmable Logic Controller
POD	Point of Distribution
PT	Pressure Transmitter
PTB	Process Toolbox
PV	Photo-Voltaic
RB	Refuge Bay
RDO	Rock Drill Operator
SA	South Africa
SP	Set Point
SQL	Structured Query Language
TOU	Time of Use
UG2	Upper Group 2
WMAPE	Weighted Mean Average Percentage Error
WPIC	World Platinum Investment Council
XC	Crosscut

CHAPTER 1: INTRODUCTION AND LITERATURE



Figure 1: Shaft on platinum mine – 06h00¹

Terence: *I was there to push people beyond what's expected of them. I believe that is... an absolute necessity. Otherwise, we're depriving the world of the next Charlie Parker.*

Andrew: *But is there a line? You know, maybe you go too far, and you discourage the next Charlie Parker from ever becoming Charlie Parker?*

Terence: *No, man, no. Because the next Charlie Parker would never be discouraged.*

- Dialogues, Whiplash (2014)

¹ WH du Preez, 2023.

1.1 Preamble

This section of the study describes the background of the South African PGM mining industry and the impact of high and increasing electrical costs. This section also attempts to identify the literature novelty in various methods addressing insufficient demand-side pressure in an underground mining compressed air network.

1.2 Background

1.2.1 Electrical energy in South Africa

Dating from 1923, South Africa's century old primary energy supplier, Eskom, provides approximately 90% of the country's electrical energy, and about 40% of the African continent's [1], [2]. This comprises the generation, transmission, distribution, and sale of electricity [1]. Owing to the various generating technologies, South Africa had a total of approximately 54 GW nominal capacity installed by 2022, with a breakdown shown in Figure 2 [3]. Additional supplementation is available from Independent Power Producers (IPP) [4].

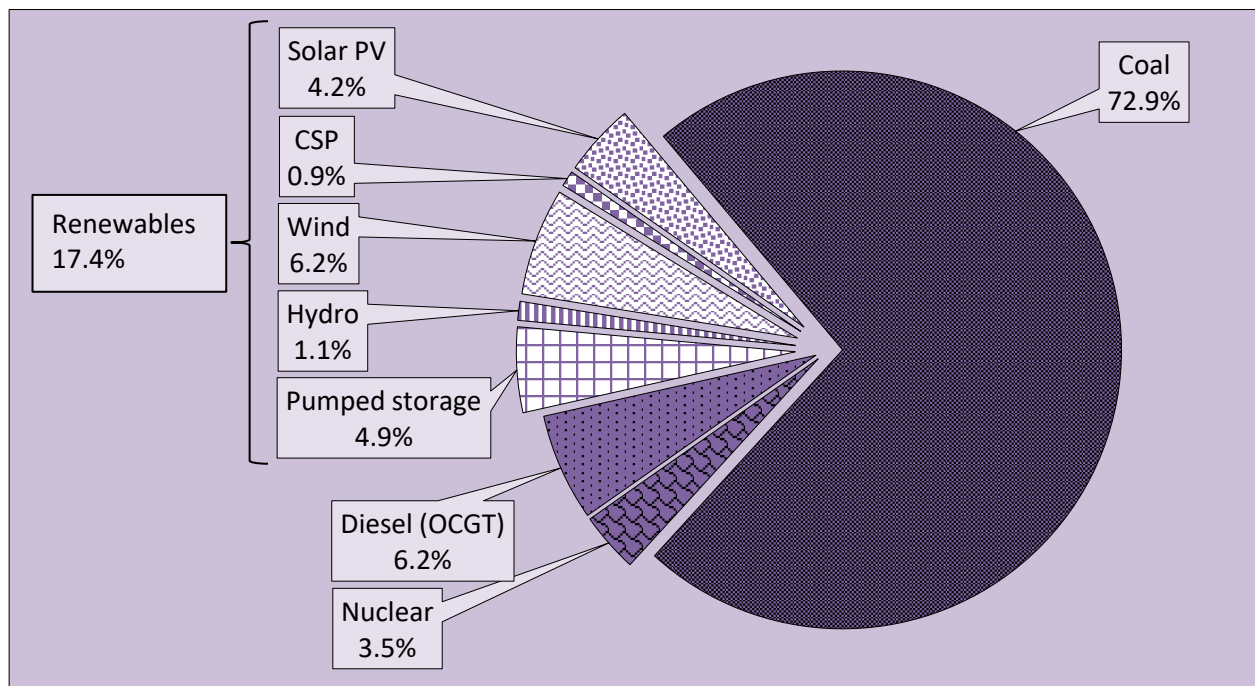


Figure 2: South African nominal energy generation capacities² [3]

² CSIR Statistics of utility-scale power generation in South Africa, February 2023.

Coal energy continues to dominate, with 80.1% contributing to system demand in 2022, contrary to a lower generation capacity of 72.9%. Although renewable energies' capacity is 17.4%, only 13.7% contributed. This may indicate an adverse effect on sustainability [3].

Unfortunately, the available supply capacity and demand varies and is often not enough to sustain the relatively high demand in South Africa [5]. The annual EAF³ observed for 2022 was 58.0% which reduced to 54.7% for 2023 [3], [6]. In 2018, an EAF of 71.8% was sustained [7]. Already low energy availability combined with this degree of decline further underlines the problem, predominantly due to generation failures from ageing and unmaintained plants, sabotage, and coal and cable theft [8], [9].

To prevent extended outages and grid failures, the integrity of the electrical grid must be maintained [5]. To ensure this, Eskom implements loadshedding, where the supply is temporarily cut to different regions across the country. Loadshedding, known to citizens since 2007, places the economy under severe strain and leads to a ripple effect across all aspects of society [5], [10]. Figure 3 indicates the annual increase in loadshedding, comparing the total amount of energy shed each year [7].

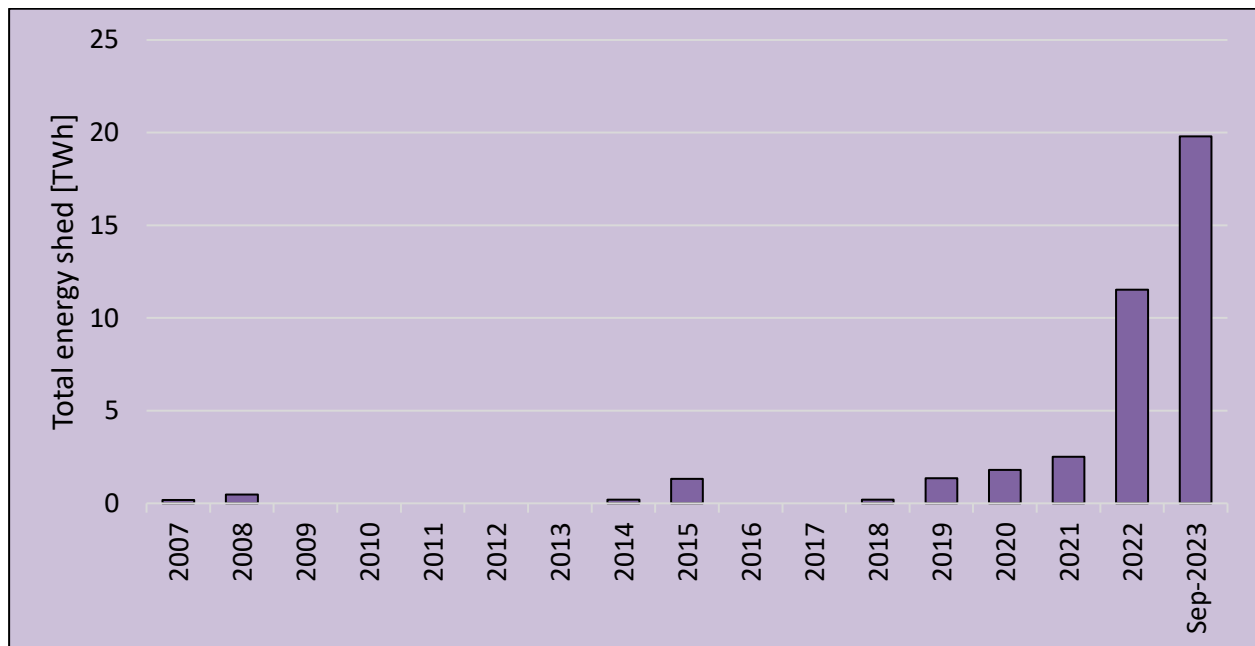


Figure 3: Comparison of total annual energy shed during loadshedding [7]

³ EAF - Ratio of available energy generation to the maximum amount of producible energy per same period.

The total energy shed in 2022 was more than all previous years combined. 2023 had a record 332 days of loadshedding, compared to the 205 days in 2022. The amount of energy shed by May 2023 already surpassed the 2022 total, with almost 20 TWh shed by September 2023 [11]. Contrary to all anticipated impacts loadshedding might have on a country and its economy, a lot of the effects were unforeseen, especially in terms of emotionality and the morale of citizens [12].

Eskom sells electrical units in the form of cent per kilowatt-hour (c/kWh) per tariff structure dependent on time, day of the week, season, transmission zone, voltage, and type of end-user [13], [14], [15]. Table 23 in Appendix A, shows a typical example of a Time of Use (TOU) tariff structure used by Eskom.

These tariffs have been increasing year-on-year at an alarming rate and are typically influenced by a multitude of factors such as inflation, available generating capacity, and change in demand, to name a few [16]. Figure 4 illustrates the annual tariff increases compared to the average annual cumulative inflation [17].

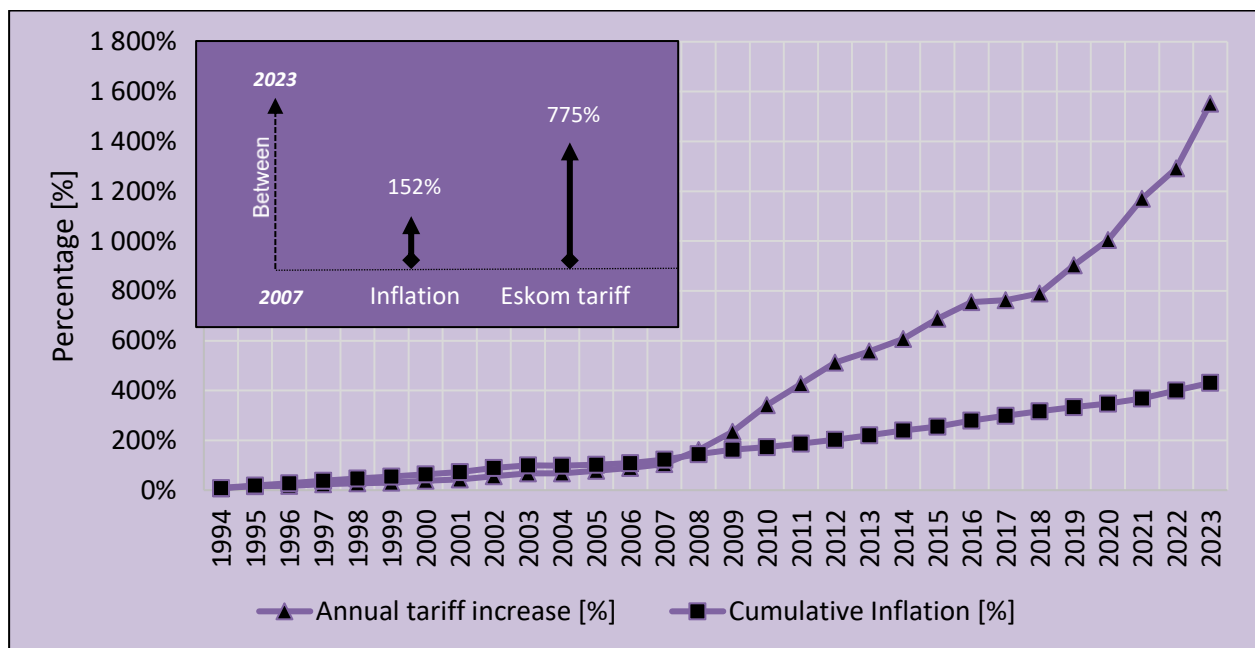


Figure 4: Annual historic increase comparison of Eskom electrical tariffs and cumulative inflation [17]

From 2007 until 2023, inflation cumulatively increased by 152%, while Eskom tariffs increased by more than five-fold over the same period. This places South Africans from all sectors under great economic and financial pressure.

The future of electricity in South Africa likely involves renewable energy sources, as energy availability has remained unstable for the past 16 years [7]. Increasingly, households have started installing photo-voltaic (PV) systems, commonly called solar systems, to mitigate the effects of loadshedding. During the 2023 budget speech, the South African government announced that businesses will be reimbursed 125% of their initial cost to install PV panels from the 1st of March 2023, and households only a 25% rebate up to a maximum of R15 000 [18]. This incentivises South Africans to consider alternative energy sources, further encouraged by Eskom's Just Energy Transition (JET) programme [2]. This involves elements such as cleaner and more sustainable electricity supply, transformational business changes, better provision for people and the planet, growing localisation and industrialisation, all aimed at achieving zero emissions by 2050 while increasing job sustainability [2].

Mining in South Africa remains one of the economy's largest energy-consuming sectors. The Minerals Council of South Africa stated in their 2022 annual report that mining operations are running 20% to 30% under capacity due to the electricity constraint, either through loadshedding or load curtailment [19].

1.2.2 South African mining industry

South Africa is well known for its available ore reserves, with 16 commodities in the top 10 globally [20]. The country is also known for its deep-level mines, with the deepest mine in the world reaching astounding depths of more than four kilometres [21].

Mining continues to contribute to the Gross Domestic Product (GDP) of South Africa, as the sector experienced a 4% growth in 2022 [19]. The GDP of a country has become a standardised measure for economic activity. It is a key indicator of stability and growth, and influences investment decisions, international trade, and policymaking [22].

The mining industry further stimulates economic growth and indirectly reduces crime [19], [23], possibly due to its role in job creation, where 15 500 more jobs have been created in 2022 [19], [24].

A record high in mineral production reached the trillion-rand mark in 2021 and was followed by a further increase to R1.18 trillion in 2022 [19], [24]. The top five commodity sales in South Africa over the past two years, categorised by mineral group and mineral, are presented in Figure 5 [25].

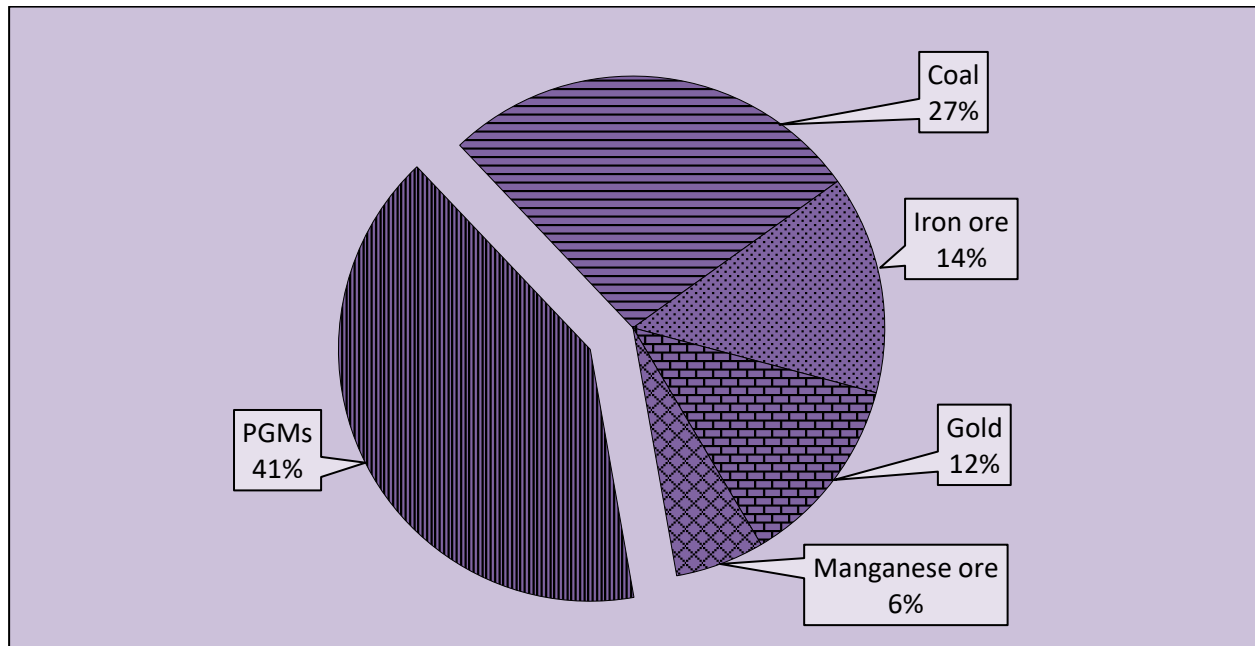


Figure 5: Mineral sales by mineral group and mineral - March 2021 to March 2023 (R million) [25]

The top recent revenue-generating sectors are PGMs and coal, followed by iron ore and gold to a lesser extent.

The two greatest ore-bearing deposits of gold and PGMs are in South Africa [26], [27]. Over one-third of all gold ever produced was produced from the Witwatersrand Basin, stretching over four provinces [26]. The Bushveld Igneous Complex, as large as Ireland, boasts more than three-quarters of the world's platinum and rhodium, and more than half of the world's palladium [27], [28], [29]. South Africa also holds 90% of the world's PGM reserves, followed by Russia and Zimbabwe respectively [30], [31], consisting of six metals, namely platinum, palladium, rhodium, ruthenium, osmium, and iridium. Recently, PGM sales overtook those of coal and became the best-selling commodity (mineral resource) in the South African mining industry [32]. PGM sales surged by 40% during the Covid-19 pandemic in 2020, despite a 15.5% decline in production [32], [33].

PGMs are known for their unique catalytic properties whilst also being highly corrosion resistant. These metals are utilised across various sectors in technology, industrial processes, and commercial applications, from chemotherapy drugs to catalysts in electrolyzers for green hydrogen production [34]. The discernible trend of PGMs' growing demand suggests an increasing role in the foreseeable future.

Despite a multitude of available prospects, the South African mining sector continues to face several difficulties. These challenges include massive demand surges, a lack of energy reliability, environmental ramifications, worker safety, supply chain disruptions, unreliable infrastructure, a lack of technical expertise, and operational security concerns [35]. These forces threaten the industry's potential to capitalise on the many opportunities [35].

With an estimated value of over US\$2.4 trillion⁴ for its non-energy minerals, South Africa stands as the preeminent mining jurisdiction globally [31]. However, these deposits have not been used as catalysts for shared prosperity [31]. By 2012, only 20% of its potential export relationships were reached, compared to a 70% exploitation of China and Germany at the time [36]. Although this might not be a recent representation, it indicates significant untapped potential.

The total global demand for platinum experienced a remarkable surge of 25% year-on-year in 2023 [37], [38]. Figure 6 shows the South African and global refined platinum supply versus the global demand. These values have been adapted from the World Platinum Investment Council (WPIC) [38].

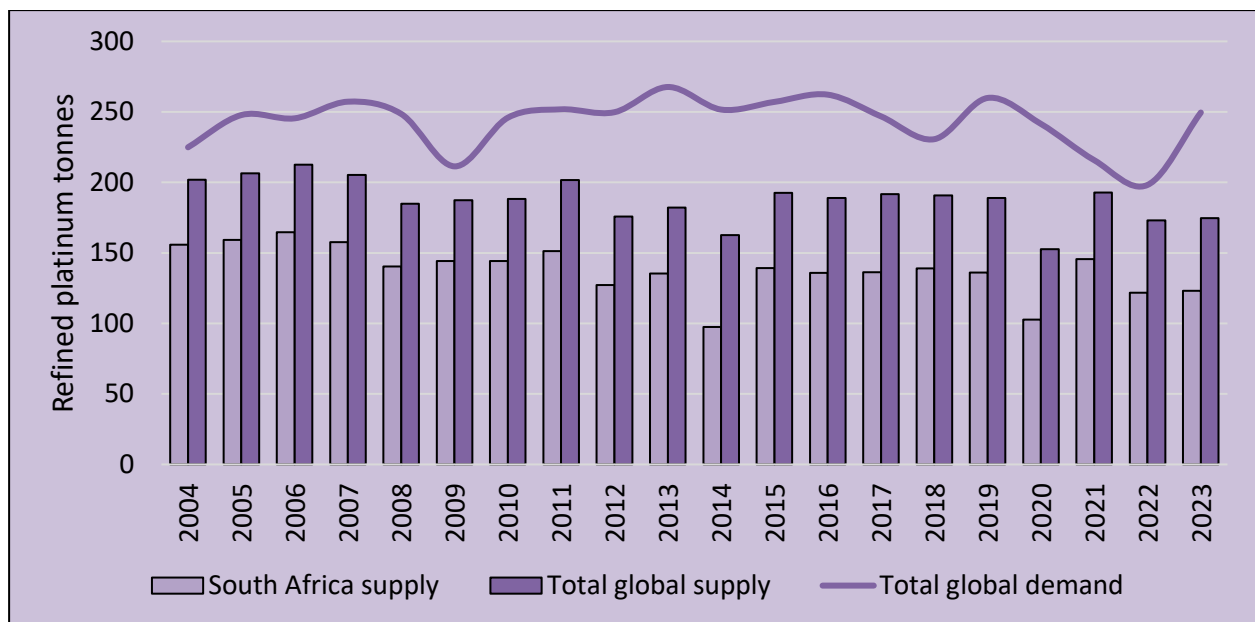


Figure 6: Refined platinum mining production in South Africa and total supply versus demand [38]

⁴ Average USD exchange to ZAR R14.50 in 2019

However, the annual rate of decline in PGM basket prices has sequentially accelerated by approximately 40% through each quarter of 2023 [39]. This decline leaves an estimated 25% of primary PGM supply as unprofitable at current spot prices [39]. This lowered profitability across the PGM mining sector, raising concerns about the long-term sustainability of several operations [39]. South African PGM miners have announced a cost-focused restructuring in response to the lower PGM basket price, as significant losses are suffered as prices and profits declined. [40]. Margins are, therefore, difficult to maintain, which has led to job cuts and postponed investments [37].

1.2.3 Underground mining utilities

Mining utilities, i.e., water and electricity, form 13% of a mine's total operational month-to-month costs [41], [42].

Underground service water is used to clear debris and cool pneumatic drill rigs during endurance drilling [43]. Dams built underground act as a buffer system, providing additional capacity and enhancing the stability, efficiency, and reliability of water distribution [44]. Potable water is also used for various purposes such as cooling, change house supply, dust suppression, top-up of dams, etc. [43], [45], [46].

The cost of electricity can form up to 90% of the total utility cost [47]. From the cumulative tariff increases shown in Figure 4, electricity costs of the mining industry have increased by 33.7% from 2022 to 2024 [48]. Due to these higher costs, the share of energy in intermediary inputs will increase from 24% to 38% in gold mining, from 22% to 27% in iron ore mining, and from 13% to 19% in the PGM sector [48]. A breakdown of electrical consumers on a typical deep-level mine is illustrated in Figure 7 [47].

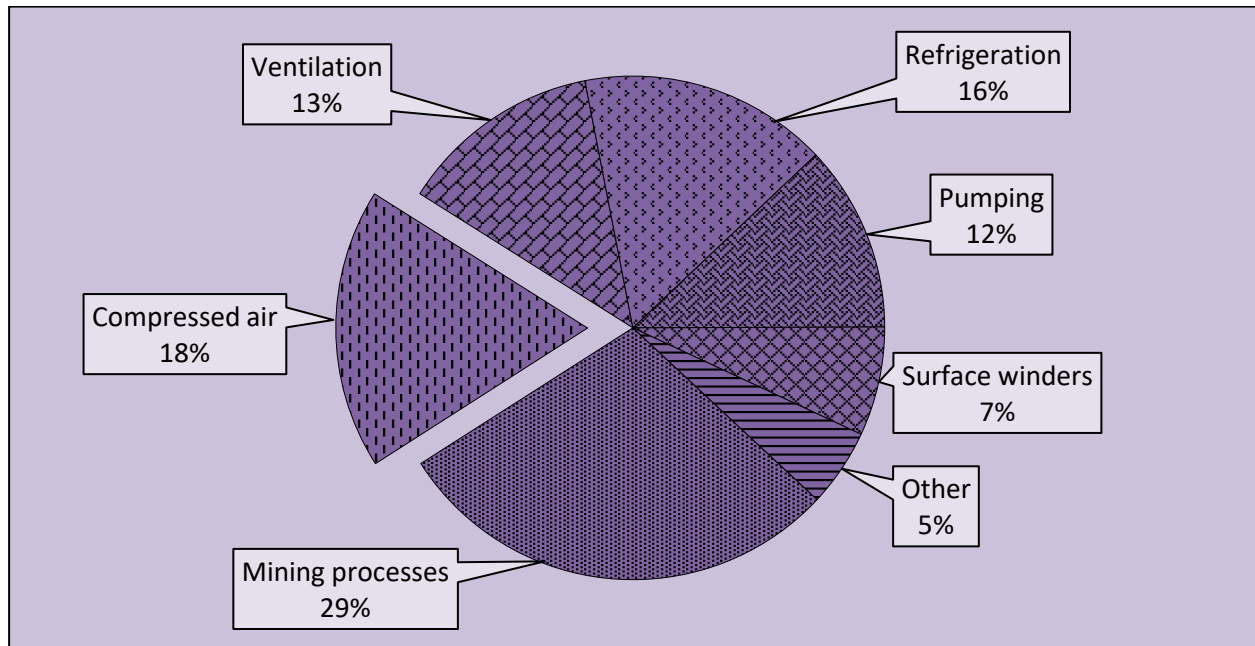


Figure 7: Breakdown of electrical consumption on a typical deep-level mine [47]

Approximately 20% of the electrical consumption is attributed to compressed air usage [45], [47], [49], [50], [51].

1.2.4 Compressed air systems in deep-level mining

Due to compressed air's versatility in mining, almost all types of equipment possess pneumatic capabilities and is also considered one of the safest available energy sources [47], [52], [53]. Although compressed air may pose exposures to dust and noise, it does not place the mining environment at risk to any flammable or toxic hazards [47], [52].

A permanent surface compressor installation supplies compressed air to surface and underground consumers. Multiple compressors of various sizes are installed for a versatile supply to meet the daily varying in compressed air demand as described in Figure 8 [41], [44]. A piping network is used to distribute air throughout the mine. Consumers are largely spread at great distances away from the source [54], and as such, reticulation piping networks spread up to tens of kilometres to supply them [44], [47]. Due to this vast complexity of networks, inefficiencies play a great role in the sufficient distribution of compressed air.

As most mining equipment is fully pneumatic, insufficient pressure directly places production rates at risk, as equipment cannot operate below a certain pressure threshold [44], [50]. It is, therefore, crucial that compressed air reach the demand-side sufficiently. Typical consumers include, but are not limited to drill rigs, loaders, loading boxes, blowers, diaphragm pumps, skips, agitation,

and refuge bays [41], [51], [54]. Each consumer is operated at different times of the day with different pressure requirements [47].

The most prominent compressed air consumers and their pressure requirements are shown in Table 1. This was summarised from Zietsman *et al.* and Van der Merwe *et al.* [44], [47].

Table 1: Prominent compressed air consumer requirements [44], [47]

Compressed air consumer	Schedule/Shift	Pressure [kPa _g]	Flow [kg/s]
Pneumatic rock drills	Drilling	450-620	0.12
Pneumatic loaders	Cleaning	400-550	0.8
Pneumatic cylinders/actuators	Drilling & Cleaning	400-500	0.004-0.1
Refuge bays	Continuous	150-200	<0.06

Pneumatic rock drills have the highest pressure requirement. Although pneumatic loaders have the highest flow demand, only one loader is used at a developing area, in contrast to multiple rock drills at stoping and developing areas. Daily mining operations usually consist of three main shifts, namely drilling, cleaning, and blasting shifts [47]. Due to the nature of varying pneumatic demands, pressure requirements vary between shifts [55]. This typically determines the shaft's daily set-point profile schedule that compressors follow to meet this varying underground demand [47]. A typical daily profile, based on the minimum pressure requirements, is shown in Figure 8 [45], [47].

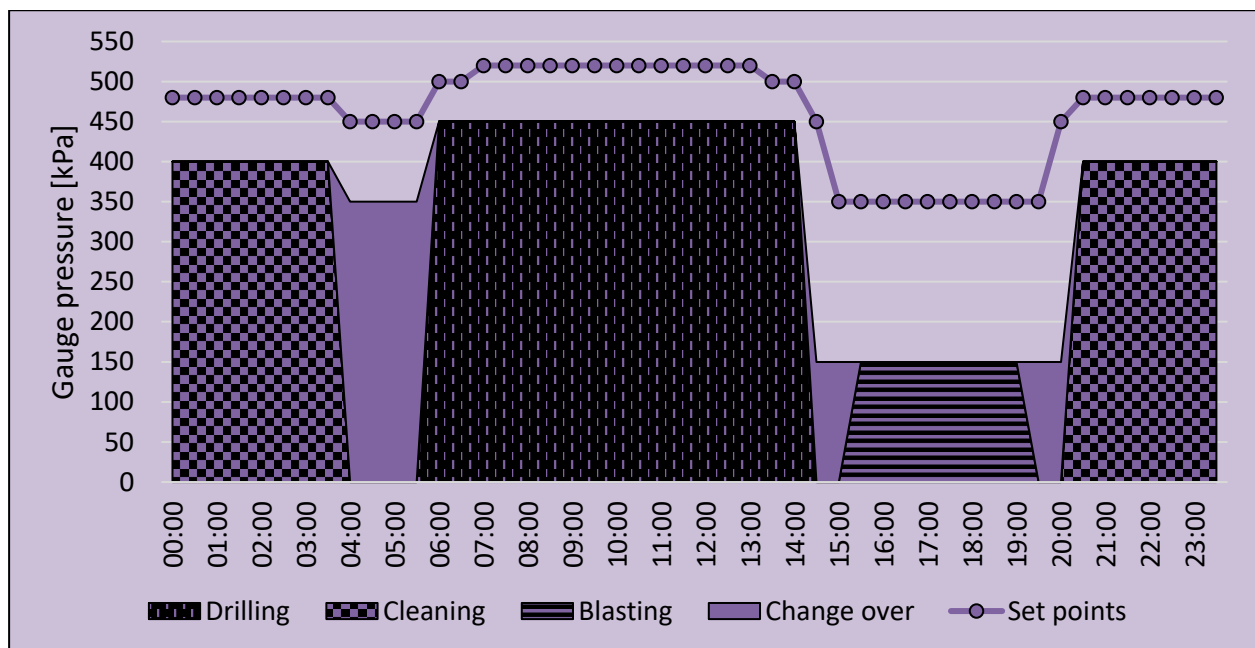


Figure 8: Typical compressed air pressure set points versus minimum requirements [45], [47]

The drilling shift is the main working shift where rock drill operators (RDOs) drill 1.2-meter-deep holes into hard rock for explosive insertions [56]. These drills have the highest minimum pressure requirement of 450 kPa_g [45], [47]. The explosives are then inserted after the drilling shift and strategically detonated during the blasting shift [51], [57]. Depending on the ventilation performance of the shaft, approximately two hours post-detonation are allocated for the extraction of harmful gas and dust residue before cleaning crews can enter the workplaces. During the cleaning shift, dislodged rocks, debris, and ore are cleared onto minecarts and conveyors to be transported or hoisted to surface [51], [58].

Simulations as a tool in mining:

Mines are typically known to use outdated technology and equipment [47], [54]. Technological advances may, therefore, provide the edge for improved sustainability and profitability. Recent utilisation of simulations as a tool in the mining industry has shown great potential in the future design, problem identification, and development of improved management and monitoring strategies [54], [59], [60], [61], [62]. A simulation tool is, therefore, ideal for a mining environment in which complexly integrated systems are involved.

Instrumentation in mining:

As previously discussed, pneumatic equipment and rate of production are dependent on sufficient air pressure delivery. Compressed air inefficiencies may hinder the distribution of pressure along a distant mining network. It is often difficult to identify inefficiencies and wastages due to the lack of instrumentation on a level. Pressure and flow instrumentation is usually only installed at the station [44], [50]; however, unlike the surface flow meter, underground flow meters are not as robust and are not deemed trustworthy. It is a known issue that underground flow meters have become inaccurate over time due to lack of maintenance, calibration, and continuous exposure to moisture [42], [51], [55], [59], [63]. There are also limited locations where portable instruments can be installed for measurement purposes [47], [51].

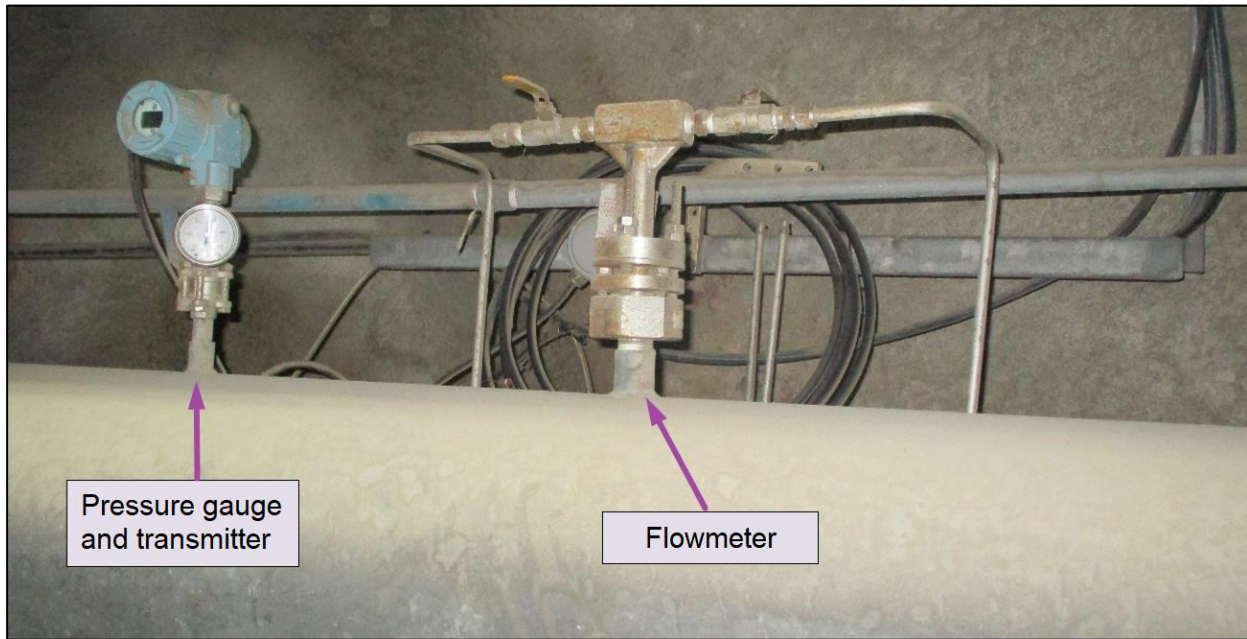


Figure 9: Example of station-installed flow meter and pressure transmitter⁵

Studying the various types of inefficiencies within a compressed air network would provide the necessary background to understand the effect and origin of any factor that pertains to delivery pressure.

1.2.5 Compressed air inefficiencies affecting delivery pressure

This section will study compressed air in principle, namely the behaviour (Ideal Gas Law), and the relationship between variables (Bernoulli's Principle), specifically in relation to pressure. This is done carefully to consider each aspect of compressed air to identify possible inefficiencies that may affect delivery pressure to pneumatic consumers. The behaviour of an ideal gas is described by the Ideal Gas Law [64].

Ideal Gas Law (mass-specific form):

$$PV = mR_sT$$

Equation 1.1

Where:

⁵ WH du Preez, October 2022

P	Absolute pressure [Pa]
V	Volume [m ³]
m	Mass [kg]
R_s	Mass-specific gas constant [J/kg·K]
T	Temperature [K]

The density of a fluid is behaviourally determined by the Ideal Gas Law. Using the density ρ , defined by Equation 1.2

$$\rho = \frac{m}{V} \quad \text{Equation 1.2}$$

Where:

ρ	Density [kg/m ³]
m	Mass [kg]
V	Volume [m ³]

And substituting into and rearranging Equation 1.1 in terms of density ρ yields [50]

$$\rho = \frac{P}{R_s T} \quad \text{Equation 1.3}$$

From Equation 1.3, for a specific gas, the density is determined by its pressure and temperature.

Ideal Gas Law limitations:

For real gases, the gas law does not hold well at very high pressures or very low temperatures [65]. Compressed air is not an ideal gas; however, in a mining environment, it is generated, distributed, and consumed at low pressures and moderate temperatures. Relating to Equation 1.3, if density is kept low, such as in compressed air, the equation should hold well. Similarly, real gases can be considered ideal for calculation purposes in either low-pressure or

high-temperature systems [66]. The Ideal Gas Law can, therefore, be used to describe the behaviour of compressed air with reasonable accuracy.

The conservation of energy in a compressed air system is further studied. The different kinds of energy possessed by a fluid particle are considered theoretically [67]. This ensures all measures are taken to consider every relationship between variables in a compressed air system that pertain to an inefficiency that could affect pressure. The pressure, potential, and kinetic energy of a fluid is considered [67]. The sum of these energies describes the total energy of a fluid and the relationship between variables is mathematically derived and described by Bernoulli's equation [41], [67], [68], [69].

Bernoulli's Equation:

$$P + \frac{1}{2}\rho v^2 + \rho gh = \text{constant along streamline}$$

Equation 1.4

Where:

P Pressure [Pa]

ρ Density of fluid [kg/m³]

v Velocity of fluid [m/s]

g Gravitational acceleration constant [m/s²]

h Height [m]

When interpreted physically, the total mechanical energy is conserved for a control volume satisfying certain conditions subject to Bernoulli's limitations. From Equation 1.4, the value of $P + \frac{1}{2}\rho v^2 + \rho gh$ will be the same at any point in a streamline fluid [67], [68].

Bernoulli's limitations:

Bernoulli's equation is limited to a control volume whereby the flow is steady, incompressible, inviscid, isothermal, and in which no change in internal energy (heat transfer and work done) occurs [70]. The constant internal energy and inviscid flow assumption is found to be equivalent [70]. These conditions are met or approached in many physical or practical systems [70].

Therefore, the application of Bernoulli's equation in a compressed air system is still viable, as it remains a suitable approximation and relationship between variables. Each term in the Bernoulli equation can be interpreted as a form of pressure [68], [69].

Pressure forms derived from each term in Bernoulli's Equation 1.4:

- **P Static (thermodynamic) pressure**
 - The thermodynamic pressure represents the pressure of the fluid as it flows. It is normally termed static pressure, as it can be measured by moving relative to the moving fluid (observing the fluid from a static point of view).
- **$\frac{1}{2}\rho v^2$ Dynamic pressure**
 - The dynamic pressure describes the kinetic energy of a fluid by virtue of its in-motion velocity.
- **ρgh Hydrostatic pressure**
 - This represents the change in pressure due to potential energy variations because of a change in elevation. The hydrostatic pressure describes the known “auto-compression” phenomenon, described in Equation 1.5 [51], [55], [57].

The sum of each term (static, dynamic, and hydrostatic pressure) is termed the total pressure P_T , and is a conversion of the total energy the fluid possesses [69].

The atmospheric pressure is higher at sea level than at a higher altitude [57]. The same is true for compressed air in a mining environment [52], [57]. As previously mentioned, compressed air also gains potential energy from auto-compression, which is the force on the fluid by virtue of its altitude and weight and may be considered adiabatic [51], [57], [71].

Auto-compression:

$$P_2 = P_1 \left[1 - \frac{g(z_1 - z_2)}{T_1 C_p} \right]^{\frac{1}{k}}$$

Equation 1.5

Where:

P_2 Final pressure [kPa_{Abs}]

P_1 Initial pressure [kPa_{Abs}]

g	Gravitational acceleration constant [m/s ²]
z_1	Initial altitude [m]
z_2	Final altitude [m]
T_1	Temperature [K]
C_p	Specific heat capacity [J/kg K]
k	Specific heat ratio [J/kg·K]

To correctly identify an inefficiency that affects delivery pressure, it is important to understand which inefficiencies potentially cause a pressure loss and how it may be lost. Considering compressed air in an enclosed system, the air flowing through a distant network is subject to various pressure losses which is a result of line friction [69], [72]. The resistive forces acted on by the internal pipe wall roughness, viscous shear stresses within the fluid, and turbulence near the pipe wall also add to these losses [72], [73]. A fluid in motion experiences both major and minor head (or pressure) losses [74], [75]. Darcy-Weisbach in Equation 1.6 describes the major pressure loss of a fluid [50], [69], [74], [76].

Major friction pressure loss (Darcy-Weisbach):

$$\Delta P_{Major} = f_D \left(\frac{L}{D_H} \right) \left(\frac{\rho \bar{V}^2}{2} \right)$$

Equation 1.6

Where:

ΔP	Major pressure drop [Pa]
f_D	Friction factor [-]
L	Pipe length [m]
D_H	Hydraulic diameter [m]
ρ	Fluid density [kg/m ³]
$\bar{V}$	Average fluid velocity [m/s]

The hydraulic diameter for a circular pipe is equal to the inner pipe diameter. The friction factor can be calculated using the implicit Colebrook-White equation or other explicit approximations such as the Swamee-Jain or Vatankhah equations [77], [78]. A Moody Diagram can be used as a simpler alternative to determine the approximate friction factor [70], [79]. The Moody Diagram is a plot of the Darcy friction factor versus the Reynolds number for a range of values of the relative roughness $\frac{\epsilon}{D}$ [70], [73].

The Darcy friction factor can be calculated for both laminar and turbulent flows:

Friction factor (laminar flow):

$$f_D = \frac{64}{Re} \text{ for } Re < 2\,000 \text{ (2\,300 in pipes)} \quad \text{Equation 1.7}$$

or

Colebrook-White (turbulent flow):

$$\frac{1}{\sqrt{f_D}} = -2 \log_{10} \left[\frac{\epsilon}{3.7D} + \frac{2.51}{Re\sqrt{f_D}} \right] \text{ for } Re > 4\,000 \quad \text{Equation 1.8}$$

Where:

f_D Darcy friction factor [-]

ϵ Absolute pipe roughness [m]

D Inner pipe diameter [m]

Re Reynold's number [-]

Or by an explicit approximation [78]:

Swamee-Jane:

$$f_D = \frac{0.25}{\left[\log_{10} \left(\frac{\epsilon}{3.7D} + \frac{5.74}{Re^{0.9}} \right) \right]^2} \quad \text{Equation 1.9}$$

Where:

f_D Darcy friction factor [-]

ϵ Absolute pipe roughness [m]

D Inner pipe diameter [m]

Re Reynold's number [-]

Pipe corrosion affects the absolute roughness of a pipe [70]. The flow regime is described by the dimensionless Reynold's number in Equation 1.10.

Reynold's number:

$$Re = \frac{\rho v D}{\mu} \quad \text{Equation 1.10}$$

Where:

Re Reynold's number [-]

ρ Fluid density [kg/m³]

v Fluid velocity [m/s]

D Inner pipe diameter [m]

μ Dynamic viscosity of fluid [kg/m.s]

Minor pressure losses are a function of the flow regime, velocity, and geometry of a component within the piping network [69], [74], [75]. The flow regime in a compressed air system is assumed to be turbulent due to the relatively large airflow speed [72]. Minor pressure losses due to the friction of localised pipe components can be calculated using dynamic loss coefficients [74], [75].

