



Improving compressed air networks on PGM mines in South Africa through continual monitoring and reporting

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ABSTRACT

The South African platinum group metals (PGM) mining industry faces significant challenges due to the energy consumption of compressed air networks, which accounts for approximately 21% of total electricity usage. With rising electricity costs and fluctuating commodity prices, PGM mines must prioritise sustainable efficiency improvements and cost reduction strategies to remain profitable. A method explained in this document shows a potential annual cost saving of R1.6 billion on compressed air networks in the South African PGM industry (across 26 identified mines). This finding further emphasises the necessity of implementing effective efficiency improvement initiatives.

A major contributor to these significant potential savings is the mismanagement and inefficient use of compressed air on the demand side. Issues such as leakages and using compressed air for ventilation in hot underground working areas continue to plague the industry. Previous studies have investigated various demand-side improvement initiatives in an attempt to address these inefficiencies.

While extensive research has been conducted on improving the efficiency of compressed air networks in the South African mining industry and identifying inefficiencies in these complex underground networks, there is a noticeable gap in the literature regarding the continual monitoring and reporting of compressed air network performance to improve the demand-side. This study aims to fill this gap by proposing a solution to improve the demand-side efficiency of compressed air networks in the South African PGM mining industry through continual monitoring and reporting.

This study presents a practical solution that was applied to a mining group in the South African PGM mining industry. The main objective of this research study was to develop a solution using continual monitoring and reporting to improve the demand side of compressed air networks in the South African PGM mining industry. This solution focused on identifying, acquiring and validating data, as well as developing reports for daily and weekly monitoring and a procedure for continual monitoring and reporting on inefficiencies. Additionally, it aimed to ensure progress is tracked in rectifying identified inefficiencies.

The objectives of this study were achieved successfully, demonstrating that continual monitoring and reporting of compressed air network performance on the demand-side can yield significant cost savings. This potential for financial benefit highlights the practicality and effectiveness of the proposed solution. The solution can be utilised to monitor and identify inefficiencies such as malfunctioning instrumentation, which saved approximately R150 000 over five weekdays in one

case study. When initiatives are implemented with managerial support – such as closing control valves during the blasting period – an annual energy reduction of up to 5.6 GWh, translating to approximately R10.6 million, may be realised. Furthermore, the developed solution proves effective for underground operations, potentially leading to an annual reduction of 3.7 GWh or R7.2 million through efficiency initiatives focused on improving ventilation controls in underground working areas.

Keywords: South African PGM mining industry, continual monitoring and reporting, energy management, compressed air demand-side management, energy savings, cost savings.

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LIST OF ABBREVIATIONS

DSM	Demand-side Management
GHG	Greenhouse Gas
GWh	Gigawatt hours
HR	Human Resources
ISO	International Organization for Standardization
MRM	Mineral Resources Management
OEM	Original Equipment Manufacturer
PDCA	Plan-Do-Check-Act
PGM	Platinum Group Metals
PID	Proportional, Integral, Derivative
PLC	Programmable Logic Controller
SA	South Africa
SCADA	Supervisory Control and Data Acquisition
SI	International System of Units
TOU	Time-of-Use

NOMENCLATURE

Symbol	Description	Unit
σ	Data set standard deviation	–
b	Average power consumption during blasting period	MW
C_{factor}	Consumption factor	%
d	Average power consumption during drilling shift	MW
DI	Demand reduction potential indicator	(kg/s)/km
E_{Comp}	Compressor energy requirement	MWh
ERR	Energy reduction ratio	%
h	Compressed air column length from station to the crosscut	m
H	Compressed air column length from station to end of development	m
L	Active underground compressed air network length	km
LCL	Lower control limit	–
P	Compressed air pressure (gauge)	kPa
P_{factor}	Production factor	%
Q	Compressed air mass flow rate	kg/s
T	Tonnes of ore mined	kt
UCL	Upper control limit	–
$\hat{x}$	Data set mean	–
Z	Depth of mine	m

CHAPTER 1: INTRODUCTION AND LITERATURE

1.1 Compressed air in industry

Compressed air is often referred to as the fourth utility, following electricity, natural gas, and steam [1]. It is commonly used in industry for numerous operations because of its safe and simple generation, manipulation, and usage [2]. However, industrial compressed air networks are known to be energy intensive and inefficient, be it the supply or demand side of the system [3], [4], [5]. Therefore, it is a double-edged sword; as an operation expands, the size and complexity of the compressed air network will likely increase, resulting in unnecessary inefficiency.

Several studies have quantified how much compressed air networks contribute to a country's industrial energy demand [6], [7], [8], [9]. Figure 1 illustrates the average industrial energy consumption of compressed air generated per country. The United States, China, Germany, as well as countries part of the European Union were selected to give perspective on the extent to which compressed air generation contributes to worldwide energy consumption. Compared with other countries, South Africa contributes a significant portion of its energy to the total industrial energy consumption.

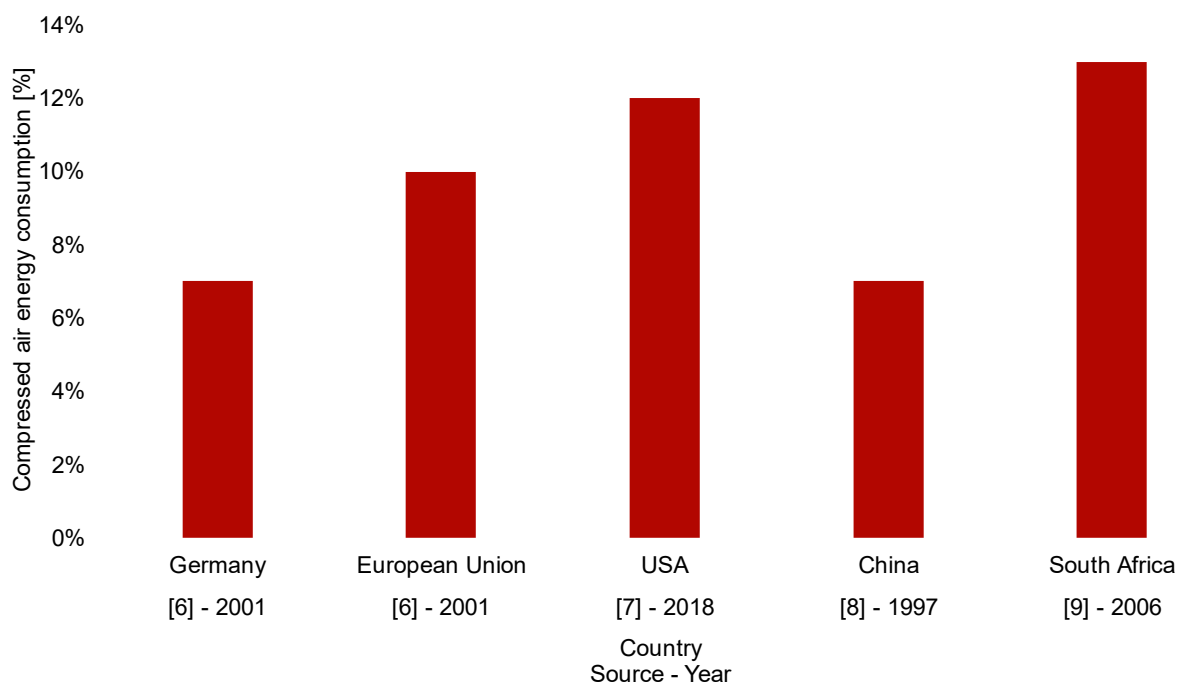


Figure 1: Compressed air energy consumption of the industrial sector per country

According to Radgen and Blaustein [6], compressed air generation accounted for 10% of the European Union's industrial sector electricity consumption in 2001, while in the United States and China, it accounted for 12% [7] and 7% [8], respectively, in 2018 and 1997. In South Africa, a

study conducted by Howells estimates the electricity consumed to generate compressed air to be approximately 13% of the industrial sector [9].

In 2020, South Africa was ranked 17th on the Mining Contribution Index, an index that was designed to improve the understanding of how the mining industry contributes to a country's economy [10]. The other countries shown in Figure 1 were all ranked below the 67th position. This likely explains why South Africa's average industrial energy consumption for generating compressed air is higher than other countries.

Howells further determined the energy consumption of different sub-industries in South Africa [9]. Figure 2 illustrates the electricity consumption of compressed air generation per sub-industry in South Africa, which further supports the notion that mining is the cause of the high energy consumption attributable to compressed air generation.

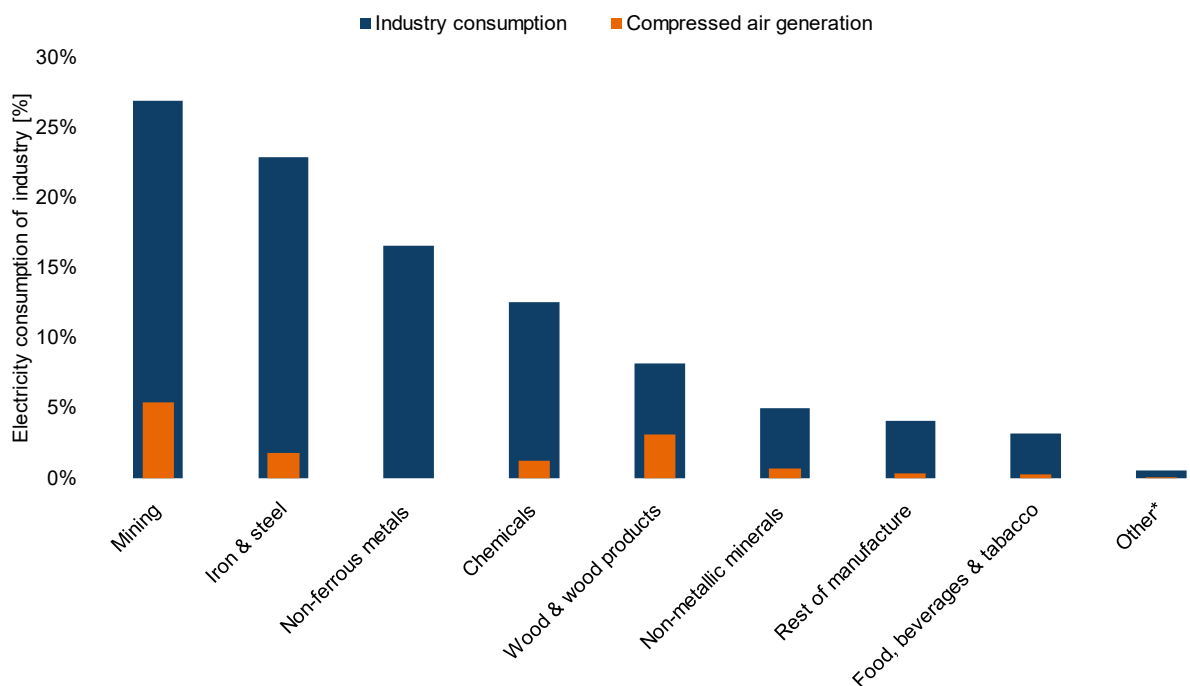


Figure 2: Industry and compressed air electricity consumption in South Africa (2006), adapted from [9]

**Other: Textile, cloth and leather, and the remainder of the basic metals*

Figure 2 shows that the largest industrial electricity consumer in South Africa was the mining industry, of which the mining of platinum group metals (PGM) consumed roughly 6% of the electricity for compressed air generation [9], totalling 7 209 GWh in 2003. Data from the operations of seven South African PGM mining companies were compiled for the year 2022, equating to roughly 12 179 GWh (as explained in Appendix A) [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22].

Howells further found that approximately 20% of electricity consumption is attributed to compressed air generation throughout the mining industry, which aligns with the assumptions made in Appendix A [9]. Therefore, it is reasonable to assume that these figures have remained consistent, indicating that South Africa's industrial energy consumption for compressed air generation surpasses that of other countries, as shown in Figure 1.

Doubting the efficiency of compressed air in the mining industry, Fraser conducted a study in 2008 comparing the efficiency of compressed air to alternative technologies [23]. The energy transport medium generation, reticulation losses (friction losses), reticulation leakages, and rock drill efficiency were compared in this study. Remarkably, the overall efficiency of compressed air networks ranked the lowest at 2%, below pumped hydropower, which ranked at 20%, as seen in Table 1.

Table 1: Relative effectiveness of energy delivered to the rockface for various energy transport mediums used in drilling, adapted from [23]

Technology	Efficiency of compressor or pump	Reticulation pressure or voltage drop	Energy left after leakages	Efficiency of drill	Overall efficiency
Compressed air	58%	75%	18%	24%	2%
Hydropower – pumped	85%	80%	95%	31%	20%
Oil electro-hydraulic	80%	80%	100%	36%	23%
Hydropower – gravity	96%	89%	90%	31%	24%
Electric drill	100%	90%	100%	35%	32%

Multiple studies have confirmed that compressed air networks have many inefficiencies [9], [11], [23], [24]. In 2006, Howells ranked compressed air savings initiatives as the most profitable demand-side management (DSM) energy savings initiative in South Africa [9]. According to Zietsman [11], compressed air savings continue to be a major focus of the DSM energy savings initiative in South Africa's gold and PGM mining industries.

If the seven PGM companies mentioned in Appendix A could achieve the reduction suggested by Zietsman [11], an average of almost 200 MW could be saved. This roughly translates to R1.6 billion per annum in electricity costs for the industry. With increasing electricity tariffs, this value supports the need for efficiency improvements on compressed air networks in the PGM mining industry in South Africa.

Compressed air networks are inefficient, but replacing or converting such an extensive system would require a significant investment of financial capital, resources, and time in the mining industry [23]. As an interim solution, the inefficiency of compressed air networks should be scrutinised and improved. According to Nehler, although numerous studies have been published on improving compressed air network efficiency [25], it is necessary to understand mining

operations and the use and management of compressed air networks to develop a sustainable solution.

1.2 Compressed air networks in South African PGM mines

This section will introduce the reader to operations relating to compressed air networks in PGM mines in South Africa. Firstly, a brief overview of a typical mining operational cycle and the utilisation of compressed air is given. Thereafter, general operations on the supply and demand side of compressed air networks in PGM mines are discussed. Finally, methods to identify and prioritise compressed air inefficiencies and their monitoring and reporting are discussed.

1.2.1 Mining operations and compressed air utilisation overview

There is an age-old practice of extracting raw materials from the earth's crust, which has provided the science and engineering fields with numerous minerals and metals for the production of the latest technological innovation.¹ Currently, 90% of the global PGM ore reserves and 5% of the global gold ore reserves are found in South Africa [26].

The mining life cycle is typically divided into the following phases [27], [28], [29]:

1. **Exploration:** Geologists and mining engineers conduct surface and underground explorations to determine the location, size, and quality of the orebody that needs to be extracted.
2. **Development:** Mine development work, which includes building access shafts, tunnels, and other underground infrastructure, starts once the orebody has been located and assessed.
3. **Extraction:** Mining ore from the mine may entail drilling and blasting the rock, followed by using locomotives and loaders to move the ore to the surface.
4. **Processing:** After being mined, the ore is taken to a facility for processing, where it is cleaned, crushed, and refined.
5. **Waste handling:** Underground mines produce a significant amount of waste that needs to be disposed of in an environmentally friendly and safe way.
6. **Mine closure:** A mine must be shut down when the orebody has been exhausted or mining is no longer profitable. This may entail recovering the mine's surface area and filling the underground workings with concrete or other materials to prevent cave-ins.