Minor friction pressure loss:

$$\Delta P_{Minor} = \sum K \left(\frac{\rho \bar{V}^2}{2} \right) \quad \text{Equation 1.11}$$

Where:

ΔP Minor pressure drop [Pa]

$\sum K$ Sum of all dynamic loss coefficients [-]

ρ Fluid density [kg/m³]

$\bar{V}$ Average fluid velocity [m/s]

Combining both major and minor pressure drops, described by Equation 1.6 and Equation 1.11, yields the total pressure loss ΔP [74], [75]:

$$\Delta P = \Delta P_{Major} + \Delta P_{Minor} \quad \text{Equation 1.12}$$

Substituted:

$$\Delta P = f_D \left(\frac{L}{D_H} \right) \left(\frac{\rho \bar{V}^2}{2} \right) + \sum K \left(\frac{\rho \bar{V}^2}{2} \right) \quad \text{Equation 1.13}$$

Simplified:

$$\Delta P = \left(f_D \frac{L}{D_H} + \sum K \right) \frac{\rho \bar{V}^2}{2} \quad \text{Equation 1.14}$$

Herewith, the major and minor pressure loss combined, described by the pressure loss coefficient ξ [74], [75].

$$\Delta P = \xi \frac{\rho \bar{V}^2}{2} \quad \text{Equation 1.15}$$

Various types of inefficiencies are often present in a vast compressed air network. This is an integral part of the system, potentially affecting the performance of pneumatic equipment. These common inefficiencies that affects delivery pressure are discussed in more detail below.

Infrastructural limitations and losses:

Undersized piping restricts the airflow in a compressed air network resulting in pressure loss [47], [53], [58]. Piping may also become restrictive due to an increased flow demand, whereby the physical infrastructure reaches its limits due to its size. The cross-sectional or wetted area of an undersized pipe cannot carry the necessary amount of air, which induces a pressure drop [58]. A one-kilometre piping scenario with the same flow demand is simulated for two identical pipes, where Pipe B has a restriction as seen in Figure 10.

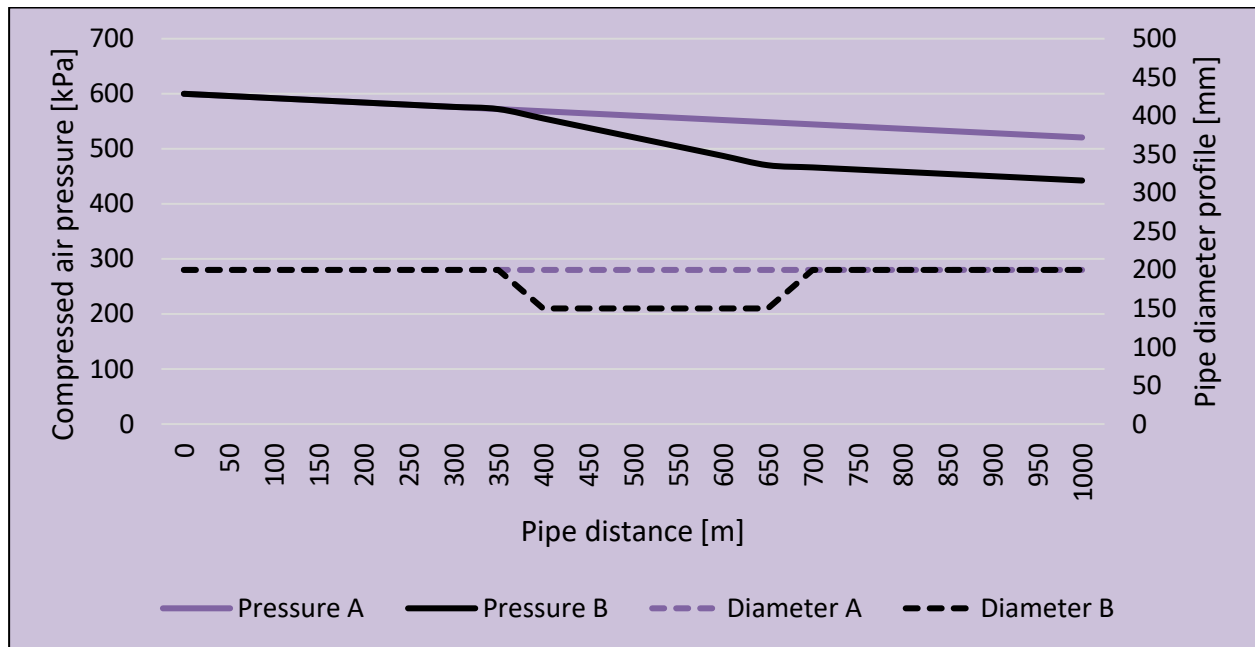


Figure 10: Infrastructural pipe restricting effects on pressure

A clear drop in pressure is observed in Pipe B due to its restrictive section. In practice, a restrictive section will have adverse effects on the downstream pressure users.

Increased flow demand:

Common inefficiencies such as leakages, misuse, and other wastages contribute greatly to the total flow demand of a compressed air network. Sometimes up to 50% of compressor flow capacity can be wasted [50], [51], [57]. Continuous and resource- and labour-intensive audits are required to identify and address these inefficiencies effectively [47]. A zero-waste baseline concept indicates the optimal operating point at which no wastage occurs for a specific system [44]. An example of this baseline is shown in Figure 11, indicating the effect of wastage [44].

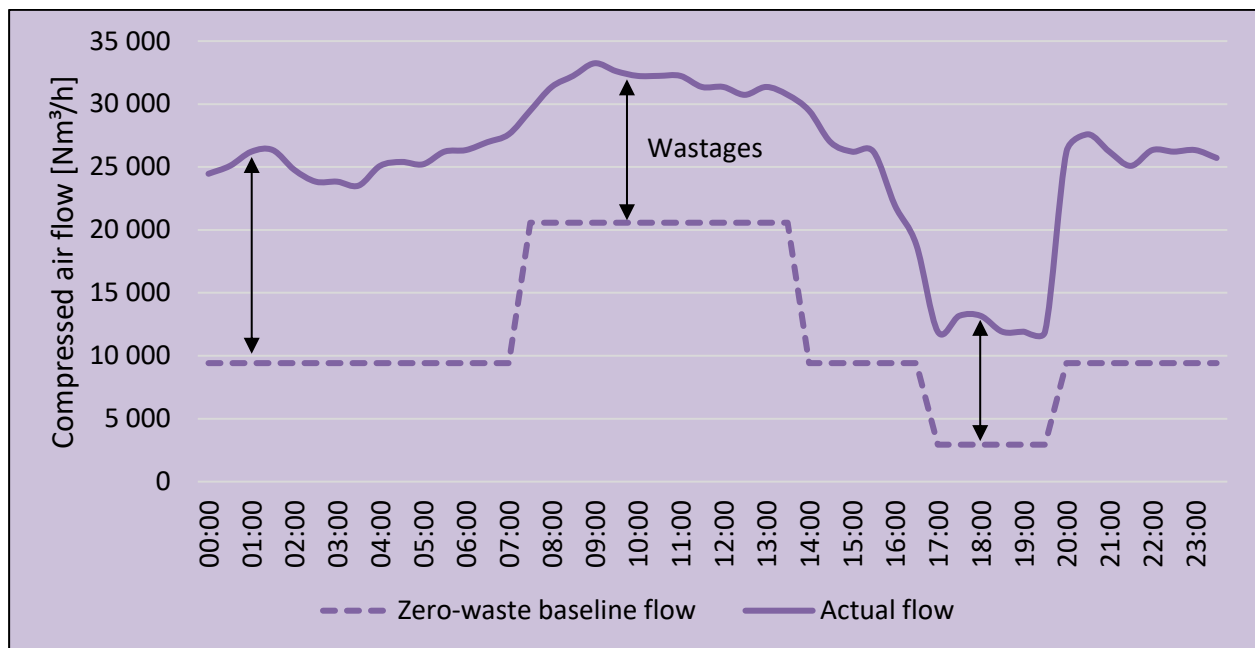


Figure 11: Generated zero-waste baseline example of a typical operational day

A clear discrepancy between the zero-waste baseline and actual demand can be observed. The actual demand is offset by the number of wastages. This indicates the proportional amount of compressed air that needs to be produced above the required amount to sustain the system at the required pressure.

Unintentional wastage:

Compressed air leakages are unintentional openings in the piping network's infrastructure. Leakages originate through improper flange fittings, worn-down seals or through pipe corrosion accelerated by a humid mining environment [45], [47], [49]. It is not always a top priority to maintain piping infrastructure as personnel are only permitted to work on a depressurised system during a non-production period [52], [54]. The compressed air used to maintain refuge bays at a positive pressure is not always regulated correctly, leading to higher than necessary consumption

[44], [45], [51]. When a crosscut becomes inactive, the compressed air valves are closed to prevent wastage; however, valve conditions deteriorate and can continue to supply an inactive crosscut without any knowledge thereof [47], [53], [55].



Figure 12: Example of unintentional wastage: Pipe leakage due to corrosion⁶

Intentional wastage:

Intentional wastage is unauthorised⁷ use of compressed air which includes punch-holes and illegal blowers, often used to cool down, ventilate or clear debris in the working areas [47], [49], [51].

⁶ Personal photo, 2022

⁷ Unauthorised herein referred to as illegal use of compressed air for purposes not intended for mining.



Figure 13: Example of intentional wastage: Compressed air hose used to dry clothing⁸

From the author's professional experience, the mufflers located on the drill rigs are tampered with for improved drilling performance at the cost of higher flow, noise, and occasional freeze build-ups.



Figure 14: Example of intentional wastage: Broken (tampered) rock-drill muffler⁹

⁸ Personal photo, 2021

⁹ WH du Preez, 2021

Inadequate compressor supply:

Due to an increased flow demand spread across a vast compressed air network, pressure is lost throughout the network. Compressors automatically ramp up – if able to – to sustain the increasing demand at the required pressure set point; however, it may become redundant once infrastructural limitations are reached [15], [58]. When air is supplied at higher pressures to accommodate deteriorating and inefficient networks, artificial demand can be induced [80].

Compressors may also supply inadequate pressure when the demand exceeds the maximum supply capabilities of the available compressor(s), particularly if the set-point value is not set too low [58], [63]. This occurrence is illustrated in Figure 15, often experienced during peak demand periods such as the drilling shift [59].

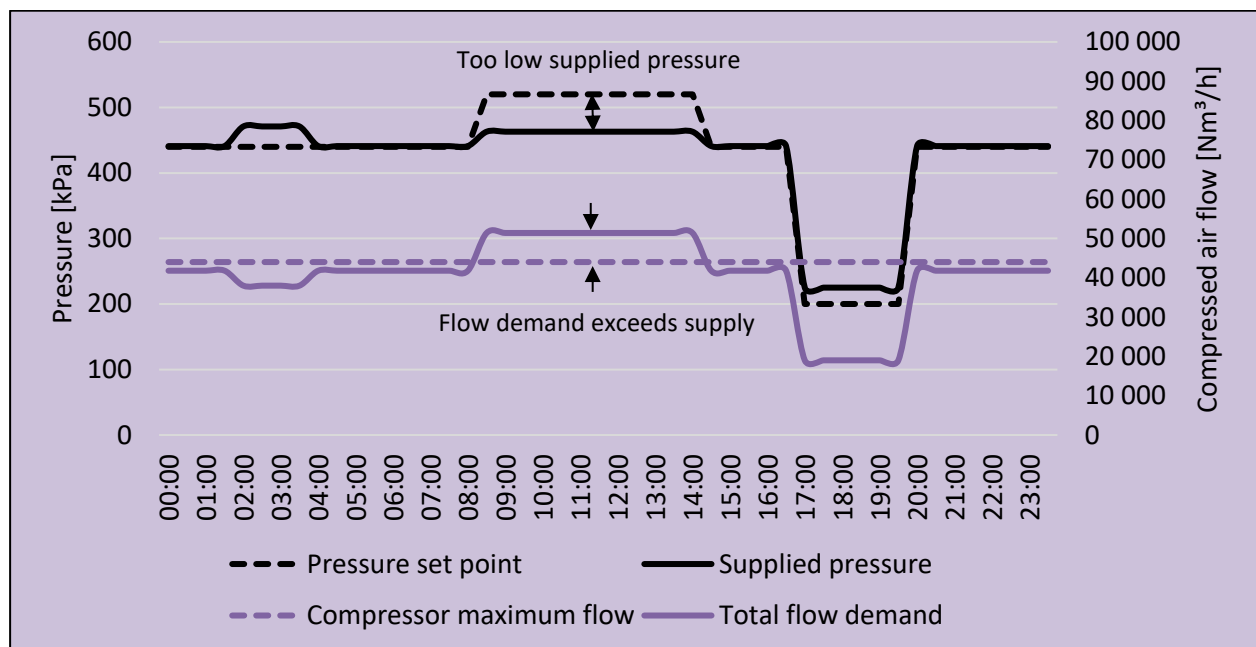


Figure 15: Typical example of inadequate compressor supply during a drilling shift

A clear relationship between pressure and flow is observed. The system's pressure is dependent on the flow capabilities of the compressor and the total compressed air flow demand. To avoid unnecessary operating costs and risk to production losses, the balance between compressor supply and shaft demand must be met as efficiently as possible.

1.2.6 Initial problem statement

Compressed air distribution is subjected to various losses due to inefficiencies in vast and complex mining networks. These inefficiencies result in reduced pressure delivery to distant downstream consumers. Insufficient¹⁰ demand-side pressure affects the performance of pneumatic equipment and may, therefore, affect production rates. This leads to increased operational costs, as the need to supply air at higher pressure increases. When air is supplied at higher pressures to accommodate deteriorating and inefficient networks, artificial demand can be induced.

1.3 Literature review and state-of-the-art

The key objective during this literature review is to critique and determine the shortcomings and limitations in previous studies when addressing low demand-side pressures.

1.3.1 Literature search strategy

Research related to the field of study and initial problem statement was conducted. The following criteria and keywords were used in various search engines such as Google Scholar, NWU Library, ScienceDirect, ResearchGate, and SciELO SA. This research strategy provided several journals, articles and studies related to the field, of which each was carefully considered in terms of relevance. This research strategy included the following criteria related to the scope of this study to ensure the literature review aligns with the boundaries of research:

- Research related to *“underground compressed air networks”*.
- Research related to *“inefficiencies in a compressed air network”*.
- Research related to *“compressed air pressures”*.
- Research related to *“methods to address inefficiencies”*.
- Research related to *“methods to improve pressure delivery”*.
- Research related to *“compressed air networks using simulation software”*.
- Research related to *“parameter prediction of compressed air networks”*.

¹⁰ Below recommended operating threshold

1.3.2 Narrative analysis

Research related to the field of study, found through the above literature search strategy, will be discussed below. Each research study is analysed in terms of its relevance, achieved results, knowledge gained from the study, and shortcomings to identify limitations within relevant studies that relate to the issue.

Study 1 [63]: *“Improved control of compressed air networks using machine learning”*.

Author(s): GJ Matthee *et al.*

Relevant research criteria: Inefficiencies in a compressed air network; compressed air pressures; compressed air networks using simulation software; parameter prediction of compressed air networks.

Overview:	This study explores existing energy management strategies for compressed air systems. The feasibility of applying a machine-learning model for real-time parameter prediction is investigated. A method is applied to develop an artificial neural network (ANN) for the accurate prediction of pressures in a mining compressed air network.
Results:	A control solution is developed, demonstrating the potential for electrical cost savings whilst maintaining sufficient pressure supply at critical demand locations. This solution verifies whether suggested compressor combinations could work more efficiently when reaching the predicted pressure demand. The accurate prediction of pressures via simulation-based software was achieved within a MAPE of 4.20%.
Relevance:	This study is relevant to the topic in terms of using a simulation-based model to predict compressed air pressures and mitigating inefficiencies.

Gained from study: A model using fundamental principles and physical relationships between parameters can describe a compressed air network effectively.

Shortcomings: The study mainly focused on compressor supply pressures on surface irrespective of underground compressed air networks.

Study 2 [51]: *“Optimising production through improving the efficiency of mine compressed air networks with limited infrastructure”.*

Author(s): D Nell *et al.*

Relevant research criteria: Underground compressed air networks; inefficiencies in a compressed air network; compressed air pressures; methods to address inefficiencies; methods to improve pressure delivery; compressed air networks using simulation software; parameter prediction of compressed air networks.

Overview: The study’s focus is to optimise compressed air network inefficiencies through existing infrastructure to mitigate the challenges faced due to rising production costs. The need arose to improve the amount of drilling time, as it was being compromised by low service delivery pressures.

Results: A developed methodology was applied to develop a solution capable of addressing a large inefficiency on a mine. Replacing specific undersized pipe sections with the correct size would reduce the existing pressure drop as found from the simulation within a 2% error. The improved service delivery pressure led to a 20% increase in drilling rate as calculated from the selected model.

Relevance: This study is significantly relevant to the researched criteria, as inefficiencies are addressed with a focus on underground compressed

air pressures. A simulation software was used to predict compressed air pressure when applying the proposed solution.

Gained from study: The impact on rock penetration rate due to increased service delivery pressures provides another means to benchmark the impact and importance of sufficient compressed air pressures to pneumatic equipment.

Shortcomings: Although all relevant criteria were met, the focus of the study was on mitigating low production rates to account for the decline in gold production. A production increase was translated from calculated improved drilling rates due to improved service delivery pressure; however, the effect was not directly measured or observed.

Study 3 [41]: “Improving mine compressed air network efficiency through demand and supply control”.

Author(s): B Pascoe *et al.*

Relevant research criteria: Underground compressed air networks; inefficiencies in a compressed air network; methods to address inefficiencies; compressed air networks using simulation software.

Overview: Through Eskom’s demand-side management (DSM) funding, cost-saving initiatives are implemented to reduce the mine’s operating expenses, simultaneously reducing the load on the Eskom grid. An initiative of automated control valves was implemented, and a theoretical study for improved compressor combination operations was simulated to quantify the potential benefits.

Results: Control philosophies were developed for relevant case studies to achieve a decrease in electricity consumption. A reduction in electrical power of 3.1 MW was realised through an automated control valve

initiative and an equivalent potential reduction in compressor power, operating through a well-developed control philosophy.

Relevance: Although this study makes use of simulation software related to compressed air networks, this study only addresses operational inefficiencies.

Gained from study: A method was developed using compressed air simulations whereby an improved compressor combination was investigated, which highlights the importance of having the correct compressor supply to sustain the dynamic daily demand of current operations.

Shortcomings: This study addressed operational inefficiencies by implementing and improving existing control philosophies; it did not consider the general inefficiencies present on the mine nor the relationship and importance of delivery pressures.

Study 4 [54]: “Future mine compressed air planning using digital twin simulations”.

Author(s): P Burger *et al.*

Relevant research criteria: Underground compressed air networks; inefficiencies in a compressed air network; compressed air pressures; methods to address inefficiencies; methods to improve pressure delivery; compressed air networks using simulation software; parameter prediction of compressed air networks.

Overview: This study identified the need for proactive compressed air planning strategies to prevent unforeseen problems typically experienced at a mine. Digital twin simulations were used to effectively identify and develop solutions to potential future inefficiencies present in a compressed air system.

Results: The proactive planning strategy, developed through the methodology, enabled an increase in half-level compressed air pressure of between

21% to 32%, and avoided any further production losses due to insufficient pressure.

Relevance: This study met all the research criteria. Although the focus was based on proactive planning strategies, the identification and solving of inefficiencies is very relevant to the field of study.

Gained from study: A method capable of identifying inefficiencies successfully was developed through a proactive compressed air planning methodology. This methodology was based on previous literature and provided guidance when developing a methodology for this study. This study has also shown that mining standards do not take the dynamic compressed air system into account when the infrastructure is built.

Shortcomings: This study mainly focused on infrastructural inefficiencies potentially present when future mining demand increases; it did not consider already existing inefficiencies that had already been reached.

Study 5 [62]: “*Simulating operational improvements on mine compressed air systems*”.

Author(s): B.M. Friedenstein *et al.*

Relevant research criteria: Underground compressed air networks; inefficiencies in a compressed air network; methods to address inefficiencies; methods to improve pressure delivery; compressed air networks using simulation software; parameter prediction of compressed air networks.

Overview: Through means of compressed air simulation modelling, a proposal to improve the compressed air system’s efficiency led to quantified scope for improvement.

Results: Through a simulated scenario of reduced refuge bay air consumption, an average power reduction of 900 kW can be realised. Additionally,

an improvement in pressure can be achieved due to the reduced flow demand.

Relevance: This study explores simulation capabilities to improve compressed air network efficiencies. The simulation results quantify the impact of a proposed solution and are, therefore, capable and used for parameter prediction. This study met almost all research criteria.

Gained from study: An integrated compressed air simulation approach can be used to identify and improve operational strategies for complex mines.

Shortcomings: This study did not physically implement identified strategies for the validation of simulation results. The focus was on efficiency gain and not direct service delivery improvement.

Study 6 [50]: “*Practical approach to analyse mine pneumatic drilling performance*”.

Author(s): CJJ van Zyl *et al.*

Relevant research criteria: Underground compressed air networks; inefficiencies in a compressed air network; compressed air pressures.

Overview: A practical holistic approach was followed to analyse mine production outputs against pneumatic drilling performance. Additionally, the effect of inadequate compressed air service delivery on production was analysed and quantified.

Results: The percentage production loss due to an inadequate compressed air supply of working areas varied between 1.3% and 4.7%. The study found that increased compressed air pressure in working areas did not contribute to increased production.

Relevance:	The relevance of this study originates from the importance and value of sufficient compressed air pressures in a compressed air network.
Gained from study:	An increase in compressed air supply pressures did not contribute to increased production. This increase only decreases the time spent drilling, as mining crews are only required to complete a full-face length. This concludes that supplied pressures can, therefore, only be sufficient within a window of upper and lower limits. Anything above would be wastage, and anything below would lead to production loss.
Shortcomings:	This study managed to define the correlation and significance of compressed air pressure; however, simulation software was not used to determine theoretical compressed air requirements based on OEM recommendations. More importantly, this study did not consider methods to address compressed air inefficiencies.

Study 7 [42]: “A practical method for compressed air leak localisation in deep-level mines”.

Author(s): N Zietsman *et al.*

Relevant research criteria: Underground compressed air networks; inefficiencies in a compressed air network; compressed air pressures; methods to address inefficiencies; methods to improve pressure delivery.

Overview:	This article introduces a new method developed to improve air leak localisation in a large and complex underground compressed air system. This method was adapted from a municipal water distribution leak auditing study, requiring fewer resources to identify large leaks.
Results:	The results of one case study's method estimate that large leaks can be identified in nearly half the time when compared to conventional audits. A daily electrical energy saving of 5.5 MWh was achieved by applying this method. Additionally, unregulated flows were found,

which increased pressure at the end of the half-level by 50 kPa when closed. Health and safety risks are lowered when using this method.

Relevance: In terms of relevance to the previously defined research criteria, this study managed to highlight the impact of underground leakages, and successfully provided an improved method for leak identification, or more relevant, inefficiency addressal.

Gained from study: From the second case study performed, it was found that the degree of reduction in compressed air flow is not the same as the significant pressure gain when closing crosscuts closer to the half-level end. This signifies the importance of leakages when nearing the end of the half-level.

Shortcomings: This study was based on physical underground measurements and did not consider simulation software to confirm or predict the same phenomenon. The influence of the distance and size of compressed air pipes between each crosscut was also not considered.

Study 8 [49]: “Energy efficiency opportunities in mine compressed air systems”.

Author(s): FW Schroeder *et al.*

Relevant research criteria: Underground compressed air networks; methods to address inefficiencies; compressed air networks using simulation software.

Overview: This study focused on the various opportunities for energy efficiency initiatives on compressed air systems. The impact, workings, and feasibilities of these opportunities were investigated and verified through simulation. Several strategies implemented at various mines were also considered in terms of the most cost-effective for capital projects.

Results:	A staggering potential of 10% to 35% of maximum demand savings can be achieved on the mines considered. Optimised compressor selection and control, system pressure control, and leak detection management programs were considered the most cost effective.
Relevance:	Methods of inefficiency addressal were described from various mines and case studies, with a focus on various compressed air initiatives for the maximum amount of energy efficiency and cost savings.
Gained from study:	The significance of supply-side control and its feasible benefits was established.
Shortcomings:	As this study focused on various feasible energy efficiency opportunities, the impact on service delivery was not considered.

Study 9 [56]: “*The effect of compressed air pressure on mining and energy demand*”.

Author(s): SJ Bester *et al.*

Relevant research criteria: Underground compressed air networks; inefficiencies in a compressed air network; compressed air pressures; methods to improve delivery pressures; compressed air networks using simulation software; parameter prediction of compressed air networks.

Overview:	This study explored the causes of an increasing energy-intensity trend that has been observed at a platinum mine over the previous decade. The investigation led to the discovery of system design inefficiencies and losses present in a compressed air network.
Results:	Surface compressor supply pressures were similar historically; however, in-stope pressures have deteriorated over time quite substantially. Theoretical simulation results indicated that certain levels’ pipelines may be undersized for the actual flow requirement.

System losses such as air leaks, water accumulation in the pipe network, and excessive ventilation using compressed air further contribute to the experienced pressure drop.

Relevance: The significance of sufficient in-stope compressed air pressure was highlighted in this study. Inefficiencies and methods of addressal and methods to improve delivery pressures were discussed. A simulation model was used to determine the theoretical requirements of each production level. This study met all relevant research criteria.

Gained from study: The shaft's compressed air baseload demand can be compared to a best practice value of 30% of the peak flow. Compressed air energy savings can be maximised by matching the rock-drill demand and eliminating gross system inefficiencies. One of these inefficiencies includes redesigning the underground network.

Shortcomings: The study aimed to improve the intensity ratio between compressed air energy and tonnes hoisted; however, a larger focus was placed on improving production through better drill penetrating rates. It was suggested that the physical infrastructure was potentially undersized, but no further investigation was done to determine whether this was the case. Further investigation regarding the status and impact of current infrastructures should be conducted.

Study 10 [52]: *“Sustaining compressed air DSM project savings using an air leakage management system”.*

Author(s): A.J.M van Tonder *et al.*

Relevant research criteria: Underground compressed air networks; inefficiencies in a compressed air network; compressed air pressures; methods to address inefficiencies.

Overview: The effect of proper leak management on compressed air systems in the mining industry was investigated. These effects pertain to the

sustainability of existing DSM projects. A Compressed Air Leakage Documentation System (CALDS) was developed and implemented on existing DSM projects.

Results: An increase of 85% in power savings was achieved through implementation of the CALDS. Improved leak management and awareness proved the value of continuous leak management.

Relevance: This study managed to quantify the importance of continuous leak management. This is relevant to the sustainable addressal of inefficiencies present in a compressed air network.

Gained from study: The quantified value of leak repairs or inefficiency improvement translates to improved energy- and cost-saving project performance and sustainability.

Shortcomings: As the focus was mainly on the sustainability of existing energy-saving projects, the impact on supply pressures was not discussed in detail. Physical audits were conducted without the need of a simulation model, and inefficiencies were addressed through a leak management method only.

Study 11 [58]: *“A systematic approach to evaluate in-stope compressed air inefficiencies in deep-level mines”.*

Author(s): PL Brits *et al.*

Relevant research criteria: Underground compressed air networks; inefficiencies in a compressed air network; compressed air pressures; methods to address inefficiencies; methods to improve pressure delivery; compressed air networks using simulation software; parameter prediction of compressed air networks.

Overview: In-stope compressed air inefficiencies and the effect thereof on drilling pressure were investigated in this study. A verified method was

developed to identify in-stope inefficiencies. The viability and efficacy of various approaches to address inefficiencies inside the stoping area were also evaluated.

- Results:** High pressure loss was identified on a case study stope, whereby the stope experienced a total pressure loss of 80 kPa from the crosscut intake to the face. From the six mitigation strategies it was found that by increasing the pipe size of the compressed air network, the flow demand can be accommodated and identified inefficiencies mitigated.
- Relevance:** Various strategies were used to identify scope for compressed air network inefficiencies using simulation software. The estimated pressure loss present was obtained through successful parameter prediction.
- Gained from study:** Inefficiencies such as pressure loss present from crosscut intakes to stope areas can be mitigated through an increase in pipe size. It is common that the flow demand is more than what the piping network can handle at the required pressure. The stoping section was identified as the highest priority for improvement using a three-variable Likert scale.
- Shortcomings:** The focus was on the stoping area and its lack of sufficient infrastructure to handle the required demand. Methods were used in identifying the scope and benefits of inefficiency improvements; however, no solutions were implemented for an actual realised result. The actual impact on rock-drill performance was not evaluated due to increased pressure.

Study 12 [44]: “Developing zero-waste baselines to identify compressed air system inefficiencies in deep-level mines.”.

Author(s): A van der Merwe *et al.*

Relevant research criteria: Underground compressed air networks; inefficiencies in a compressed air network; methods to address inefficiencies; compressed air networks using simulation software; parameter prediction of compressed air networks.

Overview: Through a developed method to identify, localise, and quantify inefficiencies in a compressed air system, a zero-wastage baseline concept was derived, acting as a comparative performance indicator.

Results: From the zero-waste baseline calculation, the major flow-consuming equipment was determined to be refuge bays, pneumatic drills, cylinders, and loaders. The error was within 5% when a physical audit was conducted, proving the potential to localise wastages.

Relevance: This study is mostly relevant to the researched criteria. The study made use of simulation models to quantify the wastages present in a compressed air system. An integral part of addressing an inefficiency is the localisation or identification thereof. This study provides a valuable method for wastage localisation.

Gained from study: The method of using a zero-waste baseline simulation provides the user with the theoretical minimum demand, thereby simplifying the identification of inefficiencies in certain areas.

Shortcomings: Although the study focused on improving inefficiencies present in an underground compressed air network, the impact and method to improve supply pressures were not investigated.

Study 13 [55]: “Reconfiguring mining compressed air networks for cost savings”.

Author(s): JIG Bredenkamp *et al.*

Relevant research criteria: Inefficiencies in a compressed air network; compressed air pressures; methods to address inefficiencies; methods to improve pressure delivery; compressed air networks using simulation software; parameter prediction of compressed air networks.

Overview:	The study originated from possible DSM implementation strategies. The focus was on the reconfiguration of mining compressed air networks on surface for cost savings. Using theoretical simulations, network responses to the proposed strategies were determined.
Results:	Substantial cost savings can be achieved through the proposed strategy to interconnect two shafts for shared use of compressor supply. Further power reduction and savings were achieved through the repair of underground leaks. The prediction model reflected an error margin of approximately 12%.
Relevance:	The study is mostly relevant to the inefficiencies within a compressed air network and simulation software use. Theoretical models were utilised as a method to predict the performance of solution strategies for addressing inefficiencies within surface compressed air networks.
Gained from study:	Knowledge was gained related to the potential and benefit of utilising simulations as a tool to predict the performance of proposed solutions. Valuable energy- and cost-saving potential was found within an inefficient compressed air distribution network.
Shortcomings:	The impact on underground delivery pressures was not considered, as the study mainly focused on surface compressed air reticulations for the benefit of cost savings.

1.3.3 State-of-the-art summary

The following state-of-the-art matrix summarises the conducted literature study. The shortcomings and criteria are identified based on the focus of the 13 research studies considered and are discussed Table 2.

Table 2: State-of-the-art matrix

Shortcomings/Criteria	Study 1 (2021)	Study 2 (2017)	Study 3 (2017)	Study 4 (2023)	Study 5 (2018)	Study 6 (2019)	Study 7 (2019)	Study 8 (2009)	Study 9 (2013)	Study 10 (2010)	Study 11 (2024)	Study 12 (2023)	Study 13 (2014)
Underground compressed air network inefficiencies		✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	
Inefficiencies in haulage/drift		✓				✓				✓		✓	
Methods to address inefficiencies		✓	✓	✓	✓		✓	✓		✓	✓	✓	✓
Compressed air supply-side pressures	✓	✓		✓		✓			✓			✓	✓
Compressed air demand-side pressures		✓		✓	✓	✓	✓		✓	✓	✓	✓	
Methods to improve pressure delivery		✓		✓	✓		✓		✓		✓		✓
Infrastructural mining or engineering standards				✓							✓		
Compressed air networks parameter prediction using simulation software	✓	✓		✓	✓				✓		✓	✓	✓

Included in study	✓
Not included in study	

From the presented studies, almost all studies focused on underground compressed air network inefficiencies, but rarely on haulage or drift inefficiencies present in a mine. Most of the studies also considered various methods and strategies to address inefficiencies, but not necessarily to improve service delivery pressure; instead, the focus was rather on surface or crosscut and in-stope wastages for the benefit of improved energy efficiency and savings. The crosscut and in-

stope areas are difficult to address, as they are considered dangerous in relation to the haulages/drifts of a mine. A safer method of addressing inefficiencies is, therefore, required.

Although Study 2 considered the existing infrastructural pipe sizes throughout the underground network, it was only used as a boundary to its simulation model [51]. Therefore, only two studies considered the infrastructural mining standards [54], [58]. Study 11 considered conformity to mining standards for a case study mine, to which it did conform to the standards [58]. Alternatively, Study 4 considered whether the established mining standards take future planning into account but did not consider whether current mining infrastructure conforms to these standards [54].

This indicates a lack of studies related to the infrastructural mining standards. Study 4 managed to identify the need for future compressed air planning using digital twin simulations. It also established the insufficiency of mining standards when taking future demands and inefficiencies into account [54]. Therefore, future planning should be incorporated into the mining standards; however, no solution is imposed when the point of insufficient air infrastructural capabilities has already been reached, and no decision was made on whether a change in current standards would be required.

Study 6 found that an increase in compressed air supply pressures did not contribute to increased production [50]. The same result was found on a platinum mine when set points were increased for the purpose of increased production rates only, see Appendix B, Figure 59. Increased working pressure only decreases the time spent drilling, as mining crews are only required to complete a full-face length [50].

A few studies made use of simulation models to identify and localise inefficiencies or quantify the savings potential to various proposed solutions. Little emphasis was placed on simulating for delivery-pressure improvement but rather on efficiency improvement. Study 12 only mentioned the potential to theoretically simulate the improvement in pressure when inefficiencies are addressed [44]. Study 11, which focused on in-stope inefficiencies, only managed to theoretically quantify its effect on drilling pressure [58]. The actual impact and effort required to implement an inefficiency solution is often, therefore, not considered.

Identified literature shortcomings in summary:

- A lot of focus was placed on high-wastage areas such as crosscut and stoping workplaces, mostly for the benefit of energy efficiency and savings.

- In these cases, the aim was to address inefficiencies and not to necessarily improve service pressure delivery.
 - The haulages or drifts of a mine were, therefore, overlooked as it assumed sufficient distribution to consumers.
- A lack of studies considered inefficiencies present in these overlooked areas (the haulages or drifts of a mine).
 - This would be a safer method of addressing inefficiencies as opposed to the common focus on dynamically complex and dangerous crosscut and in-stope areas.
- A lack of studies considered compressed air infrastructural mining standards.
 - The sufficiency of current specified standards at current demands.
 - Mining conformity to these standards.
- Little emphasis was placed on simulation models used to improve service delivery pressure.
 - The actual impact and effort required to implement an inefficiency solution were not thoroughly considered.

1.4 Need for the study

From the initial problem statement and literature study shortcomings, a clear need is identified to consider the actual effect of a solution implemented to address inefficiencies. In-stope wastages contribute greatly to insufficient demand-side pressure, but they are mostly dangerous and difficult to address [47], [58]. There is limited to no instrumentation available underground, and level flow meters are often inaccurate [42], [51], [55], [59], [63]. Simulations utilised for future compressed air planning was found to be invaluable [54]. It was found that mining standards were not sufficient at a developed mine; however, the conformity to these standards were not considered. The need is evident to investigate solutions when this would be the case, i.e., when existing infrastructure has reached its limitations, and whether mining conforms to the engineering standards' specifications.

Identified need for the study in summary:

- The need to address wastages or inefficiencies using a safer method is found.
 - Crosscuts and stopes are considered dangerous, and compressed air reticulations dynamically complex. It is difficult to investigate these areas and monitor standard practices.

- Limited instrumentation availability and accuracy.
- The need to consider mining standards in terms of sufficiency and whether mining conforms to these standards.
 - Mining standards were found not to be sufficient at developed mines.
- The need to measure the actual effect or impact of a solution implemented to address an inefficiency using simulation software.

Therefore, a simpler and safer method is required to address low workplace pressures using simulation software as well as to determine the viability of infrastructural mining standards that have reached their limitations due to unforeseen mine expansion or improper planning.

1.5 Problem statement redefined

From the state-of-the-art literature findings, shortcomings, and identified needs, the initial problem statement from Section 1.2.6 is redefined to a more inclusive problem statement.

Initial problem statement (Section 1.2.6):

Compressed air distribution is subjected to various losses due to inefficiencies in vast and complex mining networks. These inefficiencies result in reduced pressure delivery to distant downstream consumers. Insufficient demand-side pressure affects the performance of pneumatic equipment and may, therefore, affect production rates. This leads to increased operational costs, as the need to supply air at higher pressure increases. When air is supplied at higher pressures to accommodate deteriorating and inefficient networks, artificial demand can be induced.

It was found that compressed air pressure is further affected by piping's restrictive nature when further downstream demand increases as the mine expands, especially expansion beyond the initial planned life of mines [54]. Solutions to inefficiencies when infrastructural limitations had already been reached – due to insufficient mining standards – have not been thoroughly considered [54]. The lack of studies related to infrastructural engineering standards raised the question of whether mining also conforms to these standards. Certain minimum pressure thresholds must be met, as previously defined in Table 1, to prevent pneumatic equipment from affecting production rates.

The highest contributing factor to insufficient demand-side pressure is most often due to demand-side wastages present at in-stope workplaces [47], [58]. Most studies focused on crosscut and in-stope wastages for the benefit of energy efficiency and savings, and not necessarily to improve

service delivery pressure. Each stoping area is rarely entered by personnel other than the dedicated team. These areas are rarely surveilled and standard practices not monitored. Apart from being difficult to address in-stope wastages effectively – due to its dynamic nature – it is also a dangerous area to investigate. A safer method of addressing inefficiencies is, therefore, required. Infrastructural inefficiencies in the haulage or drift of mines are often overlooked. A lack of studies considered inefficiencies present in these overlooked areas. This would be a safer method of addressing inefficiencies as opposed to the common focus on dynamically complex and dangerous crosscut and in-stope areas.

Shaft personnel often increase compressor supply pressures (set points) to accommodate low workplace pressures [47], [56]. This, unfortunately, only addresses the issue symptomatically and possibly only temporarily at the current mine expansion, as the mine would require further increases as the mine expands [54].

This strategy was also found to not correlate with increased production rates [50]. This increased set-point solution, would, therefore only add to operational costs, lowering profitability, inducing artificial demand, and potentially affecting the life of mines, and consequently work availability [44], [45], [51], [55], [58]. Due to the nature and timeous process for a tonne of ore to be produced and measured, the observed effect on production rates is somewhat delayed; and due to a mine's dynamic complexity, fluctuations or alternatively “noise” in production rates cannot be directly attributed to the increased set points [50]. It, therefore, becomes challenging to revert to previous set points, as mining personnel may fear a reduction in production rates. Intervention at an early stage is, therefore, important [50].

Redefined problem statement:

Inefficiencies in compressed air distribution networks that result in insufficient demand-side pressure affect pneumatic equipment capabilities and potentially also production rates. A common solution strategy is imposed (i.e., increasing compressor set points), which further increases operational costs, reducing both the life of mines and profitability and does not automatically result in improved production rates.

High-wastage areas, such as stopes, are difficult to address due to their dynamic complexity and increased risks. Solutions to current infrastructural inefficiencies, arising from inadequate engineering standards and mining's lack of conformity to these standards are not considered sufficient.

1.6 Aim and research objectives

Aim:

This study aims to develop a safer and simpler method of improving low demand-side pressures due to inefficiencies within the haulage distributing network. Furthermore, the sufficiency of current compressed air infrastructural mining standards will be determined, and a baseline model developed to evaluate different prediction scenario solutions.

Research objectives:

The following objective outcomes are formed from the need for the study and redefined problem statement:

- **Research Objective 1:** To develop a method that utilises simulation software to identify and improve insufficient delivery pressure in underground mines through a safer and simpler method than those commonly used to address difficult and dangerous in-stope areas.
- **Research Objective 2** The model should be capable of predicting underground pressure along distant levels based on known consumers across the complex underground compressed air network.
- **Research Objective 3:** To evaluate the adequacy of existing infrastructural engineering standards.
- **Research Objective 4:** To apply the developed method to a case study mine and to validate the results based on each implemented solution.
- **Research Objective 5:** To evaluate the developed methodology based on the addressal of the problem using a comparative analysis to measure the performance.

1.7 Research methodology

This study follows the systematic research approach of empirical methods, as data collection and measurements form a large part of addressing the problem [81]. The study is quantitative and would, therefore, utilise a corresponding methodology. According to Sukamolson (2007), quantitative research is typically classified under the following methodology types [82], [83], [84]:

- **Survey** Used to generalise results from a sample to wider populations.

- **Correlational** Used to determine whether and to what degree relationships exist between two or more variables.

- **Experimental** Tests the outcome of the dependent variable when a change is made to the independent variable.

- **Causal-comparative** Tests the relationship between two or more existing groups, attempting to identify a cause-effect relationship.

According to the above methodology types, the most suitable type for this study would be correlational or causal-comparative research. Considering the redefined problem statement in Section 1.5, previous studies have already shown the limited correlation between production and working pressures [50], [56]. Emphasis will, therefore, not be placed on a correlational or causal-comparative methodology. However, since these studies did not obtain clear knowledgeable results, background information will have to be considered to understand the relationship between variables.

Further consideration of the redefined problem statement indicates that, the solution strategies most utilised to address inefficiencies have shown negative implications and non-correlative results. Scope to any alternative working strategy is identified and would be valuable. To address the origin of this issue using an alternative strategy, gaps from the literature study were considered, including that infrastructural mining standards were not considered in terms of its sufficiency. From the aim and research objectives in Section 1.6, simpler and safer methods are required.

In summary, the definite relationship between compressed air infrastructure (in safer areas) to compressed air delivery pressures will be analysed. Simulation software and modelling can be used to evaluate the sufficiency of existing mining standards and measure the effect of a proposed solution to various case studies [44], [51], [54], [56], [58], [62].

Therefore, a case study methodology using simulation software will be followed [47], [58]. This methodology is adapted to include the redefined problem from an engineering design process methodology [45]. The fundamental study of exploring relationships between variables using algebraic manipulation is also added. See a flow diagram in Figure 16, illustrating the steps of the research methodology that will be followed.