¹ N. Moodley, "PGMs shaping the world," *Business Media Mags*, <https://businessmediamags.co.za/mining/sa-mining/pgms-shaping-the-world/> (Accessed April 15, 2024).

During the development and extraction phases of the mining life cycle, a typical operational production cycle comprises three consecutive shifts: drilling, blasting, and cleaning. These shifts occur continuously during a 24-hour period [30]. Shift changes provide mining personnel with enough time to arrive at their respective working areas or return to the surface. Figure 3 illustrates a typical mining operational production cycle.

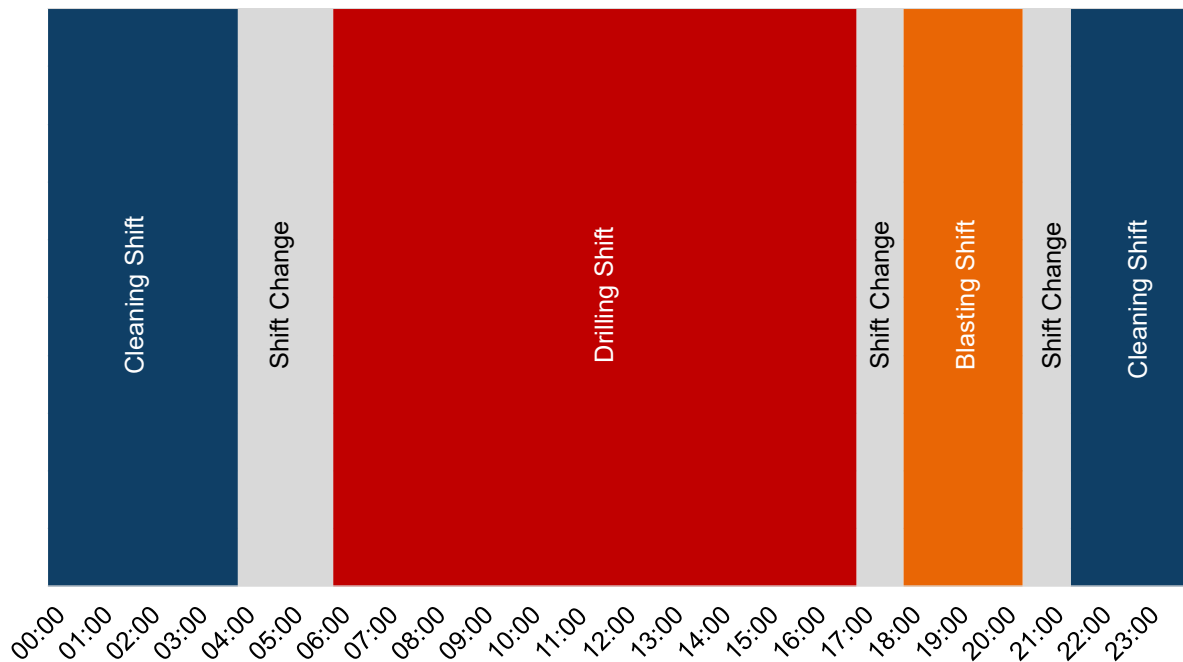


Figure 3: Typical mine production cycle

During the drilling shift, pneumatic rock drills are used to drill holes of a predetermined depth in the rockface, in which explosives are inserted. These explosives are set off at the beginning of the blasting shift, whereafter time is given so that hazardous gases can be drawn out of the workspaces using the ventilation system. During the cleaning shift, the detonated rock is swept to ore passes (holding boxes) awaiting the underground transport system [28].

Figure 4 shows the many processes and equipment in the mining production cycle that consume compressed air. Compressed air is used to operate whistles, roof bolters, water pumps, and rock drills in the working areas. Three distinct operations in the primary haulage use compressed air, namely refuge bays for safety per the Mine Health and Safety Act [31]; ore pass chutes for loading ore into locomotives (the transport system); and loaders for sweeping blasted rock in the main haulage's development sections [28].

At the main shaft (also known as the station), compressed air is used to open chutes for the main ore pass, which leads to the shaft bottom, where the loading boxes are located. It is also used for auxiliary equipment, such as pneumatic posts, which prevents the locomotives from falling into

the main shaft. Compressed air further powers the loading boxes at the shaft bottom, which load ore onto skips, transporting the product to the surface.

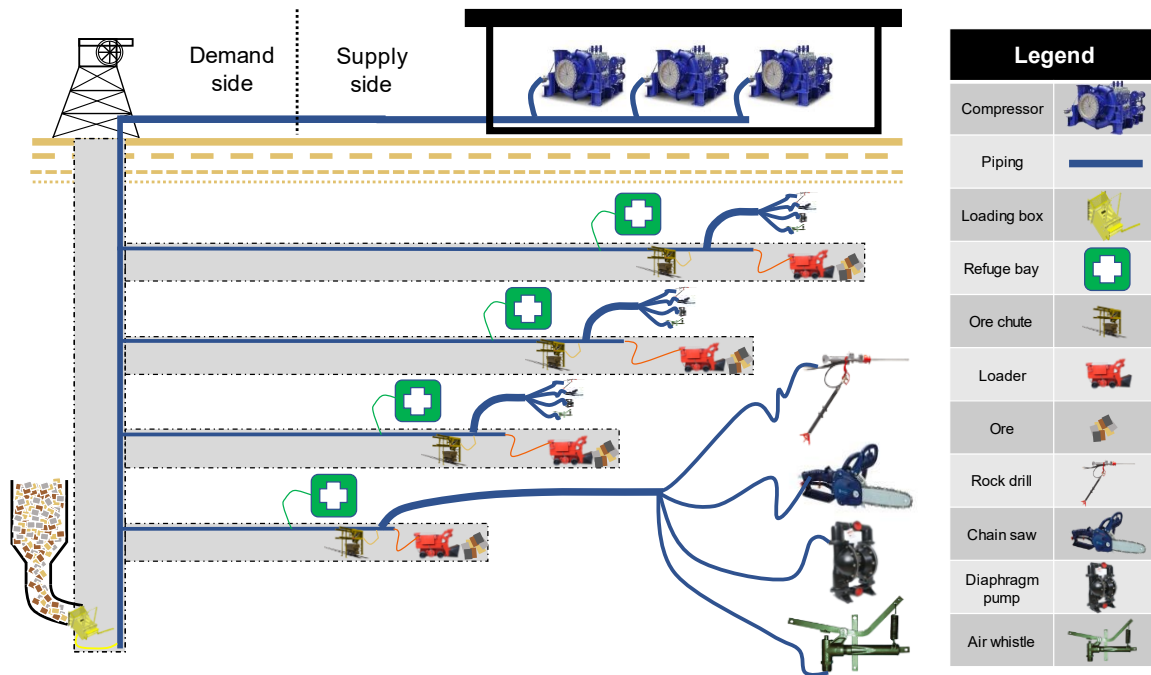


Figure 4: An overview of compressed air users on an underground mine, adapted from [24]

Compressors on the surface generate compressed air to provide the necessary energy for the equipment illustrated in Figure 4. They are positioned such that one compressor (or compressor house) provides compressed air to a single mineshaft or a ring configuration that feeds multiple shafts, as seen in Figure 5 and Figure 6 [32], [33], [34], [35], [36].

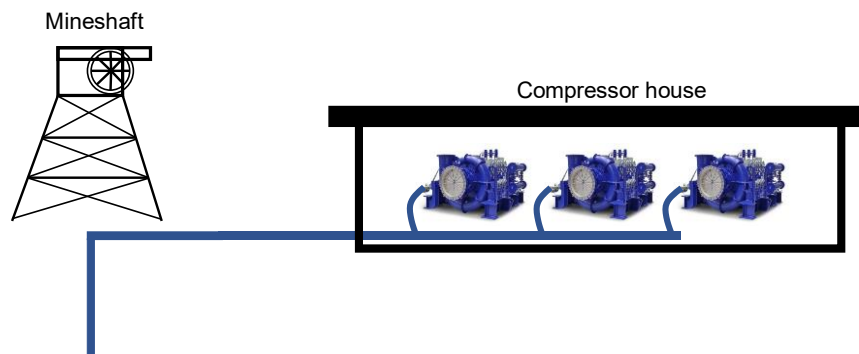


Figure 5: Example of a single mineshaft supply configuration

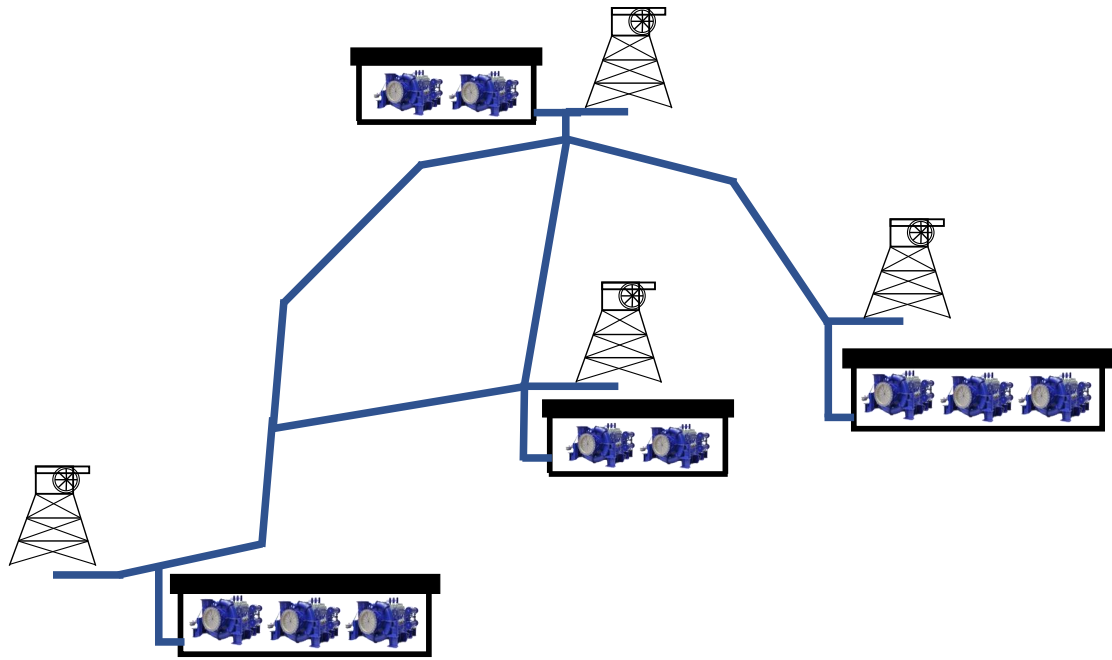


Figure 6: Example of a ring supply configuration

The ring configuration provides redundancy in the case of compressor faults, maintenance, or power failure [11]. The generated compressed air is distributed via large and intricate pipeline networks. Managing extensive systems like compressed air networks in underground mines is a complicated task not only due to their size and complexity but also the that the piping networks are underground [11].

For convenience, the system is divided into two sections, namely the supply and demand sides, as seen in Figure 4. The supply side involves the generation and distribution of compressed air, whereas the demand side is characterised as any end user that consumes compressed air [11], [23]. The following sections describe typical operations on the supply and demand side, providing the reader with an overview of a typical compressed air network in an underground mine.

1.2.2 Supply side

The supply side, responsible for generating and distributing compressed air, typically includes the following components:

Compressors: This equipment pressurises and compresses atmospheric air using mechanical and electrical energy. There are several types of compressors, each with its own unique benefits and drawbacks. Centrifugal compressors are typically used in the mining industry because they are easy to operate and maintain, and have a high supply capacity. The installed capacity of electric motors that drive compressors in mines is generally 3–5 MW, but some may be as large as 15 MW [33], [34]. One such compressor is illustrated in Figure 7.



Figure 7: Single-stage centrifugal compressor²

Air treatment: Compressed air contains contaminants such as moisture, oil, and other impurities that can damage pneumatic machinery and processes. Air treatment components, including filters, dryers, and oil/water separators, are deployed on the network's supply side to supply clean and dry compressed air. Figure 8 illustrates a typical compressed air dryer and filters.



Figure 8: Compressed air is treated via dryers³ and filters⁴

Piping network: Compressors distribute compressed air to end users via a network of pipes known as the piping network. An example is illustrated in Figure 9.

² Image from "Centrifugal Compressors: Chart Industries," chartindustries.com, <https://www.chartindustries.com/Products/Compression-Centrifugal-Compressors> (accessed April 15, 2024).

³ Image from "Types of compressed air dryer," energypurse.com, <https://www.energypurse.com/type-of-compressed-air-dryer> (accessed April 15 2024).

⁴ Image from "Compressed air and gas filters," walkerfiltration.com, <https://www.walkerfiltration.com/en-us/products/compressed-air-and-gas-filters/> (accessed April 15, 2024).



Figure 9: Multistage compressor with pipelines used to transport fluid to end users⁵

Control and monitoring system: Used to manage the compressors, air treatment components, storage tanks, and the piping network, usually from a central point, as illustrated in Figure 10.



Figure 10: Control room used as a central point where all operations can be monitored and controlled⁶

The supply side aims to meet the demand-side requirements, i.e. to ensure adequate pressures are provided to end users. The supply side must operate compressors to match the demand throughout the day, while avoiding pressure increases that could cause equipment and network failure, as well as low pressures that might result in a loss of production [33], [35].

The efficiency of the piping network is challenging to manage due to the size of the compressed air networks. One significant issue associated with the piping network is friction losses. With an increase in demand, i.e. an increase in flow rate, the pressure drop between supply and demand

⁵ Image from "DLR – Compressed air system at the DLR site in Cologne," dlr.de, <https://www.dlr.de/content/en/research-facilities/compressed-air-system.htm> (accessed April 15, 2024).

⁶ Image from "Industrial control room furniture for gas, oil and process control," thinking-space.com, <https://thinking-space.com/2020/08/18/sector-showcase-series-industrial-control-room-furniture-for-gas-oil-and-process-control/> (Accessed April 15, 2024).

will also increase. More compressors are required on the supply side to keep supplying adequate pressure. This leads to an increase in the amount of electricity required to generate compressed air. It is necessary to understand the demand side to address this issue, as explained in the following section.

1.2.3 Demand side

The supply and demand side share components mentioned in the previous section, such as air treatment, storage, piping network, and control and monitoring systems. The difference between the supply and demand side is that one generates compressed air, whereas the other consumes it, with the demand side being directly linked to mining production. Figure 11 illustrates a typical mining production action, i.e. rock drilling, which utilises a pneumatic rock drill operated by personnel.



Figure 11: Rockdrill operator drilling a hole with a pneumatically operated rock drill where explosives will be placed⁷

⁷ E. Hazelhurst, "Analysts warn of growing mine risk," *IOL*, April 8, 2013. Image by B. Ngwenya. <https://www.iol.co.za/business-report/economy/analysts-warn-of-growing-mine-risk-1496616> (Accessed April 15, 2024).

The demand side includes various pieces of equipment that continuously consumes compressed air. Table 2 lists some of this equipment as well as the shift where the equipment is used predominantly. Although not listed in Table 2, two other inefficient consumers contribute significantly to compressed air demand: mismanagement and misappropriation. Mismanaged consumers are typically open utility piping to inactive mining areas or leakages on the piping network. Examples of misappropriated consumers include ventilating with compressed air or leaving inactive equipment running [24].