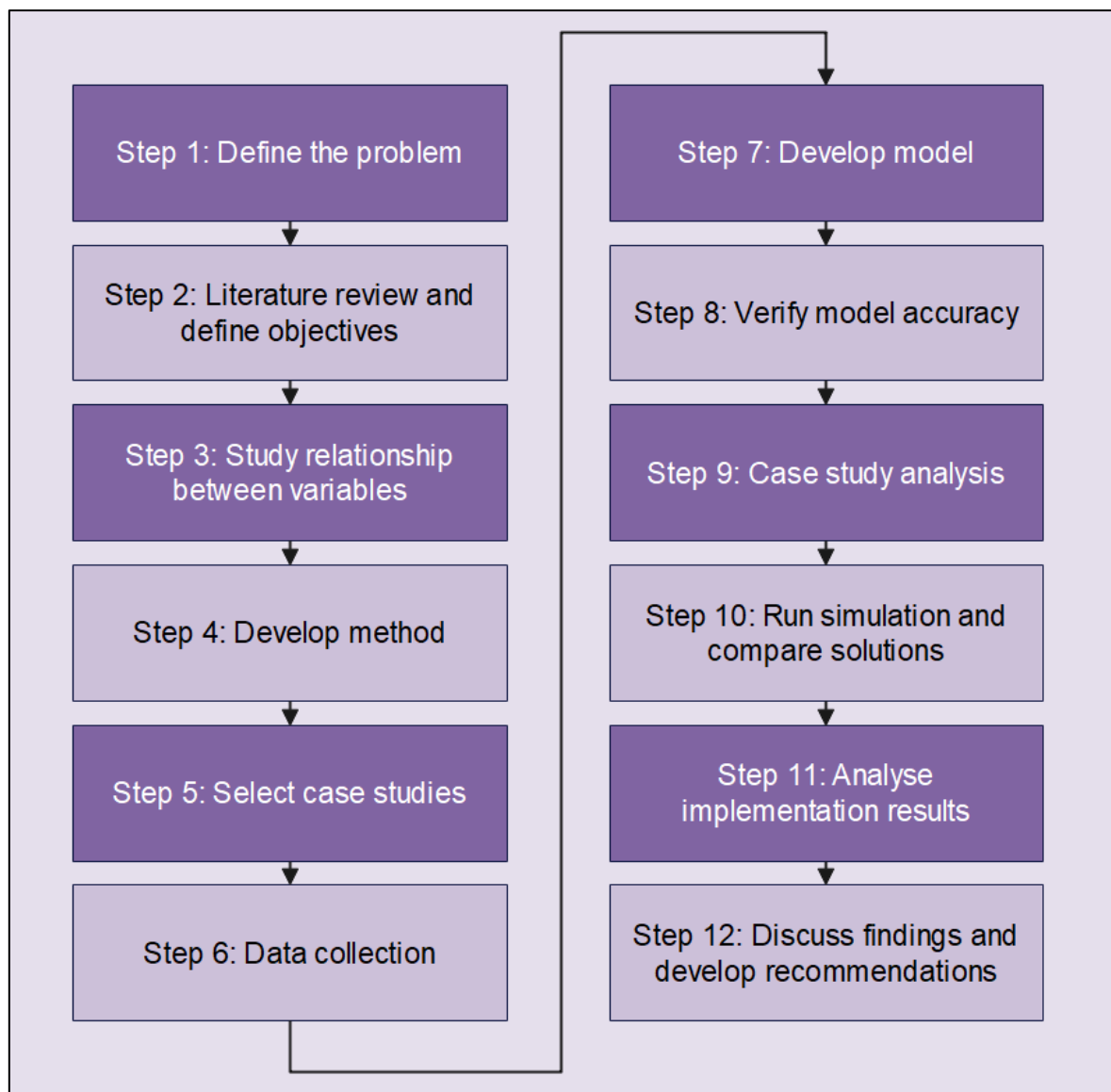
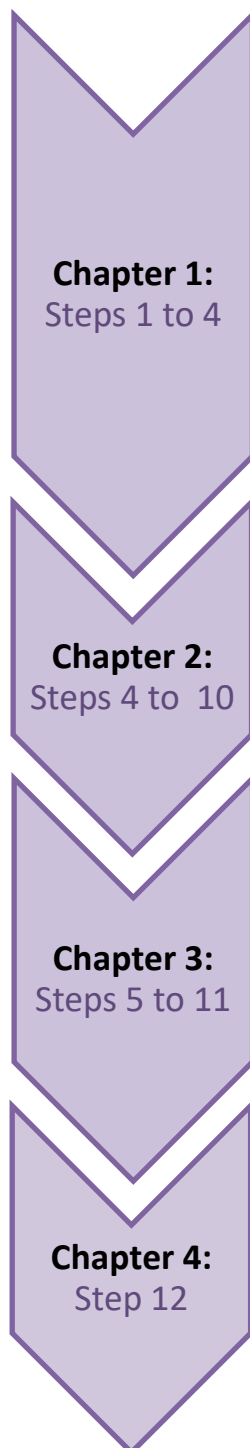


Figure 16: Adapted research methodology

1.8 Study outline



Chapter 1 provides background to the South African PGM mining industry, its high demand in energy consumption, and the impact of critically increasing electrical costs. A well-conducted literature review outlines the scope and need for the study, highlighting how compressed air mismanagement and inadequate delivery pressure affect multiple entities in mining. This chapter concludes with the aim, objectives, and research methodology that will be followed when developing the method in Chapter 2.

Chapter 2 develops a proposed method – guided by the chosen research methodology – to address the experienced issues outlined in the redefined problem statement. The generalised steps are refined during the development, adapted to fit the need for the study, address the problem statement, and duplicate the method upon other shafts.

Chapter 3 applies the refined method to the case study mine's underground compressed air network. Inefficiencies and solutions thereto are identified. The impact of various solution scenarios is predicted and compared after which the most feasible solution is chosen for implementation. The results from implementation are studied and measured according to the study's research objectives outlined in Chapter 1.

Chapter 4 concludes the background, findings, outcomes, and limitations to the study. Shortcomings and recommendations of the study are described for future reference.

CHAPTER 2: DEVELOPMENT OF PROPOSED METHOD



Figure 17: Shaft on platinum mine –12h00¹¹

"Rain cannot wash away the minerals hidden beneath the earth, just as challenges cannot deter the determined miner."

- Unknown

¹¹ Personal photo, 2023

2.1 Preamble

This section of the study will – through the aid of the literature review conducted in Section 1.3 – focus on various methods and practices to address the problem statement and achieve the study's objectives. As described in Section 1.7, the chosen methodology was developed by combining steps from other applicable methodologies to address the problem statement using an adapted strategy based on the identified literature research gaps. This chosen methodology will be used to assist in developing a method to achieve the study's objectives.

2.2 Methods to address inefficiencies affecting delivery pressure

The importance of sufficient compressed air pressure delivery to pneumatic consumers is clear from Section 1.2.5. From the state-of-the-art identified shortcomings, methods to address inefficiencies will now be considered and studied as a starting reference.

An inefficiency in the mining context is considered the state where something or someone fails to use resources such as materials, time or energy in an effective way¹². Production crews can only mine the full-face length of a working area; higher pressure would not increase the production figures, only reduce the time spent drilling [50]. Decreased pressure would, therefore, increase the time spent drilling and may lead to complaints and potential production losses if too low [56]. To prevent and reduce the frequency of the latter, inefficiencies related to delivery pressure will be considered. For the argument of improving existing inefficiencies within the distribution network, compressors and their operation will not be considered.

Bernoulli's equation in Equation 1.4 can further be extended to include the total pressure loss. This inclusion is derived from a change in total head to be equal to the change in internal energy, therefore, the energy equation for steady, adiabatic, incompressible flow in a stream tube is described, in pressure form, by Equation 2.1 [69], [70].

¹² Cambridge English Dictionary

Extended Bernoulli equation with total pressure loss ΔP :

$$P_1 + \frac{1}{2}\rho v_1^2 + \rho g h_1 = P_2 + \frac{1}{2}\rho v_2^2 + \rho g h_2 + \Delta P \quad \text{Equation 2.1}$$

Where:

- P_1 Supply pressure at Point 1 [Pa]
- P_2 Delivery pressure at Point 2 [Pa]
- ρ Compressed air density [kg/m³]
- v_1 Velocity at Point 1 [m/s]
- v_2 Velocity at Point 2 [m/s]
- g Gravitational acceleration constant [m/s²]
- h_1 Height at Point 1 [m]
- h_2 Height at Point 2 [m]
- ΔP Total pressure loss [Pa]

Further substituting Equation 1.13 into Equation 2.1 yields

$$P_1 + \frac{1}{2}\rho v_1^2 + \rho g h_1 = P_2 + \frac{1}{2}\rho v_2^2 + \rho g h_2 + f_D \left(\frac{L}{D_H} \right) \left(\frac{\rho \bar{V}^2}{2} \right) + \sum K \left(\frac{\rho \bar{V}^2}{2} \right) \quad \text{Equation 2.2}$$

This equation is expressed and further considered in terms of a typical compressed air network in a deep-level mining environment in Figure 18. This will be used as a reference to understand and clarify the relationship between variables and potential methods to improve the experienced pressure drops.

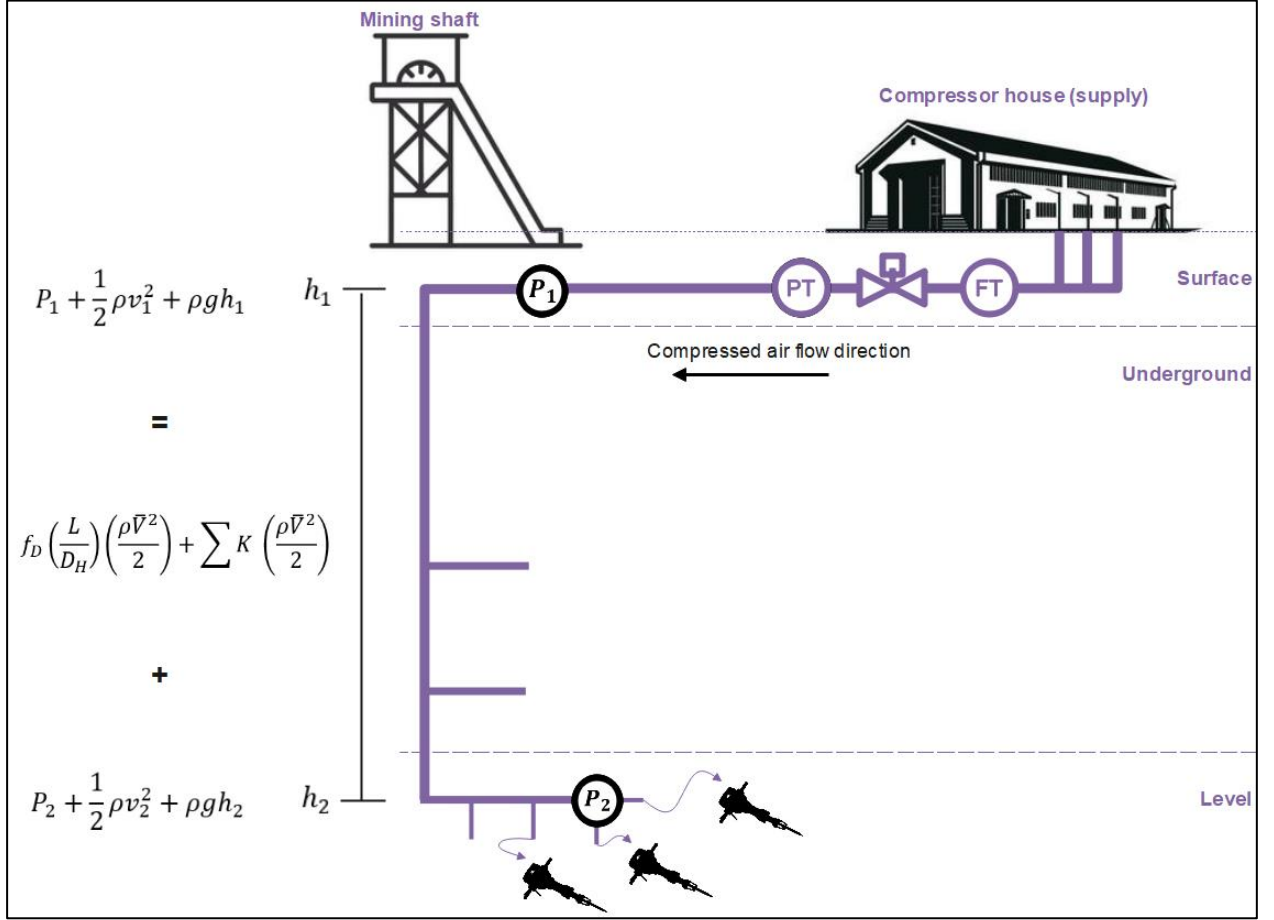


Figure 18: Equation 2.2 expressed between Point 1 and Point 2 in a typical compressed air mining reticulation

Figure 18 depicts Equation 2.2, between Points 1 and 2. The compressed air is supplied from the compressor house on surface through the relevant piping (Point 1) that reticulates down the mining shaft to the respective level and consumers (Point 2).

During Section 1.2.5, relationships were drawn between first-principle variables that would influence compressed air pressure due to any inefficiencies present in the distributing system. Methods to address inefficiencies that may result in a loss in pressure will now be considered.

Making P_2 the subject, setting reference condition ($h_1 = 0$), and simplifying yields

$$P_2 = P_1 + \frac{1}{2}\rho(v_1^2 - v_2^2) - \rho g h_2 - \left(f_D \frac{L}{D_H} + \sum K \right) \frac{\rho \bar{V}^2}{2} \quad \text{Equation 2.3}$$

Using Equation 2.3 with the compressed air system in Figure 18 as a reference, each significant term is considered in isolation to describe its effect on delivery pressure P_2 .

$$P_2 = P_1 + \frac{1}{2}\rho(v_1^2 - v_2^2) \text{ in isolation:}$$

The supplying airflow to the rock drills are limited by subsequent pipe or manifold reductions. As such, it is inevitable that $v_2 > v_1$, due to $A_2 < A_1$. Therefore, $P_2 < P_1$ in this isolated case, and delivery pressure P_2 is decreased.

$$P_2 = P_1 - \rho gh_2 \text{ in isolation:}$$

In a mining reticulation, compressed air consumers are predominantly lower in height than the point of distribution and are, therefore, subjected to the benefits of auto-compression. With the reference height as $h = 0$, the following is true $\rho gh_2 \leq 0$. Therefore, $P_2 \geq P_1$ in this isolated case, and delivery pressure P_2 is increased.

$$P_2 = P_1 - f_D \left(\frac{L}{D_H} \right) \left(\frac{\rho V^2}{2} \right) \text{ in isolation:}$$

With compressed air in motion, for any real-life mining network, the following would always hold true, $f_D \left(\frac{L}{D_H} \right) \left(\frac{\rho V^2}{2} \right) > 0$. Therefore, $P_2 < P_1$ in this isolated case, and delivery pressure P_2 is decreased due to frictional line losses.

$$P_2 = P_1 - \sum K \left(\frac{\rho V^2}{2} \right) \text{ in isolation:}$$

With compressed air in motion, in a network that consists of various geometry changes and in-line components such as in valves or water traps, the following would always hold true in practice, $\sum K \left(\frac{\rho V^2}{2} \right) > 0$. Therefore, $P_2 < P_1$ in this isolated case, and delivery pressure P_2 is decreased due to component frictional losses.

From the above considerations in a mining environment, the effect of each term on P_2 is clear. Only the last-mentioned terms, i.e., major and minor frictional losses, consist of variables that are directly changeable by the user. These losses, encompassed by the total losses ΔP , previously described in Equation 1.14, are further considered in detail with the potential to improve P_2 in practice, and is summarised in Table 3.

Table 3: Relationship of variables and methods to improve pressure drop ΔP in a compressed air system

Variable	Proportionality	Theoretical improvement	Methods for improvement
f_D	The friction factor is directly proportional to ΔP . With the flow regime assumed turbulent, this factor is mostly determined by the relative roughness $\frac{\epsilon}{D}$.	By reducing the absolute roughness of pipes, or by increasing the pipe diameter, the amount of pressure loss due to line friction is reduced .	Piping is constantly subjected to warm and humid underground conditions, and it is, therefore, not practically feasible to reduce and maintain the absolute roughness of pipes. However, it is worth considering the importance of maintaining the friction factor of existing pipes and replacing them when conditions would disturb the flow of compressed air.
L	The pipe length is directly proportional to ΔP .	By reducing the pipe length, the amount of pressure loss due to friction is reduced .	In a compressed air system, the pipe length of each level cannot necessarily be reduced, as it is often already following the approximate shortest route to demand-sides.
D_H	The hydraulic diameter is indirectly proportional to ΔP .	By increasing the pipe diameter, the amount of pressure loss due to friction is reduced .	The diameter of piping can be increased by upgrading the pipe size of the level. However, larger pipe sizes are increasingly expensive. The increase in flow area may result in a higher flow demand.
ρ	The fluid density is directly proportional to ΔP .	By reducing the density of compressed air, the amount of pressure loss due to friction is reduced .	The density of compressed air can be reduced by increasing the temperature; however, it is not recommended, as pressure is behaviourally proportional to both density and temperature.
$\bar{v}^2$	The square of the average velocity is directly proportional to ΔP .	By reducing the average velocity, the amount of pressure loss due to friction is reduced . The change in velocity is exponential and, therefore, a more significant factor.	The velocity of compressed air can be reduced either through increased pipe sizes assumed at the same demand, or through a reduction in flow demand through wastage reduction.
K	The dynamic loss coefficient is directly proportional to ΔP .	By reducing the sum of dynamic loss coefficients, the amount of pressure loss due to friction is reduced .	The sum of dynamic loss coefficients can be reduced by considering in-line equipment that possess less restrictive properties, or by reducing the number or degree of bends or in-line components.

2.3 Proposed method development

Table 4 conveys the common criteria used by various sources in the state-of-the-art literature in Section 1.3.3 for developing a method to identify and improve inefficient distribution networks utilising simulation software.

Table 4: Common literature criteria for developing a method

Criteria	Sources
Gathering of data	[41], [44], [50], [52], [54], [58], [62]
Develop baseline simulation model	[41], [44], [51], [54], [58], [62], [63]
Verification of simulation model	[41], [44], [51], [54], [58], [62], [63]
Investigation of inefficiencies	[44], [49], [50], [52], [54], [58]
Implement solutions	[41], [44], [51], [52], [54], [62], [63]
Validate results of study	[41], [44], [49], [50], [51], [54], [58], [63]

The specific methods to construct a baseline simulation model are now considered. From the state-of-the-art, seven studies utilised simulation software. These studies' methods were reviewed, and only four had clear outlined steps to develop a compressed air model [44], [54], [62], [63]. A summary is shown in Table 5.

Table 5: Summary of steps to develop a simulation model from various literature studies

Method	Matthee <i>et al.</i>	Burger <i>et al.</i>	Friedenstein <i>et al.</i>	v.d. Merwe <i>et al.</i>
Step 1	Define project scope	Information gathering	Investigate the system	Detailed site inspection
Step 2	Data gathering	Determine system requirements	Determine boundaries and parameters	Defined project parameters
Step 3	Feature selection	Audit compressed air system	Component modelling	Construct simulation
Step 4	Data treatment	Construct model	Verification of model	Calibrate simulation
Step 5	Model development	Test and evaluate accuracy	Implementation of simulation	Use digital twin for simulations
Step 6	Model implementation	Calibrate model to a finished digital twin		Evaluate performance and results

Using the above steps, a generic method will be developed to assist in identifying and addressing underground compressed air inefficiencies. With Table 4 as a reference, and combining steps from Table 5 to develop a simulation model, similar steps will be followed and are proposed below:

- Step 1: Data collection and processing
- Step 2: Model development
- Step 3: Model verification
- Step 4: Inefficiency investigation
- Step 5: Implementation
- Step 6: Validation of method results

A generic flow diagram is drafted from the above proposed steps, as seen in Figure 19.

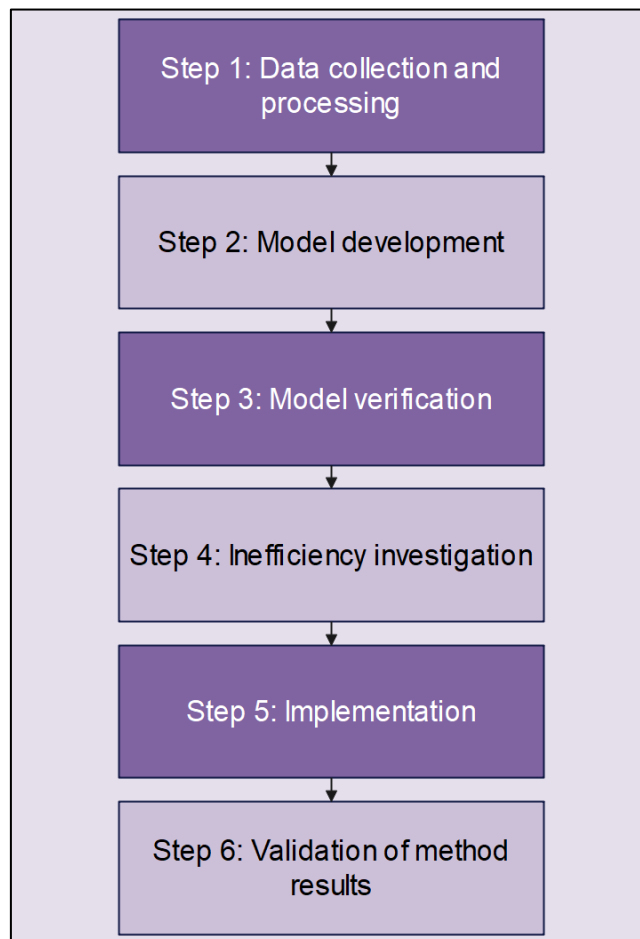


Figure 19: Summarised proposed method flow diagram

2.4 Step 1 – Data collection and processing

The initial phase of this methodology is based on the requirements for comprehensive data analysis [41], [44], [50], [52], [54], [58], [62]. This involves the collection and processing of data, which are key information required and obtained from the shaft, enabling the construction of the baseline model for simulating purposes. This data acquisition can be categorised under two main categories, namely static and dynamic inputs.

1. Static inputs: Layout and infrastructure

- Electronic vector drawings of the physical underground layout are required. These drawings are a simplistic outline of the shaft and each level's haulages. This provides an accurate three-dimensional electronic blueprint of the physical underground layout, correctly scaled from underground dimensions. It is readily available from the mine's planning department in DXF format and is updated monthly by surveyors. See an example drawing in Figure 20.



Figure 20: Example of underground layout vector diagram (DXF file)

- Compressed air mining standards for the specific case study mine should be obtained. These standards can later be used in a cross-comparison study to assess whether mining operations conform to these standards correctly and to utilise the developed model to determine if these standards are sufficient for current operational demands.

- A physical examination of all active¹³ areas will be required. To achieve this, auditors will need to walk along the compressed air pipeline from each level's station leading to the furthest point on that level, typically the development end. During this inspection, the diameters of the pipes and locations of any disturbances in the line must be logged [42], [45], [54], [62]. This includes but is not limited to any reductions, restrictions, valves, water traps, tie-offs, etc., found in the haulage. See an example in Figure 21.

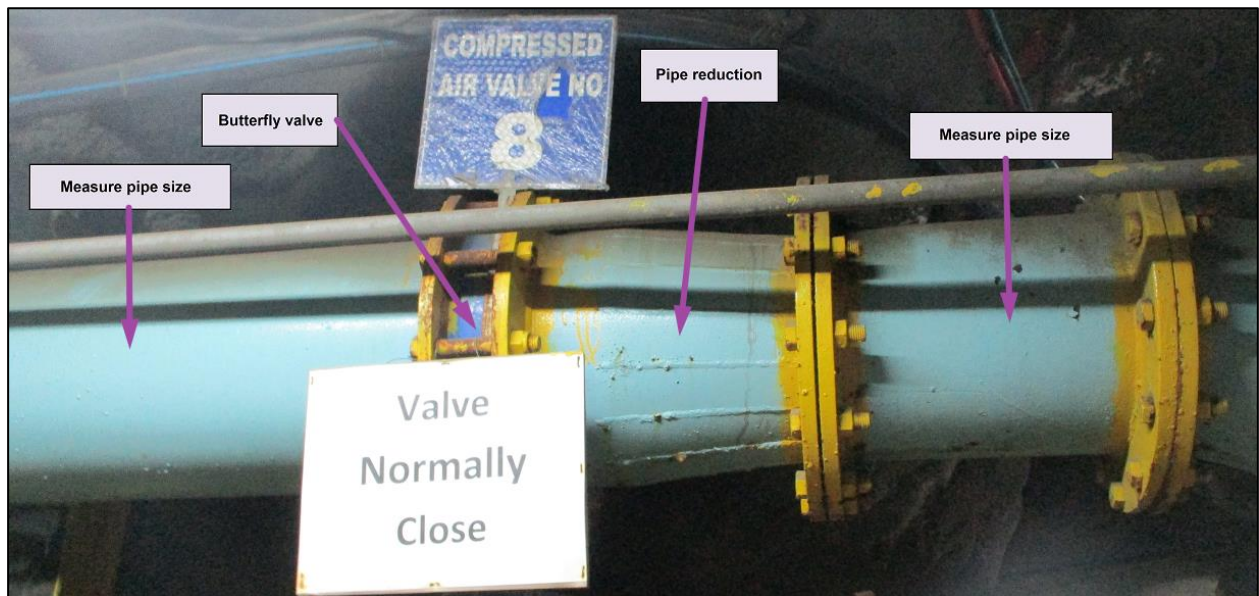


Figure 21: Example of overhead piping network with reduction and possible restriction¹⁴

2. Dynamic inputs: Compressed air and mining data

- This information serves as the current underground conditions measured by instrumentation and data logged to a PLC. In addition, mining data of active consumers in their respective areas should also be obtained. This will primarily be used to calibrate the model to an extent where a simulation is able to provide good output estimations at an area of interest across different entities such as flow or pressure [44], [51], [55], [62], [63]. Data logged by working pressure and flow transmitters and the number of crews in each working area calibrate the model to the current conditions. See an example of an installed pressure and flow transmitter in Figure 9.

¹³ Defined to be active when mining operations are present in the area and supplied by compressed air.

¹⁴ LN Zietsman, May 2022

- The current pressure set points of the shaft and levels should also be obtained for possible reference studies.
- During the audits, it is not necessary to enter stoping areas, as an approximate standardised consumption can be added to the model based on the number and type of active consumers in that area [50], [51].
- Measurements of pressure and flow, where possible, are strongly advised, as they can be used to calibrate the model to a higher degree of accuracy [44], [51], [55], [62], [63].

2.5 Step 2 – Model development

The information obtained from the previous step is arguably the most significant part of the methodology, as everything will be built upon this knowledge.

Step 2.1: Choose simulation software/package

To sufficiently analyse the system, make use of a simulation software package capable of simulating the underground workplace pressures and of importing relevant underground dimensional drawings [44], [54]. This will ensure that the model is built to scale and will simplify the model development significantly.

Step 2.2: Adding static data to model

The most recently available surveyor reticulation vector drawings, obtained during Step 1, should be imported to the chosen simulation software. This is necessary, as it allows the user to work from a frame of reference and to maintain a relatively high degree of dimensional accuracy upon which the model is built [44]. The full reticulation model should be constructed based on the underground compressed air audits.

The reticulation for each level can be built based on the standard compressed air level layout of the shaft. These can act as placeholders during the long auditing process, which could simplify the model building process. Entities can be updated at a later stage when audit findings are complete. These entities may involve pipe dimensions, type of installed valves, water traps, tie-offs to users, installed instrumentation or any other notable component [54], [58], [59].

The obtained infrastructural mining standards will not necessarily be used during this section but rather used as a reference when investigating inefficiencies during Step 4. Once each level's

compressed air reticulation model is complete and integrated with the complete system, actual data is required for a functional model of value.

Step 2.3: Adding dynamic mining data to model

The model's supply and demand profile can be compared to the data obtained from actual pressure and flow measurement data, typically located downstream of the main surface valve. These actual values are based on the compressed air supply and mining demand throughout a typical workday. The surface pressure profile represents the compressors' supplying capacity at the respective flow demand profile. This compressor capacity should be added to the model to provide the necessary supply.

The total demand of each active crosscut, refuge bay or area should be determined. Recent mining data showing the number and location of each active consumer and crew member's information should be used in conjunction with Table 1. These pneumatic demands of each known consumer at specific times-of-use can be added to the model respectively. Pressure and flow measurements taken during the audits can be used as a reference when determining the respective wastages within crosscuts.

This will be used in Step 3 when calibrating the model to baseline conditions and verifying its accuracy.

2.6 Step 3 – Model verification

Working with a verified model provides the benefit of not only accuracy and reliability but also reproducibility and saving time when adjustments need to be made in an ever-changing mining environment. Only compressed air flow and pressure will be used to calibrate and verify the model because these measures have the greatest effect on workplace performance.

The MAPE formula will be used to verify the accuracy of the developed model. This is an effective method for large datasets; however, it is sensitive to extreme data outliers [63]. The MAPE formula is described in Equation 2.4 [85].

MAPE:

$$MAPE = \frac{1}{n} \sum_{i=1}^n \left| \frac{A_i - F_i}{A_i} \right| \times 100$$

Equation 2.4

Where:

$MAPE$ Mean Absolute Percentage Error [%]

n Number of data points

A_i Actual value for the i^{th} data point

F_i Forecasted value for the i^{th} data point

Unfortunately, the MAPE only calculates the average error over time or different data points and does not differentiate the significance or priority between values or moments in time [86].

As an additional measure to address values that might be of less significance, a formula that is based on Equation 2.4 is further amended to a WMAPE. WMAPE introduces the concept of assigning different weights to individual data points based on the point or value's significance [86]. The selection of weights may be subjective and is also sensitive to outliers and zero values like MAPE and APE [85], [86]. The WMAPE formula is described in Equation 2.5 [86].

WMAPE:

$$WMAPE = \frac{1}{n} \sum_{i=1}^n w_i \left| \frac{A_i - F_i}{A_i} \right| \times 100 \quad \text{Equation 2.5}$$

Where:

$WMAPE$ Weighted Mean Absolute Percentage Error [%]

n Number of data points

w_i Attributed weight to the i^{th} data point

A_i Actual value for the i^{th} data point

F_i Forecasted value for the i^{th} data point

This is more suitable when applied to a dataset where some observations are more critical than others, such as in a compressed air mining environment [86]. For example, the blasting shift

period is not as important as the drilling or cleaning periods. Therefore, a good weight of choice might be the pressure set points obtained during Step 1.

These formulas should be applied in Step 3 to verify the accuracy of the model. Older studies have shown that error margins within 10% are sufficiently accurate, typically due to initial assumptions [87], [88]. However, newer studies deem a 5% error value as accurate [41], [44], [54], [58], [62]. Therefore, the simulation model is successfully verified when the MAPE values are below 5%.

2.7 Step 4 – Inefficiency investigation

Various types of inefficiencies are present in a large, compressed air distribution network, some of which can hinder downstream users drastically. Identifying inefficiencies in such a network is difficult, and the impact thereof is found to not be thoroughly and often considered. Compressed-air-related complaints will not necessarily provide clear information about each present inefficiency, often only indicating the work area where pressure issues are experienced.

As this would be a protracted process, and to keep the method simple, the most inefficient levels should be prioritised. Subsequently, deeper investigation into the prioritised levels will provide insight on the exact location and type of inefficiency present on the level. Once an exact inefficiency has been identified, different solution scenarios can be simulated to measure the impact of solving the inefficiencies.

The mine's compressed air infrastructural engineering standards should also be considered as an additional method to investigate potential inefficiencies. The possibility of standards that are not conformed to, or standards that have become insufficient at current demands, may provide additional means to identify inefficiencies present underground. The verified model should provide a valuable reference to compare the mining standard documents to and identify whether current piping is sufficiently sized for the current demand of downstream consumers.

2.7.1 Step 4.1 – Level prioritisation

The first step of this section will be to prioritise each level depending on the degree of inefficiencies. The total amount of pressure drop and number of complaints could indicate the degree and assist in the identification and prioritisation process of inefficient levels. As there is no instrumentation at development ends, the verified baseline model will be used for this prioritisation, as it is assumed to simulate a high level of confidence.

Each half-level i can be ranked according to the total amount of pressure drop ΔP_i experienced from the station up to the development end, described by Equation 2.6.

$$\Delta P_i = P_{supply_i} - P_{Dev\ end_i} \quad \text{Equation 2.6}$$

Where:

ΔP_i Total pressure drop of half-level i [kPa_g]

P_{supply_i} Supplied station pressure of half-level i [kPa_g]

$P_{Dev\ end_i}$ Development-end pressure of half-level i [kPa_g]

See an example of a typical underground half-level layout, describing the total pressure drop, ΔP , from the supply- and development-end locations in Figure 22.

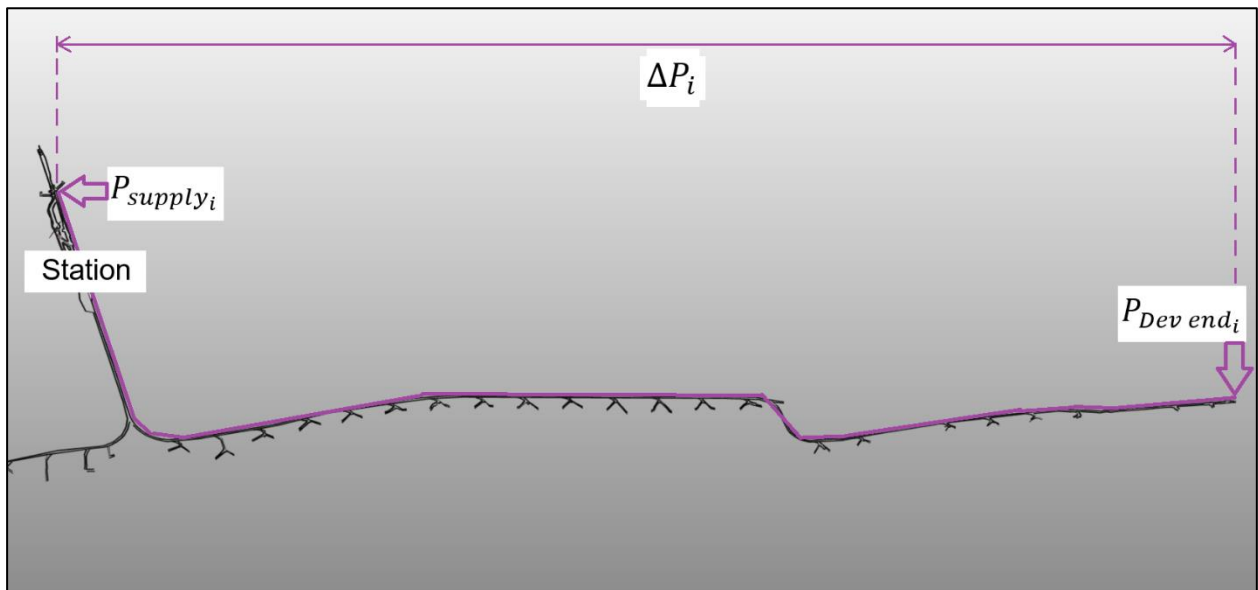


Figure 22: Example of supply- and development-end pressure locations on a half-level i

Although the amount of pressure drop implies a degree of inefficiency, it does not take the number of compressed air consumers into account. It can be argued that a level with more consumers would have a higher drop in pressure; hence, a more viable intensity-based comparison features ε_i , describing the amount of pressure drop per active drill user. This intensity, as defined in Equation 2.7, would better describe the degree of inefficiencies.

$$\varepsilon_i = \frac{P_{supply_i} - P_{Dev\ end_i}}{n_i} = \frac{\Delta P_i}{n_i} \quad \text{Equation 2.7}$$

Where:

ε_i Pressure drop per active drill-user intensity [kPa_g]

P_{supply_i} Supplied station pressure of half-level i [kPa_g]

$P_{Dev\ end_i}$ Development-end pressure of half-level i [kPa_g]

n_i Number of active drill users, on half-level i [-]

ΔP_i Total pressure drop of half-level i [kPa_g]

The number of active drill users n , on half level i , is shown as an example in Figure 23.

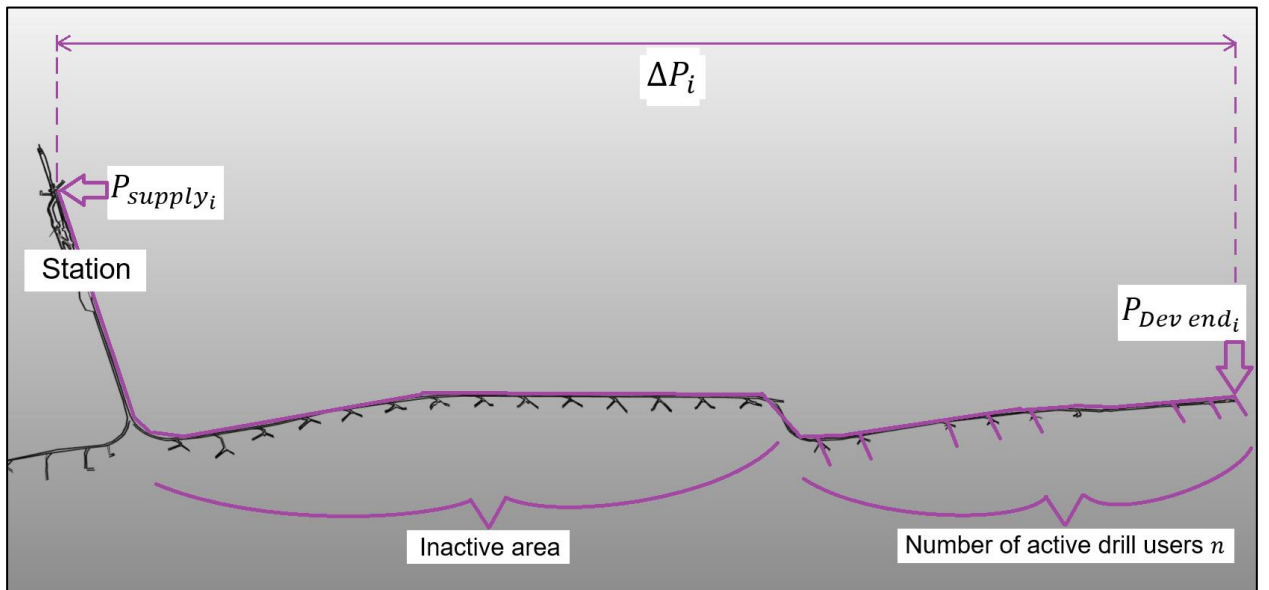


Figure 23: Example of active drill users located on a half-level i

Improving an underground inefficiency alone will not necessarily address the problem as stated in the redefined problem statement of Chapter 1. Instead, Equation 2.7 was developed to better define and prioritise a pressure drop, introducing a more practical quantification of inefficient levels.

The order of level prioritisation can shift depending on the feasibility of addressing each inefficient level. Once the levels have been prioritised, the next step will be to identify the inefficiencies responsible for reduced pressure delivery to consumers.

2.7.2 Step 4.2 – Inefficiency identification

The model can now be used to identify potential inefficiencies within the prioritised level distributing network. Comparing the mine's compressed air infrastructural engineering standards document to the built model provides a reference method to identify potential inefficiencies. For example, if the pipe size of a certain section is smaller than the engineering standard's specifications for that section, it may indicate that the piping of that section could be insufficiently sized, and that the mine is not conforming to the standards. Alternatively, the mine could conform to the standards, but a specified pipe size could be restrictive at a specific downstream flow demand.

When simulated, the model's results will be used to identify infrastructural inefficiencies from the known downstream consumer demands. One such method is to utilise a demand-side comparison bar graph, plotting the compressed air pressure at various points from the start of the level up to its development end.

This makes it easier to identify the effect that each inefficiency has on the downstream consumers. This graph should indicate the location of an experienced inefficiency along the level and can potentially assist in identifying areas lacking in pressure. An example is generated in Figure 24 that visually explains this method, as it provides an indication of an inefficiency's location present between crosscut 3 and 4.

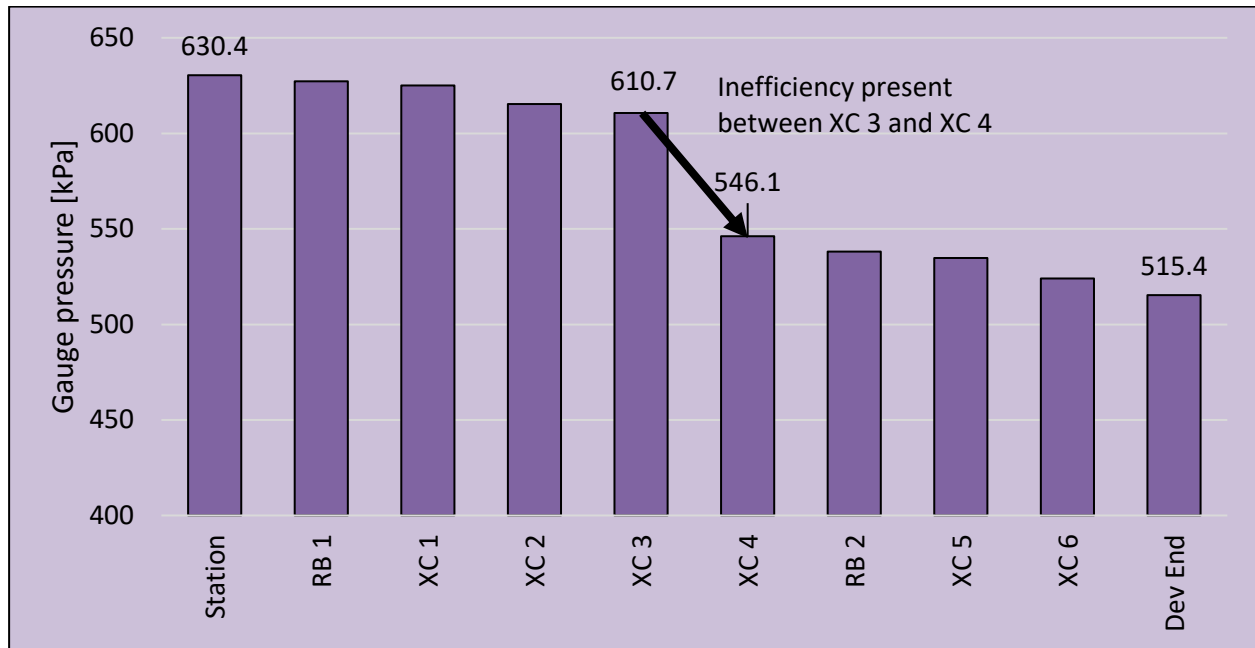


Figure 24: Example of inefficiency identified from demand-side pressure comparison

This method only makes use of theoretically calibrated pressure based on downstream consumer demands (Section 1.2.5) produced by the model to identify the inefficiency. As there is usually no instrumentation downstream of the stations, the identified inefficiency can, therefore, only be attributed to infrastructural limitations. A follow-up underground audit might be required to confirm theoretical findings. Wastages will not be identifiable during this process unless flow measurements were taken with a portable flow meter during the audits which could have indicated high wastage potential areas. Portable instruments are often incapable of measurement attempts, as the correct pipe conditions such as fittings, material, reachability or accessibility are required [47], [51].

To address this limitation of the theoretical model, a wastage-depressurisation method is adapted from the drop-test method and leak-rate equation. This method is introduced and adapted with the aim of quantifying the wastage on a level, with fewer limitations. This would further aid to indicate the possible extent of inefficient compressed air distribution on a level.

Drop-test method:

A drop test is commonly conducted to help determine the consumption of each level. Most level flow meters used by a mine are of the insertion type and are known to be problematic in providing accurate measurements [54]. Limitations to these flow meters include the velocity exposed across the sensor, blockages, drifting, or various other reasons [54]. A drop test provides an alternative

method to quantify each level's flow rate, using the more accurate surface flow meter [15], [47], [51]. During the drop test, the effect on the surface flow meter – measuring the total shaft demand – is quantified by opening or closing individual level valves for a few minutes [47], [50]. The observed difference in total flow approximates the individual level's consumption.

Drop-test method limitations:

This method can only be conducted during a time when no compressed air users are present underground, such as on a Sunday, public holiday, or during the blasting shift. Each level valve must be in working condition and sequentially opened/closed for successful flow-demand attribution. Each subsequent level can only be opened/closed once the surface flow meter stabilises due to the previous opening/closure of a level. It may, therefore, take approximately 100 minutes to conduct a full drop test on a shaft with 10 levels. The surface flow meter is assumed to be accurate due to frequent calibration [47]. Automation becomes difficult, as levels are dependent on one another and, therefore, opening/closure must be mutually exclusive.

The leak rate of a piping system can be calculated during the time the system depressurises [89].

Leak rate:

$$R = \frac{V(P_1 - P_2)}{\Delta t P_{atm}} \quad \text{Equation 2.8}$$

Where:

R Leak rate [Nm³/min]

V Volume of system [m³]

P_1 Initial pressure [kPa_g]

P_2 Final pressure [kPa_g]

Δt Time duration between interval P_1 and P_2 [min]

P_{atm} Atmospheric pressure [kPa]

Wastage-depressurisation method:

This method is derived from the known drop-test method, combined with the leak-rate equation in Equation 2.8. This method allows the user to determine the amount of wastage on a level without the need of a flow meter, using a more trustworthy level pressure meter. When isolating a level, similar to the drop test, the pressurised column depressurises over time due to downstream wastage. This time is measured and used to calculate the rate of depressurisation. This method does not need to be sequentially conducted like the drop test, which, therefore, dramatically reduces the implementation time. It is possible to automate this method to compute the daily wastage during the blasting shift provided that each level's pressure is independent of one another.

Adapting Equation 2.8 to an equation more relatable to the mining environment with simpler calculation inputs, and subtracting the known refuge bay consumption, yields the wastage-depressurisation equation.

Wastage-depressurisation:

$$Q_R = \frac{V(P_1 - P_2)}{\Delta t P_{atm}} \times 3600 - Q_{RB} \quad \text{Equation 2.9}$$

Where:

Q_R Amount of wastage on level [Nm³/h]

Q_{RB} Equivalent refuge bay consumption of level [Nm³/h]

V Total volume of level's piping [m³]

P_1 Initial pressure [kPa_g]

P_2 Final pressure [kPa_g]

Δt Time duration between interval P_1 and P_2 [seconds]

P_{atm} Atmospheric pressure [kPa]

From the data analysis conducted during Step 1 in Section 2.4, each sectional volume with the same diameter can be calculated using

$$V = AL \quad \text{Equation 2.10}$$

Where:

V Sectional pipe volume [m³]

A Flow area [m²]

L Pipe length [m]

Wastage-depressurisation method limitations:

One limitation of the wastage-depressurisation method is that the compressed air network's volume must be known. It is difficult to quantify each level's volume accurately, as the piping length is an approximated distance measured during the time of audit or by the haulage length from the drawing department. The flow area would also be an approximation, as inner pipe diameters vary between suppliers. An approximate average crosscut volume should be determined, which can be used to simplify the method and to disregard the dynamic nature of piping in crosscuts. Although the total volume is an approximation, the same approximate assumption is made for all other levels and would, therefore, still provide a relatively accurate representation and useful comparison in level wastages. A working isolation valve of the level is also required whilst not being ring-fed by other levels.

The wastage-depressurisation method will be used in this case as a supplementary measure to the identified pressure drop as shown in the example in Figure 24. This would provide further context to the extent of inefficiencies experienced on a level.

2.8 Step 5 – Implementation

Different solutions to the identified inefficiencies of the previous step will be studied. By using the verified baseline model, each proposed solution can be simulated as a different scenario. The findings and impact from each solution scenario should be compared for further investigation in terms of feasibility and practicality. It is advised that various solutions are proposed to the site engineering manager to receive their input on whether the best solution can be implemented or for adjustments to be made.

Once a consensus on the chosen solution has been made, implementation thereof can commence. The detailed process of implementation is not important for the purposes of this study.

2.8.1 Step 5.1 – Solution identification

In various scenarios of inefficiencies, numerous possible solutions exist to address them. It is, therefore, at the discretion of the experienced user and consultation of shaft engineers to ensure the problem is accurately defined to find the best solution to address or improve the experienced inefficiency. The detailed process of how a solution is obtained is not important for the purposes of this study, but typically, the process involves first eliminating the inefficiency, and if that's not possible, improving or working around it. This process is similar to the hierarchy of controls for risk management [90].

2.8.2 Step 5.2 – Case study prediction and implementation

At this point, various solutions to the inefficiencies described for each case study level have been identified. These solutions will be simulated as prediction scenarios of what the impact of implementation would be. This potential impact would play a significant role in the feasibility of implementation, and recommendations will be made for discussion with the shaft's engineering manager. The chosen solution will be motivated and implemented during this step for each separate case study based on the above-mentioned findings and recommendations.

2.9 Step 6 – Validation of method results

The results of implementation will be discussed in this section. Once the solution has been implemented for a measurable period, the performance will be measured by comparing the results to the baseline (period before implementation). The model's predicted impact will also be compared to actual results from implementation.

2.10 Verification of method

The method developed during Chapter 2 was constructed using established literature that conducted similar studies.

The following methods were considered as a basis:

- Literature studies that developed methods to address underground compressed air inefficiencies.
- Literature studies that developed simulation models to evaluate underground compressed air performance.

During Step 4.2, a limitation was identified when trying to identify an inefficiency using a theoretical model. This limitation could potentially be addressed by performing the wastage-depressurisation method, which could aid in determining the extent of wastages on a level if measurements were not sufficient during the time of audits.

From the state-of-the-art matrix in Table 2, a clear gap was identified, where inefficiencies in the haulages/drift of a mine are often not considered. This section of the underground system is regarded as less dangerous, and its compressed air infrastructure is less dynamic than in stoping areas. Additionally, a lack of studies considered the infrastructural mining standards in terms of their sufficiency and conformity.

By incorporating the identified limitations and gaps from the state-of-the-art matrix, the above basis was adapted in this section to fit the needs of this study, to address the problem.

The following key adaptations were made for additional consideration:

- Addressing inefficiencies from a safer environment (without the need to enter dangerous stoping areas).
- Considering mining standards in terms of their adequacy, and actual mining's conformity to the standards.
- Addressing the limitations of theoretically identified inefficiencies.

The above criteria and specifications were combined and adhered to in order to form a proposed solution method for the improvement of compressed air inefficiencies from a safer environment using simulation software as a tool. A summary of where these criteria and specifications are met during the method development of Chapter 2 is shown in Table 6.

Table 6: Criteria and specifications aligning with method-designed steps

Criteria or specification	Method design steps
Literature studies that developed methods to address underground compressed air inefficiencies.	Section 2.3
Literature studies that developed simulation models to evaluate underground compressed air performance.	Section 2.3
Addressing inefficiencies from a safer environment (without the need to enter dangerous stoping areas).	Section 2.7 & Section 2.8
Considering mining standards in terms of their adequacy, and actual mining's conformity to the standards.	Section 2.7, Step 4.2
Addressing the limitations of theoretically identified inefficiencies.	Section 2.7, Step 4.2

2.11 Summary and overview

The redefined problem statement states that shaft personnel typically address the issue of low-reported compressed air pressures in a non-efficient and ineffective manner. Low experienced workplace pressures lead to a short-term solution where shaft personnel increase compressed air pressures. Thereafter, this typically becomes the norm of “required supply pressures”, as it is never readjusted or properly addressed. This leads to an artificial demand, and increased compressor operating and maintenance costs, reducing the profitability of the shaft. If the initial issue of low workplace pressures is not addressed, production performance may be negatively impacted.

The shafts are, therefore, left with the choice of either reduced production performance or increased operating costs. This study aims to highlight an alternative option to instead address the actual underlying issue that initially led to low workplace pressures.

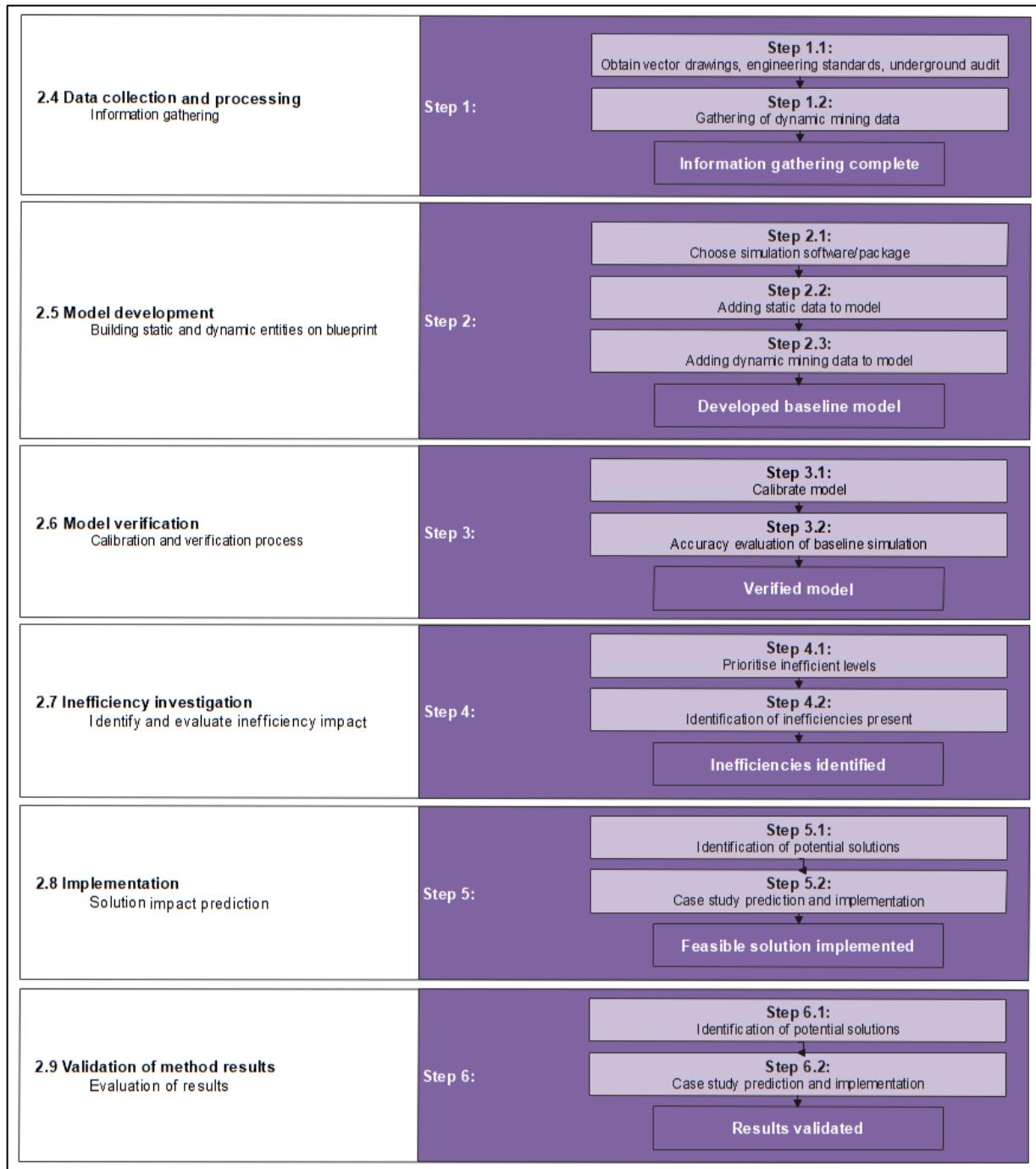


Figure 25: Final proposed detailed method

The methodology outlined in this chapter provides the proposed method to address the problem statement. This method can be duplicated and used for similarly experienced issues. It provides a well-informed prediction to a potential solution scenario. The model also allows for less resource-intensive and time-consuming audits, which would have been necessary to reinvestigate experienced issues and might not have been capable of identifying the origin of the problem.

CHAPTER 3: RESULTS AND DISCUSSION



Figure 26: Shaft on platinum mine - 18h00¹⁵

"The only thing keeping you from getting what you want, is the story you keep telling yourself about why you don't have it."

- Tony Robbins

¹⁵ E du Plessis, 2024

3.1 Preamble

This chapter will follow the final proposed method as concluded in Chapter 2, Section 2.11. The necessary information required to construct a baseline model capable of producing accurate simulation scenarios will be gathered. The model will be used to identify any existing inefficiencies. Comparing each case study solution to baseline conditions will highlight the effect of independent variables. The most feasible solution will be chosen for implementation and its performance evaluated. See a flow diagram of Chapter 3 in Figure 27, adapted from Figure 19 and Figure 25.

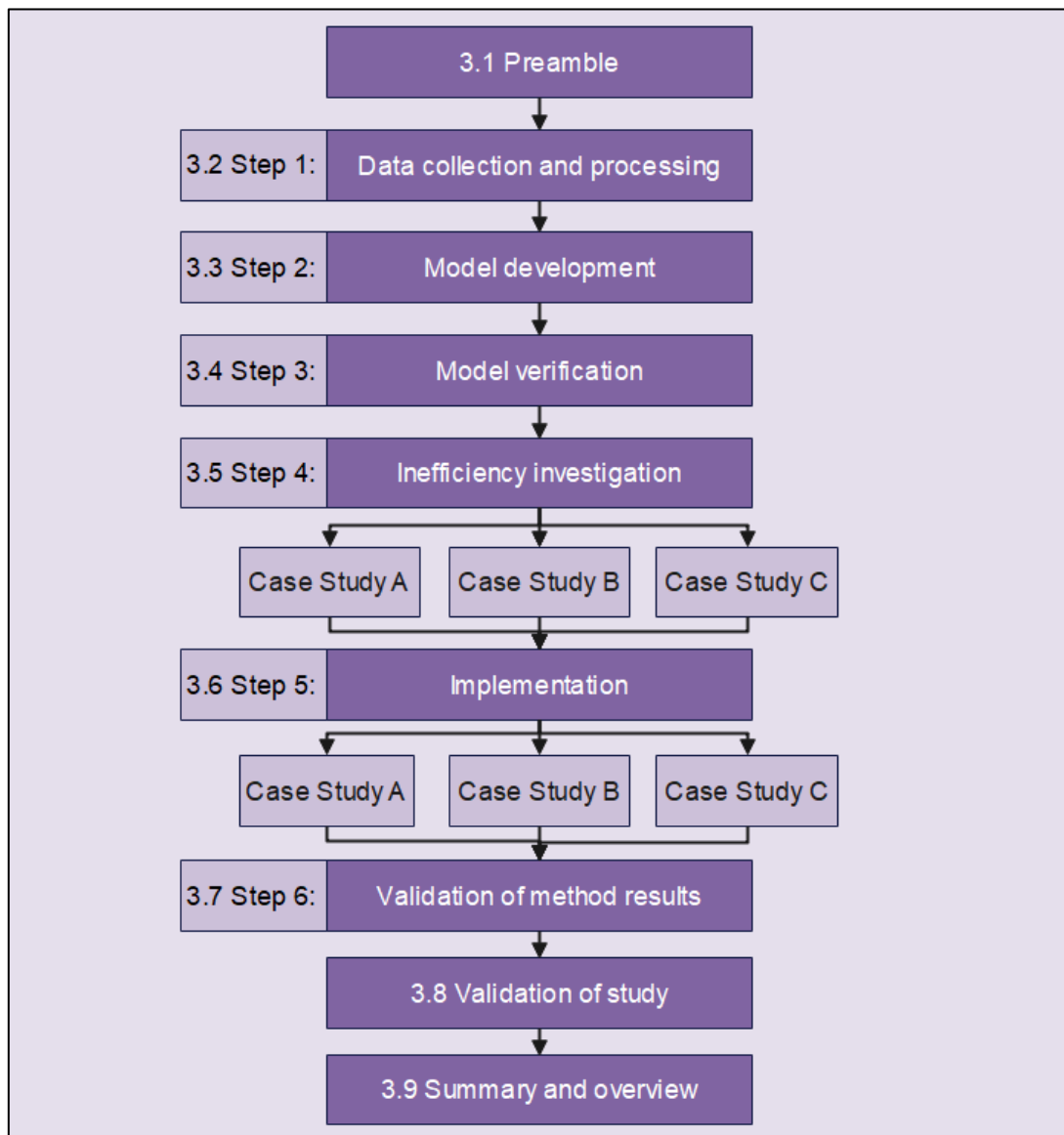
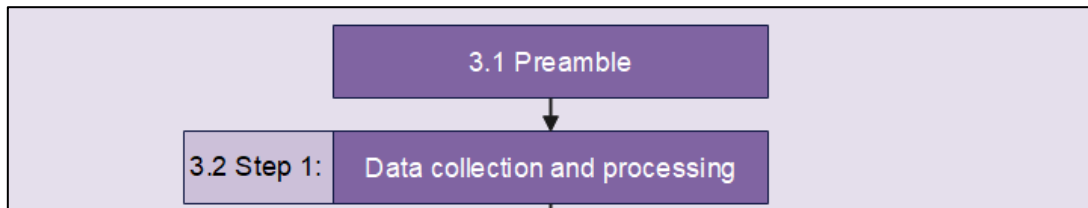


Figure 27: Chapter 3 flow diagram

3.2 Step 1 – Data collection and processing



Using Section 2, Step 1, the initial and relevant required data were obtained and are discussed below.

Step 1.1: Static inputs:

- The most recently updated surveyor drawings were obtained from the relevant shaft's planning and drawing department (received in DXF format). These vector drawings were edited by removing auxiliary information, with only the outline of the station, haulages, and crosscuts remaining.
- The mine's engineering standard, specifically the "*Underground Compressed Air Reticulation Standard's*" document was obtained from the engineering manager.
- A full underground comprehensive audit, spanning 11 weeks, was conducted at the beginning of 2022. During this period, all relevant information related to the compressed air system was logged, and many leaks from old and damaged infrastructure were found.
 - A peculiarity was observed. During the auditing period, the compressed air rate of consumption reduced by approximately 10 000 Nm³/h. It is believed that this reduction was due to regular auditor presence underground, potentially refraining the miners from compressed air misuse.

Step 1.2: Dynamic inputs:

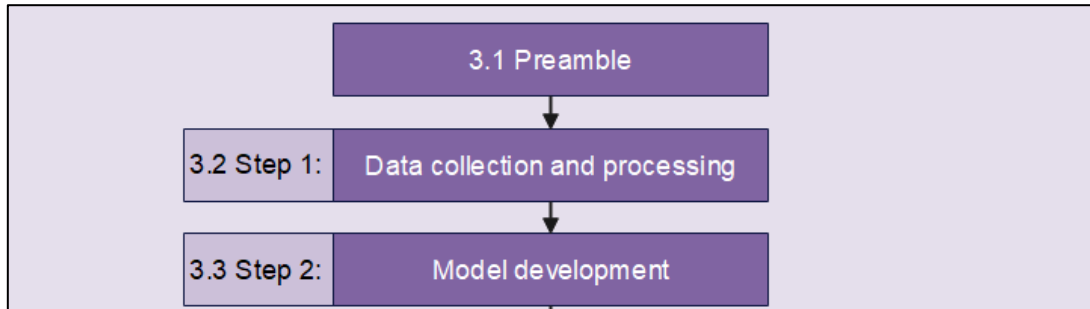
- Pressure and flow meter data from the surface main supply column and each level are extracted from the mine's historian or Structured Query Language (SQL) server for the preceding three months in hourly intervals. Additionally, mining crew data for the same period is also obtained.
- Flow measurements taken at crosscut inlets with a compressed air ultrasonic flow meter during the audits are consolidated for calibration purposes.



Figure 28: Ultrasonic flow meter with transducers

- Pressure measurements taken where a gauge could be installed are also consolidated for calibration purposes.
- An average hourly profile is then drawn respectively for the weekday operations. A specific day closest to the average profiles is then chosen as the baseline date. This specific day's data will be used to construct the baseline model that is representative of a typical day.
- The date of 06-07-2022 was found to fall within the smallest error range of the three-month average profiles. This date will, therefore, be used as the baseline date to which the simulation model will be calibrated.

3.3 Step 2 – Model development



The model will be built using an applicable simulation software package that is both simple to use and capable of simulating the compressed air network model accurately.

Step 2.1: Choose simulation software/package

Different simulation packages are considered based on discussions and listed advantages and disadvantages from various studies. For the sake of simplicity, these packages are summarised and compared in a matrix in terms of their accuracy, cost, applicability to this study, and user friendliness [47], [51], [54], [61], [63]. The matrix is based on the following conditional ratings:

- **Rating 1** – Not accurate, very expensive, not applicable or user-friendly.
- **Rating 2** – Moderately accurate, costly, applicable, or user-friendly.
- **Rating 3** – Highly accurate, low cost or easily accessible, applicable to study, user-friendly.

Averaging the rating of each study yields the following matrix as summarised in Table 7. Higher values are better.

Table 7: Comparison of different simulation packages [47], [51], [54], [61], [63]

Simulation package	Accuracy	Cost	Applicability to study	User-friendly	Total rating
SolidWorks® Flow Simulation	3.0	1.3	2.5	1.3	8.2
Flownex®	3.0	1.0	2.8	1.0	7.8
PTB®	3.0	3.0	3.0	2.5	11.5
KYPipe® GAS	2.3	2.0	1.5	2.0	7.8

All four simulation packages were considered accurate by other studies; however, KYPipe was found lacking in its applicability to the compressed air framework of the study [51], [54], [63]. Both Solidworks and Flownex were costly and not user-friendly [54], [63].

Process Toolbox (PTB) is found to be a great all-round simulation package. It integrates well with Microsoft Excel®, allowing for a better representation of results. Multiple raw data outputs can automatically be processed and compared visually once set up to do so, and underground surveyor drawings can be imported, which is applicable in the next step [47]. PTB also has built-in functions to simplify complex underground simulations and components can be modelled empirically if data such as pipe roughness is not available [47]. For these reasons, PTB will be used to construct the baseline model.

Step 2.2: Adding static data to model

The reticulation vector diagrams obtained in Step 1 is now imported to PTB as shown in Figure 29. This will be used as a reference framework and the full compressed air reticulation model will be built onto this blueprint during the next step. A significant feature of PTB is that the built compressed air reticulation automatically scales to the actual dimensions defined by the blueprint.

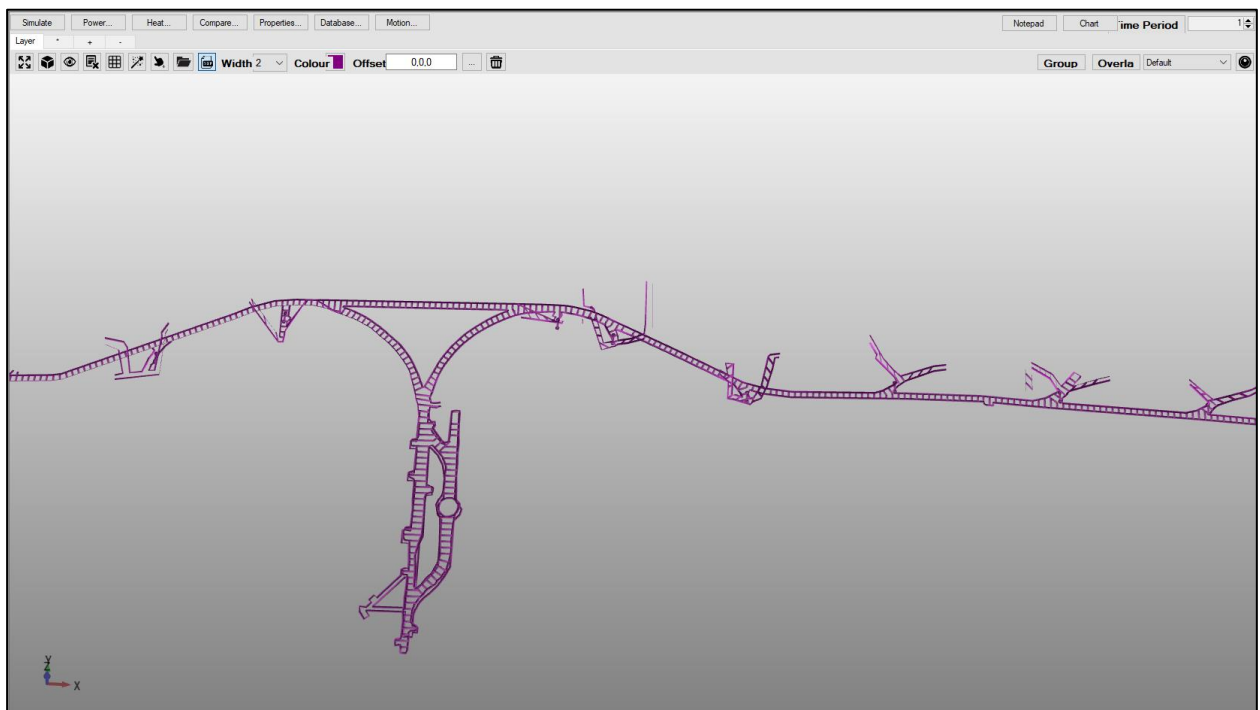


Figure 29: Vector diagram acting as blueprint, imported to PTB

The information gathered through the comprehensive audits, conducted during Step 1, is used to construct a compressed air digital twin that follows the dimensional layout of the blueprint reference. Figure 30 shows a visual of the added compressed air network to the PTB model.

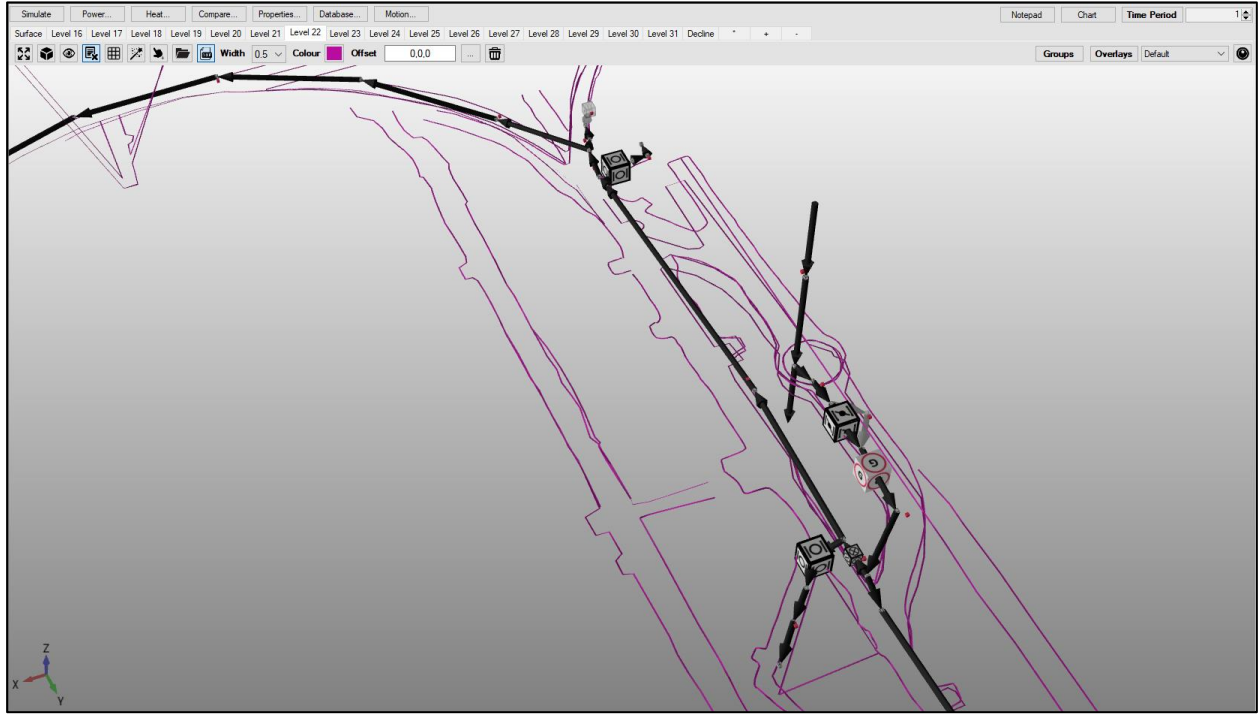


Figure 30: Compressed air network built on the vector diagram

Step 2.3: Adding dynamic mining data to model

Supply-side:

The extracted and processed instrumentation data from Step 1 needs to be integrated into the model. The dynamic supply-side data is specified through the “AirPressureBoundary” component. Compressor supply and consumer demands are usually connected to this component at reference conditions; however, in this case, this component will act as the equivalent total compressor supply. Only a few inputs are required as shown in Figure 31.

Inputs	Properties	Calculate	Import...	Export...
Specification	Name	Unit	Initial	
Coordinate	Pressure	kPa	...	
Size	Temperature	°C	...	
Orientation	Known Property		Relative ...	
Offset	Relative Humidity	%	...	
	Elevation	m	0.000	
	Reference Pressure	kPa	100.000	
	CO2	ppm	...	

Figure 31: “AirPressureBoundary” component input specifications

Where:

Pressure [kPa _{abs}]	Pressure specification, either atmospheric reference conditions or to be used as the equivalent compressor network supply
Temperature [°C]	Environment dry-bulb temperature
Known property [-]	Option to specify relative humidity or wet-bulb temperature
Relative Humidity [%]	Relative humidity at specific environment
Elevation [m]	Elevation height
Reference Pressure [kPa]	Atmospheric pressure at specific environment
CO2 [ppm]	Quantity of CO ₂ in atmospheric environment (N/A)

The weekday hourly pressure requirements, signed off by the specific case study shaft, are added as input values to this component. These values can be studied in Appendix C, Table 24.

Demand-side:

When specifying the demand-side, a representative demand is added for each known underground consumer, i.e., various drill users, refuge bays, loaders, blowers, and pneumatic pumps, using the “AirDemand” component. These demands are based on the number and type

of crews and their respective theoretical demands at specified pressures. The input specifications are shown in Figure 32.

Inputs	Properties	Unit	Initial
Specification	Name		
Coordinate	Flow	kg/s	...
Size	Inlet Pressure	kPa	...
Orientation	Outlet Pressure	kPa	...
Offset	Inlet Temperature	°C	...
	Number of Units		...
	Flow Factor		1.000

Figure 32: “AirDemand” component input specifications

Where for each type of consumer:

Flow [kg/s]	Flow demand of each specific consumer
Inlet Pressure [kPa _{abs}]	Pressure demand based on consumer specification
Outlet Pressure [kPa _{abs}]	Atmospheric pressure at the user, calculated using Equation 1.5
Inlet Temperature [°C]	Dry-bulb temperature at specified demands
Number of Units [-]	Multiplying factor, based on the number of consumers
Flow Factor [-]	Factor used to adjust consumer flow closer to an actual measured value, often to account for wastages (default value=1)

The input values for the most prominent consumer types are summarised in Table 8.

Table 8: "AirDemand" calculated input values

Input values	Cross cut	Refuge bay	Development end
Flow [kg/s]	0.12	0.06	0.8
Inlet Pressure [kPa _{abs}]	650	650	650
Outlet Pressure [kPa _{abs}]	94 – 99.8	94 – 99.8	94 – 99.8
Inlet Temperature [°C]	40	40	40

Number of Units [-]	# of drill users in crosscut	1	1
Flow Factor [-]	1	1	1

These prominent consumer inputs were added to the model at the respective locations based on the gathered information.

The total compressor supply and various underground demands have now been specified at each relevant location within the compressed air network model. The theoretical model is, therefore, now complete and will be calibrated and verified to a baseline model in the next step. The fully constructed compressed air model is shown in Figure 33.

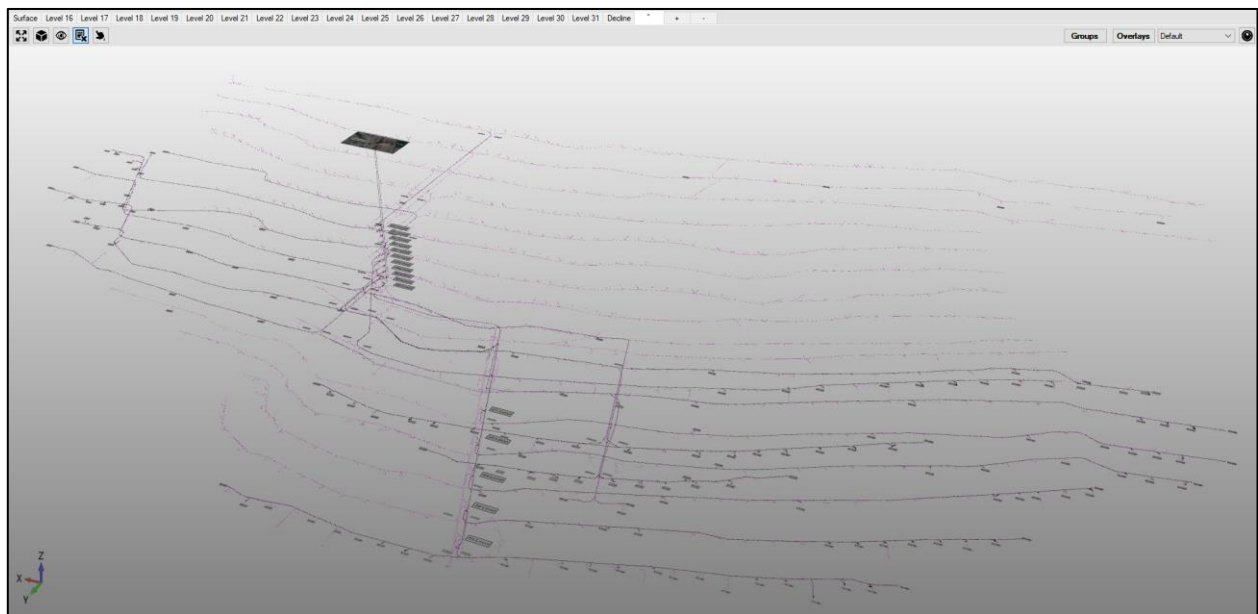
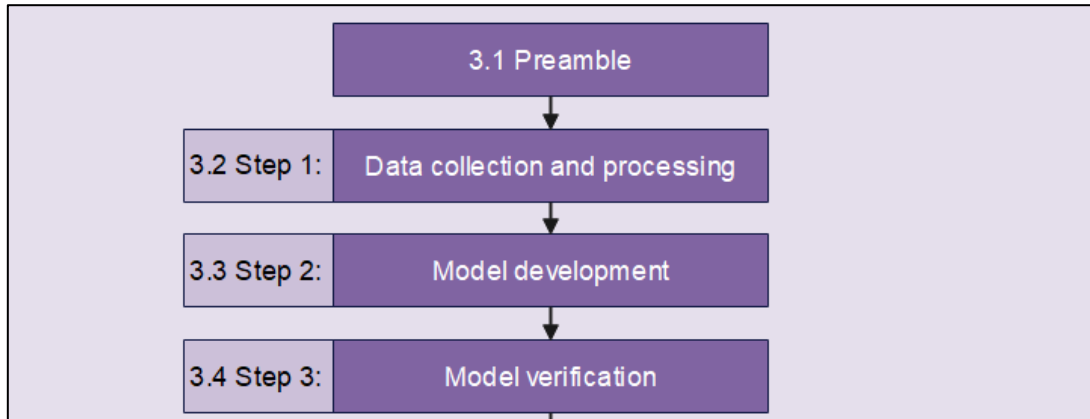


Figure 33: Overview of built compressed air model

3.4 Step 3 – Model verification



For the model, developed in the previous step, to be verified, it needs to produce simulated values within reasonable accuracy when compared to the actual measured values. Pressure and flow values need to correspond within the acceptable error ranges as defined in Section 2, Step 3. This provides a valuable baseline model used for further studies related to the compressed air network.

The total simulated and actual flow demand (measured from the surface flow meter) is compared in Figure 34.

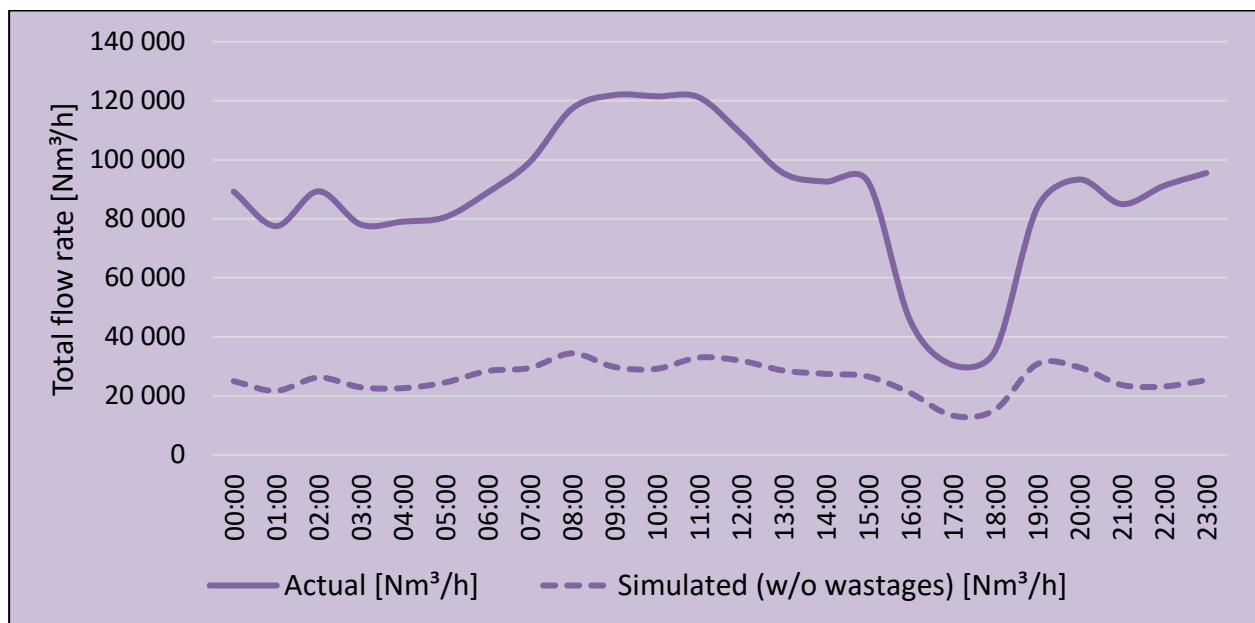


Figure 34: Actual flow demand versus model's flow demand

The simulated flow demand is significantly lower than the actual flow demand as wastages have not been added to the model. This simulated demand portrays the zero-waste baseline of the shaft. For a more accurate representation and model of practical use, crosscut wastages will also be added through another parallel “AirDemand” component.

Wastages were added to each crosscut based on the respective ultrasonic flow and gauge pressure measurements. Crosscuts where flow could not be measured were assumed to consume an additional 30% to 50% of the theoretically attributed crosscut flow. This margin and actual pressure and flow measurements collected during audits were used to calibrate each of the 12 active levels to the correct pressure profile in conjunction to the surface total flow demand. Each individual level is calibrated to achieve a MAPE below 10%. The surface flow and pressure result from level calibration is shown in Figure 35 and Figure 36 respectively.

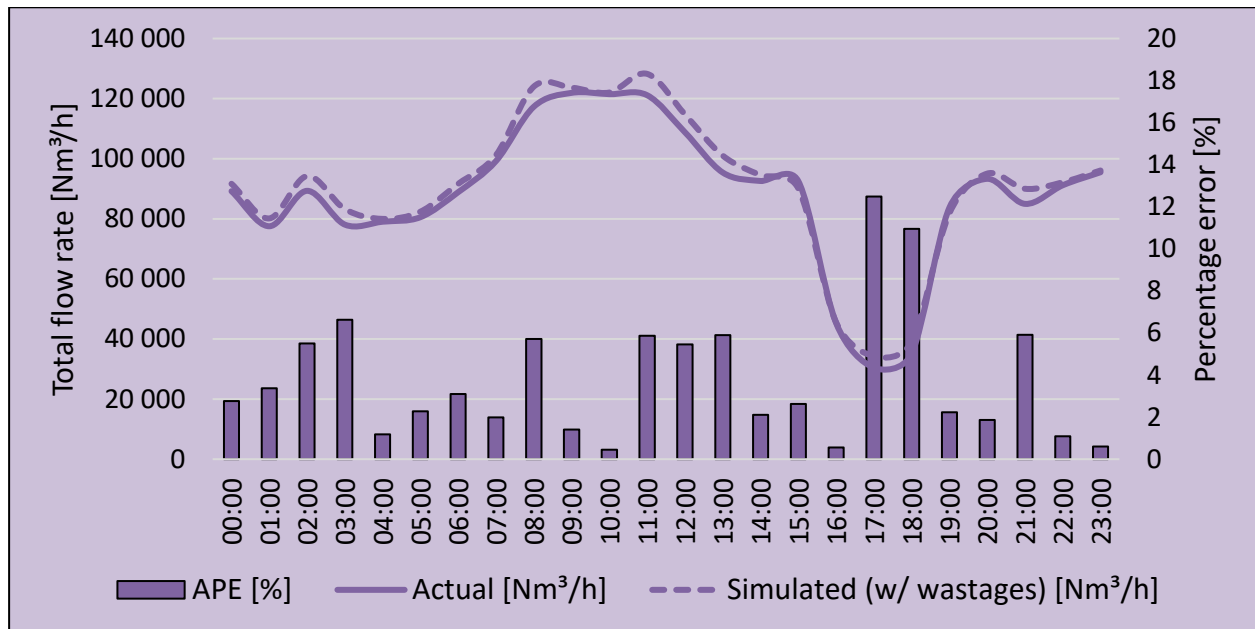


Figure 35: Actual flow demand versus model’s flow demand with added wastages

A MAPE of 3.84% is achieved for the total surface flow demand, indicating that the shaft’s flow demand is within acceptable accuracy.

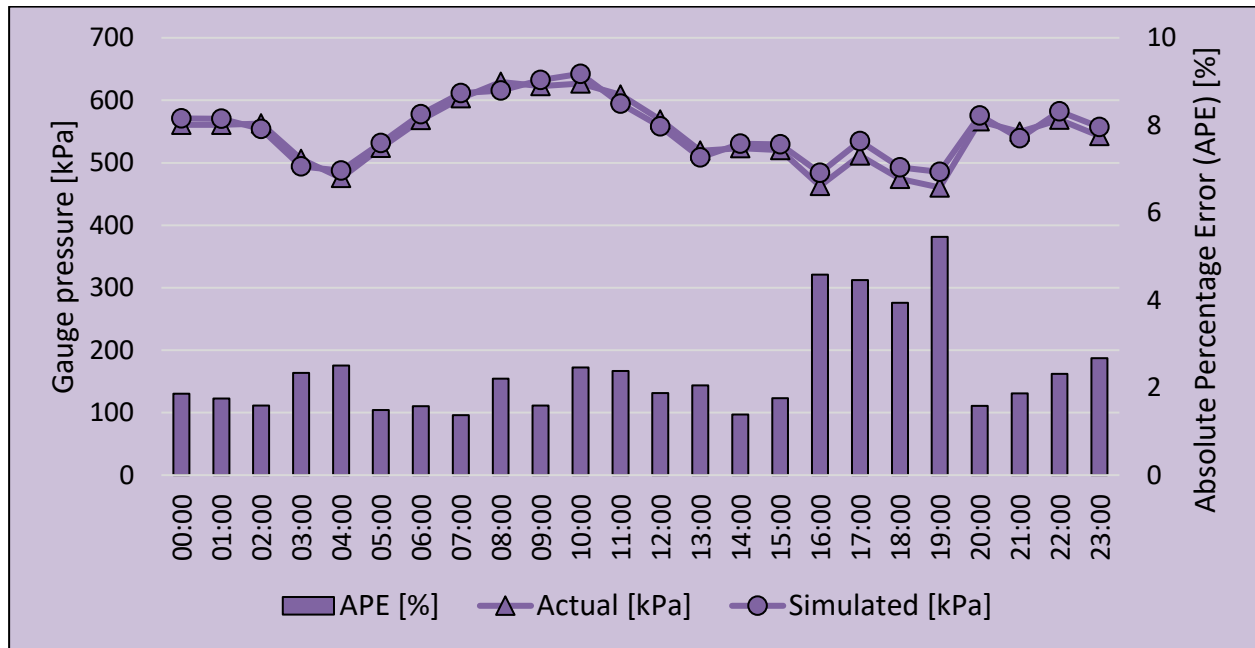


Figure 36: Model's hourly performance comparison of the surface supply pressures

The surface pressure corresponds well within a MAPE of 2.38% to the actual measured values.

Considering both Figure 35 and Figure 36, a lesser correspondence or higher error value is only experienced during lower flow and pressure values. This is because lower values result in a larger error percentage. The MAPEs were calculated using Equation 2.4, and a tabulated summary is provided in Appendix D, in Table 25 and Table 26, for the surface flow and pressure respectively.

As the underground flow meters were inaccurate and often not in working condition, level flows could not be used for calibration purposes. Since the loss in delivery pressure is the focus of this study, only the calibration of level pressures will be considered sufficient. Due to the low pressure supply during the blasting shift period (16h00 – 20h00), the observed APE skews the MAPE for some levels. This is especially clear when observing the individual level comparisons. Since the blasting shift is a period during which no mining is conducted, a MAPE calculation that excludes the blasting shift was, therefore, also conducted.

Instead of excluding the blasting shift completely, WMAPE introduces the concept of assigning different weights to individual data points based on their importance, as stated in Section 2, Step 3 using Equation 2.5. This approach acknowledges that compressed air pressure and importance have a positive correlation in mining. The weights will be based on the shaft's hourly pressure set-point requirements as shown in Appendix C, Figure 60. This is an additional method of verifying each individual level. A summary of these verification results is shown in Table 9.