Table 2: Various compressed air end users, adapted from [24], [37], [38], [39]

Shift	Equipment	Purpose
Blasting	Refuge bays	Providing a safety area in case of emergency.
Cleaning	Loaders	Loading ore from the development ends into track-bound hopper cars.
	Ore chutes	Transferring ore collected from stopes into track-bound hopper cars.
	Air whistles	Signal moving of equipment or moving of ore by winches.
	Shotcrete machine	Coating haulage walls with shotcrete to prevent falling rocks.
	Refuge bays	Providing a safety area in case of emergency.
Drilling	Rock drills	Drilling holes in the rockface.
	Explosive charges	Loading explosives into drilled holes in the rockface.
	Diaphragm pumps	Pumping water away from the rockface.
	Air whistles	Signalling moving equipment or moving of ore by winches.
	Ore chutes	Transferring ore collected from stopes into track-bound hopper cars.
	Refuge bays	Providing a safety area in case of emergency. Ventilated with compressed air.
	Pneumatic actuators	Operating valves on utility piping.
Shift changes	Refuge bays	Providing a safety area in case of emergency.

Zietsman highlighted the extent to which these inefficiencies affect the total compressed air consumption of a shaft [11]. Figure 12 compares the simulated theoretical consumption of authorised end users with the actual consumption of a typical underground mine. The key point that Figure 12 illustrates is that there is a significant discrepancy between actual and theoretical consumption. This leads to the conclusion that compressed air is being used for purposes other than initially intended, i.e. mismanagement and misappropriation.

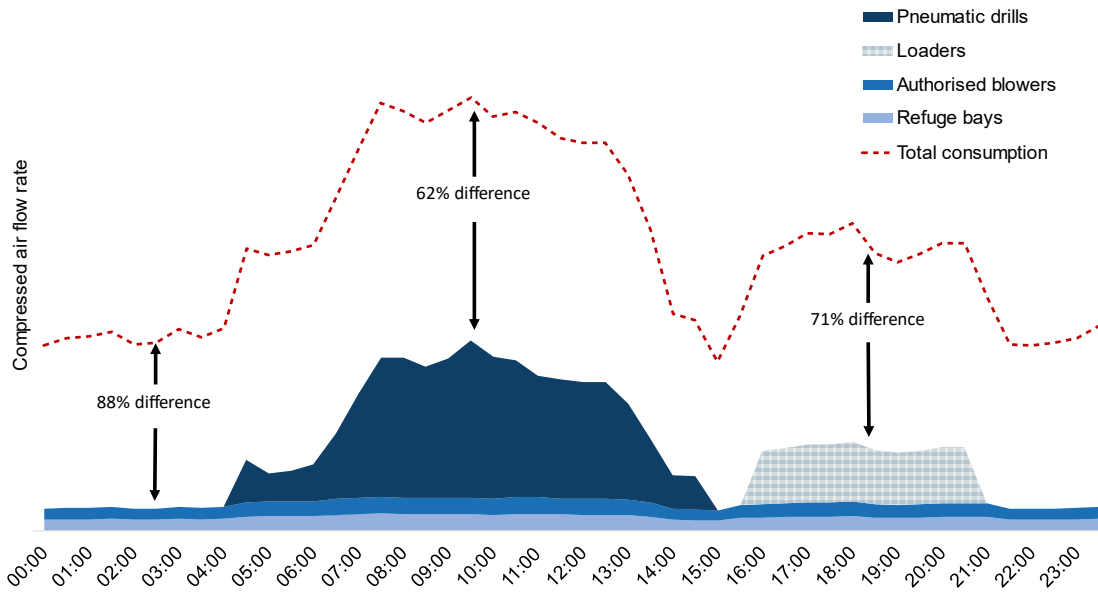


Figure 12: Comparison of the simulated theoretical consumption of authorised compressed air end users versus the actual consumption of a mine, adapted from [11]

In the context of mining operations, two main factors contribute to each previously mentioned inefficient consumer, namely the virgin rock temperature and dynamic nature of the mining production cycle [30], [39], [40].

Jones found that the Bushveld Indigenous Complex (PGM mining) has a higher geothermal gradient than the Witwatersrand Basin (gold mining) due to different rock types. This means that PGM mining requires more cooling than gold mining at the same depth. Nonetheless, it is widely known that deeper mines require more cooling due to higher virgin rock temperatures [40].

In the case of reaching the capacity of ventilation and refrigeration systems, it is likely that personnel will resort to ventilating with compressed air as an alternative. It is often found that personnel do not comply with ventilation controls underground and resort to the inefficient practice of ventilating with compressed air, leading to inefficiencies in the ventilation system [11], [24], [39].

The other cause of mismanaged or misappropriated users is the dynamic nature of the mining production cycle. As work areas are being mined, new areas are developed to facilitate continuous production. This often leads to mining areas becoming abandoned without utility piping to these working areas being sealed because there may still be a small amount of ore that can be mined from the 'abandoned' working area [11], [24].

1.2.4 Identifying compressed air network mismanagement and misappropriation

From Figure 12 it is evident that misappropriation and mismanagement contribute significantly to unnecessarily high electricity bills. Determining the location of these inefficiencies quickly is of

utmost importance to continually improve the efficiency of a compressed air network in underground mines, thereby reducing cost and improving pressure in the working areas [11], [30], [41].

Identifying compressed air network inefficiencies can be compared with finding a needle in a haystack. This study contributes to finding the needles faster and, to an extent, automating the search and reporting procedure to ensure this occurs continually. However, it is necessary to gain an understanding of the current methods for identifying compressed air inefficiencies in underground mines.

Referring to Figure 4 and Figure 13, a mine typically consists of levels that are divided into half-levels, which are designed to access the orebody. The entry or resting areas before the working areas are found in crosscuts, which are found in the half-levels (or drives). From the working area, a travelling way leads to the centre gully, which connects to strike gullies (or advanced strike gullies) and, furthermore, the panels at which drilling operations take place. Further along the haulage of the half-levels are the end of the development areas, which are in the process of being developed to acquire more access to the orebody.

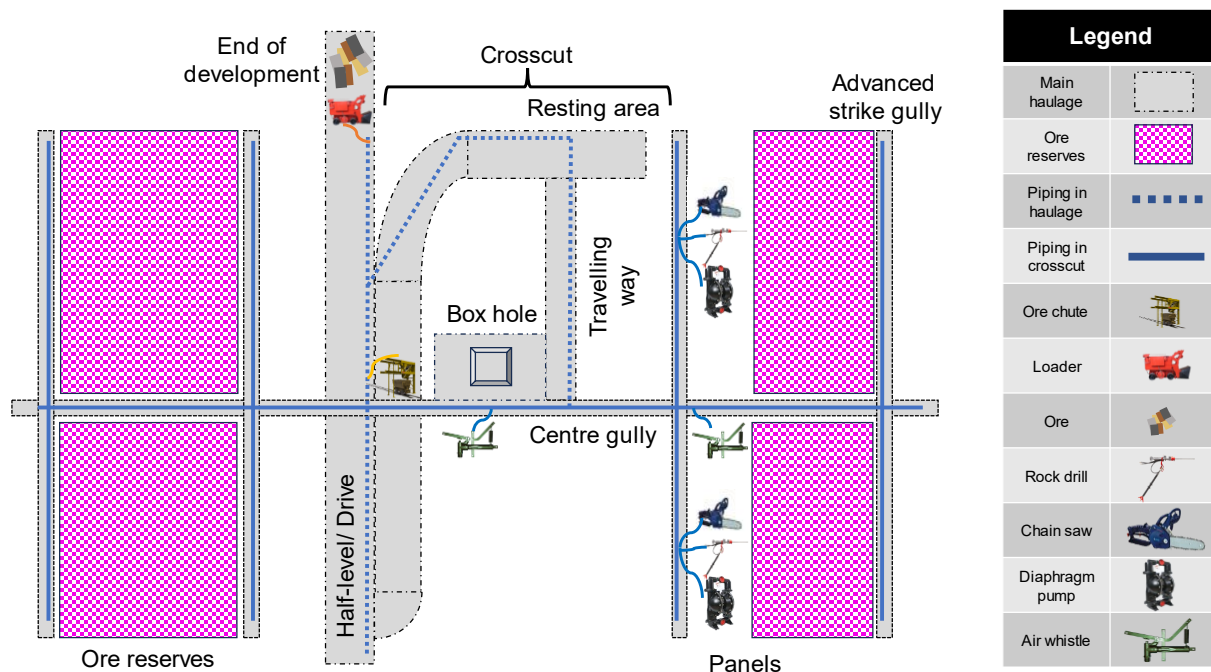


Figure 13: Typical illustration of an underground working area

Compressed air columns are installed all along the haulage. They are designed to provide adequate pressure to the working areas, which occasionally span a few kilometres. Conventional methods entailed auditing the entire shaft to identify and prioritise areas where the most or largest leakages are found. One such method was detailed in the study by Fouché [42]:

A day before the actual leak audit, the following must be checked against the pre-auditing checklist:

1. Compile an underground layout indicating problem levels.
2. Request details from mine personnel regarding heads of various levels, shafts, etc.
3. Indicate the underground areas for leak auditing to the responsible mine personnel.
4. Prepare all documentation and accessories (bright flashlight, camera, notebook, and layouts of underground levels).
5. Organise an underground site visit.
6. Study all the levels beforehand.

Once the pre-auditing checklist has been completed, the approach is continued by developing the actual leak auditing process:

7. While travelling down the shaft, note the leaks and the nearby level.
8. At the station, audit the mainline and refuge bays.
9. When a leak is identified, take a picture and note the level, location, pipe diameter, leak diameter, priority, and what can be done to fix the leak.
10. Develop a report when the leakage audit is finished.
11. Present the leak report and high-priority leaks with suggestions to the responsible mine personnel for the necessary repairs to be done on the identified leaks.

While this method may be adequate for finding inefficiencies, it is still laborious. Fortunately, a few authors have determined that research on compressed air auditing requires attention and have since developed improved methods for acquiring adequate information on inefficient consumers.

In the mining industry, a top-down approach is usually followed by prioritising a specific shaft as a focus for efficiency initiatives through different methods of benchmarking [11], [41], [43]. Thereafter, methods such as those developed by Du Plooy [44] and Zietsman [11] can further be used to identify specific areas of inefficiency. These areas are audited visually (as detailed above) to identify the elements causing inefficiency, whether it be mismanagement or misappropriation.

The different methods can be categorised into two application areas: surface and underground. Table 3 categorises the methods by four different authors and states where they can be applied to a network of multiple shafts.

Table 3: Categorised application of previously developed methods for the identification and prioritisation of compressed air network inefficiencies and opportunities

Method	Surface	Underground
Zietsman [11]	X	X
Vermeulen [41]	X	

Cilliers [43]	X
Du Plooy [44]	X

In this study, the methods developed for surface applications will not be discussed in detail due to the focus on improving compressed air network performance in working areas underground (demand side). Before discussing the underground methods, it is essential to define their aim, which is to localise compressed air wastage to manageable areas and acquire information on the inefficiencies.

1.2.4.1 Compressed air inefficiencies

In Section 1.2.3, it was shown that acts of mismanagement and misappropriation often lead to the high consumption of compressed air. As illustrated in Figure 14, audits should identify practices of mismanagement and misappropriation. They will list inefficiencies, typically seen as open-ended hoses, leakages in piping, and substandard ventilation controls.

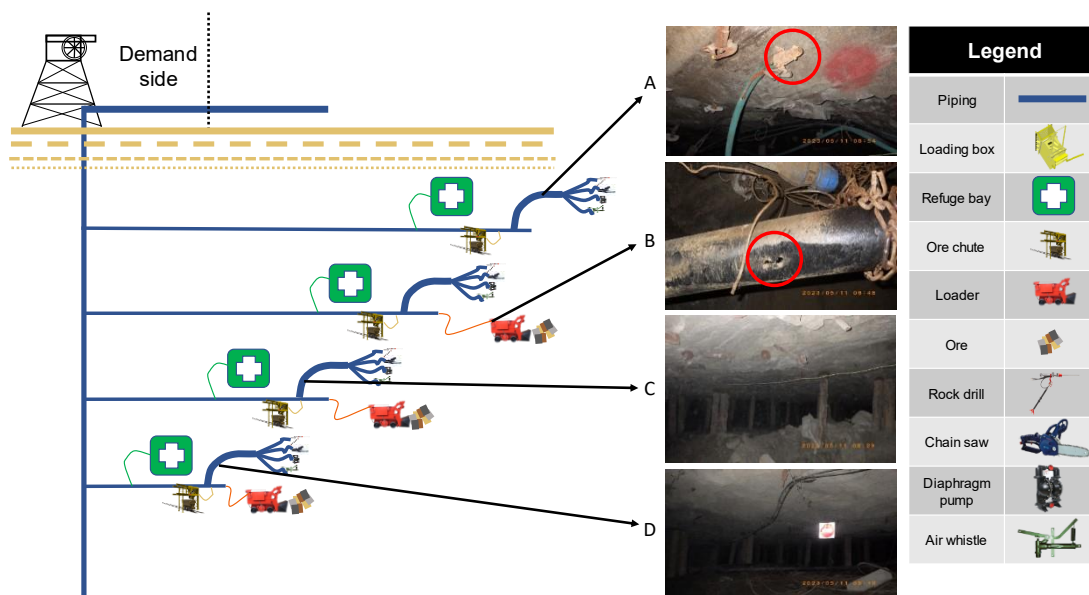


Figure 14: Inefficiencies illustrated in images A-D: A) Open-ended hose; B) Large leakage on high-density polyethylene piping; and C & D) Substandard ventilation controls. Adapted from Figure 4

1.2.4.2 Methods for localising compressed air inefficiencies

This section details the underground methods developed by Zietsman and Du Plooy, with the aim of applying them to identify working areas where the most inefficient compressed air consumption practices are prevalent.

Zietsman [11] determined that non-mining industry leak-detection methods are more developed than the techniques currently applied to compressed air networks in the mining industry. One

such method, namely step-testing, is suitable for the identification of high compressed-air-consuming areas in mines. Step-testing involves measuring the fluid mass flow rate of the network at the start of the network and closing valves to specific areas one by one. The difference in the fluid mass flow rate before and after valve closure is subtracted to acquire a value for the compressed air consumption of the specific area. This method is illustrated in Figure 15.