Table 9: Model's performance of individual level pressures

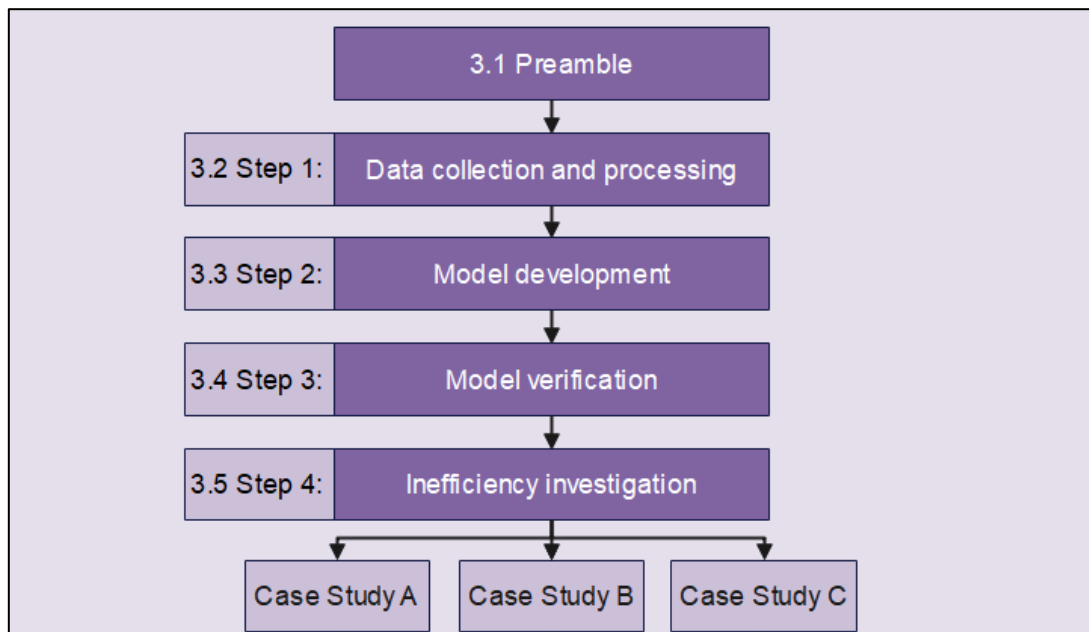
Location	MAPE [%] (incl. blasting shift)	MAPE [%] (excl. blasting shift)	WMAPE [%] (incl. blasting shift)
Surface	2.38	2.33	2.35
18-Level station	2.57	2.49	2.50
19-Level station	0.74	0.71	0.71
20-Level station	1.32	0.53	1.03
21-Level station	7.97	0.91	3.58
22-Level station	7.67	2.69	4.05
23-Level station	4.65	0.82	2.50
24-Level station	1.46	1.41	1.47
25-Level station	2.88	2.65	2.85
26-Level station	3.92	3.78	3.89
27-Level station	9.02	2.00	4.74
28-Level station	7.73	1.98	4.26
29-Level station	6.53	3.09	4.46
30-Level station	4.52	2.28	3.21
31-Level station	2.84	2.14	2.67
Average	4.56	1.96	2.99

Table 9 highlights the significant effect the blasting shift has on each individual level's MAPE. Each level was successfully calibrated to a MAPE within 10%, and WMAPE within 5%. A full disclosure of individual-level results can be found in Appendix E.

The WMAPE was calculated to address the incompatibility of MAPE with smaller values during the blasting shift that are less significant for the purposes of mining activity and, therefore, for this study.

From the above results, an average MAPE of 1.96% is observed for all levels when the blasting shift is excluded, and an average MAPE and WMAPE of 4.56% and 2.99% respectively when included. Since this is below the 5% error threshold, the model is within acceptable range and considered calibrated and verified. This model can now be utilised as the baseline model.

3.5 Step 4 – Inefficiency investigation



Level prioritisation (Step 4.1):

The following levels will initially be filtered, as discussed in Section 2, Step 4:

1. Levels with the most compressed-air-related complaints.
 - This is based on the importance and impact of complaints on the underlying problem where shaft personnel may increase compressor set points.
2. All levels with a pressure drop of more than 100 kPa to any of its half-level development ends.
 - This is based on the engineering standards' recommendation in Figure 38.

This does not identify the location or type of inefficiencies present on the level yet. Equation 2.7 will subsequently be used to identify and prioritise the most inefficient levels as case studies in Step 4.2. A full shaft evaluation will be conducted by simulating the verified baseline model from the previous step.

Inefficiency investigation (Step 4.2):

Each identified case study level will explore the possible inefficiencies present on the level. Each case study is considered separately to identify the highest contributing inefficiencies.

PTB has a high standard colour scaling functionality, visually highlighting the built simulation network based on the value of the chosen entity. It also features a threshold selection, visually grading above and below the selection. In other words, throughout the network, dynamic changes in the chosen entity can be visually observed. This can assist in identifying an inefficiency.

An example of this colour scaling functionality that is based on the flow rate entity at a threshold set at 2 kg/s is shown in Figure 37. The set threshold is always scaled to be yellow. Colours to the right of yellow indicate higher flow, and colours to the left indicate flow lower than the set threshold.



Figure 37: Example of PTB colour scaling functionality

Each identified inefficient level, can be subjected to the above functionality for a rapid visual inspection.

The engineering standards document, obtained during Step 1, describes the underground compressed air reticulation standards. The standard sizing of haulages, crosscuts, and raise/stope areas, obtained from this document, is defined from Figure 38 to Figure 40.

- 2.1.15 A pressure gauge must be installed at all stations and the recommended air pressure is 5,5 bar during drilling operations.
- 2.1.16 The recommended air pressure at the work place entrance should be 4,5 bar.

Figure 38: Engineering standard: Station and workplace gauge pressure recommendations

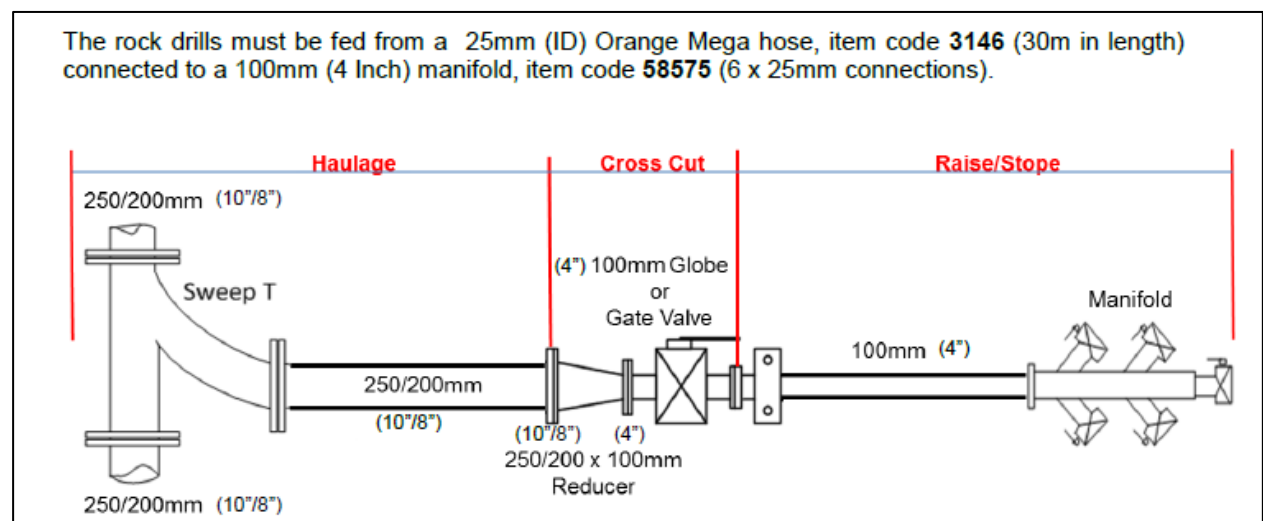


Figure 39: Engineering standard: Leading face to raise piping standard

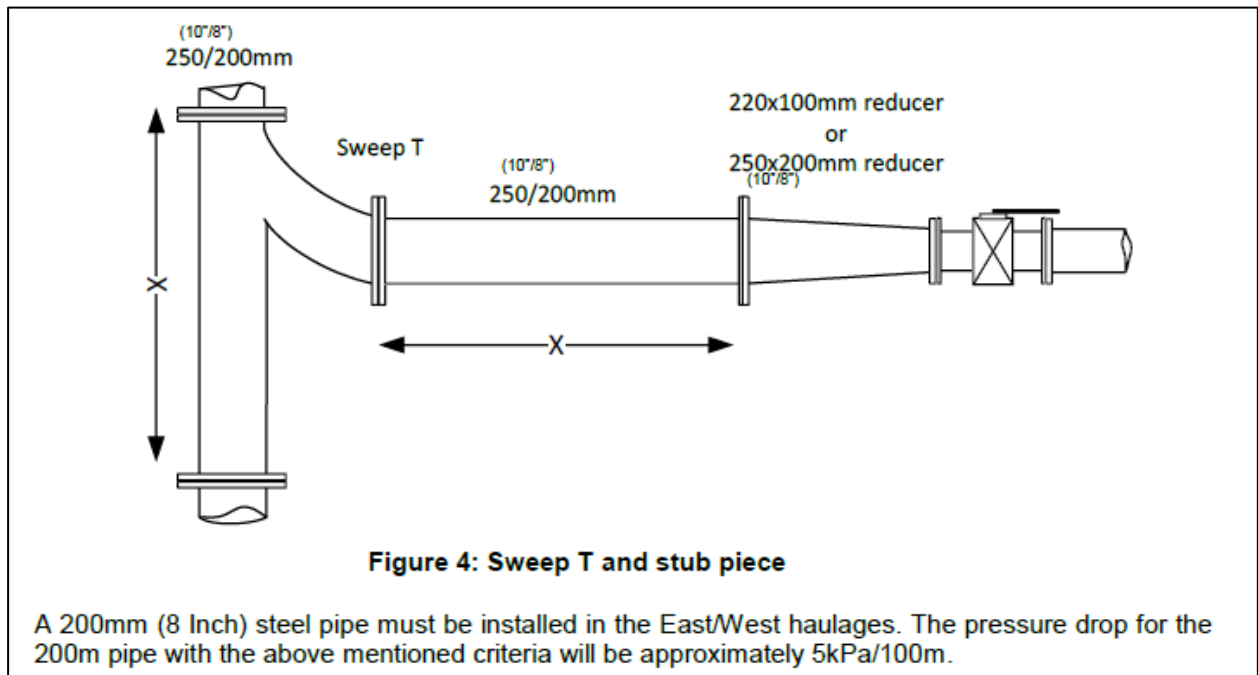


Figure 40: Engineering standard: Haulage cross-cut raise connection

These standards will be used in conjunction with the simulation model to identify possible inefficiencies present on each level.

Studying the inefficiencies to be identified will utilise PTB's colour scaling functionality, engineering standards, and a demand-side comparison graph for each case study during the peak drilling shift period. This is conducted for case studies A, B, and C during Step 4.2 once the three most inefficient levels have been prioritised in Step 4.1.

3.5.1 Step 4.1 – Level prioritisation

The verified baseline model is evaluated in terms of the pressure drop of each active level. It was found that more than 50% of the shaft's active levels experience a drop in pressure of more than 50 kPa, and 30% of the levels experience a drop of more than 100 kPa.

According to the engineering standards' recommendations, levels that experience a pressure drop of more than 100 kPa during the peak drilling period (07h00 - 12h00) to any of their half-levels' development ends will be evaluated first. All 12 active levels, alongside their half-levels, are tabulated in Table 10.

Table 10: Levels with more than 100 kPa drop in pressure during the peak drilling period

Inefficient level	Station pressure [kPa _g]	Half-level	Development-end pressure [kPa _g]	Drop in pressure [kPa _g]
	P_{supply_i}	i	$P_{Dev\ end_i}$	ΔP_i
Level 20	644.97	UG2 East	643.31	1.7
Level 21	647.58	UG2 East	646.91	0.7
Level 22	649.93	UG2 East	628.73	21.2
		Merensky West	588.98	61.0
Level 23	651.39	UG2 East	548.41	103.0
Level 24	655.37	UG2 East	646.19	9.2
		Merensky East	525.82	129.5
		Merensky West	553.44	101.9
Level 25	648.21	UG2 East	639.06	9.1
		UG2 West	621.00	27.2
		Merensky East	626.20	22.0
		Merensky West	626.40	21.8
Level 26	658.82	UG2 East	580.03	78.8
		UG2 West	537.41	121.4
		Merensky East	565.56	93.3
		Merensky West	565.65	93.2
Level 27	632.43	UG2 West	585.66	46.8
Level 28	632.63	UG2 West	527.46	105.2
Level 29	630.01	UG2 West	628.09	1.9
Level 30	626.69	UG2 West	452.45	174.2
Level 31	627.50	UG2 West	556.54	71.0

Six half-levels have been identified on five main levels that experience more than 100 kPa drop in pressure and are outlined in bold.

The intensity-based pressure drop per drill user, $\mathcal{E}$, from Equation 2.7, provides a more practical comparison, and will be used as a ranking measure. The number of complaints regarding inadequate compressed air pressure on a half-level does not accurately represent an experienced problem, as it remains a human factor. However, minimising user complaints may alleviate the

pressure on shaft personnel who determine the change in compressed air supply pressure set points.

The above-mentioned intensity has been calculated for each of the five identified levels, and their half-levels is summarised in Table 11. The number of complaints in the past three months and past year are added for reference. The area with the highest drop in pressure per drill user, ε , is considered the most inefficient half-level. The number of drill users on a half-level is indicated as a fraction of the total drill users present on the level.

Table 11: Half-level pressure drop per drill user and user complaints

Inefficient level	Half-level	Drop in pressure [kPa _g]	Number of drill users/ total drill users	Pressure drop per drill user [kPa _g]	Number of complaints past three months	Number of complaints past year
	i	ΔP_i	n	ε_i	-	-
Level 23	UG2 East	103.0	49/49	2.10	5	8
Level 24	UG2 East	9.2	28/188	0.33	2	6
	Merensky East	129.5	60/188	2.16	0	0
	Merensky West	101.9	100/188	1.02	12	24
Level 26	UG2 East	78.8	4/164	19.7	1	1
	UG2 West	121.4	66/164	1.84	17	17
	Merensky East	93.3	24/164	3.89	0	0
	Merensky West	93.2	70/164	1.33	2	2
Level 28	UG2 West	105.2	52/52	2.02	7	12
Level 30	UG2 West	174.2	54/54	3.22	4	4

The top three levels with the highest (worst) intensity have been outlined in bold. Level 26 has two half-levels with the highest intensity, followed by Level 30 and Level 24. The number of complaints does not appear to have any clear correlation. Due to the human factor and insignificant correlation, the number of complaints will not be used as a prioritisation method [45], [50], [61].

Due to such high pressure drops, each level in Table 11 should be considered separately as their own unique case study. For the sake of simplicity, the three most inefficient levels determined by the pressure drop per drill-user intensity $\mathcal{E}$, will be considered as case studies.

Each level is prioritised accordingly:

Case Study A: Level 26

- According to the intensity-based $\mathcal{E}$, this level has two of the worst-performing half-levels and coincidentally also had the most complaints on one of its half-levels. This level will, therefore, be addressed first.

Case Study B: Level 30

- This level has the second worst intensity and experiences a significantly higher drop in pressure when compared to the other levels, especially for a level with activity on only one half-level.

Case Study C: Level 24

- As the level with the third most inefficient intensity and the most users present on a level, this level will be considered as the final case study.

During the next step, PTB's colour scaling functionality will be used as a supplementing measure, as discussed at the beginning of this section. Each following case study will be considered during a period that best portrays the visual change in colours. Gauge pressure will be used as the measured entity, as it indicates the lack of pressure best in certain areas. With the threshold set at the minimum allowable rock-drill-place pressure of 450 kPa_g, areas receiving less pressure provide a good indication of a potential problem.

A demand-side comparison bar graph will also be drawn for each level during the next step as discussed in Section 2, Step 4.2. This would further aid in pinpointing the location of potential inefficiencies.

3.5.2 Step 4.2 – Inefficiency identification – Case Study A

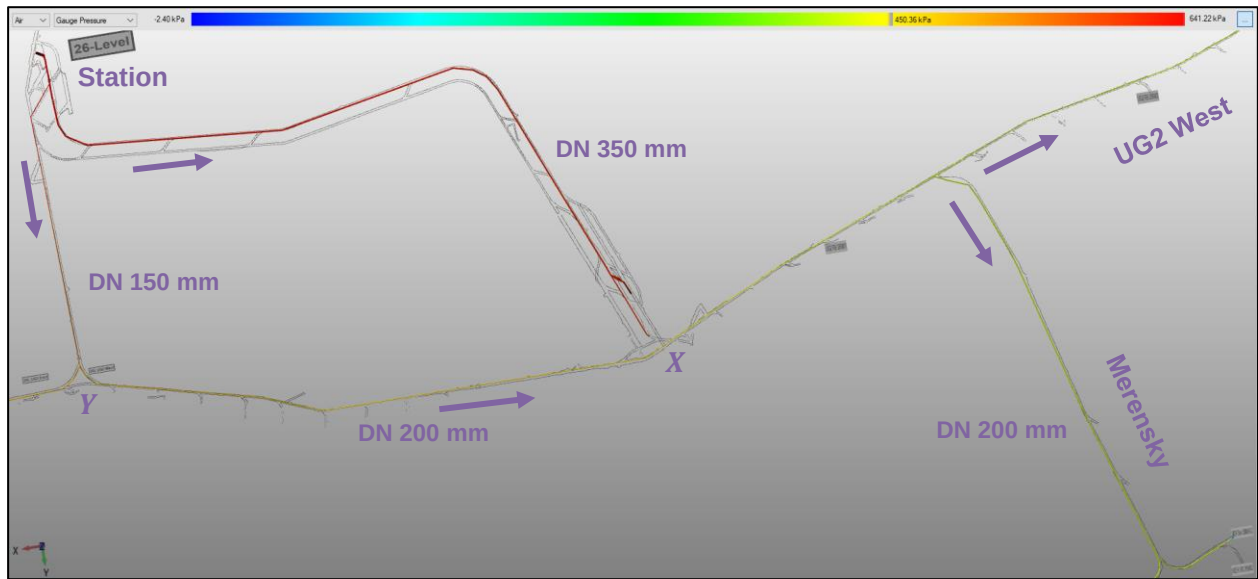


Figure 41: Case Study A, visual model representation of potential inefficiency locations

With reference to Figure 41, compressed air is fed from the station to all active mining areas via the DN 150 mm pipeline. It is visually clear how quick pressure drops over this route. Up until Point Y, compressed air is fed by a DN 150 mm column. According to the engineering standards, this section should be using DN 200 mm or DN 250 mm columns. When studying the norm on the neighbouring shafts, most levels supply their half-levels with a DN 350 mm column, and only at the start of the half-level are the columns reduced to DN 200 mm. This is also described in the standards, Figure 40, where “A 200 mm (8-inch) steel pipe must be installed in the East/West haulages.” The DN 150 mm pipeline is, therefore, considered a severe restriction, as it is more than four times smaller in flow area than the norm of neighbouring shafts’ levels.

That four half-levels consisting of DN 200 mm piping are supplied by a single DN 150 mm column confirms that this level is not conforming to the correct pipe sizing set out by the engineering standards. The existing DN 350 mm column does not feed any active mining areas, as it is not interconnected at Point X. It is unclear why this DN 350 mm column has not been linked to the active infrastructure at this Point X. There are only a few workshops and refuge bays that currently tie off from this pipeline.

The node outputs from the verified baseline model have been exported to Excel. A demand-side pressure comparison is developed for Case Study A that compares the subsequent drop in pressure to each working area of interest during the peak drilling shift (07h00 - 12h00). This facilitates the identification of the impact each consumer or inefficiency has on downstream

consumers. Subsequent locations with insignificant pressure drops are omitted from Figure 42 for simplicity's sake.

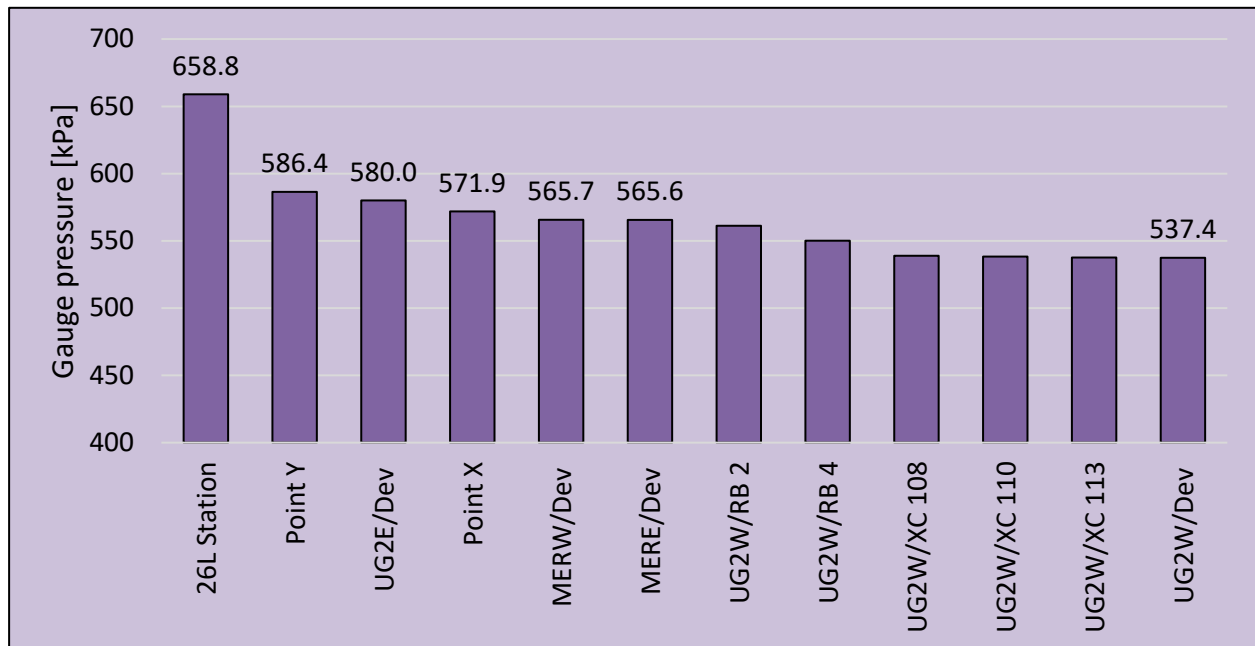


Figure 42: Case Study A, demand-side pressure distribution comparison

Figure 42 depicts the station receiving a high amount of pressure, where a drop in pressure of more than 70 kPa is already observed up to Point Y. With no consumers between the station and this point, a large inefficiency must be present. From Point Y, a subsequent drop of less than 10 kPa to the UG2 Eastern Development End is observed, and approximately 20 kPa to the Merensky development ends. These drops are not significant and will not be considered as inefficient. The UG2 Western Development End receives approximately 120 kPa less than station-supplied pressure. This would include consumer demands, wastages, inefficiencies along the level, and the effect of the Merensky tie-off.

Case Study A, Wastage-depressurisation:

The wastage-depressurisation method – discussed in Section 2.7.2, Step 4.2 – will be used to determine the rate of depressurisation due to wastages present on the level. This indicates the degree of wastage present on the level responsible for further pressure losses. A drop test was conducted on 12-06-2022 and the result for this level is shown in Figure 43.

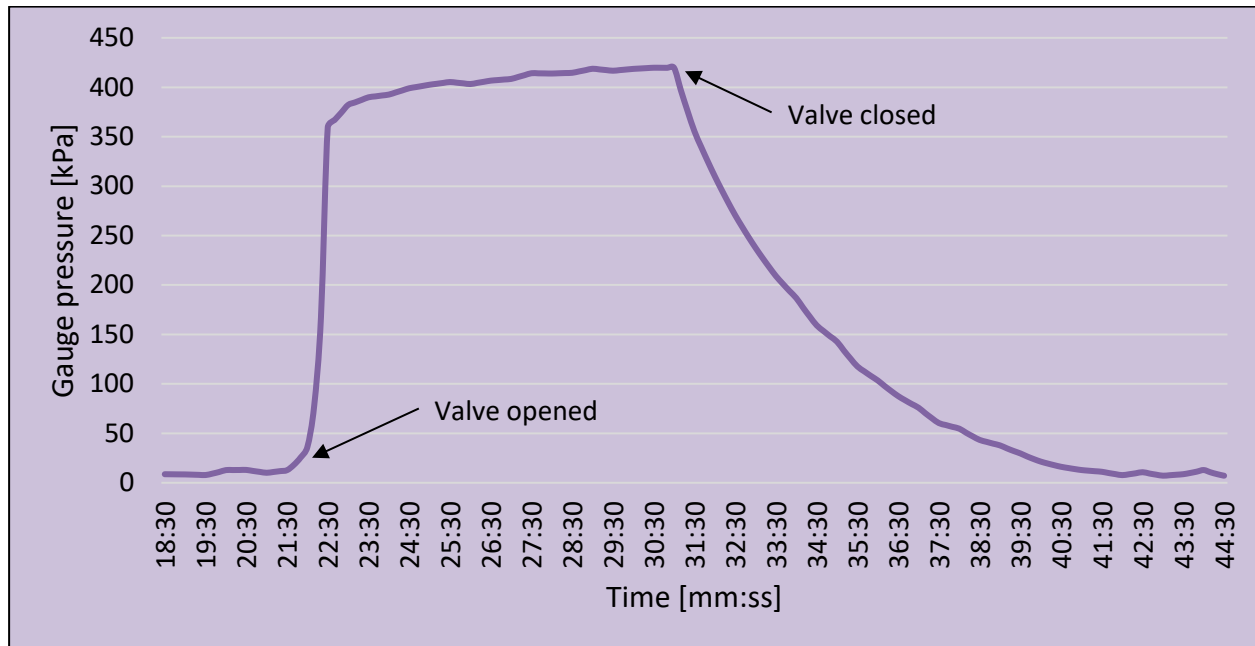


Figure 43: Case Study A, drop-test result

Relevant information from the model in Figure 41 was used to calculate the network piping volume on this level. Using the total network volume, drop-test result, and Equation 2.9, the following wastage-depressurisation results were calculated and obtained for Case Study A as summarised Table 12.

Table 12: Case Study A, wastage-depressurisation calculation summary

Section		Length[m]	Pipe size [mm]	Quantity	Volume [m³]
Station to Point <i>X</i>		1 510	DN 350	1	139.44
Station to Point <i>Y</i>		540	DN 150	1	11.06
Half-levels to Dev ends		7 630	DN 200	1	268.26
Crosscuts		15	DN 150	4	2.43
		30	DN 100	4	
		15	DN 25	~16	
Refuge bays		30	DN 50	6	0.42
Development ends		30	DN 100	4	1.10
Total level volume					422.73
<i>V</i> [m³]	<i>P</i> ₁ [kPa _g]	<i>P</i> ₂ [kPa _g]	Δ <i>t</i> [s]	<i>P</i> _{atm} [kPa]	<i>Q</i> _{RB} [Nm³/h]
422.73	419.63	9.84	640	97.6	1 058.0
Total approximate wastage [Nm³/h]					8 925.8

The total wastage is approximated to consume almost 9 000 Nm³/h. Although this is a significant amount, the identified restriction between the station and Point Y greatly impacts the pressure at downstream locations as shown in Figure 42. These issues contribute to the complaints and difficulties related to low pressure experienced at this level.

Case Study A, Observations:

This level does not conform to the mine's specified engineering standards. A DN 150 mm column feeds four half-levels comprising DN 200 mm piping as opposed to the recommended DN 200 mm or DN 250 mm piping from the standards. Larger piping should have been considered when the compressed air pipes were initially installed. When the norm of neighbouring shafts' levels was studied, it was found that for similar cases, larger DN 350 mm piping was used in sections that would supply multiple half-levels. The large pressure drop over this section is, therefore, due to the restriction, as there are also no consumers in this area. The specified engineering standard of DN 200 mm or DN 250 mm columns for all haulages may potentially be insufficient and warrants further investigation.

This level has an approximate wastage of 9 000 Nm³/h; however, this is the largest case study level with four active half-levels. The most significant finding is the pressure drop between the station and Point Y. Addressing the inefficiency responsible for this drop will improve the reduced pressure on the UG2 Western side.

A maximum pressure drop (ΔP_{max_A}) of 121.4 kPa is observed. A follow-up underground audit is recommended to further investigate the losses near RB2 and RB4, ensuring that these refuge bays don't consume undue airflow.

3.5.3 Step 4.2 – Inefficiency identification – Case Study B

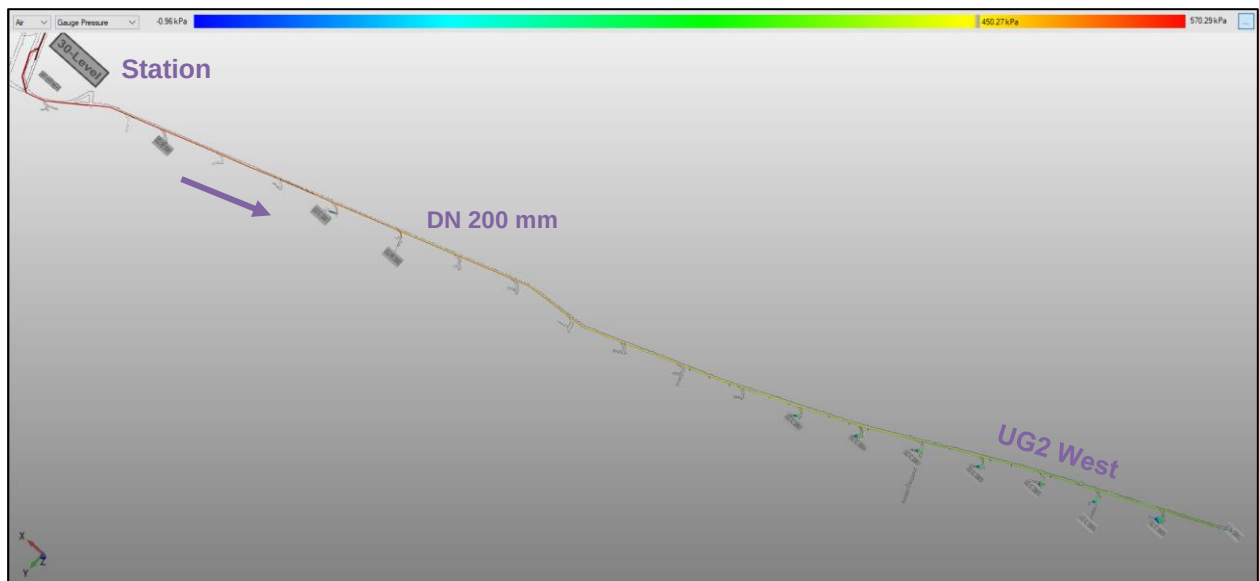


Figure 44: Case Study B, visual model representation of potential inefficiency locations

Figure 44 depicts compressed air being fed from the station to the active working areas via a DN 200 mm column. It is only the UG2 Western section that actively mines on this level. This level conforms to the mine's specified engineering standards correctly. The colour grading changes gradually over the whole half-level, making it difficult to pinpoint a potential inefficiency. However, the total drop in pressure is significant and is likely due to a restriction, unauthorised use or high wastages.

The node outputs from the verified baseline model have been exported to Excel. A demand-side pressure comparison is developed for Case Study B, comparing the subsequent drop in pressure to each working area of interest during the peak drilling period. This makes it easier to identify the effect that each consumer or inefficiency has on the downstream consumers. See Figure 45.

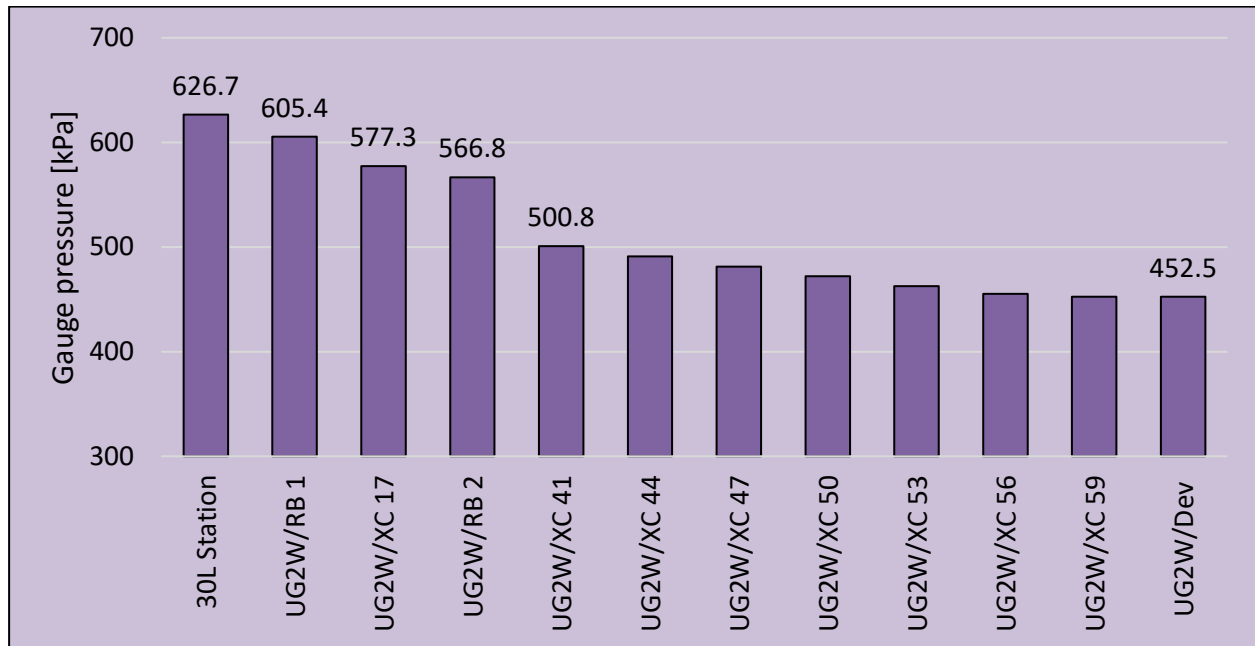


Figure 45: Case Study B, demand-side pressure distribution comparison

The pressure distribution shows significant drops to each subsequent location, particularly the first four locations. More than 120 kPa is lost from the station to the start of the active consumer areas. As previously mentioned, only the UG2 Western section is active on this level. The level's station receives almost 630 kPa_g dropping by approximately 20 kPa to the first refuge bay (RB1) and a further 40 kPa to the second refuge bay (RB2). This is considered high for the amount and type of consumers present. From RB2 to XC 41, a loss in pressure of approximately 70 kPa is experienced. This is a significant loss, likely due to the distance between the two locations, and warrants further investigation. Seven subsequent crosscuts reduce the pressure by less than 50 kPa to the development end, justified by the number of active consumer workplaces.

Case Study B, Wastage-depressurisation:

The wastage-depressurisation method – discussed in Section 2.7.2, Step 4.2 – will be used to determine the rate of depressurisation due to wastages present on the level. This indicates the degree of wastage present on the level responsible for further pressure losses. A drop test was conducted on 12-06-2022 and the result for this level is shown in Figure 46.

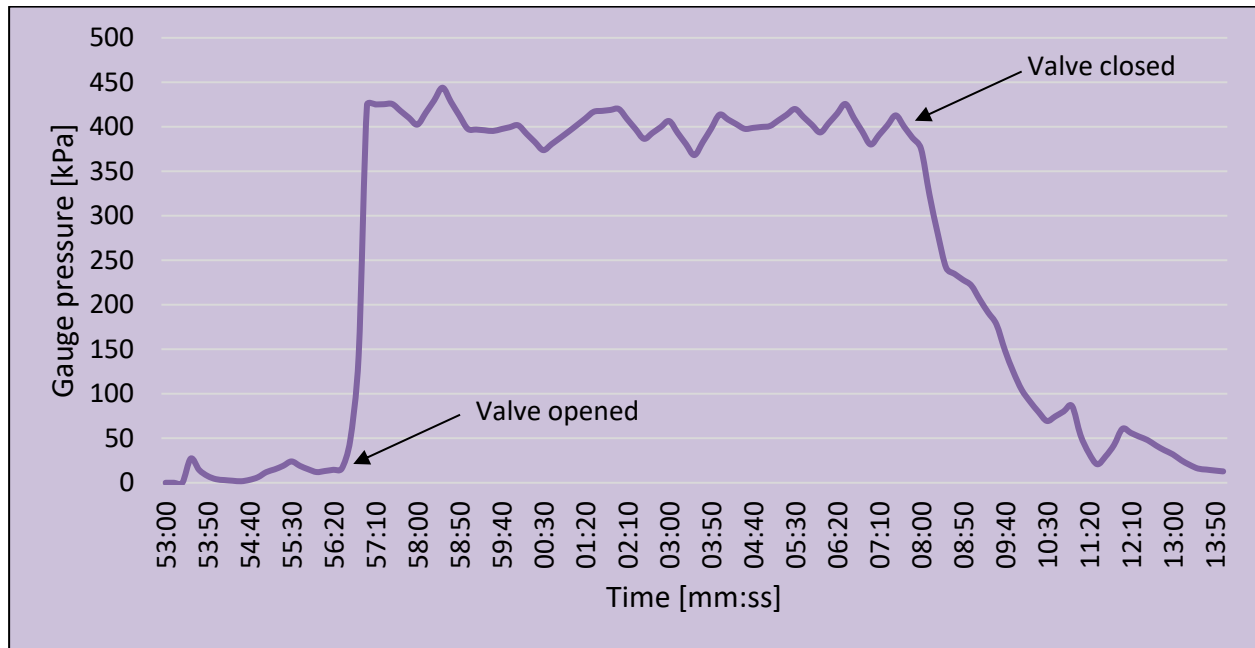


Figure 46: Case Study B, drop-test result

The relevant level information from the model in Figure 44 was used to calculate the piping volume of the compressed air network on the level. Using the drop-test result, total network volume, and Equation 2.9, the following wastage-depressurisation results were calculated and obtained for Case Study B as summarised in Table 13.

Table 13: Case Study B, wastage-depressurisation calculation summary

Section		Length [m]	Pipe size [mm]	Quantity	Volume [m ³]
Station to half-level		110	DN 350	1	10.16
Half-level to Dev ends		2 520	DN 200	1	88.60
Crosscuts		15	DN 150	8	4.86
		30	DN 100	8	
		15	DN 25	~32	
Refuge bays		30	DN 50	2	0.14
Development ends		30	DN 100	1	0.28
Total level volume					104.04
V [m ³]	P_1 [kPa _g]	P_2 [kPa _g]	Δt [s]	P_{atm} [kPa]	Q_{RB} [Nm ³ /h]
104.04	412.82	69.44	180	99.0	352.7
Total approximate wastage [Nm ³ /h]					6 861.6

The total wastage is approximated to consume almost 7 000 Nm³/h, a significant amount considering this level only has one half-level (in contrast to Case Study A that has four half-levels). This is likely why subsequent drops along the distributing network are so high, as observed in Figure 45.

During the audits, a flow rate of ~4 400 Nm³/h was measured at XC 59 during the cleaning shift. Since no drill users are present during this time, the amount of flow to this crosscut's stopping area is indicative of wastages, likely causing the loss in pressure.

Case Study B, Observations:

This level conforms to the mine's specified engineering standards correctly. However, as the half-level is approximately 2 500 meters long, a significant pressure drop would be experienced according to Table 3, as increased piping length would increase the drop in pressure. Considering the standards from Figure 40, "The pressure drop for the 200 mm pipe with the above-mentioned criteria will be approximately 5 kPa/100 m." The standard, therefore, predicts a drop of approximately 125 kPa over this distance, which is contrary to the recommended values in Figure 38. This drop is significant, and the standards document does not specify or provide a limit in piping distance. The mine's engineering standards, therefore, do not sufficiently consider that some haulages are distant and may require a larger column size.

High wastage was calculated through the wastage-depressurisation method. The high subsequent pressure drops indicate a potentially high downstream demand. A large consumption was found during the audits that likely induces the drop along the level due to the high downstream demand at XC 59.

A maximum pressure drop (ΔP_{max_B}) of 174.2 kPa is observed. Addressing the possible restriction at the start of the half-level will likely improve the low workplace pressures. XC 59 warrants an investigation to determine its wastage potential due to the high flow demand from this crosscut.

3.5.4 Step 4.2 – Inefficiency identification – Case Study C

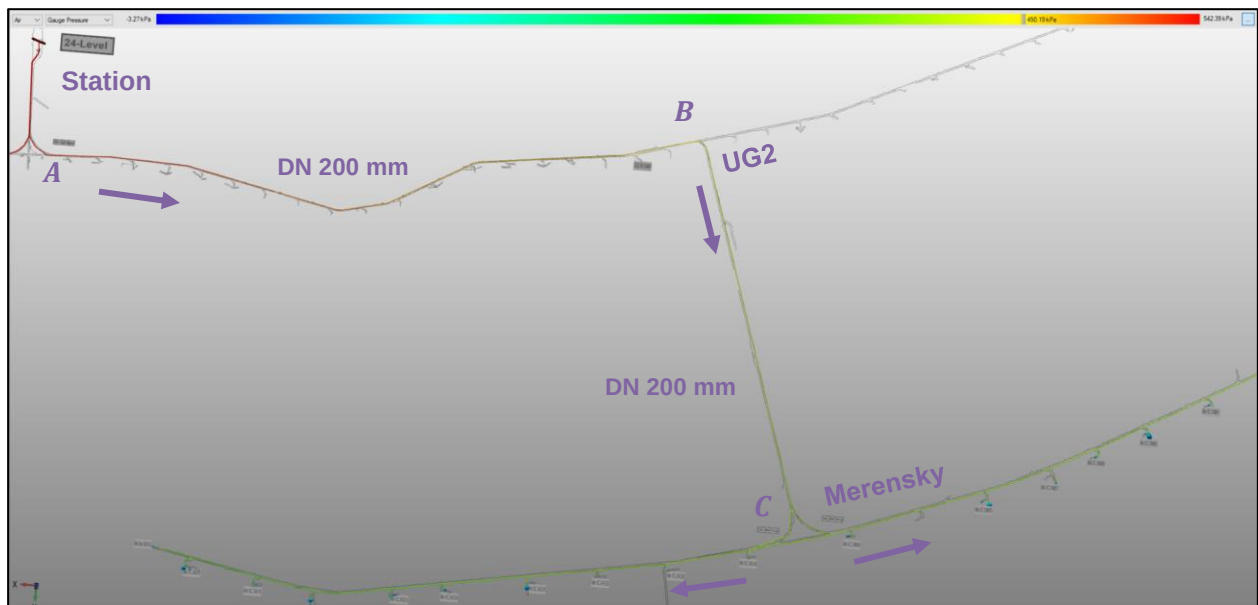


Figure 47: Case Study C, visual model representation of potential inefficiency locations

Figure 47 depicts compressed air being fed from station to the active working areas of UG2 East and Merensky. UG2 West is inactive. UG2 East workplaces have been omitted from Figure 47 and Figure 48, as the entire section receives sufficient pressure and is hence not problematic. This level conforms to the mining standards set out in Figure 39. The pressure drops substantially towards the Merensky split (between Point B and Point C). Apart from RB1, located just before Point B, there are no known compressed air consumers between the station and the Merensky section (between the station and Point C), indicating a restriction.

The node outputs from the verified baseline model have been exported to Excel. A demand-side comparison bar graph is developed for Case Study C, comparing the subsequent drop in pressure to each working area of interest during the peak drilling period, allowing for easier identification of the effect that each consumer or inefficiency has on the downstream consumers. Subsequent locations with insignificant pressure drops are omitted from Figure 48. The development end of the UG2 Eastern section was added as reference.