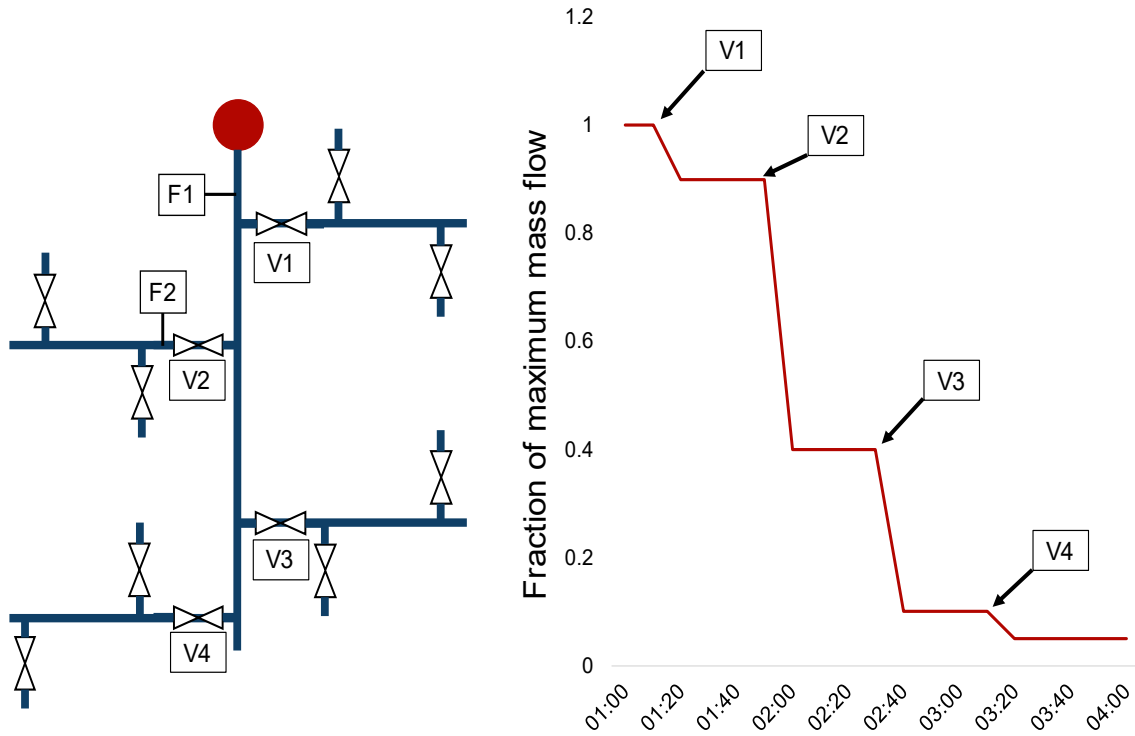


Figure 15: Step-testing method example to identify high-consuming areas in underground mines, adapted from [11]

Du Plooy [44] developed a methodology for localising compressed air leakages by benchmarking the specific level or half-level intensity. This method determines which levels or half-levels use compressed air the most efficiently. Equation (1) was developed to normalise data and acquire a better indication of how levels should be prioritised:

$$Section_{indicator} = KPI \times \left(\frac{C_{factor} + P_{factor}}{2} \right) \quad (1)$$

where:

- KPI = Key performance indicator – total compressed air consumption divided by total ore production in that section [(m³/h)/t]
- C_{factor} = Consumption factor – section consumption divided by shaft consumption [%]
- P_{factor} = Production factor – section production divided by shaft production [%]

Considering the data requirements of these two methods, the primary determinant of frequent application depends on the extent to which a mine is furnished with instrumentation and control equipment. Therefore, the monitoring and reporting of a compressed air network pivots on the

automation of data capturing. The succeeding section provides an overview of monitoring and reporting on compressed air network performance.

1.2.5 Monitoring and reporting on compressed air network performance

It is critical to monitor and report on events in a process to ensure stability and performance. Reporting refers to the verification, monitoring, and analysis of the use of different process variables and events [53], [55]. This section provides an overview of monitoring and reporting strategies, key performance indicators to consider compressed air network performance, the operational hierarchy, and its importance in managing compressed air network performance.

1.2.5.1 Monitoring and reporting

In compressed air networks in the PGM mining industry in South Africa, a multitude of variables are constantly being monitored to ensure that end users receive adequate service delivery on the demand side and equipment is maintained on the supply side. Table 4 lists Van der Zee's [48] requirements for a monitoring and reporting management strategy. They modelled electricity cost risks of deep-level gold mines in South Africa and implemented a strategy for the monitoring and reporting thereof.

Table 4: Steps for monitoring and reporting on electricity cost risks of deep-level gold mines in South Africa

Step	Description
1	Determine report requirements
2	Identify relevant stakeholders
3	Prioritise reports among resources
4	Develop reports
5	Automate reporting procedures
6	Ensure reports are delivered
7	Ensure correspondence to reports

Van der Zee had focused on a strategy for the continual improvement of the specific mining group's electricity usage. Bredenkamp [49] later successfully implemented this strategy as part of an integrated energy management system for gold mines in South Africa. However, this strategy did not discuss the details of how to identify performance anomalies and regular operations, which will be discussed in this study in Section 2.2.

Another valuable method for monitoring a process variable is found in the knowledge of statistical process control, which has multiple methods for analysing and identifying anomalies. This entails using statistical techniques to analyse and identify causes of variation in the process. Visual aids such as control charts are used to simplify the control of a process further. Control charts compare data to control limits, which are used to determine whether a process is operating normally. These

limits are known as the upper and lower control limits in relation to the control line, commonly known as the average of a set of data points. Specific zones have also been identified between the upper and lower control limits that could be used to further analyse the process according to a set of rules [50].

The upper and lower control limits are calculated by adding or subtracting three standard deviations from the mean of the data set, as illustrated in Equation (2):

$$UCL/LCL = \hat{x} \pm 3\sigma \quad (2)$$

where:

UCL/LCL = Upper or lower control limit
 $\hat{x}$ = Data set mean
 σ = Data set standard deviation

In sizable compressed air networks, it is often found that the process is too volatile to control with precision. This study will, therefore, only use the simple statistical process control technique discussed above to identify any anomalies that may decrease the performance of a compressed air network.

1.2.5.2 Key performance indicators for a compressed air network

Compressed air performance should be scrutinised in terms of service delivery and efficiency. The goal of compressed air network service delivery is to maintain the compressed air pressure that is delivered to the rockface where drilling operations take place. Low pressure leads to loss of production as rock drill operators are not able to drill at a suitable rate for production [23].

Compressed air network efficiency refers to the amount of compressed air used compared with what is required. In this study, the focus will be on compressed air efficiency, but as a side effect, increased production may be seen in the results [11]. If misappropriation or mismanagement were addressed, this would likely increase compressed air pressure, leading to better conditions for production.

A few authors have attempted to develop targets against which compressed air network efficiency can be measured [11], [38]. These methods quantify the target compressed air consumption through simulation. Compressed air consumption is typically illustrated as a 24-hour profile, as shown in Figure 16. It should be noted that the target will usually present ample opportunity for efficiency improvement, as illustrated below.

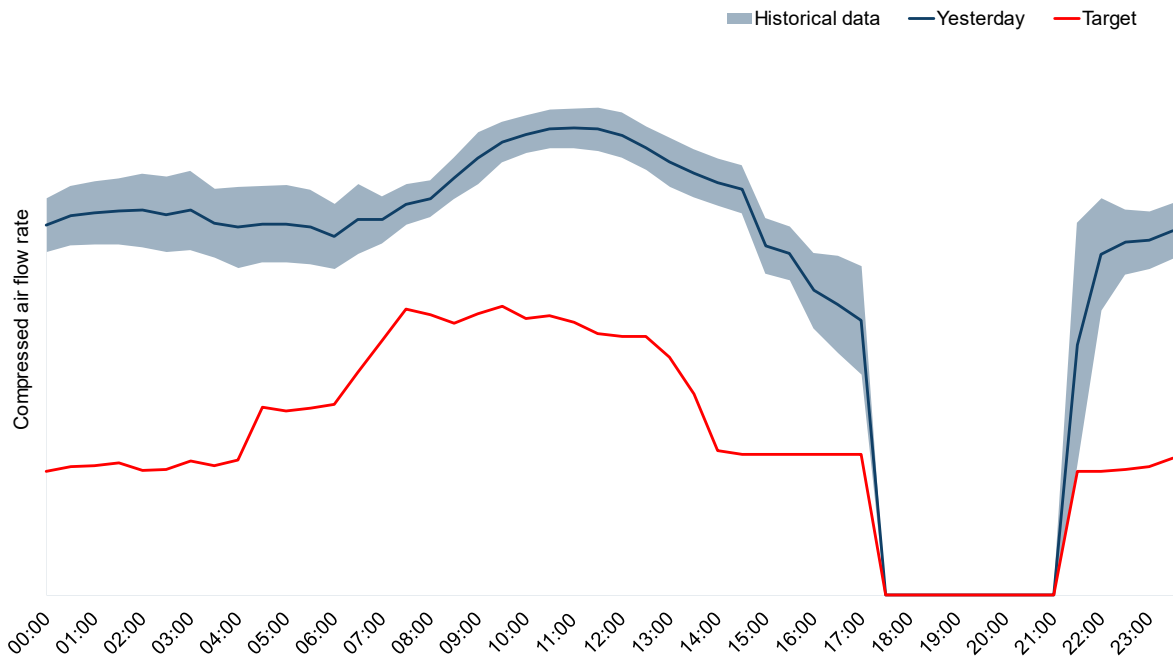


Figure 16: Typical weekday consumption monitored against historical data

Wastage can also be quantified during non-production periods (typically Sundays). Tests, such as step tests, can be conducted and the results may indicate inefficient use of compressed air [11], [24], [37]. Since no production takes place during these times, any additional use will be deemed unnecessary. This wastage, calculated as the difference between target and actual consumption, can be used to prioritise where to focus efficiency initiatives.

Chapter 2 will provide more detail on underground compressed air consumption and control valve performance. The remainder of this section provides an overview of typical operational hierarchies in a mining group.

1.2.5.3 Operational hierarchy and its importance

Once it has been determined where efforts should be focused, the information needs to be communicated to that specific section's relevant and responsible personnel to further apply efforts by conducting a step test or visual audit. Here, it is important to understand the operational hierarchy and know which person should receive reported information for action, as well as with whom arrangements must be made to acquire information or conduct tests and audits.

In general, there is not much difference between the operational hierarchies of the different mining groups [49], [51]. The mineshaft or business unit is managed by a general manager responsible for the entire operation's performance. The general manager appoints responsible personnel for managing the day-to-day production (mining), engineering, health and safety, human resources (HR), and financial operations.

The mining and engineering branches are responsible for reporting important information such as compressed air performance. However, the specific area of responsibility may vary depending on the section under scrutiny. Typically, these branches have an engineering or mining manager, an engineer or mine overseer, a foreman or shift supervisor, and a technician/artisan or miner. An example of an employee hierarchy on mineshafts is illustrated in Figure 17.

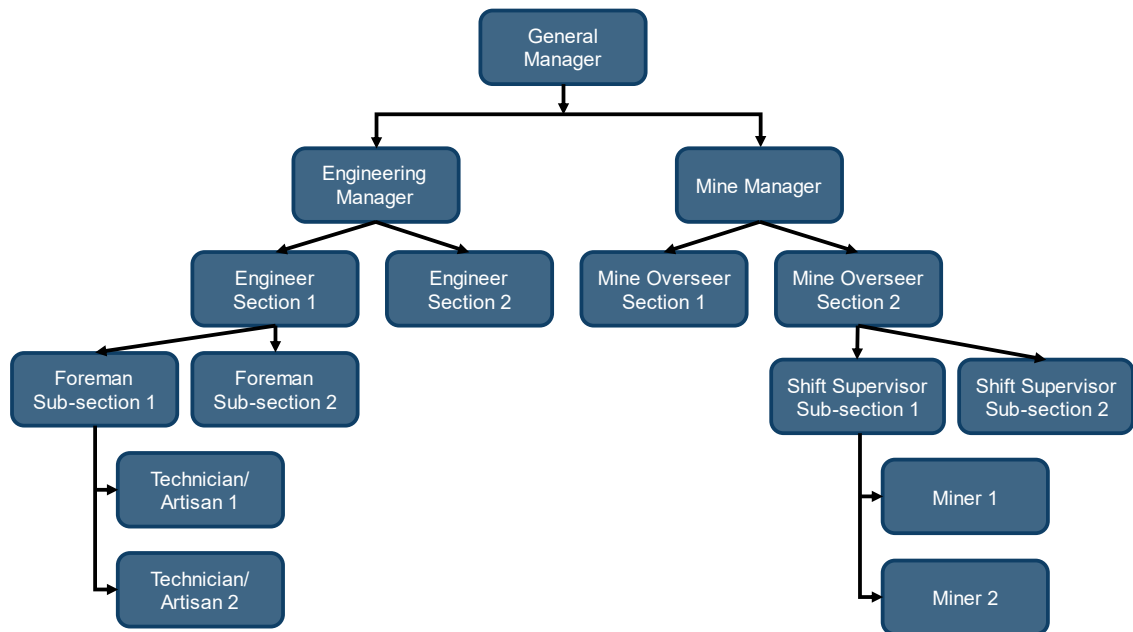


Figure 17: Example of an employee hierarchy structure on Mineshaft A of Mine Group A

It is essential that the correct information be distributed to the appropriate personnel to arrange the necessary audits or tests to identify inefficiencies. Once a visual audit for a specific working area has been completed, the audit results are typically reported to that section's engineer or mine overseer. The results are distributed so that corrective action may be taken to fix the problems highlighted in the audit report. A typical example of an audit report is illustrated in Figure 18.

The example illustrates the essential information required for reporting inefficiencies, such as the location of the inefficiency, a description of the issue, the required action to rectify the issue, and a picture of the inefficiency. To rectify inefficiencies, the action plan should contain a deadline for completion and the name of the person responsible for it. Audit reports are valuable tools for keeping personnel accountable.

Shaft	Section	Problem	Action	Photo	Responsible Person	Completion date	Status	Signature
Shaft A	Level 2 Crosscut 6	Open 2" hose from manifold	Remove 2" hose if it is not being used – take temperature and report to ventilation.					
Shaft A	Level 2 Crosscut 7	4" pipe torn	Replace 4" pipe with new one.					
Shaft A	Level 2 Crosscut 7	Puncture hole in 32" hose	Remove 32 mm hose and replace with new hose.					
Shaft A	Level 2 Crosscut 8	Puncture hole in 32" hose	Remove 32 mm hose and replace with new hose.					

Figure 18: Typical audit report of findings related to compressed air inefficiency

Once the audit report has been distributed, it is expected that the performance of that section will improve in the upcoming weeks, and it is monitored for this reason. Following this period, the performance is reported to the relevant personnel to gauge whether the audit results have increased performance and whether further action is necessary.

A follow-up visual audit usually determines whether the responsible personnel have corrected the problems. If the identified problems have not been fixed within the agreed-upon time frame, the audit findings and performance are escalated to the next person in the employee hierarchy.

Although it seems simple to rectify, personnel usually ignore compressed air inefficiencies until operational production or safety is affected. If the relevant information is reported effectively, instances such as these may be avoided. The following section describes the focus of this study and critically analyses existing literature to understand current research in this area better.

1.3 Literature review

This section provides the study's problem statement, an overview of the research area, a critical analysis of eleven studies selected from the literature, and identified objectives that must be achieved to complete the study.

1.3.1 Problem statement

Compressed air networks in the PGM mining industry are often inefficient and require continual implementation of efficiency initiatives for sustained improvement. After reviewing the literature,

it was found that there is still ample room for research on continually monitoring and reporting on the demand side of compressed air networks in the PGM mining industry. Therefore, there is a need for improving compressed air networks in the PGM mining industry through continual monitoring and reporting.

1.3.2 Overview of research area

This section discusses and extracts essential themes from the work done by Bredenkamp [49] and Groenewald [52]. Bredenkamp [49] developed an integrated energy management system for a gold mining group in South Africa and Groenewald [52] developed a framework for managing compressed air networks in the PGM mining industry in South Africa.

Bredenkamp's [49] integrated energy management system is based on the ISO 50001: Energy Management System standard and was applied to a gold mining operation with multiple shafts. It employs the continual improvement strategy of Plan-Do-Check-Act (PDCA). The PDCA cycle is illustrated in Figure 19.

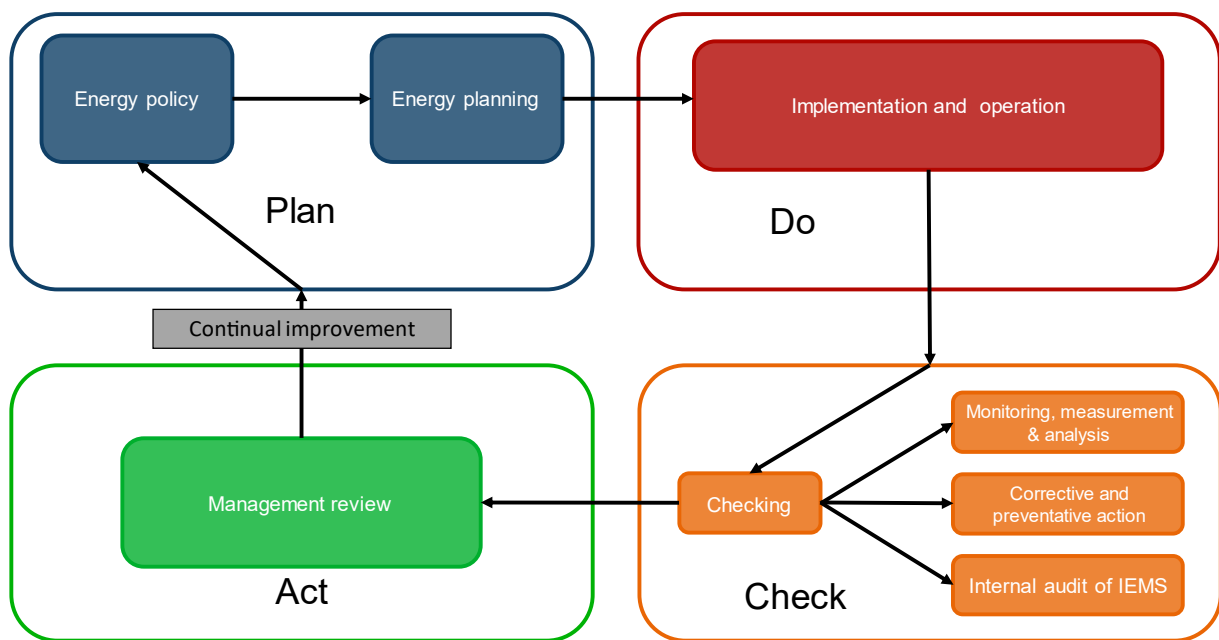


Figure 19: PDCA cycle of the ISO 50001 energy management standard

The significance of the PDCA cycle in this research is that a fundamental phase in the cycle, specifically the Check phase, has not been investigated thoroughly in the demand side of compressed air networks on PGM mines. This study reviews the literature with a specific focus on continual monitoring and reporting on compressed air inefficiencies in the PGM mining industry to promote improvement.

Furthermore, from the study conducted by Groenewald [52], the author established a framework for exploring the management of compressed air networks in the PGM mining industry. This framework was used to identify the most feasible efficiency initiatives (or priorities as specified in the study), emphasising quick return on investment and impact, for implementation. This study aimed to develop a solution to the following problems identified by the author:

- Reducing wastage:
 - Managing leakages.
 - Blanking off compressed air utility piping to inactive working areas.
 - Monitoring the efficiency of ventilation in working areas to prevent the misuse of compressed air.
- Accessing information:
 - Using instrumentation such as flowmeters on mining levels to allow the detailed monitoring of compressed air consumption.
 - Benchmarking underground working areas in terms of compressed air consumption versus production to determine problem areas.
 - Implementing automated frequent compressed air efficiency reports.
 - Using different levels of data abstraction to prevent an overload of information.
 - Inspecting underground working areas frequently to find leakages and other compressed air inefficiencies.

To ensure that the research review would be conducted thoroughly within the boundaries of this study, it was evaluated according to the following criteria on the demand side of compressed air networks in the PGM mining industry:

- Benchmarking compressed air efficiency.
- Identifying and prioritising high compressed air wastage on the demand side.
- Monitoring and reporting continually on compressed air efficiency.
- Improving compressed air network performance.

Eleven studies were identified as the most relevant to the topics. These studies are discussed to evaluate their relevance to the above-mentioned criteria.

Study 1 [49]

Title: An integrated energy management strategy for the deep-level gold mining industry

Author(s): JIG Bredenkamp

Keywords: South African deep-level gold mining, integrated energy management system, continual energy performance improvements, electrical energy management

Year: 2016

The author developed an energy management system for the gold mining industry that conforms to the ISO 50001 standard. This system ensures that energy systems in gold mines are improved continually.

Bredenkamp, who used a reporting procedure from another author, touched on the topic of reporting on energy systems [48]. The author further identified the steps needed to ensure accurate and timely feedback for continual improvement. Bredenkamp also provided a general guideline for reporting to the different levels of hierarchy in the mining industry, allocating different types of reports to different personnel.

The primary purpose of reporting in this study was to continually track and improve the performance of the energy systems by creating awareness among the responsible personnel and top management.

A limitation of this study is that although a guideline was developed for reporting, no formal procedure was put in place and verified to achieve the stated outcomes. The other limitation is that although the study was conducted only on the gold mining industry, the author did, however, recommend that this methodology be applied to other industries. Table 5 evaluates the outcomes from this study according to the previously mentioned criteria.

Table 5: Evaluation of Study 1 against predetermined criteria

Criteria	Relevant	Notes
PGM mining industry		
Benchmarking compressed air efficiency		
Identifying and prioritising compressed air wastage		
Monitoring and reporting on compressed air network efficiency	X	A reporting procedure was improved and a guideline developed for reporting to different levels in the employee hierarchy.
Improving continually	X	This study emphasises the need for reporting to ensure continual improvement as it creates awareness among the responsible personnel, and therefore promotes a continual drive for improvement of energy systems.

Study 2 [53]

Title: Real time energy performance control for industrial compressed air systems: Methodology and applications

Author(s): M Benedetti, F Bonfà, V Introna, A Santolamazza, and S Ubertini

Keywords: Energy efficiency, compressed air systems, energy data analysis, energy measures, performance control, operations, maintenance, energy accounting

Year: 2019

The authors investigated the importance of monitoring and controlling energy performance in the supply and demand side of compressed air networks. The study contributes to the areas of energy efficiency by introducing a novel methodology based on measured data and baseline definition through statistical modelling and control charts.

The methodology was tested on an industrial compressed air network of a pharmaceutical manufacturing plant to verify its effectiveness and applicability. Energy deviation and cumulative sum control charts were used to monitor and track the performance of the compressed air network, which is useful for analysing trends in energy performance behaviour. Although this study analysed, monitored, and reported events and performance on the supply side of the network, the methods and calculations can also be implemented for analysing and monitoring on the demand side of compressed air networks.

This study specifically focused on real-time monitoring and control of compressed air networks. It identified events that have a negative effect on the compressed air network through deviations from a predetermined system baseline. Once events were identified, relevant investigations were conducted to characterise and solve the issue. This contributed to the continual improvement of the compressed air network in this study. Table 6 evaluates the outcomes from this study according to the previously mentioned criteria.

Table 6: Evaluation of Study 2 against predetermined criteria

Criteria	Relevant	Notes
PGM mining industry		
Benchmarking compressed air efficiency		
Identifying and prioritising compressed air wastage		
Monitoring and reporting on compressed air efficiency	X	Compressed air network energy performance was monitored, and events that degrade network performance were reported so that action could be taken.
Improving continually	X	It is mentioned several times that by implementing this methodology, continual improvement can be achieved.

Study 3 [45]

Title: A target-based performance tracker for mine energy monitoring
Author(s): TM Masuku
Keywords: Energy management, energy efficiency, information system, benchmarking
Year: 2021

This study identified the limitations of mine monitoring systems owing to energy inefficiency, and it developed a solution that addressed these limitations. More specifically, the author aimed to develop a procedure for implementing a model-accurate baseline and target creation for the implementation of a visual platform and SMS notification system. Masuku detailed the procedure for acquiring quality and timely frequency data and developed a performance tracker to monitor energy-wastage events.

Evaluating this study against the four previously mentioned criteria, it is evident that no benchmarking of compressed air networks or identification and prioritisation of compressed air consumption/performance was conducted. Nevertheless, the procedure for accurate baseline and target profile creation was developed in a general sense, which leads to the conclusion that it could be used for the two criteria mentioned.

Furthermore, this study detailed an alarm/monitoring system used to monitor and report energy efficiency events. The system under scrutiny was developed according to best practice reporting requirements and can be used for continuous monitoring and reporting. The fundamental concept of this study is that a solution was developed to keep energy efficiency projects sustainable; therefore, continual improvement is the underlying topic. This study developed a solution for an integral part of the PDCA cycle, namely checking. Table 7 evaluates the outcomes from this study according to the previously mentioned criteria.

Table 7: Evaluation of Study 3 against predetermined criteria

Criteria	Relevant	Notes
PGM mining industry		
Benchmarking compressed air efficiency		
Identifying and prioritising compressed air wastage		
Monitoring and reporting on compressed air efficiency	X	The author developed a solution for monitoring and reporting on energy-wastage events that lead to sustainable energy saving projects.
Improving continually	X	Sustainable projects are key to continual improvement.

Study 4 [54]

Title: Efficient monitoring of mine compressed air savings

Author(s): P Goosen

Keywords: Mine compressed air savings, electricity savings, demand-side management (DSM), reporting system

Year: 2013

Goosen investigated the project feedback method of a specific energy services company. The method detailed the manual collection of data from mines in South Africa, and how it is used to manually generate reports that provide feedback on energy savings projects implemented by the energy services company. This led to the observation regarding the significant number of man-hours required to develop reports for providing feedback.

The author identified the need to reduce the number of man-hours spent developing and generating reports. Goosen developed and implemented a new method that was used to monitor DSM projects on mine compressed air savings. This method included collecting reliable data from mines, and processing and storing the data in a central database, which could be used to generate feedback reports on specific projects. The main benefit of this method is that it can be automated daily and scaled easily according to the number of compressed air projects on a mine.

Goosen also developed reports for daily and monthly monitoring of compressed air energy savings, which were implemented on four projects as case studies. This study was only conducted on gold mines. The author developed reports for detecting anomalies in the compressed air consumption of mines, which could be classified as identifying and prioritising compressed air wastage. These reports were used to monitor and report on compressed air efficiency with the aim of improving the compressed air network continually. Table 8 evaluates the outcomes from this study according to the previously mentioned criteria.

Table 8: Evaluation of Study 4 against predetermined criteria

Criteria	Relevant	Notes
PGM mining industry		
Benchmarking compressed air efficiency		
Identifying and prioritising compressed air wastage	X	Reports were developed to identify anomalies in compressed air energy consumption.
Monitoring and reporting on compressed air efficiency	X	Reports were developed to identify anomalies in compressed air energy consumption.
Improving continually	X	The data collection and reporting system was automated to reduce the number of man-hours, which increased the response time to anomalies in the compressed air network.

Study 5 [48]

Title: Modelling of electricity cost risks and opportunities in the gold mining industry
Author(s): LF van der Zee
Keywords: Electricity cost risk, modelling, electricity cost savings, ISO management, DSM strategies, electricity reporting and management system
Year: 2014

Van der Zee investigated cost risk and mitigation strategies for the South African gold mining industry and developed such a strategy by accurately predicting the impact of electricity cost risks and identifying strategies that could alleviate the cost implications of these risks.

In this study, the author identified a need for reporting the energy performance of electrical systems based on and in compliance with the ISO 50001 standard. Van der Zee proceeded to develop reports for the mining personnel responsible for managing energy and the technical staff responsible for maintaining the electrical systems.

This study provides a clear and comprehensive method of monitoring and reporting on the mine to improve energy efficiency through the identification of inefficiencies. Monitoring and reporting were mainly done on electrical systems, which does not clearly highlight compressed air inefficiencies.

Reporting on compressed air network conditions, such as pressure and mass flow rate, will give more insight into system performance. Although the monitoring and reporting strategy was implemented, the study was submitted for examination before results were acquired to clarify the extent to which it contributed to energy performance. Table 9 evaluates the outcomes from this study according to the previously mentioned criteria.

Table 9: Evaluation of Study 4 against predetermined criteria

Criteria	Relevant	Notes
PGM mining industry		Study only conducted on gold mining industry.
Benchmarking compressed air efficiency	X	Electricity data was used to benchmark compressed air performance for further analysis.
Identifying and prioritising compressed air wastage		
Monitoring and reporting on compressed air efficiency	X	Methodology developed for monitoring and reporting on electrical energy system performance on a frequent basis.
Improving continually	X	Thesis submitted for examination before results could be acquired.

Study 6 [51]

Title: A customisable data analysis interface for an online electrical energy information system

Author(s): RAP Fockema

Keywords: Data analysis interface, data mining, enterprise energy management, reporting

Year: 2014

Fockema identified the need for developing a customisable data analysis interface to sustain energy efficiency initiatives in underground mines. This study describes the factors that were considered, namely data acquisition, data mining (analysis), information reporting, and access.

The developed data analysis interface was implemented on gold and platinum mining groups as well as steel manufacturing, cement plants, and glass manufacturing groups, which were used as case studies. It was found that although the operations of the gold mining groups and personnel were quite similar, different information was required.

The author specifically highlighted the benefit of saving man-hours by automating the analysis and reporting of data and information for significant energy consumers. The interface can also be used to monitor specific issues. Table 10 evaluates the outcomes from this study according to the previously mentioned criteria.

Table 10: Evaluation of Study 5 against predetermined criteria

Criteria	Relevant	Notes
PGM mining industry	X	Case study conducted on a PGM mine.
Benchmarking compressed air efficiency		
Identifying and prioritising compressed air wastage		
Monitoring and reporting on compressed air efficiency	X	An interface for analysis of data and the reporting thereof was developed in this study.
Improving continually		

Study 7 [38]

Title: Using zero-waste baselines to identify compressed air system inefficiencies in deep-level mines

Author(s): A van der Merwe, AGS Gous, CSL Schutte

Keywords: Compressed air system, compressed air inefficiency, zero-waste baseline, simulation, digital twin, deep-level mines

Year: 2022

The authors identified the need to develop a zero-waste approach to identifying and quantifying compressed air inefficiencies in deep-level mines, locating inefficiencies at a low cost, and identifying savings initiatives and opportunities. The method developed used the most recent stoping and development plans as well as the most recent mass flow rate, pressure, and power data.

The method entailed developing a digital twin of the deep-level mine, calibrating it with actual data, and simulating the actual demand of end users (such as listed in Table 2). The zero-waste baseline was compared with the actual compressed air mass flow rate to determine the periods during which the inefficiencies occurred most. Further investigations were conducted on the sections during the identified periods to determine the problem and propose a solution.

The method detailed in the study is laborious because it involves developing a simulation of the compressed air network in the specific deep-level mine, which requires numerous measurements (if instrumentation is not available on the mine). The authors did not mention how often the simulation should be calibrated to actual data to deliver accurate results.

The study did not mention monitoring and reporting on this method. However, if the limitations surrounding data and simulation calibration can be resolved, a powerful tool for continual monitoring and reporting can be developed, which can promote continual improvement. Table 11 evaluates the outcomes from this study according to the previously mentioned criteria.

Table 11: Evaluation of Study 6 against predetermined criteria

Criteria	Relevant	Notes
PGM mining industry		
Benchmarking compressed air efficiency		
Identifying and prioritising compressed air wastage	X	The authors developed a method to develop a zero-wastage baseline for identifying compressed air inefficiencies.
Monitoring and reporting on compressed air efficiency		
Improving continually		

Study 8 [11]

Title: Novel solutions for compressed air demand management on deep-level mines
Author(s): LN Zietsman
Keywords: Audits, baseload, benchmarking, compressed air, deep-level mining, energy efficiency, leaks, localisation, step-testing
Year: 2020

Zietsman developed multiple methods to identify, quantify, and prioritise compressed air energy savings opportunities in underground mines and further integrated these methods into a top-down approach. These methods include a novel benchmarking model to prioritise mineshafts based on the scope for underground demand reduction, a leak auditing method used in the potable water industry for application on compressed air networks in underground mines, and a novel savings quantification method.