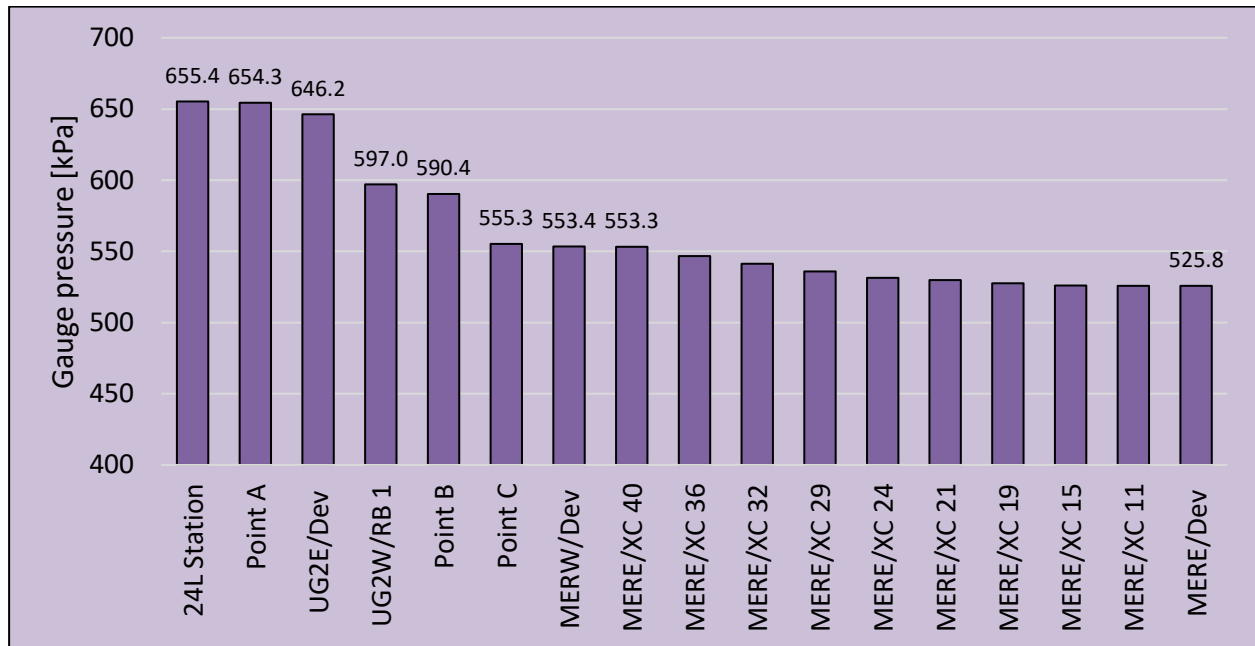


Figure 48: Case Study C, demand-side pressure distribution comparison

Figure 48 depicts the relatively low experienced pressure on both the West and East Merensky sections. The furthest point of UG2 East receives sufficient pressure, and for this reason, its workplaces are omitted from the figure. However, from Point A to RB1, a pressure of approximately 60 kPa is lost. This is a significant loss, as there are no consumers upstream of this refuge bay. Point B to Point C experiences a drop of 35 kPa, which is considered high for a section that has no consumers. A total drop of 100 kPa is observed from station to the Merensky split (Point C), and almost no pressure drop from this point up to the Western development end, whereas a drop of approximately 30 kPa is experienced on the Eastern side. This, however, will remain lower priority as there are ten downstream consumers present on this half-level.

Case Study C, Wastage-depressurisation:

The wastage-depressurisation method – discussed in Section 2.7.2, Step 4.2 – will be used to determine the rate of depressurisation due to wastages present on the level. This indicates the degree of wastages present on the level responsible for further pressure losses. A drop test was conducted on 12-06-2022 and the result for this level is shown in Figure 49.

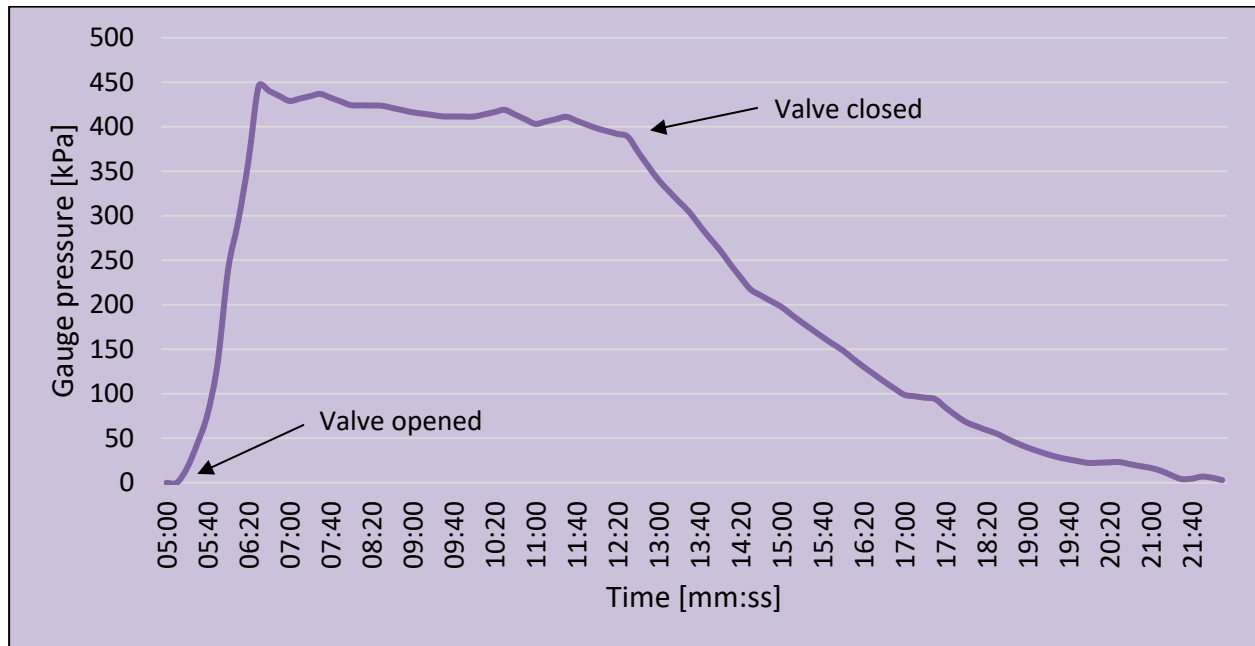


Figure 49: Case Study C, drop-test result

The information from the model in Figure 47 was used to calculate the volume of the level's compressed air network. Using the calculated network volume, the drop-test result, and Equation 2.9, the following wastage-depressurisation results were calculated and obtained for Case Study C as summarised in Table 14.

Table 14: Case Study C, wastage-depressurisation calculation summary

Section		Length [m]	Pipe size [mm]	Quantity	Volume [m³]
Station to half-level		220	DN 350	1	20.32
Half-level to Dev ends		8 050	DN 200	1	283.03
Crosscuts		15	DN 150	20	12.15
		30	DN 100	20	
		15	DN 25	~80	
Refuge bays		30	DN 50	5	0.35
Development ends		30	DN 100	3	0.83
Total level volume					316.68
V [m³]	P_1 [kPa _g]	P_2 [kPa _g]	Δt [s]	P_{atm} [kPa]	Q_{RB} [Nm³/h]
316.68	388.89	106.05	260	96.7	881.7
Total approximate wastage [Nm³/h]					11 939.6

This level has one less half-level than Case Study A, but with a total approximated wastage consumption of 12 000 Nm³/h, the highest of the case study levels. This level has the highest number of consumers, increasing the likelihood of possible misuse within crosscuts.

Case Study C, Observations:

Although this level conforms to the mine's specified engineering standards, the same issue experienced in Case Study B is present in Case Study C. The section from Point A to Point C is approximately 2 400 meters; from the proportionality of variables, summarised in Table 3, and the engineering standards estimation, Figure 40, a large pressure drop of 120 kPa due to this distant network will be experienced. This is a significant drop. Since the standards document does not take distant networks into account, it is insufficiently defining the required compressed air infrastructures.

This level may have a significant amount of wastage, and the likelihood of misuse is high. However, it is worth considering that the two active Merensky areas are very distant from the station and are fed through a single DN 200 mm pipeline, which would induce a significant pressure drop. The experienced pressure drop is lower than the standards' estimation.

A maximum pressure drop (ΔP_{max_C}) of 129.6 kPa is observed. Addressing the two identified areas contributing to the highest drops in pressure will most likely improve the reduced pressure delivery to the Merensky sections.

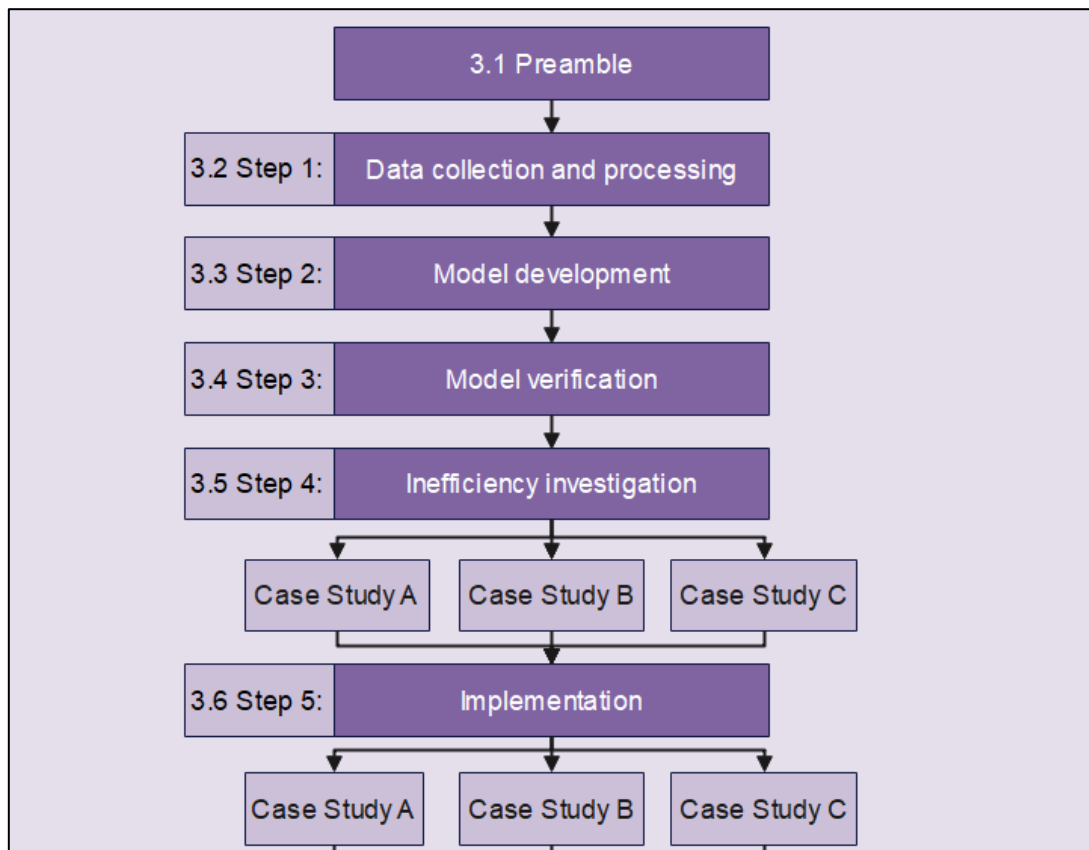
3.5.5 Summary of investigation

The identified inefficiencies, derived during Step 4.2 for each case study, is summarised in Table 15. This table summarises the theoretical analysis that was conducted throughout this section and will be used as reference during the implementation of scenario-based solutions for each case study during Step 5.

Table 15: Summary of inefficiencies identified on various case studies

Case study	Inefficiencies identified
A	Compressed air is supplied to the Merensky and UG2 sections via a smaller-than-usual piping infrastructure as opposed to the required engineering standard and to the norm of neighbouring shafts' levels. This pipe is four times smaller in flow area (DN 150 mm versus DN 350 mm). The current DN 350 mm is not purposed for mining activities. • A drop of 70 kPa is observed from the station to Point Y. ○ No mining consumers present. ○ This section is highly likely to be restrictive.
B	Compressed air is supplied via a DN 200 mm pipeline over 2.5 km, posing an estimated pressure drop of 125 kPa over this distance, according to the standards. The initial part of this section is potentially restrictive as observed from large pressure drops so early in the level. • A drop of 60 kPa is experienced from the station to RB2. • A further drop of 66 kPa is observed from RB2 to XC 41. ○ No consumers present. • High wastage potential at XC 59.
C	Compressed air is supplied over a long distance (2.4 km) to the Merensky section via a DN 200 mm pipeline from Point A to Point C. This may be restrictive over this distance, with an estimated pressure drop of 120 kPa, according to the standards. • A drop of 60 kPa is experienced between Point A and RB 1. ○ No consumers present. • A further drop of 35 kPa is observed from Point B to Point C. ○ No consumers present.

3.6 Step 5 – Implementation



Inefficiencies from the various case study levels have been identified during the previous step and are summarised in Table 15. These inefficiencies need to be addressed by applying applicable solution strategies. In the following section, different solutions will be explored and simulated as prediction scenarios to measure their effect when compared to the baseline model.

The most suitable solution will be selected based on the predicted impact on the baseline, feasibility, and recommendations from the shaft engineering manager, following which the solution will be implemented. The specific process of implementation is not important for the purposes of this study. However, the actual performance of implementation will be measured and validated in Step 6.

3.6.1 Step 5.1 – Solution identification

Table 16 summarises the scenario-based solutions identified for each case study that could potentially address the inefficiencies. For simplicity, only two solutions are considered each.

Table 16: Summary of potential solution scenarios for each case study

Case study	Scenario	Potential solutions to identified inefficiencies
A	1	Upgrade the DN 150 mm pipe sections between the station and Point Y to the norm DN 350 mm. Estimated distance of 550 m.
	2	Allow the DN 150 mm pipeline to continue feeding the UG2 Eastern side. Connect the existing DN 350 mm pipeline to the DN 200 mm pipeline at Point X. Estimated distance of 60 m in piping required to make the connection.
B	1	Upgrade the initial 1.5 km section of the existing 2.5 km long DN 200 mm pipeline, that runs from the station to XC 44, to a DN 300 mm.
	2	Reduce consumption (wastage) of XC 59 by 85% (similar to other normal crosscuts).
C	1	Upgrade the pipe section between Point A and Point B from DN 200 mm to DN 300 mm. Estimated piping length upgrade of 1.5 km required.
	2	Upgrade the pipe section between Point A and Point C from DN 200 mm to DN 300 mm. Estimated piping length upgrade of 2.4 km required.

Each solution scenario will be simulated, and its effect measured and compared against the verified baseline model for further reference.

3.6.2 Step 5.2 – Case Study A – Prediction and implementation

Table 17 provides an integrated summary of the inefficiency analysis combined from Table 15 and Table 16 for Case Study A.

Table 17: Case study A - Summary of inefficiency analysis

Case study	Inefficiencies identified
A	Compressed air is supplied to the Merensky and UG2 sections via a smaller-than-usual piping infrastructure as opposed to the required engineering standard and to the norm of neighbouring shafts' levels. This pipe is four times smaller in flow area (DN 150 mm versus DN 350 mm). The current DN 350 mm is not purposed for mining activities. • A drop of 70 kPa is observed from the station to Point Y. ○ No mining consumers present. ○ This section is highly likely to be restrictive.
Scenario	Potential solutions to identified inefficiencies
1	Upgrade the DN 150 mm pipe sections between the station and Point Y to the norm DN 350 mm. Estimated distance of 550 m.
2	Allow the DN 150 mm pipeline to continue feeding the UG2 Eastern side. Connect the existing DN 350 mm pipeline to the DN 200 mm pipeline at Point X. Estimated distance of 60 m in piping required to make the connection.

Prediction:

Both scenario solutions are simulated in PTB, and the results are added to the respective demand-side comparison chart developed in Step 4.2, seen in Figure 50. This clearly indicates the effect the scenario solutions would have on downstream consumers when implemented. The potential benefits and feasible outcomes are apparent from this result.

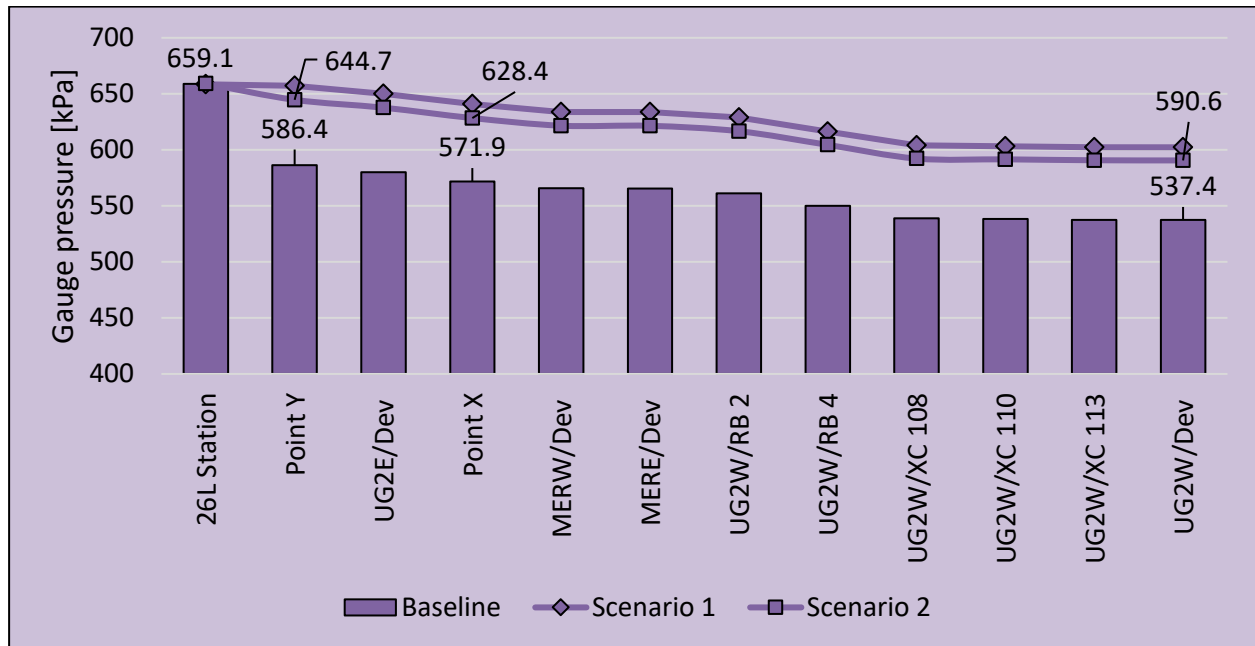


Figure 50: Case Study A, impact of solution scenarios on demand-side pressures

Considering Figure 50, the identified solutions offer significant improvement potential, increasing the available pressure at all downstream locations by at least 50 kPa in both scenarios. The difference between the two scenarios is less than 2%. For this reason, the feasibility of the chosen solution will play a large role.

Implementation:

The issue was raised with the shaft's engineering manager that this section does not conform to the mine's specified engineering standards. From this discussion, Scenario 2 was chosen for implementation because it was significantly cheaper and quicker to implement than Scenario 1. Almost 10 times more piping would be required to implement Scenario 1 compared to Scenario 2. The engineering manager also suggested that the unused intermediary pipe section between Point Y and Point X be blanked for further potential, as compressed air leaks were known to be in this area.

On 18-08-2022, the mechanical foreman and boilermakers followed the engineering manager's instruction and blanked the old intermediate compressed air route between Point Y and Point X, and made the required 60-meter DN 350 mm connection at Point X.

3.6.3 Step 5.2 – Case Study B – Prediction and implementation

Table 18 provides an integrated summary of the inefficiency analysis combined from Table 15 and Table 16 for Case Study B.

Table 18: Case study B - Summary of inefficiency analysis

Case study	Inefficiencies identified
B	Compressed air is supplied via a DN 200 mm pipeline over 2.5 km. This section is potentially restrictive, risking an estimated pressure drop of 125 kPa over this distance, according to the standards. • A drop of 60 kPa is experienced from the station to RB2. • A further drop of 66 kPa is observed from RB2 to XC 41. ○ No consumers present. • High wastage potential at XC 59.
Scenario	Potential solutions to identified inefficiencies
1	Upgrade the initial 1.5 km section of the existing 2.5 km long DN 200 mm pipeline, that runs from the station to XC 44, to a DN 300 mm.
2	Reduce consumption (wastage) of XC 59 by 85% (similar to other normal crosscuts).

Prediction:

Both scenario solutions are simulated in PTB, and the results are added to the respective demand-side comparison chart developed in Step 4.2, seen in Figure 51. This clearly indicates the effect of the scenario solutions on downstream consumers when implemented. The potential benefits and feasible outcomes are apparent from this result.

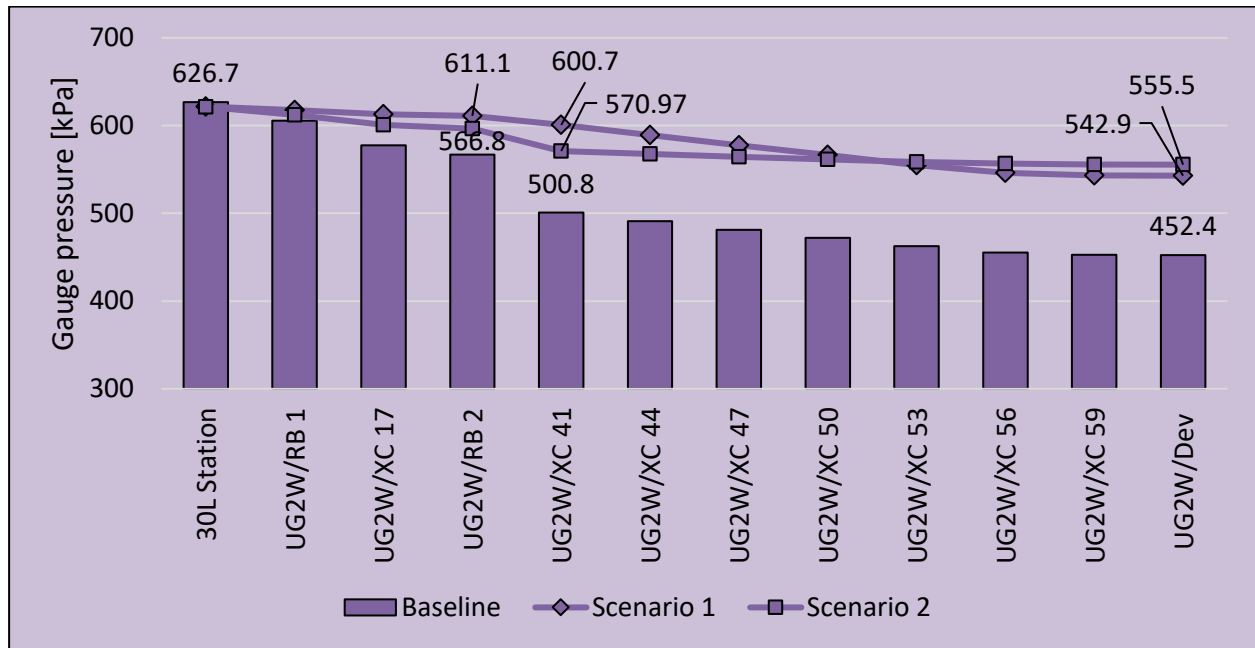


Figure 51: Case Study B, impact of solution scenarios on demand-side pressures

Figure 51 depicts the identified solutions that provide great improvement potential, increasing the available pressure for consumers downstream of RB2 by at least 70 kPa for both scenarios. The high drops could greatly be reduced. It is worth noting that prediction Scenario 1 maintains a ~60 kPa drop in pressure from XC 41 to the development end compared to Scenario 2 which only drops by ~15 kPa. However, Scenario 2 does not address the drop between RB 2 and XC 41 as effectively.

Considering the differences between the scenarios, one solution imposes an improvement in flow area, where the other reduces the downstream flow demand. The development end's pressure could be increased from ~450 kPa_g to more than ~540 kPa_g. The difference between the two scenarios is less than 1%.

Implementation:

The high flow consumption from XC 59 was initially discussed with the engineering manager at the time of the audit. When both solutions were presented, the wastage had already been addressed, as confirmed by the manager. Although Scenario 1 was an expensive consideration, it was still selected for implementation. Three kilometres of DN 300 mm piping was ordered (1 500 m allocated for both Case Studies B and C). Unfortunately, by the time of delivery, the ordered piping had to be used for a different service required by the shaft, as the pressure on this level had already improved. This implementation was, therefore, placed on hold.

3.6.4 Step 5.2 – Case Study C – Prediction and implementation

Table 19 provides an integrated summary of the inefficiency analysis combined from Table 15 and Table 16 for Case Study C.

Table 19: Case study C - Summary of inefficiency analysis

Case study	Inefficiencies identified
C	Compressed air is supplied over a long distance (2.4 km) to the Merensky section via a DN 200 mm pipeline from Point A to Point C. This may be restrictive over this distance, with an estimated pressure drop of 120 kPa according to the standards. • A drop of 60 kPa is experienced between Point A and RB 1. ○ No consumers present. • A further drop of 35 kPa is observed from Point B to Point C. ○ No consumers present.
Scenario	Potential solutions to identified inefficiencies
1	Upgrade the pipe section between Point A and Point B from DN 200 mm to DN 300 mm. Estimated piping length upgrade of 1.5 km required.
2	Upgrade the pipe sections between Point A and Point C from DN 200 mm to DN 300 mm. Estimated piping length upgrade of 2.4 km required.

Prediction:

Both scenario solutions are simulated in PTB, and the results are added to the respective demand-side comparison chart developed in Step 4.2, seen in Figure 52. This clearly indicates the effect the scenario solutions would have on downstream consumers when implemented. The potential benefits and feasible outcomes are apparent from this result.

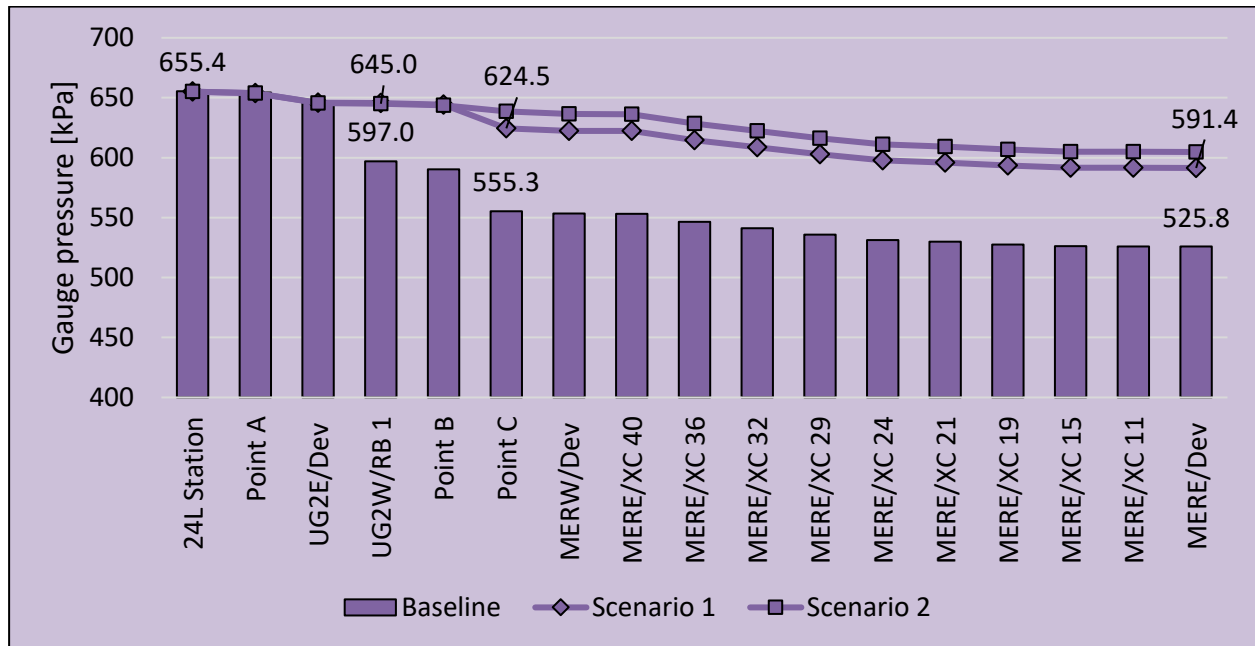


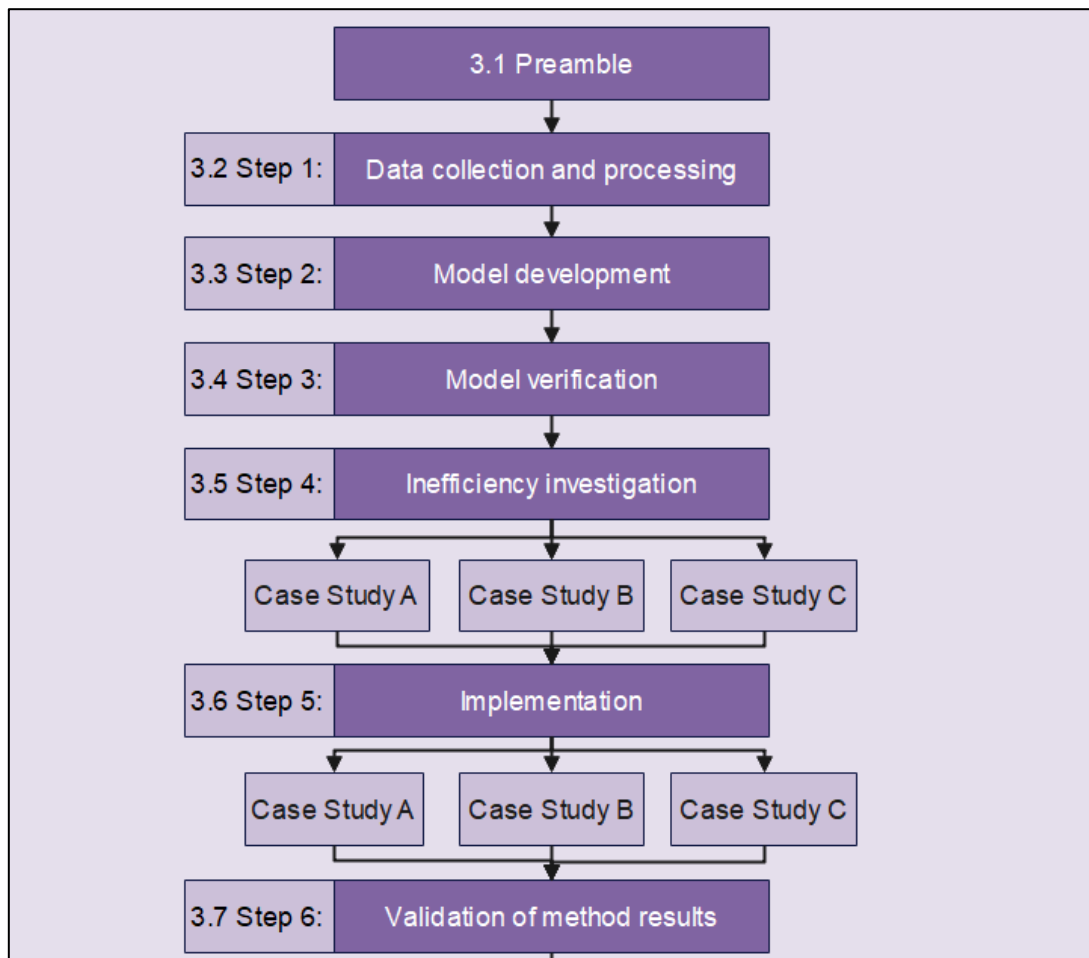
Figure 52: Case Study C, impact of solution scenarios on demand-side pressures

Figure 52 depicts the improvement potential of the identified solutions. The available pressure of downstream locations at the Merensky section is predicted to increase by approximately 70 kPa for both scenarios when implemented. The most feasible scenario will be selected for implementation, as the difference between the two scenarios is less than 1%.

Implementation:

Scenario 1 is preferred over Scenario 2, as it requires approximately one kilometre less piping. Upgrades to the network will also be completed in a shorter timeframe because less work is required. However, as previously mentioned, the pipes that were ordered by the engineering manager for both solutions to Case Studies B and C had to be used for another higher priority service that the mine required. This implementation was, therefore, also placed on hold.

3.7 Step 6 – Validation of method results



The aim of this section is to validate the performance of the implemented solutions of each case study. The predicted performance of implementation from the previous section will be compared to the actual performance of implementation. To ensure proper validation, the same entities from the simulation model will be compared hourly to the actual results of implementation measured by the respective instrumentation at the same location. This validation process is conducted and discussed further below for each case study.

3.7.1 Case Study A – Validation

From the previous section, Scenario 2 was successfully implemented. The predicted outcome seemed favourable and will be compared to the actual performance of implementation. With reference to Figure 41 and for the purposes of validation, Point *X* will be considered as the simulating point of interest, as this is the furthest location downstream where an existing pressure

transmitter is already installed. This pressure transmitter will be used to validate the findings since it was also downstream of the implemented solution.

Using the model as a comparison, the simulated baseline is compared to the implementation performance of Scenario 2 at Point X for a normal weekday hourly profile, seen in Figure 53.

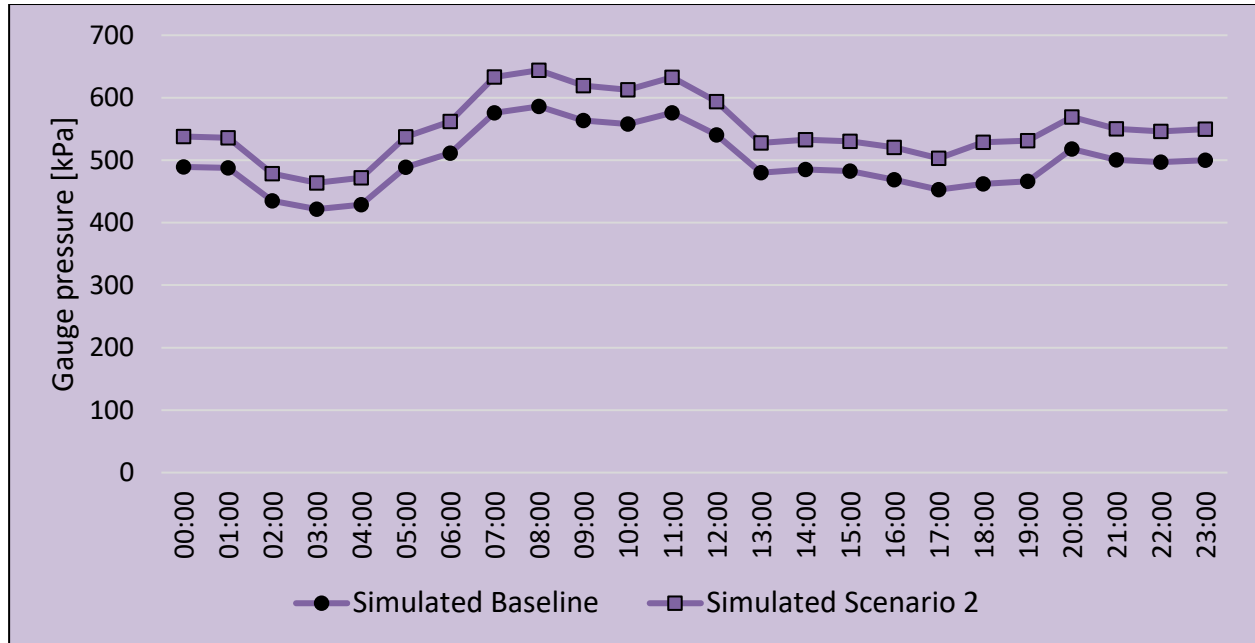


Figure 53: Model prediction: Simulated baseline versus simulated Scenario 2 at Point X (Case Study A)

The prediction model shows an improvement in working pressures by 51.6 kPa (10.4%) on average at Point X.

The actual results will be measured from the existing underground pressure transmitter installed at Point X. A 24-hour weekday profile was constructed, using a three-month average of before and after implementation, from hourly pressure measurements at Point X. The solution implemented on 18-08-2022 yielded the following actual improvement, seen in Figure 54.

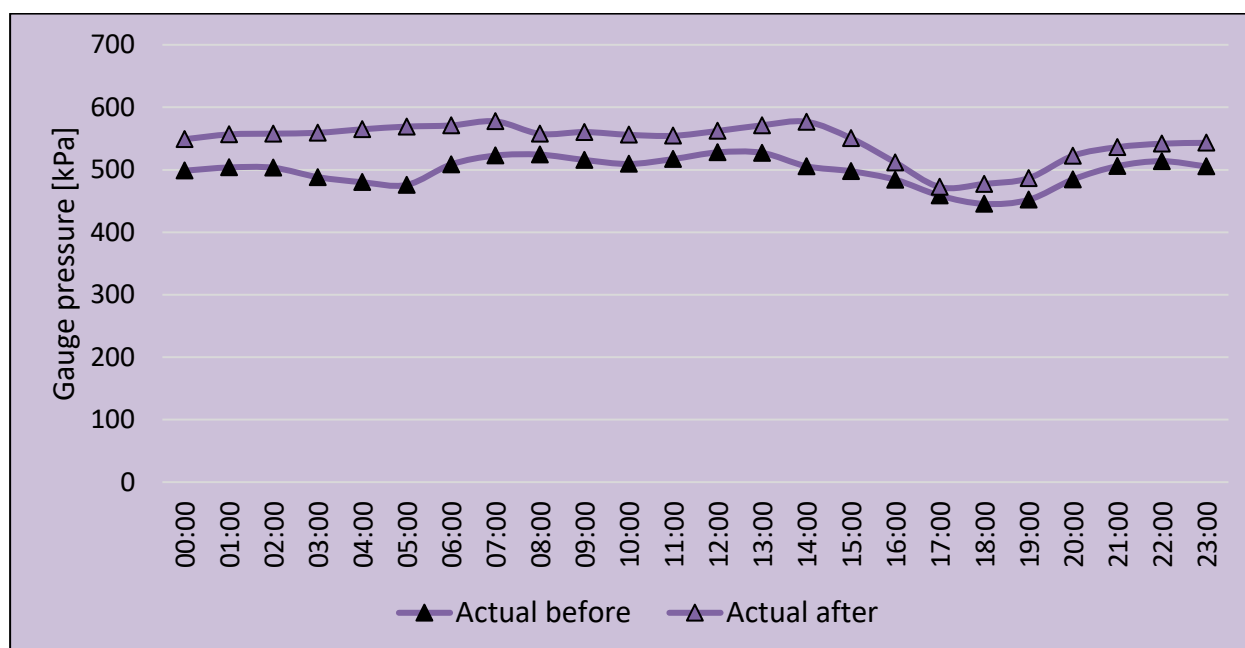


Figure 54: Actual implementation result of Scenario 2 measured at Point X

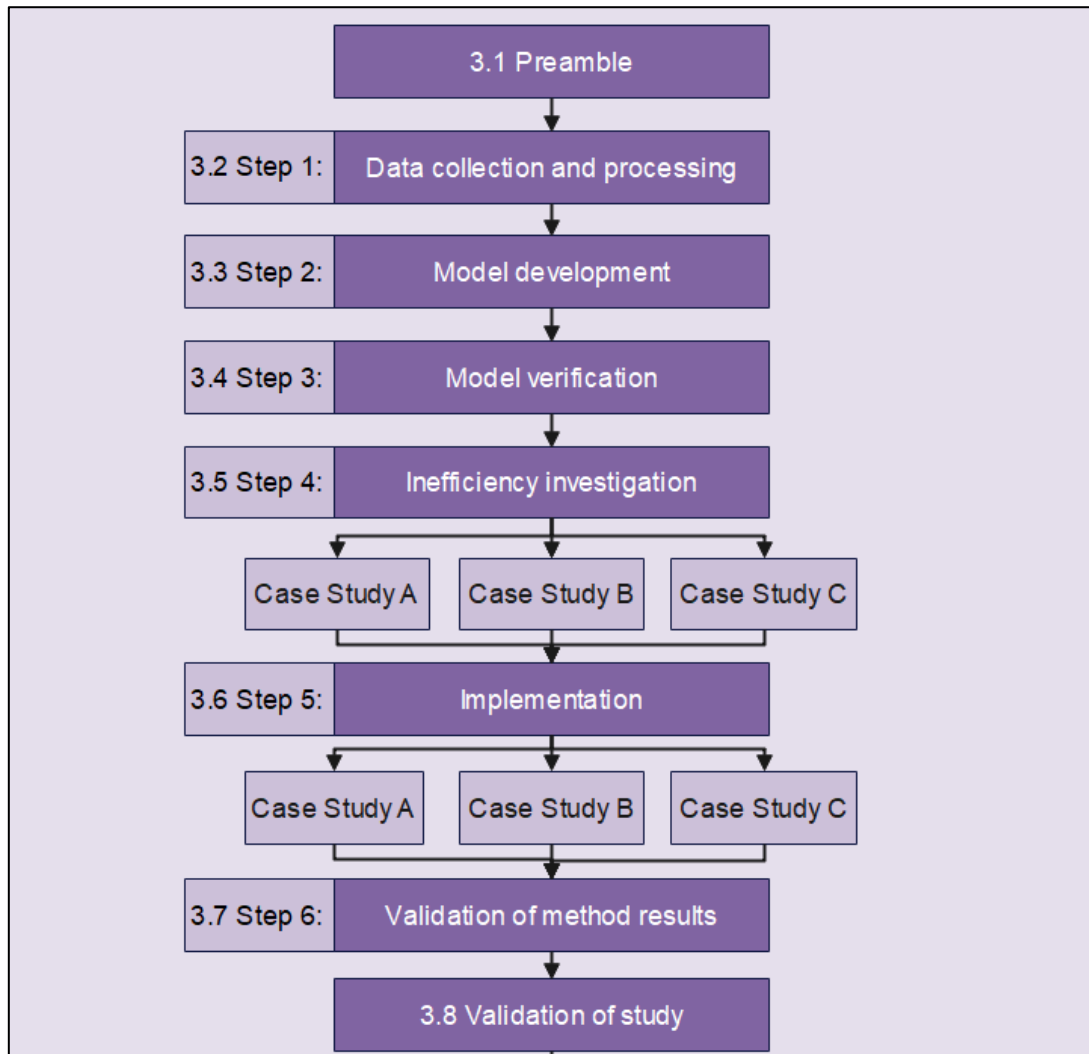
The actual performance after implementing Scenario 2 indicates an average improvement in pressure of 47.1 kPa (9.5%). The engineer gave positive feedback regarding the performance on this level and commented that no complaints have been lodged on the level since implementation.

3.7.2 Case Study B and C – Validation

Unfortunately, as previously mentioned, the implementation of solutions to Case Studies B and C were placed on hold. Due to a change in priority to repurpose the piping that was ordered, these case studies were rendered unfeasible at the time. The wastage consumed in XC 59 in Case Study B was also addressed, it is, however, difficult to measure the impact, as the station pressure transmitter would not account for downstream pressure increases. It would instead require another underground audit where pressure is measured and logged at the development-end manifold. Therefore, the mentioned case studies cannot be validated in this section.

A feasibility study regarding the benefits of improved pressures on these levels can be furthered from the theoretical predictions in Step 5. Although these two case study levels did conform to the mine's specified engineering standards, the predictions have shown that the pipes may be insufficiently sized for the current known demand on these levels. Should the actual improvements also be close to predictions, pressure set-point reductions can be made to reduce the compressor energy consumption and make the potential solutions more feasible.

3.8 Validation of study



The validation process is integral to measuring the success of this study by highlighting the outcomes and accomplishments from the set objectives. Each research objective previously presented in Section 1.6 will be discussed in this section.

Research Objective 1:

To develop a method that utilises simulation software to identify and improve insufficient delivery pressure in underground mines through a safer and simpler method than those commonly used to address difficult and dangerous in-stope areas.

The method developed in Section 2.7 uses a simulation model, developed in Section 3.3, to identify and address low delivery pressures due to inefficiencies underground. First principles were used to consider the relationships of variables that could induce inefficiencies. Additionally, the wastage-depressurisation method was used to quantify the amount of wastage present on each level. This has provided a clear indication of wastage potential on the level, indicating the proportionality and possibility of restrictive infrastructural behaviour.

This method provides the user with a safer method where no physical investigation of stoping and dangerous workplaces is required.

Research Objective 2:

The model should be capable of predicting underground pressure along distant levels based on known consumers across the complex underground compressed air network.

The model developed in Section 3.3 has been set up based on theoretically known consumer demands. When simulated, the model uses downstream consumer demands to determine respective pressure drops along the distant network. In the case of this study, pressure distribution along this level is the unknown entity.