The novel benchmarking method offers a straightforward approach applicable to any compressed air network in underground mines, given that data on surface pressure, total compressed air mass flow rate, and active underground compressed air network length is available. The methods developed for leakage identification can also be applied to all working areas underground to determine the compressed air consumption of end users in these sections quite quickly, given that the appropriate portable instrumentation is available.

The author detailed the data required for each method and how to acquire it. While the continual implementation of the developed methods was not mentioned, it is noted that these methods could be used continually, depending on the availability of data.

Interestingly, the author explicitly mentioned in his recommendations that “there is a need for more studies to be done on the automation of energy audits, such as compressed air leak detection in underground mines”. Table 12 evaluates the outcomes from this study according to the previously mentioned criteria.

Table 12: Evaluation of Study 7 against predetermined criteria

Criteria	Relevant	Notes
PGM mining industry	X	Studies conducted on multiple mines.
Benchmarking compressed air efficiency	X	Novel benchmarking method developed.
Identifying and prioritising compressed air wastage	X	Methodology from potable water industry applied in underground mines to identify leakages.
Monitoring and reporting on compressed air network efficiency		
Improving continually		

Study 9 [41]

Title: Simplified high-level investigation methodology for energy saving initiatives on deep level mine compressed air systems

Author(s): J Vermeulen

Keywords: Compressed air systems, simplified investigation methodology, benchmarking to rank scope for improvement, quantify potential energy savings targets

Year: 2018

Zietsman identified the need to develop a new and straightforward benchmarking method for use during deep-level mine compressed air systems investigations and simplify existing tools used to quantify potential energy savings. The solutions to these needs were further combined into an integrated investigation methodology, which provided a simplified high-level investigation methodology to reduce the time, cost, and resources required by energy services companies while investigating new energy savings initiatives.

The single variable benchmarking method requires only average power consumption during the peak drilling and blasting period to identify potential energy savings and prioritise shafts for energy efficiency initiatives. Power data is usually available for significant energy consumers and is relatively easy to acquire.

This is relevant to this study as the benchmarking of the performance of compressed air networks can be implemented on a continual basis (not explicitly mentioned by the author) due to the availability of power data, which is often used for monthly electrical billing. This method can also be used to validate other benchmarking methods. Table 13 evaluates the outcomes from this study according to the previously mentioned criteria.

Table 13: Evaluation of Study 8 against predetermined criteria

Criteria	Relevant	Notes
PGM mining industry		Study only conducted on gold mining industry.
Benchmarking compressed air efficiency	X	Novel benchmarking method developed.
Identifying and prioritising compressed air wastage	X	Simplified existing tools used to quantify potential energy savings of a compressed air network.
Monitoring and reporting on compressed air network efficiency		
Improving continually		

Study 10 [43]

Title: Benchmarking electricity use of deep-level mines
Author(s): C Cilliers
Relevance: Energy consumption, energy benchmarking, deep-level mines, compressed air system, cooling system, dewatering system, ventilation system, hoisting system, energy efficiency initiatives, energy budgeting
Year: 2016

Cilliers recognised the importance of being aware of the performance of high-energy demand systems in deep-level mines. Furthermore, it was noted that many benchmarking studies have been conducted on commercial and industrial systems, with the focus on increasing awareness. Through this, new benchmarking models were created using actual data from South African deep-level mines for both average and best practice performance evaluation.

The author also developed a novel technique for determining the priorities of energy efficiency initiatives and a new method for determining operational energy budgets, using the above-mentioned models to promote real-time awareness.

The benchmarking models used in this study can be used continually to prioritise where to focus efforts on energy savings initiatives. Furthermore, this method is limited to weekly or monthly applications due to the availability of production data. Table 14 evaluates the outcomes from this study according to the previously mentioned criteria.

Table 14: Evaluation of Study 9 against predetermined criteria

Criteria	Relevant	Notes
PGM mining industry	X	Studies conducted on multiple mines.
Benchmarking compressed air efficiency	X	Novel benchmarking method developed.
Identifying and prioritising compressed air wastage	X	Novel method developed to prioritise where energy efficiency initiatives should be implemented.
Monitoring and reporting on compressed air efficiency		
Improving continually		

Study 11 [44]

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

Author(s): D du Plooy, P Maré, J Marais, and MJ Mathews

Keywords: Local benchmarking, inefficient compressed air usage, compressed air management tool

Year: 2018

The authors found that identifying compressed air inefficiencies underground is challenging and laborious. This study introduced a novel method to locate these inefficiencies in an underground mine using the correlation between production and compressed air supply. The method was applied to the underground compressed air network of a PGM mine.

This method is similar to Cilliers's benchmarking method [43] and will help accurately identify where to focus underground energy efficiency efforts. Furthermore, if the required data is available, this method can also be used to validate the results of Zietsman's methods [11].

Production data is difficult to acquire more frequently than weekly or monthly, and even more so for underground working areas. Nevertheless, if these limitations can be overcome, the continual application of this method will improve compressed air networks in underground working areas. Table 15 evaluates the outcomes from this study according to the previously mentioned criteria.

Table 15: Evaluation of Study 10 against predetermined criteria

Criteria	Relevant	Notes
PGM mining industry	X	Case study conducted on PGM mine.
Benchmarking compressed air efficiency	X	Novel benchmarking method developed.
Identifying and prioritising compressed air wastage	X	Novel method developed to prioritise where energy efficiency initiatives should be implemented.
Monitoring and reporting on compressed air efficiency		
Improving continually		

1.3.3 Critical analysis of previous studies

The studies mentioned in the preceding section exhibit a combination of strengths; however, if they are evaluated holistically, the opportunity for further research is identified. Table 16 summarises the studies discussed and highlights their focus. The first column shows the relevant criteria, while the header row shows the studies included.

Table 16: Critical evaluation of studies against previously mentioned criteria

Criteria	Study 1	Study 2	Study 3	Study 4	Study 5	Study 6	Study 7	Study 8	Study 9	Study 10	Study 11
PGM mining industry						X		X		X	X
Benchmarking compressed air efficiency					X			X	X	X	X
Identifying and prioritising compressed air wastage				X			X	X	X	X	X
Monitoring and reporting on compressed air efficiency	X	X	X	X	X	X					
Improving continually	X	X	X	X	X						
Comments	2	2	2	1,4	2,3	1,2	4	1,3,4	1,3,4	1,3,4	1,3,4

The following comments highlight the shortcomings of the studies in Table 16:

1. These studies all considered identifying and prioritising compressed air networks on **PGM mines** as opportunities for energy efficiency improvements through developed methods.
2. Limited research on improving compressed air networks through **continual monitoring and reporting** in the PGM mining industry has been done.
3. Multiple studies considered performance benchmarking of the compressed air network of mineshafts. Only two considered **benchmarking underground working areas (demand side)**.
4. Half of the studies considered identifying and prioritising compressed air consumption for possible action; none considered **continually implementing** developed methods.

As seen above, compressed air networks in PGM mines present ample opportunity for sustainable energy efficiency improvements, but there is limited research on continual monitoring and reporting of the demand side for the aim of improvement in the PGM mining industry. This study aims to fill the gaps and provide a more complete solution to current research.

1.3.4 Objectives

The main objective of this study is to develop a solution using continual monitoring and reporting for improving the demand side of compressed air networks in the South African PGM mining industry. To ensure this objective is met, the following secondary objectives are devised:

1. Determine, acquire, and validate the required data to analyse and report the performance of compressed air networks on PGM mines.
2. Investigate methods and techniques used for analysing the performance of compressed air networks.
3. Develop reports that use the above-mentioned methods or techniques.
4. Develop a procedure for continual monitoring and reporting that uses the developed reports.
5. Implement the developed solution on case study mineshafts.

This section outlined the problem statement and delineated the specific objectives necessary to ensure the study's comprehensiveness from past research. The subsequent section details the research methodology that will be used to validate the findings of the study.

1.4 Research methodology

With the objectives mentioned above, the case study methodology is selected as the research methodology for this study [55], [56], [57]. This approach promotes a detailed analysis of applying a generalised theoretical methodology to specific real-life cases, which may offer additional insights into the problem that would otherwise not be achieved with alternative research methodologies.

The case study methodology is especially applicable to this study due to its novelty, as continual monitoring and reporting have not yet been thoroughly researched in compressed air networks on PGM mines in South Africa. Figure 20 illustrates the case study methodology [56], of which the first two steps have been completed. Using this research methodology, the developed solution will be validated through application on multiple case studies.

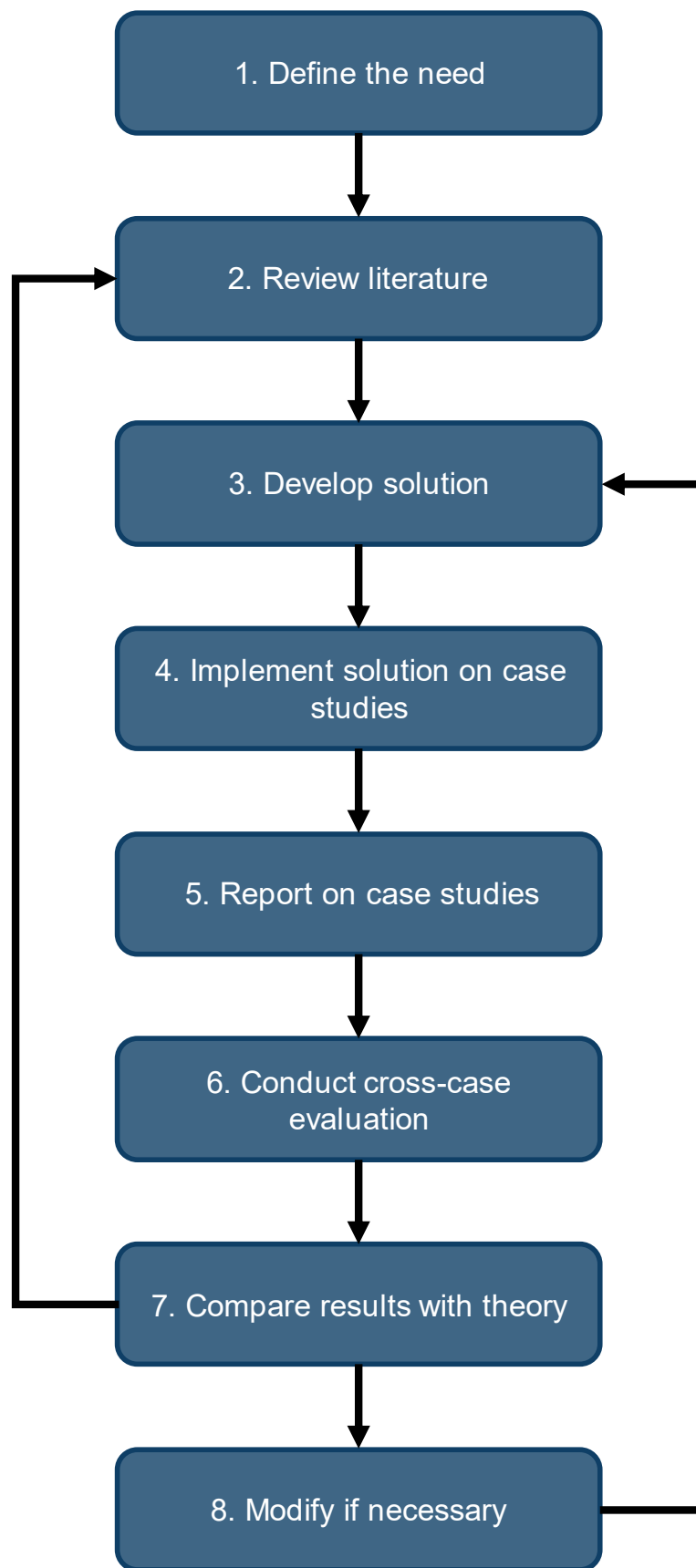


Figure 20: Case study methodology, adapted from [56]

1.5 Dissertation overview

Chapter 1: Introduction and Literature

Chapter 1 highlighted the background of compressed air network inefficiency and the extent to which it plagues the PGM mining industry in South Africa. Furthermore, the literature was surveyed for studies focusing on improving the demand side of compressed air networks in the PGM mining industry through continual monitoring and reporting. From this, a need for the study and study objectives were formulated.

Chapter 2: Development of Solution

Chapter 2 discusses the sequential steps to develop a solution that meets the secondary research objectives. The objectives include identifying, acquiring, and validating the required data; investigating various analysis techniques or methods; developing reports that will be utilised in a developed procedure for continual monitoring and reporting; and acting on inefficiencies. The accomplished objectives are combined to develop the solution for improving compressed air networks through continual monitoring and reporting.

Chapter 3: Results and Validation

In Chapter 3, the proposed solution is implemented in three case studies. The implemented solution is validated to ensure that all study objectives are clearly met, completing the final secondary objective. The results of the implemented solution are presented and explained.

Chapter 4: Conclusion and Recommendations

Chapter 4 concludes the study and provides recommendations for further improvement of this research.

CHAPTER 2: DEVELOPMENT OF SOLUTION

In Chapter 1, it was identified that existing research solutions for improving the performance of compressed air networks on PGM mines have several shortcomings. The lack of research on continual monitoring and reporting on a compressed air network's demand side necessitates a solution that promotes continual performance improvement. This chapter focuses on developing a solution geared towards meeting the objectives devised in Section 1.3.4 to accommodate the identified shortfalls.

The first secondary objective of this study, as stated in Section 1.3.4, is to identify, acquire, and validate the necessary data for monitoring the demand-side performance of a compressed air network. This objective will be achieved by considering the compressed air network's demand-side variables and various factors associated with business outlooks, such as operational costs and intensity.

The second secondary objective is dependent on the first, as data will be subjected to analysis methods and techniques that will evaluate and provide insights into the performance of the compressed air network. Investigating various performance indicators and the analysis thereof will achieve this objective. The third secondary objective entails the development of reports for three areas of performance, namely specific underground section performance, mineshaft performance overview, and control equipment performance.

The fourth secondary objective is to develop a procedure for continual monitoring and reporting on compressed air network demand-side performance, specifically about the organisational hierarchy of a typical mining company in the PGM mining industry. This objective will be achieved by establishing a procedure that will be followed to ensure performance improvement based on information acquired from analyses.

Combining each solution for the secondary objectives will result in a comprehensive solution for improving the demand-side performance of a compressed air network through continual monitoring and reporting. The following section details the solution for the first secondary objective, namely data identification, acquisition, and validation.

2.1 Data identification, acquisition, and validation

To address the first secondary objective, namely, to identify, acquire, and validate the necessary data for demand-side performance monitoring and reporting, one must consider the role a compressed air network plays in a typical PGM mineshaft. This, along with the stakeholders who share responsibility for the compressed air network in their respective areas, can be used to

continually monitor and report on compressed air network performance. This section discusses the data sources considered in this study.

2.1.1 Identify and acquire

This section discusses the different types of data required for the solution, as well as the validation procedure that must be implemented to ensure a complete and accurate dataset.

2.1.1.1 Process data

Process data refers to any data regarding the process under investigation. In this study, compressed air is scrutinised. Data relevant to this utility can be summarised as energy consumed by compressed air generation, pressure, mass flow rate, and control valve performance indicators.