During the inefficiency investigation of Section 3.5, Step 4.2, the pressure distribution throughout each entire level was explored. Any large change or drop in pressure indicates a potential infrastructural inefficiency. From the demand-side pressure distribution comparison graphs in Step 4.2 for each case study, it is clear that the model can predict the underground compressed air pressure from the stations to development ends. This research objective is, therefore, successfully achieved and has provided a method to identify inefficiencies across a complex underground compressed air network.

Research Objective 3:

To evaluate the adequacy of existing infrastructural engineering standards.

During the inefficiency investigation in Section 3.5, the most inefficient level did not conform to mining standards. The implemented solution to this case study level confirmed that a restrictive pipe section was the cause of the low delivery pressures.

The remaining two case study levels did conform to the standards; however, both levels utilised the lower option, i.e., DN 200 mm sizing from the haulage standard. It is argued from both the engineering standards (Figure 39 and Figure 40) and the prediction results that for these specific levels, upstream pipe sizes of DN 200 mm would not be sufficient due to the distant network on these levels. The standards predict a pressure drop of approximately 120 kPa to 125 kPa for both levels using only the DN 200 mm piping infrastructure. The suggested increase in upstream pipe sizing (Table 18 and Table 19) from DN 200 mm to DN 300 mm has shown promising potential clearly indicating that mining standards are insufficiently specified. The engineering standards do not take distant networks into account nor the number of downstream half-levels or consumers.

Research Objective 4:

To apply the developed method to a case study mine and validate the results based on each implemented solution.

During this study, the developed method was applied and conducted at a case study mine. Several underground audits were conducted to enable the construction of a baseline model. The audit findings were discussed with mine personnel daily and refined the process of building the model.

Using the completed and verified baseline model to simulate prediction scenarios identified multiple opportunities for improvement. The three identified levels for improvement have shown promising prediction results for proposed solutions. Unfortunately, due to the previous-mentioned circumstantial events, only solutions to Case Study A were implemented. The impact of apparent wastage reduction at XC 59 in Case Study B could not be validated. A summary of Case Study A's implementation findings can be found in Table 20.

Table 20: Average prediction versus implementation results

Case Study A		Scenario 1	Scenario 2
Prediction	Figure 53	+60.4 kPa (+12.1%)	+51.6 kPa (+10.4%)
Actual	Figure 54	Not implemented (N/A)	+47.1 kPa (+9.5%)

Both scenario solutions had great potential, with solution Scenario 1 being practically more feasible when compared to Scenario 2. The implementation of Scenario 2 achieved an average improvement of 9.5% compared to the predicted increase of 10.4%.

Research Objective 5:

To evaluate the developed methodology based on the addressal of the problem using a comparative analysis to measure the performance.

The methodology developed in 1.7 was combined and adapted from various other research methodologies to fit the redefined problem statement and aim of this study. This methodology followed a case study structure that utilises simulation software, the engineering design process step, and the algebraic manipulation step.

Various comparative analysis techniques were utilised throughout the proposed method. These techniques were based on each respective step's requirements to study the data and compare findings for further subsequent analysis. This method prioritised the most critical levels and identified the largest contributing factors to each respective inefficiency. During the implementation phase, predictions have shown potential performance improvements comparatively, indicating the degree of impact and the most feasible solutions. Comparing the predicted results to the actual results, within marginal accuracy, demonstrates the success of this methodology.

3.9 Summary and overview

By cross comparing the case studies, similar findings are observed on all three levels:

- High pressure drops were experienced on these levels.
- Distribution networks were insufficiently sized for the known consumer downstream demands.
- Infrastructural engineering standards did not account for future pressure drops, which these distant levels experienced as they developed.
- High wastage could influence the identification of infrastructural inefficiencies.

Case Study A did not conform to the mining standards and was improved by supplying through a larger pipe diameter. The result of the actual implementation was similar to the prediction model. Case Study B was temporarily improved by addressing a high wastage area but could not be improved further. Case Study C could not be improved during this study, as larger ordered pipes had to be repurposed for another higher-priority service.

The proposed method was generic and has proven to be successful. The research objectives have been met and the proposed method identified and improved inefficient deep-level mine compressed air distribution networks.

It is, however, important to note that certain conditions must be met in future implementations and are discussed below:

- Individual compressed air networks should not be ring-fed from other levels.
 - This may influence results.
- Level pressure transmitters must be in working condition.
- Underground measurements deeper into the level are crucial for proper model calibration.
 - Crosscut flow measurements during non-peak times provide the benefit of measuring approximate wastages within a crosscut or stoping area.
 - This ensures that conclusions are more correct, and inefficiencies better identified.
- Increasing the reliability of the demands at various locations improves this method's ability to identify and improve inefficient compressed air distribution networks.

CHAPTER 4: CONCLUSION



Figure 55: Shaft on platinum mine - 00h00¹⁶

"Sometimes you will never know the value of a moment until it becomes a memory."

- Dr. Seuss

¹⁶ E du Plessis, 2024

4.1 Preamble

This section provides an overview of the study, discussing the background and development, results, and achieved objectives. The limitations and recommendations for future work and research are also discussed.

4.2 Summary of study

4.2.1 Study background and development

Electrical availability in South Africa poses several challenges and has significant knock-on effects. The annual EAF declined from 71.8% in 2018 to 54.7% in 2023. This is predominantly due to generation failures from ageing and poorly maintained plants, sabotage, and coal and cable theft. This reduced availability puts strain on the generation capacity of the country, necessitating the implementation of loadshedding to maintain the integrity of the electrical grid. The total annual energy shed has increased from 2.5 TWh in 2021 to approximately 20 TWh near the end of 2023. From 2007 to 2023, inflation cumulatively increased by 152%, and Eskom tariffs cumulatively increased by 775% over the same period. This five-fold increase above inflation places significant economic and financial pressure on all South African sectors.

These trends have a significant impact on the South African economy, causing several unanticipated difficulties to citizens. Since mining is one of the largest energy-consuming sectors in the country, operations are running at 20% to 30% below capacity due to the energy reliability constraint of loadshedding or load curtailment. The tariff increases also resulted in severe operating costs, lowering profitability of mining ore deposits.

Mines are known to use outdated technology and equipment, and technological advances can improve sustainability and profitability. The recent utilisation of simulations in the mining industry has shown great potential in the future of mining design, problem identification, and the development of improved management and monitoring strategies.

One of the most common energy sources used in mining is compressed air, an inefficient energy source but the most simple and safest for extensive distribution to underground workplaces. Since most of the mining equipment is fully pneumatic, sufficient pressure delivery is key for successful production operations. Unfortunately, the supply integrity is compromised by factors such as insufficient compressor supply capabilities, infrastructural limitations, increased flow demand due to wastages, unregulated flows, and misuse of compressed air. The inefficient distribution of

compressed air is a major contributing factor to a decrease in production and may result in increased compressor costs when operating set points are increased.

Compressed air inefficiencies that affect delivery pressure to pneumatic consumers were considered using first principles. The behaviour and relationship between variables were studied for a comprehensive understanding of a compressed air distribution network.

An initial problem statement was formulated based on compressed air network inefficiencies and the result of these inefficiencies. From the literature study shortcomings and identified need, the initial problem statement was redefined to provide a more inclusive statement.

Redefined problem statement:

Inefficiencies in compressed air distribution networks that result in insufficient demand-side pressure affect pneumatic equipment capabilities and potentially also production rates. A common solution strategy is imposed (i.e., increasing compressor set points), which further increases operational costs, reducing both the life of mines and profitability and does not automatically result in improved production rates.

High-wastage areas, such as stopes, are difficult to address due to their dynamic complexity and increased risks. Solutions to current infrastructural inefficiencies, arising from inadequate engineering standards and mining's lack of conformity to these standards, are not considered sufficient.

4.2.2 Results of study

The need for the study was satisfied and the redefined problem statement addressed using the proposed method developed in Chapter 2. A baseline model was constructed and verified within a MAPE of 4.56%, averaged from all underground level pressures. Existing underground flow meters could not be used to verify level-flow accuracies, as they were not in reliable conditions. Individual levels' MAPEs were below 10%. High error values were observed during the blasting shift due to lower relative pressure values. When the blasting shift is excluded from the error calculations, individual levels had MAPEs below 4%. A WMAPE was introduced to address this limitation during the blasting shift. Using the shaft's pressure set-point profile as the weight, each individual level has a WMAPE smaller than 5%. A WMAPE of 2.99% is achieved for all levels on average.

Inefficient levels were prioritised based on compressed-air-related complaints, high pressure drops to development ends, and using a developed intensity-based pressure drop per drill user present for each individual level. Inefficient case study levels were identified using this prioritisation method.

Inefficiencies were identified using the mine's engineering standard and PTB's colour scaling functionality in conjunction with a demand-side pressure comparison graph for each case study level. During this process, a limitation was observed where the simulation is only capable of identifying inefficiencies based on reliable inputs. Theoretical consumer demands were assumed reliable, but it was difficult to account for wastages if they were not successfully measured during the audits.

To address this limitation, a wastage-depressurisation method was developed that could assist with providing an approximate indication of wastage on the level. This was used as an additional measure when considering all findings of a level. This approximate value can be used to calibrate the total estimated wastages on a level.

Case Study A was found to not be conforming to the mine's compressed air engineering standards. Case Study B and C utilised the lower end of the pipe size requirement. From the latter case studies, the compressed air standards are not sufficient for distant-developed levels, particularly considering that the latest standards were last revised on 2018-07-03, which was more than five years ago at the time of this study.

The following pressure observations and results were found for each case study:

Table 21: Case study summary of results

	Observations	Prediction	Actual
Case study A	Pressure drop of 72.4 kPa experienced from the station to point Y.	Reduce drop to 14.4 kPa	Not able to verify
	Pressure drop of 86.9 kPa experienced from the station to point X.	Reduce drop to 30.7 kPa	Experienced drop reduced to 36.4 kPa
	ΔP_{max_A} of 121.4 kPa experienced from the station to UG2 West Development End.	Reduce ΔP_{max_A} to 68.5 kPa	Not able to verify
Case study B	Pressure drop of 21.3 kPa experienced from the station to RB1.	Reduce drop to 9.0 kPa	Not able to verify
	Pressure drop of 38.6 kPa experienced from RB1 to RB2.	Reduce drop to 15.8 kPa	Not able to verify
	Pressure drop of 66.0 kPa experienced from RB2 to XC41.	Reduce drop to 25.5 kPa	Not able to verify
	ΔP_{max_B} of 174.2 kPa experienced from the station to UG2 West Development End.	Reduce ΔP_{max_B} to 56.8 kPa	Not able to verify
Case study C	Pressure drop of 57.3 kPa experienced from Point A to RB1.	Reduce drop to 8.5 kPa	Not implemented
	Pressure drop of 35.1 kPa experienced from Point B to Point C.	Reduce drop to 19.7 kPa	Not implemented
	Pressure drop of 100.1 kPa experienced from the station to Point C.	Reduce drop to 30.6 kPa	Not implemented
	ΔP_{max_C} of 129.6 kPa experienced from the station to Merensky East Development End.	Reduce ΔP_{max_C} to 63.7 kPa	Not implemented

From Table 21, the maximum drop in pressures (ΔP_{max}) was predicted to improve by 68.5 kPa, 56.8 kPa, and 63.7 kPa for the selected implementation scenarios of Case Studies A, B, and C respectively.

The implementation of Case Study A was predicted to improve the average pressure by 51.6 kPa (10.4%); the actual result from implementing the Scenario 2 solution yielded an average increase of 47.1 kPa (9.5%). The maximum drop in pressure for Case Study A (ΔP_{max_A}) after

implementation could not be verified because there was no pressure gauge or transmitter located at the development end of this level. A portable logger would need to be installed.

The high demand measured at XC 59 of Case Study B was confirmed to a result of wastages and had been addressed. The three-kilometre DN 300 mm pipes that were ordered for Case Studies B and C's solutions had to be repurposed for another prioritised service at the mine and could, therefore, not be implemented. Considering the accuracy of Case Study A, it is believed that Case Studies B and C would achieve similar results to that of its predictions.

4.2.3 Achieving the objectives

From the study validation in Section 3.8, the following research objectives were achieved as summarised in Table 22.

Table 22: Achieved research objectives

Research objectives	Description	Sections
Research Objective 1	To develop a method that utilises simulation software to identify and improve insufficient delivery pressure in underground mines through a safer and simpler method than those commonly used to address difficult and dangerous in-stope areas.	2.2; 2.3; 2.7; 3.3
Research Objective 2	The model should be capable of predicting underground pressure along distant levels based on known consumers across the complex underground compressed air network.	3.5
Research Objective 3	To evaluate the adequacy of existing infrastructural engineering standards.	3.5; 3.6
Research Objective 4	To apply the developed method to a case study mine and to validate the results based on each implemented solution.	3.2 - 3.8
Research Objective 5	To evaluate the developed methodology based on the addressal of the problem using a comparative analysis to measure the performance.	3.6 - 3.8

4.3 Limitations of study and recommendations for future research

During this study, several difficulties were experienced and limitations identified. Recommendations for these limitations are discussed below.

Results limitations and recommendations:

From the results, distribution infrastructure or networks in the haulages were found to be restrictive to downstream consumers. Since this was a common finding in all three case studies, the potential for further restrictions downstream exists. The engineering standards were also found to be insufficiently specified. It is, therefore, recommended that crosscuts and in-stope networks be studied and considered in the same manner. The standard practices in these areas are assumed to be not monitored regularly.

- Since only Case Study A could be implemented, Case Studies B and C should still be feasible for implementation. It is unfortunate that the shipped piping for these case studies had to be repurposed.
- From the wastage-depressurisation method utilised during the inefficiency investigation in Section 3.5, the only baseload demand considered was that of refuge bays. However, other potential baseloads that may be shaft-specific should also be taken into consideration. A good example of this would be pneumatic agitators. The case study shaft did not have any agitators. The method should, therefore, be adapted to the specific shaft at hand when duplicating the investigation.
- Utilising simulation software to identify inefficiencies theoretically, based on known consumers, poses the limitation that unauthorised use or wastages such as leaks are not considered. The wastage-depressurisation method was used to provide an approximate amount. However, an ultrasonic flow meter is recommended to measure presumably inefficient or low-delivery-pressure areas or levels to account for flow more accurately. Measured flow at crosscut intakes can be used to calibrate the model to a more practical value. The total demand of the crosscut can then be split between known consumers and known wastage. This can also be used to benchmark areas by comparing it to a zero-waste baseline for the same area.

Engineering standards limitations and recommendations:

During this study, when the engineering standards were considered, the focus was on the distribution network sections. It is recommended that other parts of the standard should be

considered. This includes but is not limited to water traps, isolation valves and their intervals, pressure recommendations at stations and workplaces, HDPE or PVC piping in haulages, minimum pipe wall thicknesses, manifold sizing, etc. The conformity of these components and specifications as well as whether these specifications are sufficient for all sections of a mine should also be explored. When the engineering standards were reviewed, the following potential inefficiencies were identified:

- Whether mining conforms to the specified process of pipe reclamation during a stope development should be explored, not only for the benefit of reclaimed piping infrastructure but also to reduce the compressed-air-wastage potential in these areas.
- From the water trap requirements, it was specified that “water traps must be installed on all stations and installed not further than 100 m from the first working place where stoping/development takes place.” During the audits, it was found that water traps at the stations were full of water and not regularly drained. There were little to no water traps present at the working places, contributing to the inefficiencies experienced at the workplaces [56], [58].



Figure 56: Station water trap discharge showing accumulation of water

- From the isolation valve requirement, “all main haulages control/isolating valves must be installed at 500 m intervals as well as at every breakaway from the main column.” During the audits, little to no isolation valves were present at breakaways from the main columns to crosscuts. Therefore, air to these areas cannot be isolated during non-working periods.
- From the pressure recommendations it was specified that all stations should receive 550 kPa_g during drilling operations and 450 kPa_g at the entrance to workplaces. From Section 3.5, all stations received pressures well above 600 kPa_g, subsequently dropping as low as 450 kPa_g to some development ends. This indicates that the pressure supply from surface was not the issue but rather that the issue was within the distribution network.
- Pipe wall thicknesses should be measured and inspected yearly to four yearly, depending on the thickness specified in the engineering standard. Should this inspection not be conducted, and piping not replaced when required, leakages may occur and risk to injuries may increase. An example of an ultrasonic thickness gauge is shown in Figure 57.



Figure 57: Ultrasonic thickness gauge

- “Rock drills must be fed from a DN 25 mm hose (30 m in length), connected to a DN 50-100 mm manifold (6x DN 25 mm connections).” However, the expected pressure drop to each manifold size is not specified, as both have six DN 25 mm connection points. It was found that manifolds are adapted to fit more than six hose connections as shown in Figure 58.



Figure 58: Compressed air manifold modified to supply eight hoses¹⁷

The adapted manifold could potentially add to the pressure drop experienced by consumers due to the induced bottleneck properties. It is, therefore, recommended that further studies are conducted on in-stope distribution and connections to determine the restrictive nature and measure the degree of impact on delivery pressures.

Other limitations and recommendations:

Limited underground instrumentation is available because almost all instrumentation is located at the stations of levels. Level flow meters were found to be inaccurate, and most were not in working condition. Due to this flow meter limitation, level flows could not be used for calibration purposes. The identification of inefficiency locations was also approximated, and where flow could not be

¹⁷ LN Zietsman, 2022

measured. Some crosscuts were assumed to consume an additional 30% to 50% of the theoretically attributed crosscut flow due to wastage. This amount was based on literature, which was also in line with the audit findings. Wastages identified during audit flow measurements were assumed to remain the same and instrumentation accuracies was not considered part of the simulating error during this study. It is recommended that instrumentation error should also be used as a measure to simulation accuracies [62]. It is further recommended that other statistical analysis tools be explored to calibrate a baseline model.

The likelihood of increased misuse due to a higher number of consumers on a level, as in Case Study C, would require multiple crosscuts to be audited and compared. However, this could not be validated due to resource and time constraints, and the auditing of these areas did not fall within the boundaries of this study.

Although there are other studies that have provided different methods to prioritise and identify the most inefficient levels, it was not in the scope to use the most accurate method for prioritisation [61], [91]. Instead, the method of prioritisation was only used as a starting point to identify and improve inefficiencies within a level's distribution network. The most inefficient levels identified in this study can, therefore, be considered subjective.

It is recommended that a development-end, zero-waste pressure baseline be developed for levels based on the expected pressure drop from the station pressure transmitters to development ends, due to theoretically known consumer demands. This can be used as a reference when low workplace pressures are reported.

A similar approach to further the study to other industries and utilities such as water and ventilation is recommended. It is possible that other utilities and industries experience similar inefficiencies that could benefit from improved losses.

4.4 Reflection

During this study, several practical challenges were faced when developing the solution. The collection of information and data was the most difficult part of this process.

- This required frequent visits to the case study mine to conduct underground audits. These audits were mostly conducted during the evening's cleaning shifts, during which several kilometres were walked in humid and warm environments. The daily schedules had to be adjusted so as not to work more than the specified hours per 24 hours. Authorisation to

go underground took approximately five months, as several health and safety processes and clearances were required.

- Although Non-Disclosure Agreements (NDAs) were in place, initial authorisation from the planning department to receive surveyor drawings remained a difficult and tedious process.
- Mine personnel are not necessarily willing to conduct meetings and to assist with arrangements.

Extended underground audits and endless discussions with mine personnel refined the knowledge and process of this study. The author hopes to achieve an improvement in inefficient underground distribution networks and engineering standard specifications for the benefit of improved pressure delivery to mining services to ensure that production rates are no longer affected by insufficient pressures and that compressor operating costs can be reduced through more efficient compressed air distribution.

BIBLIOGRAPHY

- [1] “Eskom Factor 2.0,” 2018. Accessed: Apr. 04, 2023. [Online]. Available: https://www.eskom.co.za/wp-content/uploads/2021/02/Eskom_Factor_2.0.pdf
- [2] “Eskom Heritage: Empowering the Future Together 1923 - 2023,” Eskom. Accessed: May 11, 2023. [Online]. Available: <https://www.eskom.co.za/heritage/>
- [3] R. Binneman, “Eskom weekly system status reports 2023.” Accessed: May 09, 2023. [Online]. Available: <https://www.eskom.co.za/eskom-divisions/tx/system-adequacy-reports/>
- [4] “Avon and Dedisa Peaking Power,” Hulisani. Accessed: May 09, 2023. [Online]. Available: <https://hulisani.co.za/project/avon-and-dedisa-peeking-power>
- [5] J. Igamba, “How Eskom & The Government Can Put An End To Loadshedding in South Africa,” Greenpeace blog. Accessed: Apr. 05, 2023. [Online]. Available: <https://www.greenpeace.org/africa/en/blogs/53187/how-the-government-eskom-can-put-an-end-to-load-shedding/>
- [6] “Eskom ‘clarifies’ low energy availability numbers,” *BusinessTech*, Feb. 22, 2024. Accessed: Jul. 07, 2024. [Online]. Available: <https://businesstech.co.za/news/energy/754415/eskom-clarifies-low-energy-availability-numbers/>
- [7] W. Pierce and M. Le Roux, “Statistics of utility-scale power generation in South Africa,” 2022.
- [8] Staff Writer, “Sabotage, coal theft and the other high-level crimes rocking Eskom,” *BusinessTech*, News report. Accessed: Apr. 05, 2023. [Online]. Available: <https://businesstech.co.za/news/energy/635783/sabotage-coal-theft-and-the-other-high-level-crimes-rocking-eskom/>
- [9] I. N. Kessides, “The Decline and Fall of Eskom: A South African Tragedy,” 2020. Accessed: Apr. 05, 2023. [Online]. Available: <https://www.thegwpf.org/content/uploads/2020/06/Decline-Fall-Eskom.pdf>

- [10] “Socio-economic impact study for the shutdown and repurposing of Komati Power Station: Final integrated report,” Pretoria, Oct. 2022. Accessed: Apr. 05, 2023. [Online]. Available: https://www.eskom.co.za/wp-content/uploads/2022/11/Komati_SEIA_Final_Integrated_Report_October_2022.pdf
- [11] G. Ntsaluba, “Load shedding in South Africa: From 2007 to it’s ‘not the end of the world,’” *The South African*, Feb. 14, 2024. Accessed: Jul. 07, 2024. [Online]. Available: <https://www.thesouthafrican.com/news/load-shedding-not-the-end-of-the-world/>
- [12] M. Moloi, L. Pretorius, and M. Malan, “By the numbers: What load shedding does to your mental health,” *News24*, Apr. 12, 2023. Accessed: May 11, 2023. [Online]. Available: <https://www.news24.com/life/wellness/mind/by-the-numbers-what-load-shedding-does-to-your-mental-health-20230412-2>
- [13] C. Carter-Brown, “Understanding Eskom’s Tariff Structure and Its Impact on the Mining Sector,” *Journal of Energy in Southern Africa*, vol. 29, no. 4, Dec. 2018.
- [14] “Tariffs & Charges Booklet 2023/2024,” 2023. Accessed: Apr. 25, 2023. [Online]. Available: https://www.eskom.co.za/distribution/wp-content/uploads/2023/04/2023_24-Tariff-Book_01042023.pdf
- [15] C. J. R. Kriel and M. Kleingeld, “Modernising underground compressed air DSM projects to reduce operating costs,” Master of Engineering in Mechanical Engineering, North-West University, 2014.
- [16] E. Ferreira, “Eskom: interdicting necessary tariff hike will be catastrophic for the country,” *Mail & Guardian*, Feb. 22, 2023. Accessed: May 11, 2023. [Online]. Available: <https://mg.co.za/news/2023-02-22-eskom-interdicting-necessary-tariff-hike-will-be-catastrophic-for-the-country/>
- [17] “Inflation, consumer prices (annual %) - South Africa,” International Monetary Fund, World Bank, International Financial Statistics and data files. Accessed: Apr. 12, 2023. [Online]. Available: https://data.worldbank.org/indicator/FP.CPI.TOTL.ZG?end=2021&locations=ZA&name_desc=true&start=1994&view=chart

- [18] J. Basson, "Solar tax incentives for individuals and businesses," *Sage*, Apr. 04, 2023. Accessed: May 11, 2023. [Online]. Available: <https://www.sage.com/en-za/blog/solar-tax-incentives-for-individuals-and-businesses/>
- [19] "Facts & Figures Pocketbook 2022," *Minerals Council South Africa*, pp. 6–9, Feb. 2023.
- [20] Wits Mining Institute, "The South African mining sector," Wits Mining Institute. Accessed: Oct. 03, 2023. [Online]. Available: <https://www.wits.ac.za/wmi/about-us/the-south-african-mining-sector/>
- [21] R. Funnell, "The Deepest Gold Mine In The World Plunges 4 Kilometers Into The Earth," *IFLScience*. Accessed: Oct. 30, 2023. [Online]. Available: <https://www.iflscience.com/the-deepest-gold-mine-in-the-world-plunges-4-kilometers-into-the-earth-69955>
- [22] J. Steven Landefeld, Eugene P. Seskin, and Barbara M. Fraumeni, "Taking the Pulse of the Economy: Measuring GDP," *Journal of Economic Perspectives*, vol. 22, no. 2, pp. 193–216, 2008.
- [23] N. G. Tshabalala, "Crime and unemployment in South Africa; revisiting an established causality: Evidence from the Kwazulu Natal Province," *Mediterr J Soc Sci*, vol. 5, no. 15, pp. 519–528, 2014.
- [24] "South Africa's mine production value remains above R1 trillion despite logistics constraints. Warning lights are flashing.," *Facts & Figures Pocketbook 2022*, Cape Town, Feb. 06, 2023. [Online]. Available: www.mineralscouncil.org.za
- [25] "Statistical Release P2041 Mining: Production and sales March 2021-2023," Pretoria.
- [26] M. Handley, "Where is all the gold?," *J South Afr Inst Min Metall*, vol. 123, no. 4, pp. 175–192, Apr. 2023.
- [27] N. Deseta, "Geology of the PGE Deposits in the Bushveld Complex, South Africa," Sep. 2020. Accessed: Oct. 30, 2023. [Online]. Available: <https://www.geologyforinvestors.com/geology-of-the-pge-deposits-in-the-bushveld-complex-south-africa/>
- [28] "Ore Reserves and Mineral Resources report," 2022. [Online]. Available: www.angloamericanplatinum.com/

- [29] World Bank, "List of Countries by Area," Statistics Times. Accessed: Oct. 30, 2023. [Online]. Available: <https://statisticstimes.com/geography/countries-by-area.php>
- [30] U. S. Geological Survey, "Mineral commodity summaries 2022," Reston, VA, 2022. [Online]. Available: <https://pubs.usgs.gov/publication/mcs2022>
- [31] "Digging Beneath the Surface, An Exploration of the Net Benefits of Mining in Southern Africa," 2019. Accessed: May 23, 2023. [Online]. Available: <https://openknowledge.worldbank.org/server/api/core/bitstreams/ed8ff7bd-934a-5925-9ed8-085d07b01349/content>
- [32] "PGM sales surge due to higher prices," StatsSA. Accessed: May 01, 2024. [Online]. Available: <https://www.statssa.gov.za/?p=14225>
- [33] S. Smit, "Platinum records for South African mines - The Mail & Guardian." Accessed: May 25, 2022. [Online]. Available: <https://mg.co.za/business/2021-05-16-platinum-records-for-south-african-mines/>
- [34] GCIS, "Official Guide to South Africa 2021/22," Pretoria, 2022. Accessed: Oct. 03, 2023. [Online]. Available: <https://www.gcis.gov.za/sites/default/files/docs/gcis/Official%20Guide%20to%20South%20Africa%202021-22.pdf>
- [35] J. Carew, "Achieving success in an industry rife with challenges," *Mail & Guardian*, Feb. 20, 2023. Accessed: Sep. 19, 2023. [Online]. Available: <https://mg.co.za/special-reports/2023-02-20-achieving-success-in-an-industry-rife-with-challenges/>
- [36] B. Chipandam, "South Africa's super-exporters," Aug. 2014. Accessed: May 23, 2023. [Online]. Available: https://www.tips.org.za/files/policy_brief_-_south_african_super-exporters.pdf
- [37] S. Nadig, "Platinum mining in uncertain times: producers navigate revenue losses and weaker demand," *Mining Technology*, May 15, 2024. Accessed: Jul. 07, 2024. [Online]. Available: <https://www.mining-technology.com/features/platinum-mining-in-uncertain-time/>
- [38] "Supply & Demand Historical Data," World Platinum Investment Council. Accessed: Jul. 07, 2024. [Online]. Available: <https://platinuminvestment.com/supply-and-demand/historic-data>

- [39] E. Sterck, W. Napier, J. Hayhurst-Worthington, and B. Clifford, “WPIC Platinum Essentials: Platinum’s consecutive market deficits could deepen as lower PGM prices increase mine supply risks,” 2023. [Online]. Available: www.platinuminvestment.com
- [40] E. Sterck, W. Napier, J. Hayhurst-Worthington, and B. Clifford, “WPIC Platinum Perspectives: Platinum’s supply risks cannot be overlooked as PGM prices remain weak and miners reduce capex,” 2024. [Online]. Available: www.platinuminvestment.com
- [41] B. Pascoe, “Improving mine compressed air network efficiency through demand and supply control,” Master’s thesis, North-West University, 2017.
- [42] N. Zietsman, J. Marais, and W. Schoeman, “A practical method for compressed air leak localisation in deep-level mines,” in *AIUE Proceedings of the 17th Industrial and Commercial Use of Energy (ICUE) Conference*, Cape Town: ICUE, Jul. 2019, pp. 1–5. Accessed: Apr. 17, 2024. [Online]. Available: <https://ssrn.com/abstract=3650457>
- [43] P. Fraser, “The energy and water required to drill a hole,” in *The 4th International Platinum Conference, Platinum in transition “Boom or Bust,”* Randburg: The Southern African Institute of Mining and Metallurgy, 2010.
- [44] A. Van der Merwe, “Developing Zero-Waste Baselines to Identify Compressed Air System Inefficiencies in Deep-Level Mines,” Master of Engineering in Industrial Engineering, Stellenbosch University, 2023.
- [45] W. T. Gerber, “Developing a demand-driven compressed air management system for energy efficiency in deep-level gold mining,” Master of Engineering in Industrial Engineering, Stellenbosch University, 2024.
- [46] H. Vella, “Managing water consumption in mining,” Aug. 2013. Accessed: Jul. 13, 2023. [Online]. Available: <https://www.mining-technology.com/features/feature-managing-water-consumption-mining-global-shortage/>
- [47] N. Zietsman, “Novel solutions for compressed air demand management on deep-level mines,” PhD Thesis, North-West University, 2020.
- [48] “Minerals Council South Africa is dismayed at the latest damaging price increases for Eskom,” 2023. [Online]. Available: www.mineralscouncil.org.za

- [49] F. Schroeder, “Energy efficiency opportunities in mine compressed air systems,” Master’s thesis, North-West University, 2009.
- [50] C. van Zyl, “Practical approach to analyse mine pneumatic drilling performance,” Master’s thesis, North-West University, 2019.
- [51] D. Nell, “Optimising production through improving the efficiency of mine compressed air networks with limited infrastructure,” Master of Engineering in Mechanical Engineering, North-West University, 2017.
- [52] K. Van Tonder, “Sustaining compressed air DSM project savings using an air leakage management system,” Master of Engineering in Mechanical Engineering, North-West University, 2010.
- [53] D. du Plooy, P. Maré, J. Marais, and M. J. Mathews, “Local benchmarking in mines to locate inefficient compressed air usage,” *Sustain Prod Consum*, vol. 17, pp. 126–135, Jan. 2019, doi: 10.1016/J.SPC.2018.09.010.
- [54] P. Burger, “Future mine compressed air planning using digital twin simulations,” Master of Engineering in Mechanical Engineering, North-West University, 2023.
- [55] J. Bredenkamp, “Reconfiguring mining compressed air networks for cost savings,” Master of Engineering in Mechanical Engineering, North-West University, 2014.
- [56] J. Bester, D. Le Roux, and D. Adams, “The effect of compressed air pressure on mining production and energy demand,” in *Proceedings of the 10th Industrial and Commercial Use of Energy Conference*, Pretoria: IEEE, 2013, pp. 1–4.
- [57] J. De la Vergne, *Hard Rock Miner’s Handbook*, 5th ed. Stantec Consulting, 2014.
- [58] P. L. Brits and J. Marais, “A systematic approach to evaluate in-stope compressed air inefficiencies in deep-level mines,” Master of Engineering in Mechanical Engineering, North-West University, 2024.
- [59] J. Watkins, “Trade-off between simulation accuracy and complexity for mine compressed air systems,” Master of Engineering in Mechanical Engineering, North-West University, 2019.

- [60] C. Miskinis, "How ore mining will be improved using digital twin simulations," Challenge Advisory. Accessed: Jun. 11, 2024. [Online]. Available: <https://www.challenge.org/insights/digital-twin-in-mining/>
- [61] M. de Jager, "Using simulation to prioritise implementation of platinum mine compressed air efficiency solutions," Master of Engineering in Mechanical Engineering, North-West University, 2021.
- [62] B. M. Friedenstien, C. Cilliers, and J. van Rensburg, "Simulating operational improvements on mine compressed air systems#," *South African Journal of Industrial Engineering*, vol. 29(3), no. Special Edition, pp. 69–81, 2018, doi: 10.7166/29-3-2049.
- [63] G. Matthee, "Improved control of compressed air networks using machine learning," Master of Engineering in Mechanical Engineering, North-West University, 2021.
- [64] T. L. Brown and E. LeMay Jr., "Chemistry - The Central Science (TextMap of Brown & Lemay's book), 10.4: The Ideal Gas Equation," LibreTexts Chemistry. Accessed: Jun. 08, 2024. [Online]. Available: [https://chem.libretexts.org/Bookshelves/General_Chemistry/Map%3A_Chemistry_-_The_Central_Science_\(Brown_et_al.\)/10%3A_Gases/10.04%3A_The_Ideal_Gas_Equation](https://chem.libretexts.org/Bookshelves/General_Chemistry/Map%3A_Chemistry_-_The_Central_Science_(Brown_et_al.)/10%3A_Gases/10.04%3A_The_Ideal_Gas_Equation)
- [65] T. L. Brown and E. LeMay Jr., "Chemistry - The Central Science (TextMap of Brown & Lemay's book), 10.9: Real Gases - Deviations from Ideal Behaviour," LibreTexts. Accessed: Jun. 08, 2024. [Online]. Available: [https://chem.libretexts.org/Bookshelves/General_Chemistry/Map%3A_Chemistry_-_The_Central_Science_\(Brown_et_al.\)/10%3A_Gases/10.09%3A_Real_Gases_-_Deviations_from_Ideal_Behavior](https://chem.libretexts.org/Bookshelves/General_Chemistry/Map%3A_Chemistry_-_The_Central_Science_(Brown_et_al.)/10%3A_Gases/10.09%3A_Real_Gases_-_Deviations_from_Ideal_Behavior)
- [66] K. M. Tenny and J. S. Cooper, "Ideal Gas Behavior," StatPearls. Accessed: Jun. 08, 2024. [Online]. Available: <https://www.ncbi.nlm.nih.gov/books/NBK441936/>
- [67] "What is Bernoulli's equation?," Khan Academy. Accessed: Jun. 08, 2024. [Online]. Available: <https://www.khanacademy.org/science/physics/fluids/fluid-dynamics/a/what-is-bernoullis-equation>
- [68] OpenStax, "University Physics I - Mechanics, Sound, Oscillations, and Waves, 14.8 Bernoulli's Equation," LibreTexts Physics. Accessed: Jun. 09, 2024. [Online]. Available:

- [https://phys.libretexts.org/Bookshelves/University_Physics/University_Physics_\(OpenStax\)/Book%3A_University_Physics_I_-_Mechanics_Sound_Oscillations_and_Waves_\(OpenStax\)/14%3A_Fluid_Mechanics/14.08%3A_Bernoullis_Equation](https://phys.libretexts.org/Bookshelves/University_Physics/University_Physics_(OpenStax)/Book%3A_University_Physics_I_-_Mechanics_Sound_Oscillations_and_Waves_(OpenStax)/14%3A_Fluid_Mechanics/14.08%3A_Bernoullis_Equation)
- [69] B. R. Munson, T. H. Okiishi, W. W. Huebsch, and A. P. Rothmayer, *Fundamentals of Fluid Mechanics*, 7th ed. John Wiley & Sons, Inc., 2013.
- [70] J. R. Welty, G. L. Rorrer, and D. G. Foster, *Fundamentals of Momentum, Heat and Mass Transfer*, 6th Edition. Hoboken, NJ: Wiley, 2014.
- [71] M. Kleingeld, “Automated mine compressed air control for sustainable savings,” Master of Engineering in Mechanical Engineering, North-West University, 2016.
- [72] R. Pelzer, “Energy efficiency opportunities resulting from splitting a compressed air ring,” in *Proceedings of the 8th Conference on the Industrial and Commercial Use of Energy. IEEE*, Jan. 2011. [Online]. Available: <https://www.researchgate.net/publication/252048638>
- [73] “Experiment #4: Energy Loss in Pipes, Applied Fluid Mechanics Lab Manual,” Mavs Open Press. Accessed: Jun. 17, 2024. [Online]. Available: <https://uta.pressbooks.pub/appliedfluidmechanics/chapter/experiment-4/#:~:text=Major%20losses%20are%20associated%20with,to%20overcome%20the%20frictional%20resistance>
- [74] “Minor Head Loss - Local Losses,” Nuclear Power. Accessed: Jun. 09, 2024. [Online]. Available: <https://www.nuclear-power.com/nuclear-engineering/fluid-dynamics/minor-head-loss-local-losses/>
- [75] “Pressure Loss Coefficient - PLC,” Nuclear Power. Accessed: Jun. 09, 2024. [Online]. Available: <https://www.nuclear-power.com/nuclear-engineering/fluid-dynamics/bernoullis-equation-bernoullis-principle/head-loss/pressure-loss-coefficient-plc/>
- [76] M.-P. Eduard and P. Igor, “Effects of boundary roughness and inertia on the fluid flow through a corrugated pipe and the formula for the Darcy–Weisbach friction coefficient,” *Int J Eng Sci*, vol. 152, Jul. 2020.

- [77] Q. B. Travis and L. W. Mays, "Relationship between Hazen–William and Colebrook–White Roughness Values," *Journal of Hydraulic Engineering*, vol. 133, no. 11, pp. 1270–1273, Nov. 2007, doi: 10.1061/(asce)0733-9429(2007)133:11(1270).
- [78] R. T. Renata, F. F. S. Pereira, T. B. G. da Silva, E. R. Castro, and J. C. C. Saad, "The performance of explicit formulas for determining the darcyweisbach friction factor," *Engenharia Agricola*, vol. 40, no. 2, pp. 258–265, Mar. 2020, doi: 10.1590/1809-4430-ENG.AGRIC.V40N2P258-265/2020.
- [79] E. F. Adiutori, "Why the Fluid Friction Factor should be Abandoned, and the Moody Chart Transformed," *The Open Mechanical Engineering Journal*, vol. 3, pp. 43–48, 2009.
- [80] P. Heney, "Compressed air fail: Artificial demand," *Pneumatic Tips*. Accessed: Jul. 07, 2024. [Online]. Available: <https://www.pneumatictips.com/compressed-air-fail-artificial-demand/>
- [81] V. Dan, "Empirical and Non-Empirical Methods," *The international encyclopedia of communication research methods*, vol. 2. Wiley-Blackwell, pp. 623–625, 2017. [Online]. Available: <https://www.researchgate.net/publication/309922961>
- [82] O. D. Apuke, "Quantitative Research Methods: A Synopsis Approach," *Kuwait Chapter of Arabian Journal of Business and Management Review*, vol. 6, no. 11, pp. 40–47, Sep. 2017.
- [83] S. Sukamolson, "Fundamentals of quantitative research," *Language Institute Chulalongkorn University*, vol. 1, no. 3, pp. 1–20, 2007.
- [84] P. Bhandari, "What Is Quantitative Research? | Definition, Uses & Methods," *Scribbr*. Accessed: Jul. 08, 2023. [Online]. Available: <https://www.scribbr.com/methodology/quantitative-research/>
- [85] N. Azaria, "A Comprehensive Guide to Mean Absolute Percentage Error (MAPE)," *Aporia*. Accessed: Jun. 19, 2024. [Online]. Available: <https://www.aporia.com/learn/a-comprehensive-guide-to-mean-absolute-percentage-error-mape/>
- [86] M. Riva and M. Aibin, "Understanding Forecast Accuracy: MAPE, WAPE, WMAPE," *Baeldung*. Accessed: Jun. 19, 2024. [Online]. Available: <https://www.baeldung.com/cs/mape-vs-wape-vs-wmape>

- [87] S. W. Van Heerden, "Developing a dynamic control system for mine compressed air networks," Master of Engineering in Computer and Electronic Engineering, North-West University, 2014.
- [88] J. Venter, "Development of a dynamic centrifugal compressor selector for large compressed air networks in the mining industry," Master of Engineering in Mechanical Engineering, North-West University, 2012.
- [89] "Derivation of Pressure loss to Leak Rate Formula from the Ideal Gas Law," Cincinnati Test Systems, Inc. Accessed: Nov. 25, 2023. [Online]. Available: <http://www.cincinnati-test.cn/documents/PDFs/AB143.pdf>
- [90] "Identifying Hazard Control Options: What Is the Hierarchy of Controls?" [Online]. Available: <https://www.osha.gov/safety-management>
- [91] E. du Toit, "A structured approach to prioritise industrial energy efficiency measures by assessing feasibility criteria," Master of Engineering in Mechanical Engineering, North-West University, 2021.