Energy data is usually acquired from a third party that provides measuring and monitoring services to the mining group. Acquiring this data will likely require contacting the responsible manager and signing a non-disclosure agreement. Once agreed upon, further contact with the third party will be necessary to acquire the energy data. Note that the energy consumed by compressors is usually measured due to it being a significant energy user and, in the case of a ring network, billed electricity will need to be allocated to the specific mineshaft based on the amount of compressed air consumed by that end user.

A supervisory control and data acquisition (SCADA) system is typically used to monitor and control processes from a remote location, for example, a network of multiple compressors supplying compressed air to multiple mineshafts. This data is recorded and saved in a database (also known as a historian), which can be accessed to analyse process events. Process variables such as mass flow rate, pressure, and control valve performance indicators can be acquired from this database frequently for analysis. A non-disclosure agreement will also be required to obtain access to the historian.

As described in Section 1.2.3, compressed air is used for various operations. These operations usually include equipment that requires compressed air and that is designed at a certain pressure and mass flow rate. Although these two variables suffice as performance indicators, it is essential to connect them with a business outlook, particularly regarding energy consumption and the costs associated with it. Higher compressed air network pressures will lead to increased compressed air generation costs. The power consumption of compressors supplying mineshafts with compressed air may be used to acquire an operational cost. In the case of a ring network, this becomes slightly more complex as is further explained in Appendix C.

Another necessary area of performance monitoring is the operation of control valves. They are often installed to assist with artificially controlling demand during non-production times [24], which benefits the mineshaft by saving energy and cost. Control valves consist of a mechanical valve and an electrical or pneumatic actuator. They have multiple variables that can be monitored to ensure energy and cost savings are realised. A typical schematic of a control valve set-up is shown in Figure 21. This schematic depicts two pressure sensors and one mass flow rate sensor, as well as a controller that utilises the downstream pressure sensor to control the final control element of the actuator to achieve the necessary set point.

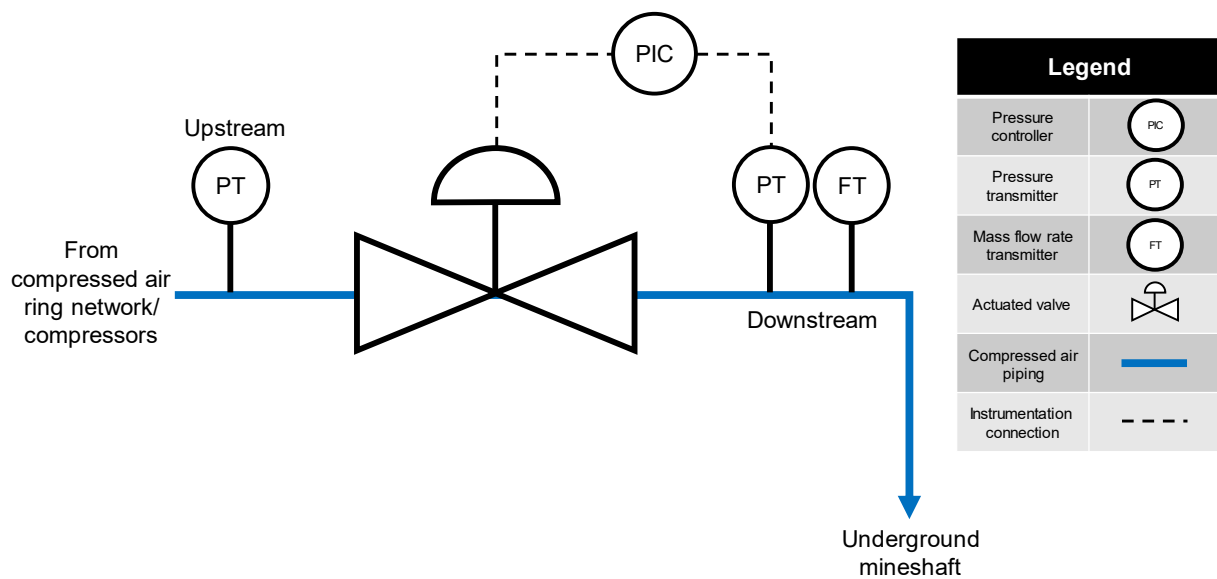


Figure 21: Typical control valve set-up on a compressed air pipeline

The variables required for monitoring control valve performance are listed below:

- Upstream and downstream pressure.
- Mass flow rate.
- Valve position (controlled by an actuator).
- Controller output (programmable logic controller [PLC]).
- Remote or local control setting (actuator).

Depending on the control philosophy, upstream pressure, downstream pressure, and mass flow rate may be used to control either according to a set point or just one of these variables (typically downstream pressure). The valve position and controller output determine whether automated control is performed correctly. In contrast, the remote or local control setting can be used to determine whether the control valve has been switched to automatic mode after maintenance. Detail on control valve performance monitoring is given in Section 2.2.2.

2.1.1.2 Production

Another essential variable is production (tonnes of ore produced), which can be used to acquire an intensity figure from the above-mentioned data. Intensity figures are often found to be useful indicators of performance. Production data is measured as frequently as daily and can be acquired from the mineral resources management (MRM) or survey department.

2.1.1.3 Organisational hierarchy

The organisational hierarchy of a mineshaft is important data that will be used to identify the critical stakeholders – the personnel responsible for sections and, therefore, responsible for its performance. This data will also determine who must be informed when specific tests/audits are conducted.

Typically, the organisational hierarchy is illustrated in a diagram known as an organogram, which can be acquired from the HR department. The frequency of acquiring this information will depend on how frequently personnel changes are made. Information is usually conveyed faster through word-of-mouth than official documents.

As detailed in the method used by Van der Zee [48], this step is important because personnel responsible for the performance of a specific working area will need to be held accountable. This step is simple because an organogram will identify these personnel and their managers. It is important to notify said managers if their personnel are not complying with efficiency initiatives.

The key stakeholders responsible for compressed air network performance in a mineshaft are the mining and engineering branches, as discussed in Chapter 1.2.5.3 and visually depicted in Figure 17. Generally, the mining branch's area of responsibility starts at the work areas, i.e. the crosscuts and end-of-development areas, whereas the engineering branch manages the remainder of the compressed air network.

2.1.1.4 Mineshaft layouts

To further understand the mineshaft where applicable initiatives are to be implemented, it is necessary to acquire haulage drawings that specify the underground services infrastructure, such as water and compressed air piping, and which personnel are responsible for specific sections. The data gained from these layouts is essential to pinpoint compressed air network inefficiencies and localise them to more manageable areas. Mineshaft layouts can be acquired from the MRM, survey, electrical, and instrumentation departments.

The frequency of acquiring data depends on the type. Typically, process and energy data can be acquired in intervals as short as seconds, but hourly or intervals are sufficient for calculating operational costs using Eskom tariffs [22]. The frequency of acquiring production data is usually limited to daily, whereas other data, such as mineshaft layouts and organisational hierarchy, does not change frequently and would need to be acquired at the start of the initiative and updated as necessary.

2.1.2 Validate

Data validation is necessary to ensure the data set is accurate and complete. Other studies have listed these primary and minor considerations to ensure a trustworthy and accurate data set [58], [59]. For the mineshaft layouts, organisational hierarchy, and production data, it is assumed that the data acquired from the respective sources are trustworthy and accurate. For process data, the following necessary tests are implemented:

1. Constant value check.
2. Measurement unit check.
3. Sensor range check.
4. Boundary check.
5. Redundancy check.
6. Correlation check.

The process data will be subject to each of the tests listed in the order above. The validation procedure assists in identifying faulty or broken instrumentation, which is reported to the relevant technician and their superior. The remaining data is used for further analysis, monitoring, and reporting. A flow diagram for the validation procedure is illustrated in Appendix B.

For this study, it is assumed that the continual and, therefore, automated acquisition and validation of data has been arranged, much like in the studies conducted by Fockema [51] and Masuku [45]. This implies that an automated system that distributes populated reports consisting of the data has already been established and will be used during the implementation of this solution. With the first secondary objective completed, the summarised data set is available in the frequencies listed in Table 17. To ensure all information has been acquired, Table 17 can be used as a checklist during the data acquisition step of the methodology.

Table 17: List of necessary data

Data and information	Frequency	Source
Organisation hierarchy	As necessary	HR Department/word-of-mouth
Mineshaft layouts (haulage and control & instrumentation)	As necessary	MRM, survey, electrical, or instrumentation departments

Data and information	Frequency	Source
Production	Daily	MRM/survey department
Energy consumed by compressed air generation	Hourly	Electrical department/third party
Mass flow rate of compressed air	Hourly	Instrumentation department/third party
Compressed air pressure	Hourly	Instrumentation department/third party
Valve position	Hourly	Instrumentation department/third party
Controller output	Hourly	Instrumentation department/third party
Remote or local control	Hourly	Instrumentation department/third party

2.2 Analysis techniques

This section discusses the analysis techniques used on the performance indicators of compressed air networks for mineshafts, underground working areas, and control valves. It aims to discuss insights made by evaluating compressed air consumption or control valve process data. Once these insights have been identified, clear and concise reports will be developed for continual monitoring.

2.2.1 Compressed air consumption performance

For this solution, several steps are followed to understand the typical demand behaviour of a mineshaft and to investigate any deviations from this norm. The analysis will be automated in the form of frequent reports to improve DSM of compressed air. These reports will discuss the consumption changes and possible corrective measures with the section's responsible personnel. The first step in understanding compressed air demand behaviour is to gauge a daily consumption chart, as seen in Figure 22.

Tracking daily consumption provides one with the changes that have occurred daily. Figure 22 depicts the daily consumption of a mineshaft over an arbitrary period of 55 days, which can be used to evaluate current performance. During the past 55 days, the compressed air consumption has increased to a range above the upper control limit. Further investigation is necessary to determine the cause of this increase to identify potential solutions to rectify the issue.

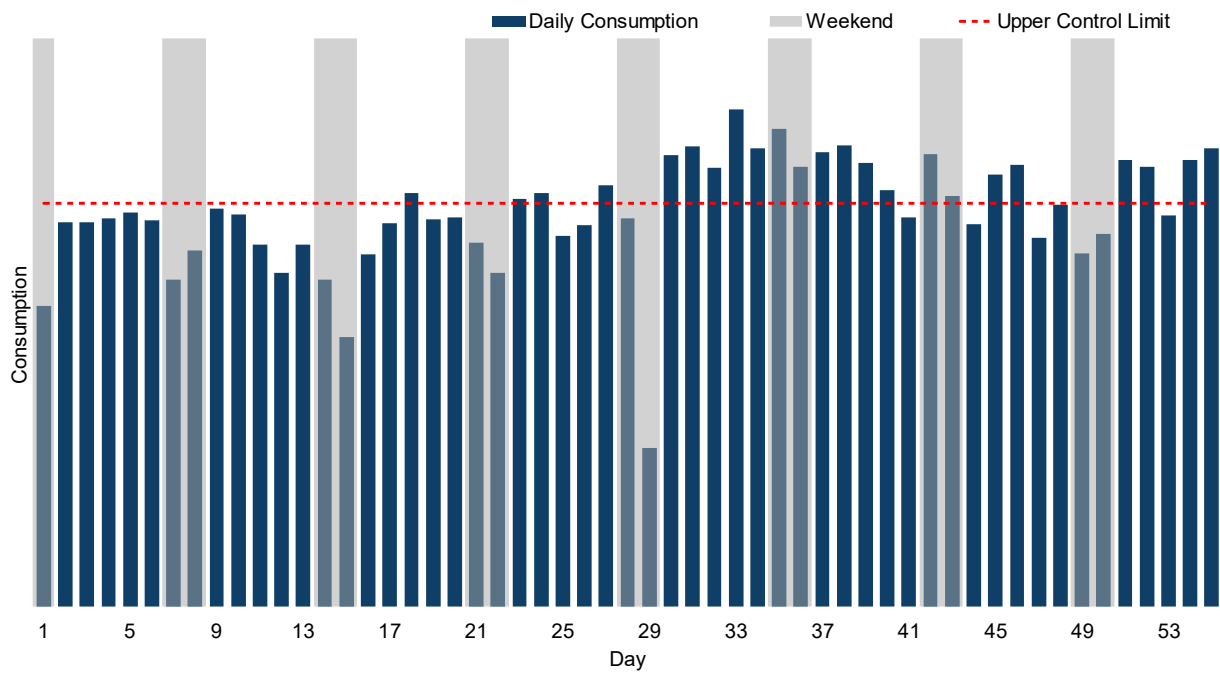


Figure 22: Example of a daily compressed air consumption chart

Note that weekdays and some Saturdays are typically classified as production days, whereas the remaining Saturdays and Sundays are classified as non-production days. It is further important to note that consumption behaviour must be compared with similar instances. For example, consumption on a production day must be compared with consumption on other production days. Taking the average consumption of both production and non-production days, gives a false representation of the compressed air network performance, leading to incorrect conclusions.

Unfortunately, the data illustrated in Figure 22 can only be used to determine whether the consumption of a mineshaft has changed. Further investigation is prompted to gain a deeper and more comprehensive understanding of the change in consumption. As mining production involves a cycle of consecutive shifts, with varying equipment used in each shift, it is important to compare the consumption of each shift with its equivalent instance. For the sake of simplicity, Figure 23 proposes a chart illustrating a 24-hour actual consumption profile along with its historical average and target.

In Figure 23, the actual consumption profile from the previous day is compared with the historical average of the previous week and an expected target profile. This is what is meant by comparing consumption with similar instances. This depiction clearly indicates an increase in consumption over the 24-hour period rather than during a specific period, such as a cleaning shift.

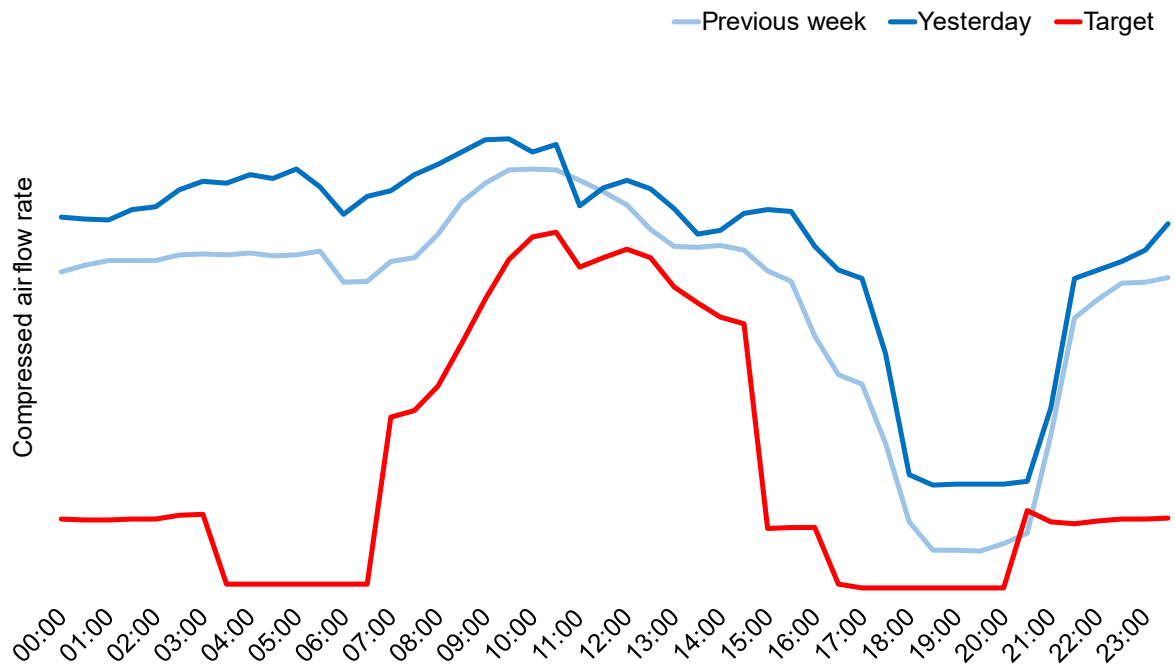


Figure 23: Typical historical and theoretical target comparison of compressed air consumption of an underground working area

Two approaches to compressed air analysis on a 24-hour profile are discussed in detail. First, recent actual consumption data will be compared with a historical average period, followed by the comparison of recent actual consumption data with a theoretical target or zero-wastage baseline. Other types of analyses are also briefly discussed that may be used to further one's understanding of compressed air consumption behaviour.