APPENDIX A

Table 23: MEGAFLEX - Non-local authority charges 2023/2024

		Active energy charge [c/kWh]					
		High demand season (Jun-Aug)			Low demand season (Sep-May)		
Transmission zone	Voltage	Peak	Standard	Off Peak	Peak	Standard	Off Peak
≤ 300km	< 500V	542.79	165.14	90.17	177.74	122.64	78.19
	≥ 500V & < 66kV	534.27	161.85	87.91	174.26	119.96	76.10
	≥ 66kV & ≤ 132kV	517.35	156.71	85.12	168.78	116.13	73.72
	> 132kV*	487.58	147.68	80.22	159.10	109.47	69.46
> 300km and ≤ 600km	< 500V	547.21	165.80	90.02	178.52	122.91	77.98
	≥ 500V & < 66kV	539.60	163.45	88.76	176.05	121.14	76.85
	≥ 66kV & ≤ 132kV	522.43	158.24	85.91	170.41	117.29	74.42
	> 132kV*	492.47	149.21	80.97	160.63	110.53	70.11
> 600km and ≤ 900km	< 500V	552.66	167.42	90.89	180.28	124.10	78.70
	≥ 500V & < 66kV	545.02	165.13	89.66	177.79	122.38	77.63
	≥ 66kV & ≤ 132kV	527.77	159.88	86.80	172.15	118.51	75.19
	> 132kV*	497.43	150.66	81.87	162.25	111.66	70.86
> 900km	< 500V	558.22	169.17	91.81	182.12	125.32	79.53
	≥ 500V & < 66kV	550.44	166.73	90.51	179.53	123.54	78.39
	≥ 66kV & ≤ 132kV	533.06	161.46	87.67	173.87	119.67	75.92
	> 132kV*	502.27	152.22	82.70	163.94	112.88	71.64

APPENDIX B

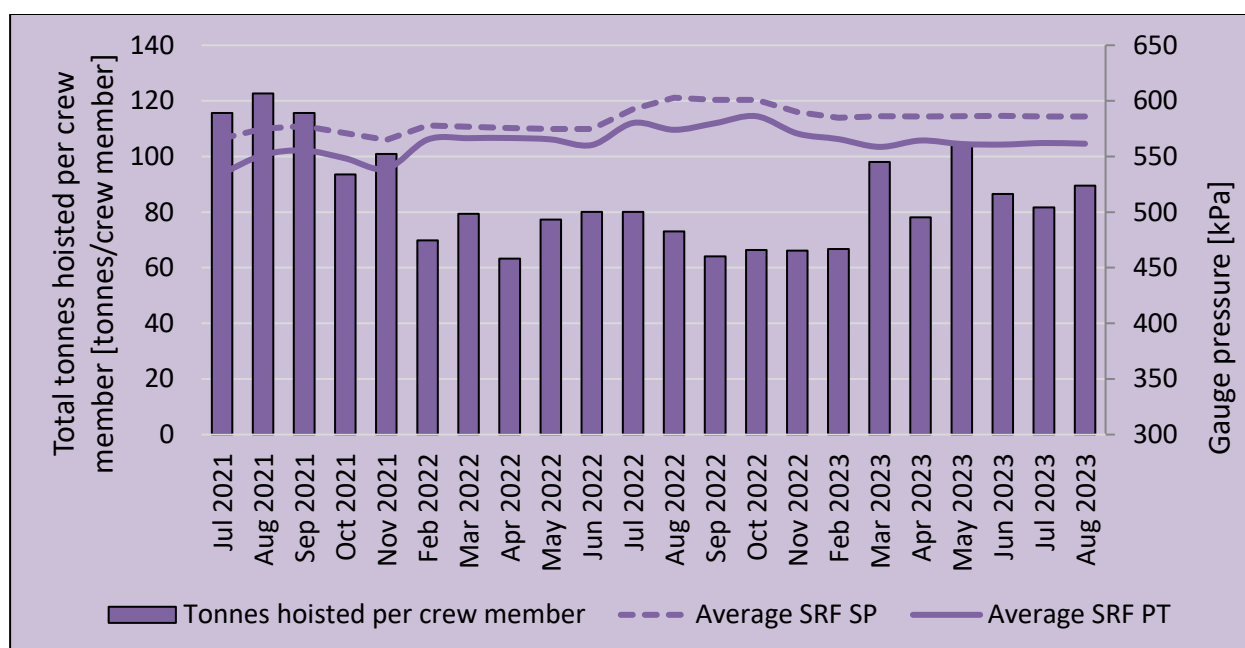


Figure 59: Tonnes hoisted per crew member versus average surface supplied pressure

APPENDIX C

Working Weekday		Working (On) Saturday		Sunday		Off Saturdays (Non-working)	
Time	Pressure [kPa]	Time	Pressure [kPa]	Time	Pressure [kPa]	Time	Pressure [kPa]
00:00 – 06:00	590	00:00 – 06:00	590	00:00 – 18:00	450	00:00 – 23:59	450
06:00 – 16:00	590	06:00 – 16:00	590	18:00 – 23:59	550		
16:00 – 20:00	450	16:00 – 20:00	450				
20:00 – 23:59	590	20:00 – 23:59	590				

Figure 60: Surface pressure set-point profile requirements - signed off on 15-02-2022

Table 24: "AirPressureBoundary" component inputs

Time	Pressure [kPa _{abs}]	Temperature [°C]	Relative Humidity [%]	Elevation [m]	Reference Pressure [kPa]
00:00	678.62	20	50	1135.046	88.62
01:00	678.62	20	50	1135.046	88.62
02:00	678.62	20	50	1135.046	88.62
03:00	678.62	20	50	1135.046	88.62
04:00	678.62	20	50	1135.046	88.62
05:00	678.62	20	50	1135.046	88.62
06:00	678.62	20	50	1135.046	88.62
07:00	678.62	20	50	1135.046	88.62
08:00	678.62	20	50	1135.046	88.62
09:00	678.62	20	50	1135.046	88.62
10:00	678.62	20	50	1135.046	88.62
11:00	678.62	20	50	1135.046	88.62
12:00	678.62	20	50	1135.046	88.62
13:00	678.62	20	50	1135.046	88.62
14:00	678.62	20	50	1135.046	88.62
15:00	678.62	20	50	1135.046	88.62
16:00	538.62	20	50	1135.046	88.62
17:00	538.62	20	50	1135.046	88.62
18:00	538.62	20	50	1135.046	88.62
19:00	538.62	20	50	1135.046	88.62
20:00	678.62	20	50	1135.046	88.62
21:00	678.62	20	50	1135.046	88.62
22:00	678.62	20	50	1135.046	88.62
23:00	678.62	20	50	1135.046	88.62

APPENDIX D

Table 25: Flow comparison of surface supply and calculation of MAPEs

Time	Actual [Nm ³ /h]	Simulated (w/o wastages) [Nm ³ /h]	Simulated (w/ wastages) [Nm ³ /h]	APE [%]	
00:00	89 195	24 973	91 662	72.00	2.77
01:00	77 523	21 702	80 132	72.01	3.36
02:00	89 316	26 198	94 230	70.67	5.50
03:00	78 068	22 914	83 245	70.65	6.63
04:00	79 036	22 607	79 972	71.40	1.18
05:00	80 544	24 525	82 383	69.55	2.28
06:00	88 882	28 417	91 635	68.03	3.10
07:00	99 231	29 466	101 209	70.31	1.99
08:00	117 296	34 400	123 996	70.67	5.71
09:00	121 925	29 779	123 644	75.58	1.41
10:00	121 489	29 160	122 027	76.00	0.44
11:00	121 135	32 984	128 237	72.77	5.86
12:00	108 814	31 890	114 757	70.69	5.46
13:00	95 418	28 565	101 043	70.06	5.90
14:00	92 593	27 460	94 539	70.34	2.10
15:00	92 566	26 535	90 130	71.33	2.63
16:00	45 343	20 948	45 594	53.80	0.56
17:00	30 440	13 310	34 243	56.27	12.49
18:00	35 181	15 271	39 034	56.59	10.95
19:00	83 724	30 731	81 852	63.29	2.24
20:00	93 307	29 636	95 052	68.24	1.87
21:00	84 975	23 695	90 003	72.12	5.92
22:00	91 174	23 181	92 169	74.58	1.09
23:00	95 500	25 305	96 077	73.50	0.60
Mean Absolute Percentage Error (MAPE)				69.19	3.84

From the results in Table 25, a MAPE of 3.84% is observed for the surface flow, simulated with wastages, using Equation 2.4.

Table 26: Pressure comparison of surface supply and calculation of MAPE

Time	Actual [kPa _g]	Simulation [kPa _g]	APE [%]
00:00	560.7	571.1	1.86
01:00	560.8	570.7	1.75
02:00	562.9	554.0	1.59
03:00	505.9	494.1	2.34
04:00	475.5	487.4	2.51
05:00	523.8	531.6	1.49
06:00	568.5	577.4	1.58
07:00	603.2	611.4	1.37
08:00	629.4	615.5	2.21
09:00	622.7	632.6	1.59
10:00	627.0	642.4	2.46
11:00	608.8	594.3	2.38
12:00	569.0	558.3	1.88
13:00	519.2	508.6	2.06
14:00	523.3	530.6	1.39
15:00	520.4	529.5	1.76
16:00	462.6	483.8	4.58
17:00	511.6	534.5	4.46
18:00	474.0	492.7	3.94
19:00	460.4	485.5	5.45
20:00	566.5	575.4	1.58
21:00	549.3	539.1	1.87
22:00	568.9	582.1	2.32
23:00	542.6	557.1	2.68
Mean Absolute Percentage Error (MAPE)			2.38

From the results in Table 26, a MAPE of 2.38% is observed for the surface pressure using Equation 2.4.

APPENDIX E

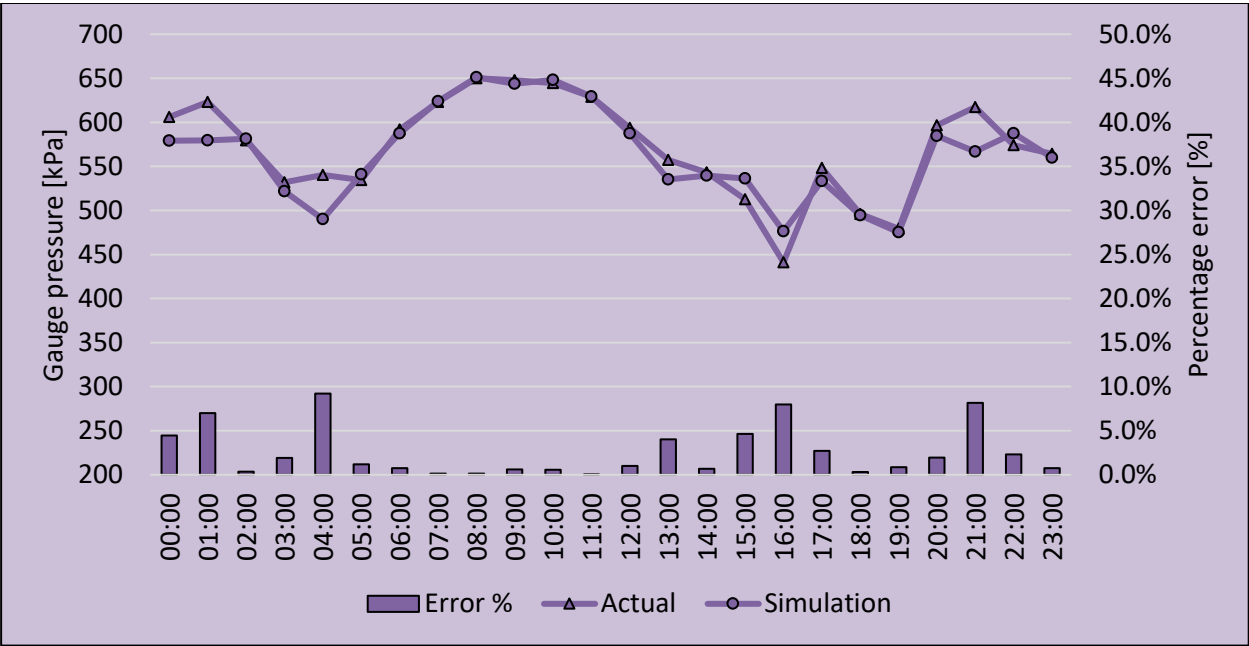


Figure 61: Hourly model performance comparison of 18-Level

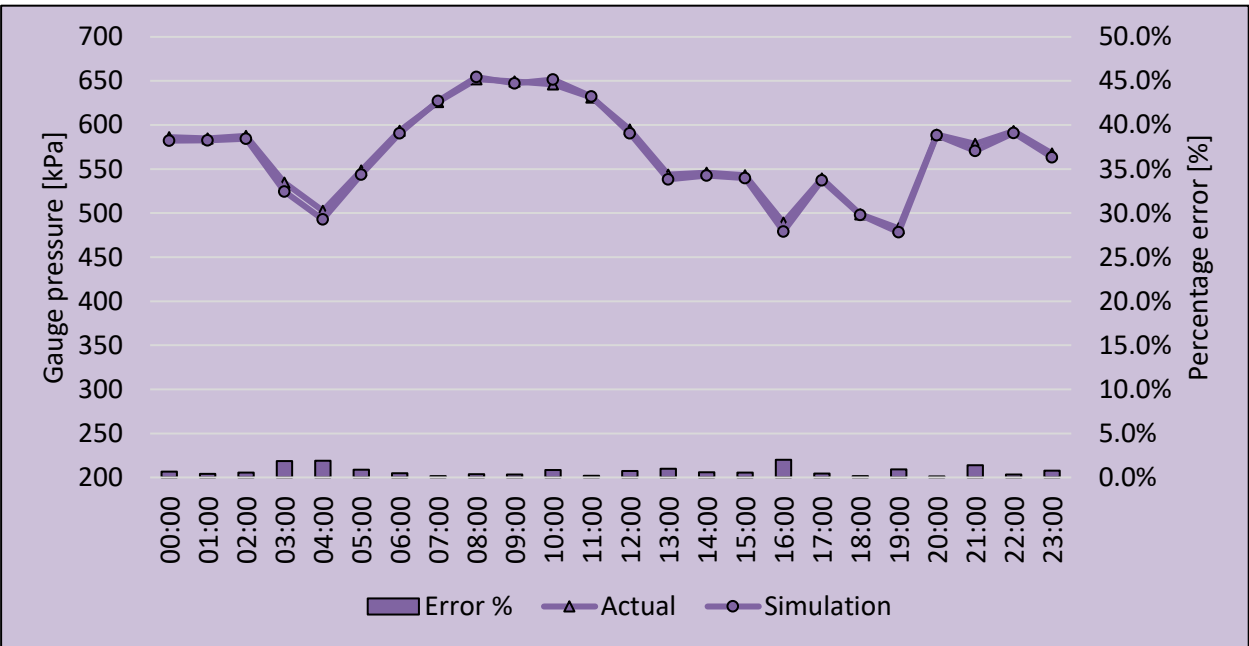


Figure 62: Hourly model performance comparison of 19-Level

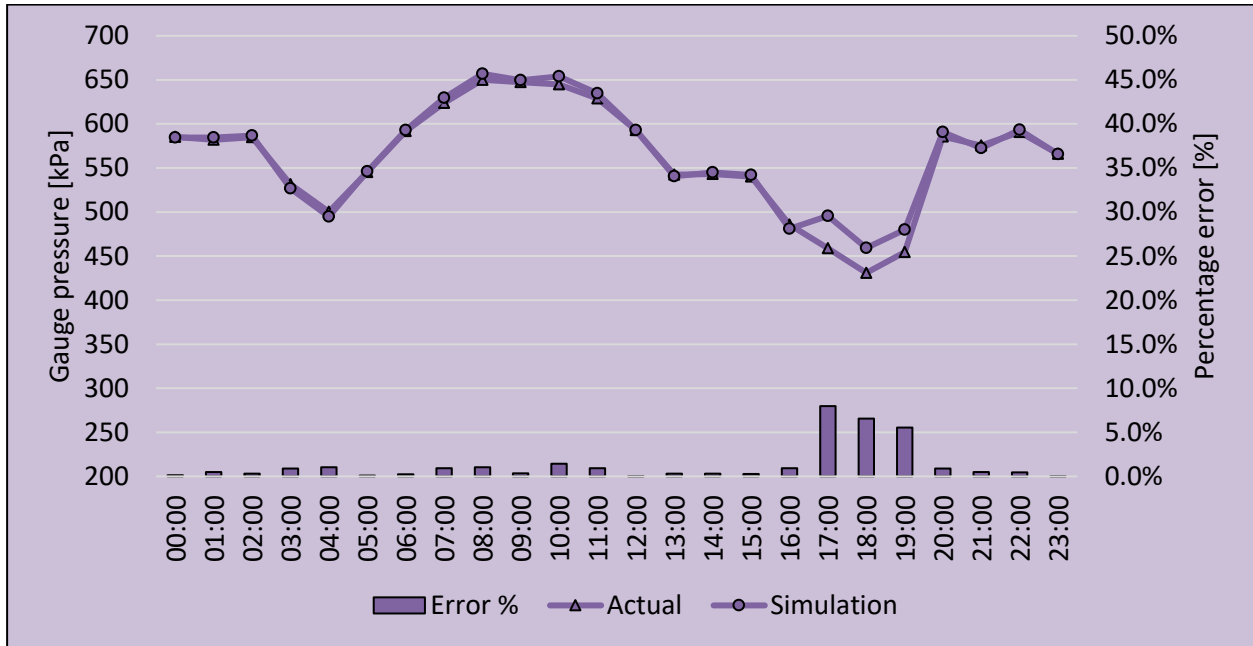


Figure 63: Hourly model performance comparison of 20-Level

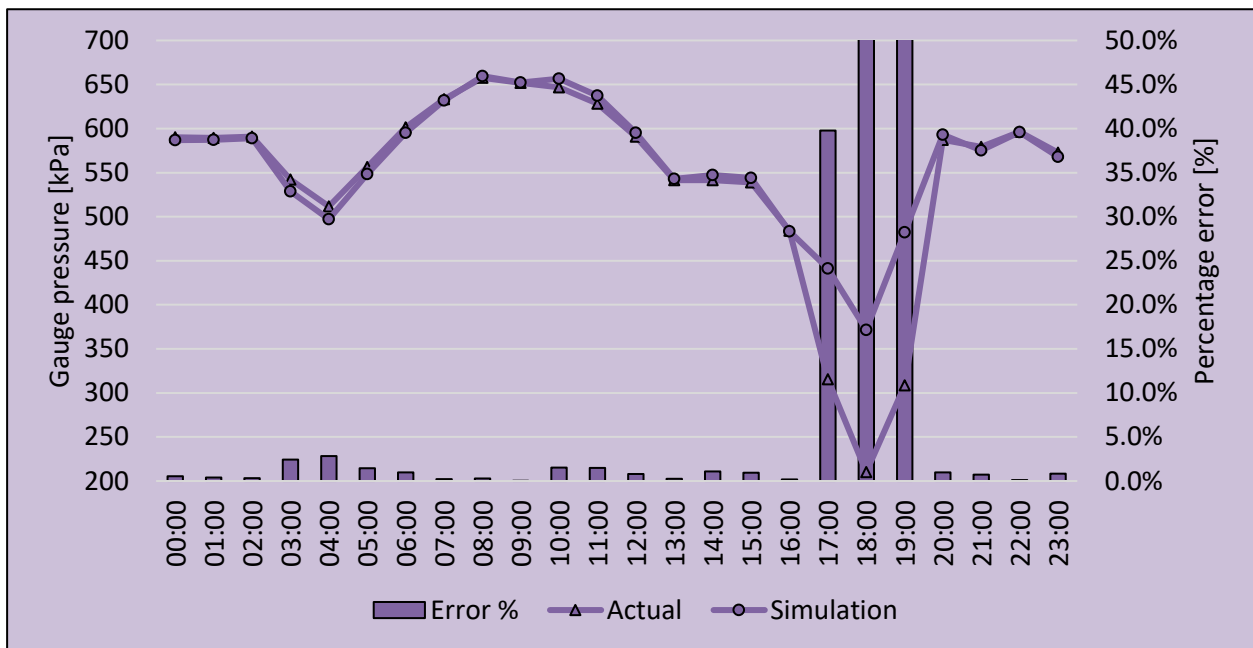


Figure 64: Hourly model performance comparison of 21-Level



Figure 65: Hourly model performance comparison of 22-Level

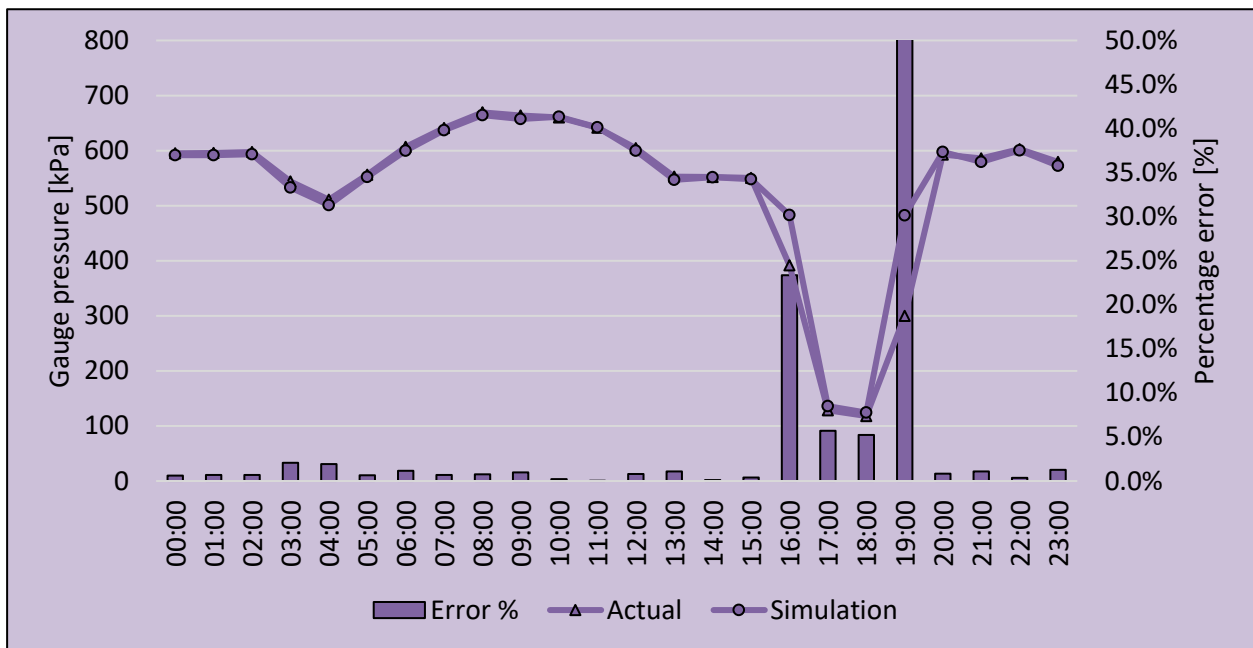


Figure 66: Hourly model performance comparison of 23-Level

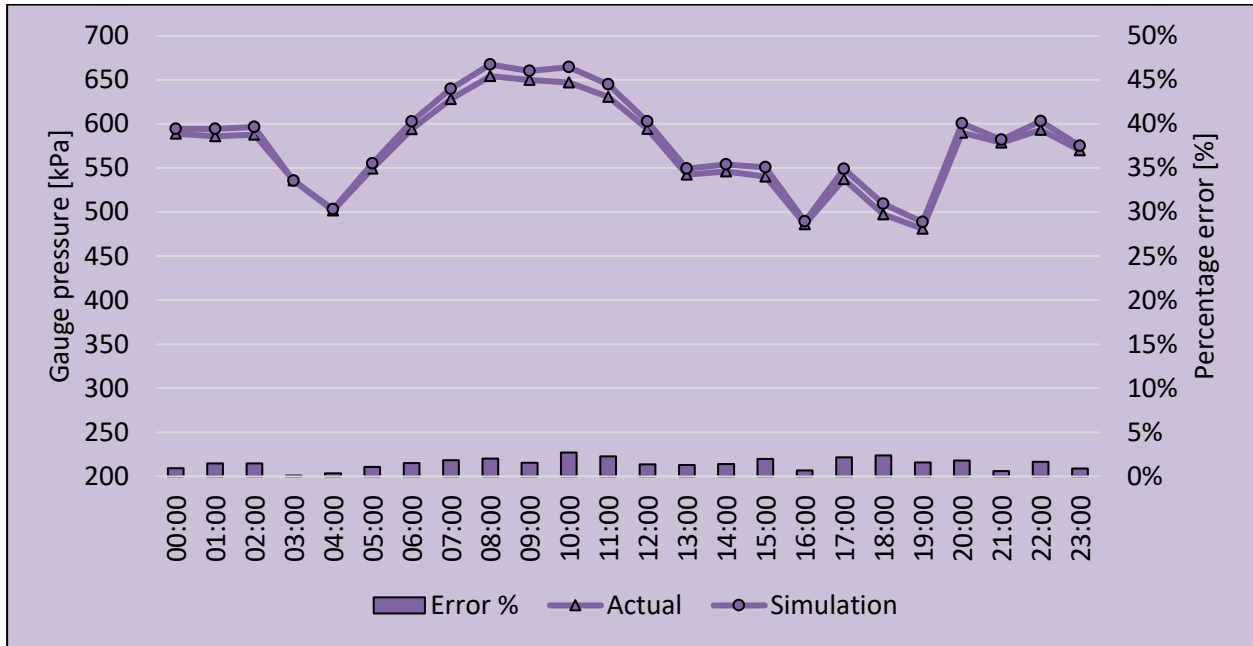


Figure 67: Hourly model performance comparison of 24-Level

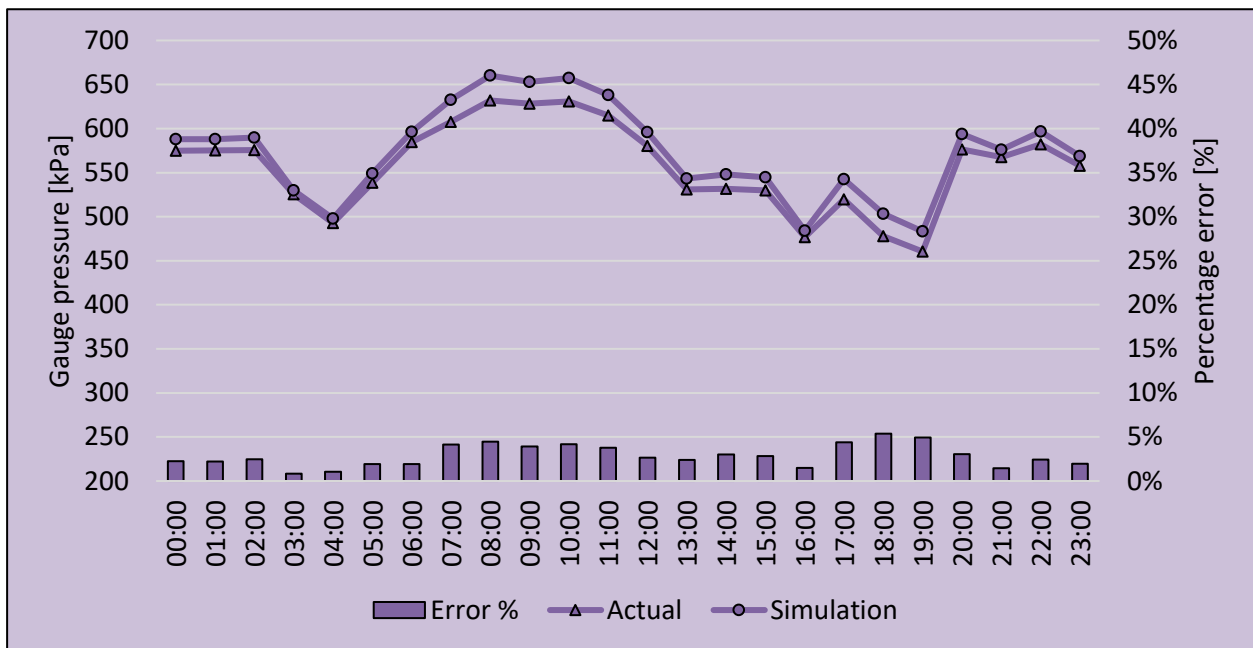


Figure 68: Hourly model performance comparison of 25-Level

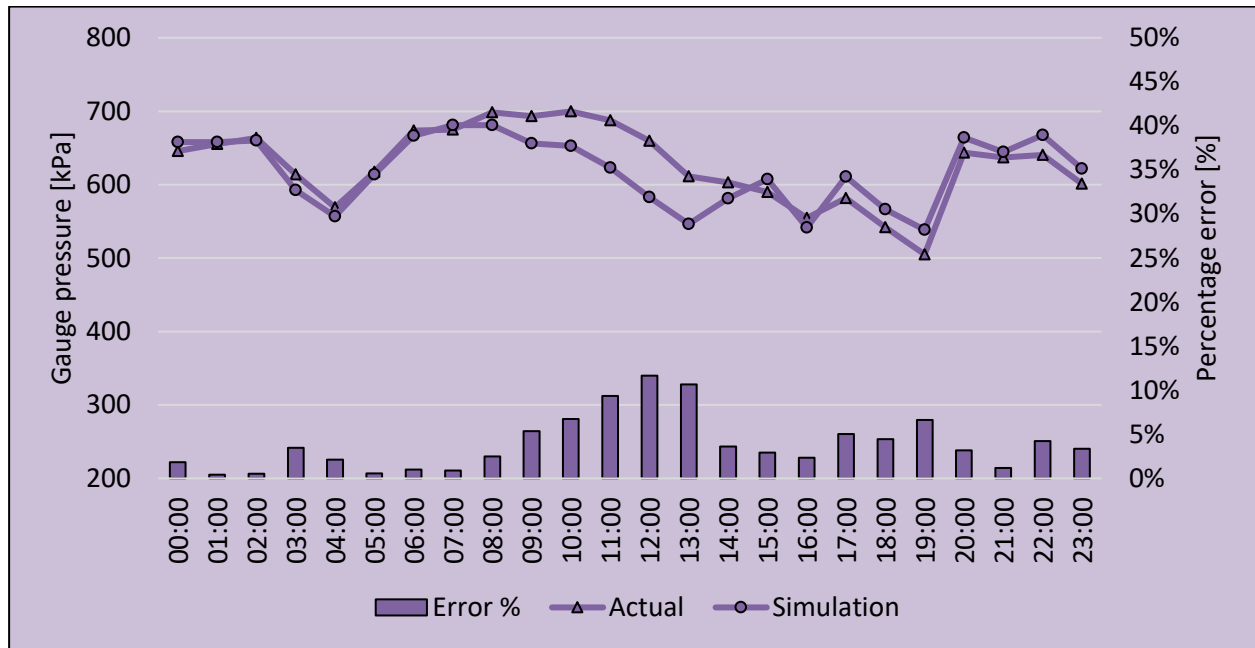


Figure 69: Hourly model performance comparison of 26-Level

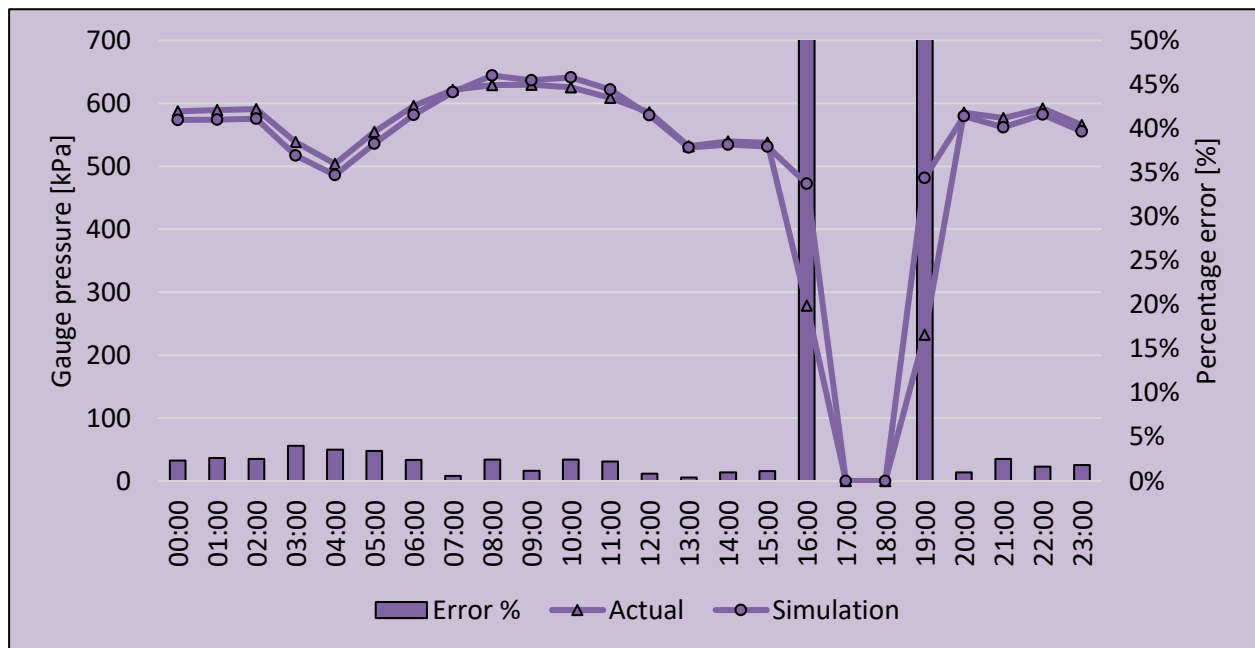


Figure 70: Hourly model performance comparison of 27-Level

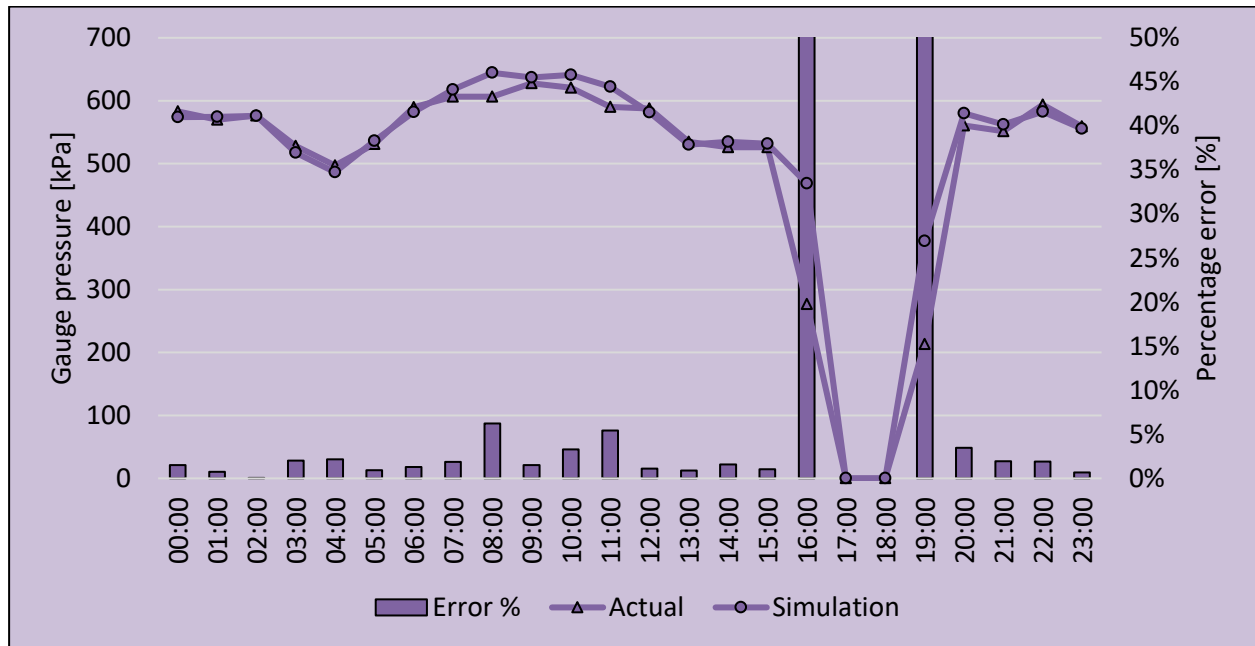


Figure 71: Hourly model performance comparison of 28-Level

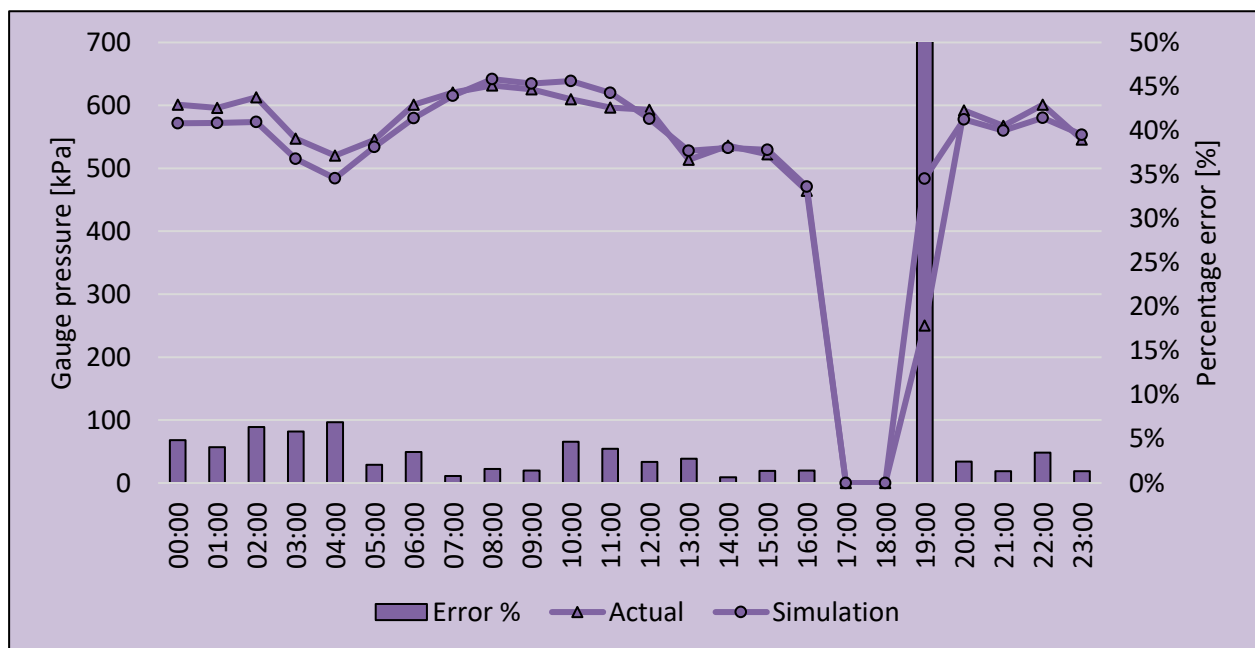


Figure 72: Hourly model performance comparison of 29-Level

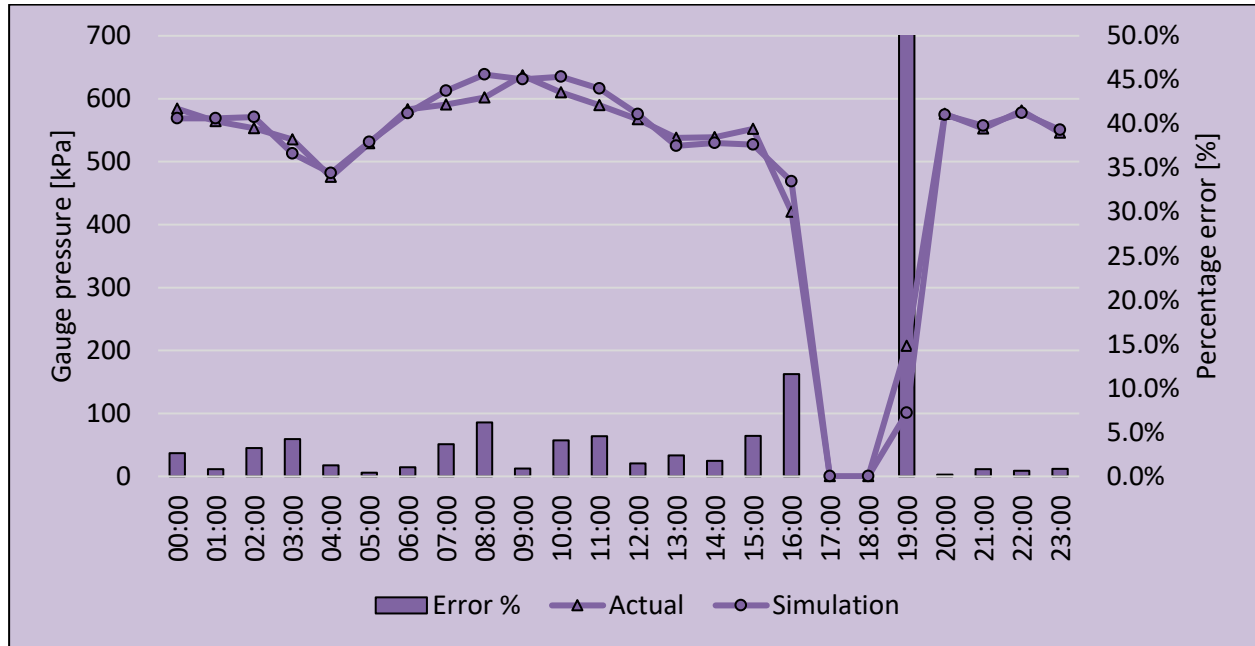


Figure 73: Hourly model performance comparison of 30-Level

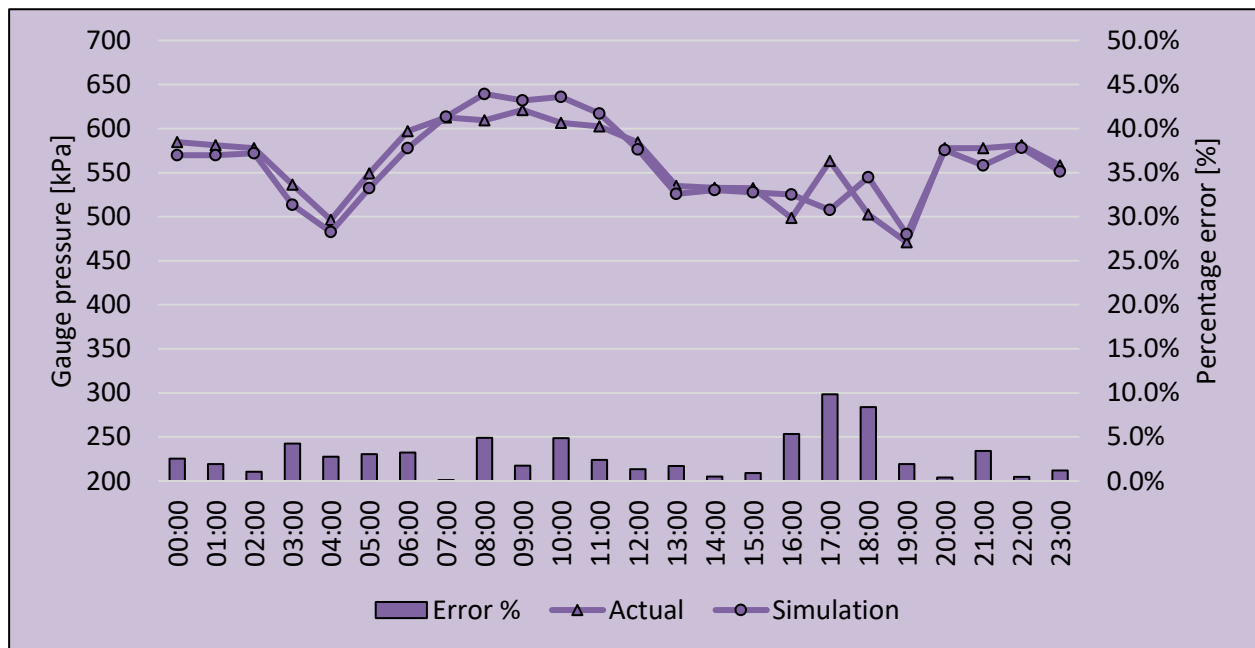


Figure 74: Hourly model performance comparison of 31-Level

Table 27: Baseline date mining crew data

Crew area and type	Number of drill users
Merenskey_22W_StopingNumCrews	0
Merenskey_24E_OnReefDevNumCrews	8
Merenskey_24E_StopingNumCrews	50
Merenskey_24E_WasteDevNumCrews	2
Merenskey_24W_OnReefDevNumCrews	14
Merenskey_24W_StopingNumCrews	80
Merenskey_24W_WasteDevNumCrews	6
Merenskey_25E_OnReefDevNumCrews	10
Merenskey_25E_StopingNumCrews	55
Merenskey_25E_WasteDevNumCrews	2
Merenskey_25W_OnReefDevNumCrews	12
Merenskey_25W_StopingNumCrews	105
Merenskey_25W_WasteDevNumCrews	8
Merenskey_26E_OnReefDevNumCrews	22
Merenskey_26E_WasteDevNumCrews	2
Merenskey_26W_OnReefDevNumCrews	14
Merenskey_26W_StopingNumCrews	50
Merenskey_26W_WasteDevNumCrews	6
UG2_21E_WasteDevNumCrews	4
UG2_22E_WasteDevNumCrews	2
UG2_23E_OnReefDevNumCrews	6
UG2_23E_StopingNumCrews	15
UG2_23E_WasteDevNumCrews	8
UG2_24E_OnReefDevNumCrews	10
UG2_24E_StopingNumCrews	10
UG2_24E_WasteDevNumCrews	8
UG2_25E_OnReefDevNumCrews	6
UG2_25E_WasteDevNumCrews	4
UG2_25W_OnReefDevNumCrews	18
UG2_25W_WasteDevNumCrews	4

UG2_26E_OnReefDevNumCrews	2
UG2_26E_WasteDevNumCrews	2
UG2_26W_OnReefDevNumCrews	10
UG2_26W_StopingNumCrews	50
UG2_26W_WasteDevNumCrews	6
UG2_27W_OnReefDevNumCrews	8
UG2_27W_StopingNumCrews	50
UG2_27W_WasteDevNumCrews	6
UG2_28W_OnReefDevNumCrews	6
UG2_28W_StopingNumCrews	40
UG2_28W_WasteDevNumCrews	6
UG2_29W_OnReefDevNumCrews	6
UG2_29W_StopingNumCrews	40
UG2_29W_WasteDevNumCrews	2
UG2_30W_OnReefDevNumCrews	16
UG2_30W_StopingNumCrews	30
UG2_30W_WasteDevNumCrews	8
UG2_31W_OnReefDevNumCrews	16
UG2_31W_StopingNumCrews	90
UG2_31W_WasteDevNumCrews	2