The process of comparing the most recent data with a historical average requires comparing the compressed air network data from the latest complete period (day, week, or month) of a mineshaft or working area with the historical average. Typically, the average 24-hour profile of a day is compared with the same section's previous week or month, as depicted in Figure 23. This approach offers the advantage of identifying changes that occur during specific shifts using the most recent data, making them easily recognisable.

Once a change has been identified, immediate action is required to ensure consumption returns to previous or reduced levels. In Figure 23, the example clearly demonstrates an overall increase in consumption, indicating a significant leakage or misappropriation that has likely occurred downstream of the mass flowmeter installed on the network. Failure to address this issue promptly will result in excessive cost implications. In summary, profile comparison is used for monitoring, reporting, and discussing changes in the consumption behaviour of the mineshaft or underground working area.

The approach of comparing the most recent data against a theoretical target usually considers a first-principles approach to target setting. In essence, the most recent complete period of

compressed air consumption (24-hour profile) is compared with a theoretical consumption or zero-wastage baseline, as seen in Figure 23. This target is typically used as a reference point to gain a multitude of insights, such as calculating the theoretically required compressed air at specific pressures, identifying and prioritising worst-performing sections or shifts, and determining time-of-use opportunities for cost saving.

The method developed by Van der Merwe *et al.* [38] considered the equipment listed in Table 2 and developed a digital twin model of a mineshaft by conducting surveys of the mineshaft's compressed air network. After completing the digital twin model, scenarios were simulated at various surface pressures to determine the mass flow rates of compressed air for specific sections of the mineshaft. This data can be used in typical illustrations such as Figure 23 to identify the most significant potential for efficiency initiatives across the different shifts.

Depending on the consumption profile of the specific mineshaft, efficiency initiatives must be prioritised according to the amount of savings and ease of implementation. Initiating a simple project, such as closing a section's valve during the blasting period (when no personnel are in the section), is much simpler than identifying and acting on each leakage or act of misappropriation during the cleaning and drilling shift.

This discussion highlights the performance indicators that require monitoring, including the 24-hour profile consumption of a mineshaft or section and theoretical target consumption. By comparing historical data with current figures, valuable insights can be gained to assess whether the scrutinised section is operating optimally. Other analyses that promote a deeper understanding of the mineshaft's compressed air consumption behaviour may be helpful in communication with the mineshaft personnel include:

- **Intensity analysis:** Du Plooy [44] utilised intensity analysis, a comparative technique for sections with the same mining method. This technique may be used to prioritise less efficient mineshafts or sections for efficiency initiatives. A graphical representation of the technique is illustrated in Figure 24. In this case, Shaft 1 is prioritised as the most inefficient operator due to the highest intensity.

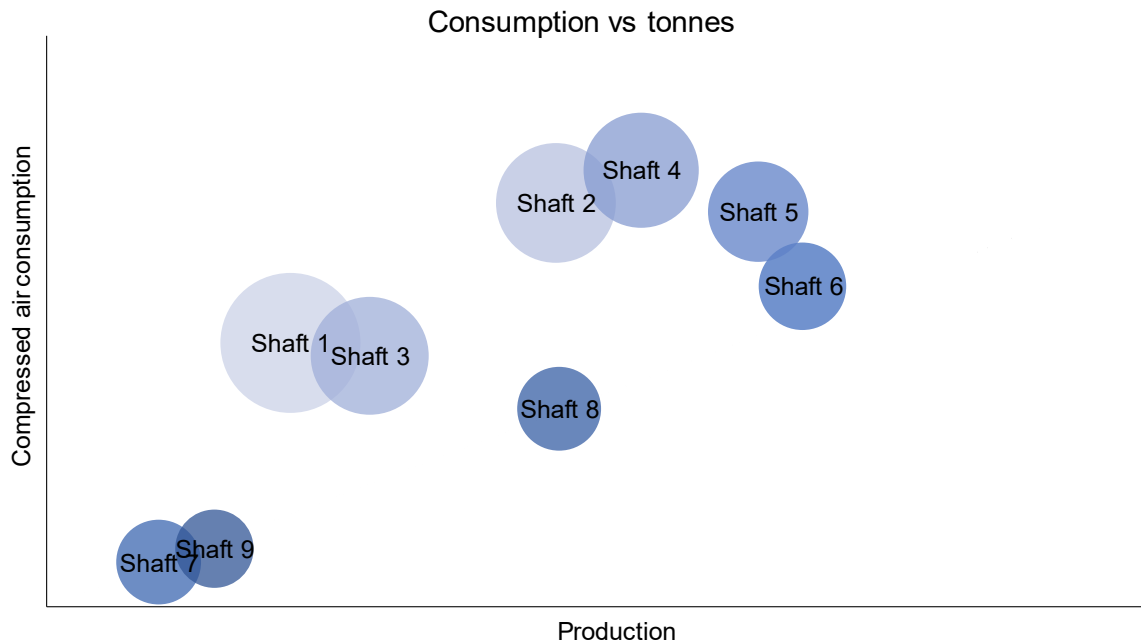


Figure 24: Typical illustration of an intensity comparison between multiple mineshafts

Figure 24 illustrates the intensities of various shafts. This information can also be extended to underground sections, provided that instrumentation, such as mass flowmeters, is available, along with frequent production measurements. In Figure 24, reducing compressed air consumption or increasing production would result in a lower intensity value, which indicates improved performance. This illustration is a valuable tool for communicating with mining personnel. It can be used to motivate collaboration or competition between different sections, with the aim of improving the compressed air network.

- Step test analysis:** Taken from Zietsman's study [11], this technique entails conducting a step test during a non-production period. The benefit of this analysis is that it shows that all the compressed air consumed during the test was used for non-production purposes, such as refuge bays, which highlights the inefficiency of the specific mineshaft or section when it comes to compressed air usage. A typical step test result is illustrated in Figure 25 and Table 18. It is clear that Level 2 consumes the most compressed air during non-production periods and should be prioritised when investigating possible efficiency initiatives.

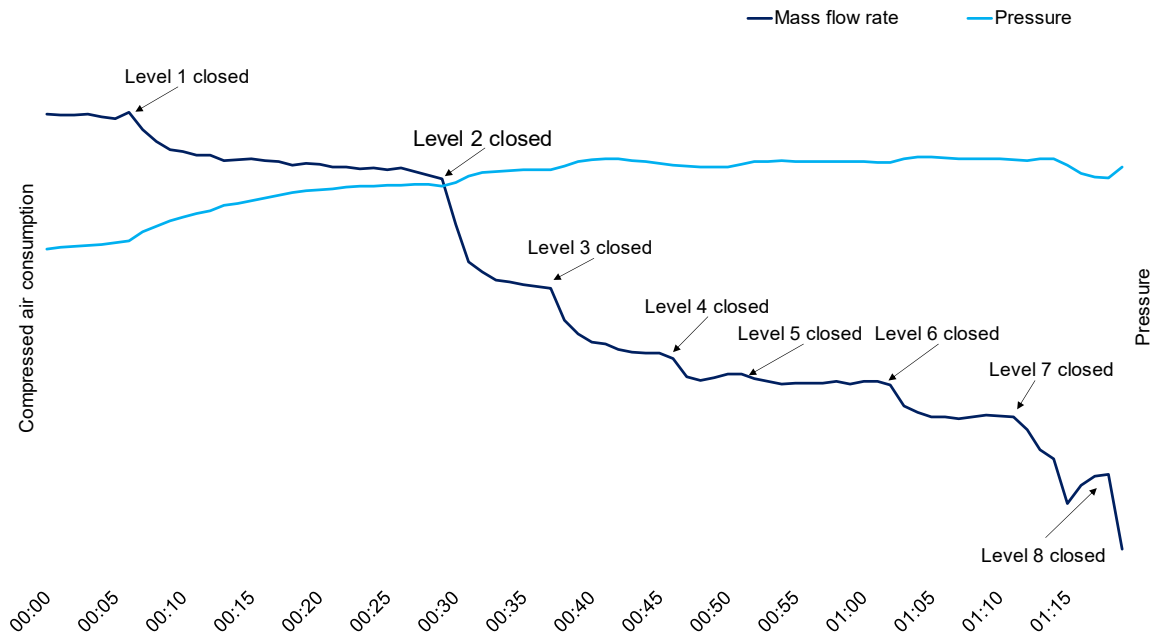


Figure 25: The compressed air consumption of an actual step test on a mineshaft

Using the example step test illustrated in Figure 25, the fractions of compressed air consumption were calculated and are shown in Table 18. Levels 2, 8, and 3 should be prioritised for efficiency initiatives as they have been proven to consume the highest amount of compressed air during non-production times.

Table 18: Resulting compressed air consumption fractions from step test

Level	Compressed air consumption
Level 1	13%
Level 2	24%
Level 3	16%
Level 4	8%
Level 5	2%
Level 6	8%
Level 7	9%
Level 8	20%

Conducting step tests frequently is a simple method of determining and tracking inefficient compressed air usage on a mineshaft. This is especially useful if no instrumentation, such as mass flowmeters or pressure transmitters, is available on underground sections.

In summary, the first part of analysing a compressed air network's demand-side behaviour should include familiarising oneself with the daily consumption totals for the specific mineshaft or underground section. After this, the blasting period should be scrutinised for any unnecessary consumption, as no personnel are permitted underground; therefore, no compressed air consumption is necessary. The final check would be to scrutinise the cleaning shift and prioritise

the implementation of efficiency initiatives, which may range from installing control valves to improving ventilation controls in underground sections. The following section details the monitoring and reporting of another aspect of compressed air networks, namely control valve performance.

2.2.2 Control valve performance

Control valves are installed on a mineshaft's compressed air network to reduce consumption during non-drilling periods. The schedule for a control valve pressure set point typically follows the profile illustrated in Figure 26. During the drilling shift, high pressure (± 600 kPa on the surface) is required to operate rock drills at the rockface. During the non-drilling shifts, lower pressure (± 200 kPa to ± 450 kPa) is required for operations such as loading boxes, pneumatic loaders, and refuge bays.

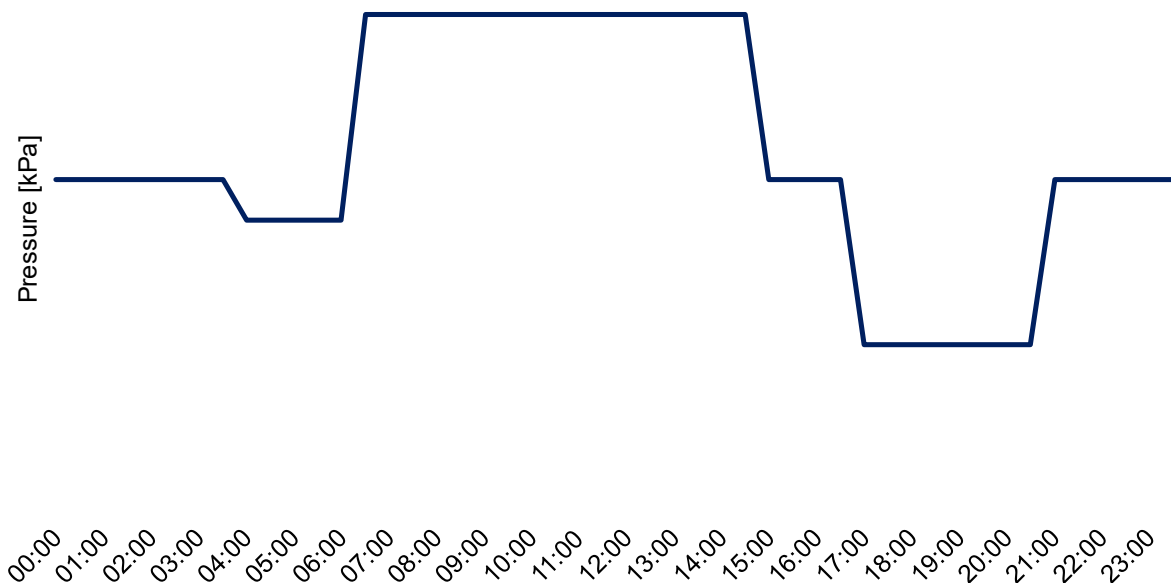


Figure 26: Typical compressed air control valve pressure set point schedule on a mineshaft

Control valves are pivotal to improving the efficiency of a compressed air network on a mineshaft [24]. It is essential that control valves are operating in accordance with the predetermined control philosophy. Monitoring control valve operation entails tracking set points, monitoring operational modes correctly, and monitoring valve closures during times when no personnel are underground. Each of these performance indicators is briefly described below.

- **Set point tracking:** This indicator considers how well the control valve and its control configuration (e.g. proportional, integral and derivative [PID] parameters) control according to the predetermined set point.

- **Operational mode detection:** This indicator considers whether the control valve mode is under remote or local control. Local control is selected when the valve needs to be operated manually and is typically used when maintenance is conducted on the control valve. Remote control settings refer to automated valve control according to the predetermined control philosophy.
- **Valve closure:** This indicator considers the closure of control valves, typically during the blasting period when there are no personnel underground.

Control valves should be monitored daily for any changes from the predetermined control philosophy. To avoid oversight and maintain efficiency initiatives, the above-mentioned performance indicators can be combined into a single report.

These techniques are useful for gaining an understanding of the compressed air consumption behaviour of a mineshaft or underground section. Automating these analysis techniques in the form of daily or weekly reports and providing them to the stakeholders at the mineshafts facilitate continual improvement in the management of the compressed air network. The insights obtained from analysing the data discussed in this section are especially valuable in the context of managing energy in a mineshaft. The succeeding section describes the necessary reports for continual monitoring and reporting in the pursuit of improved efficiency, energy, and cost reduction on compressed air networks.

2.3 Report development

This section develops three reports: a section performance report, a mineshaft performance overview report, and a control valve performance report. The information in the reports is inferred from the analysis techniques described in the previous section. The use of these reports will be discussed in the succeeding chapter when different use cases are explored. This section details the required specifications of the reports, as mentioned as the first step in Van der Zee's study [48], with examples of reports illustrated in Appendix D to Appendix F. The specifications for each report are detailed, with each set of specifications described in figures or tables.

2.3.1 Section performance report

The section performance report must be developed for a specific section for daily use and should include the following as detailed in Goosen's study [54] and expanded to include the target figures:

- A historical daily consumption chart with an upper control limit (as seen in Figure 22).
- An overview of the day's consumption performance in the form of a 24-hour graph illustrating (as seen in Figure 27):

- The actual (previous day), historical (previous week), and target compressed air consumption.

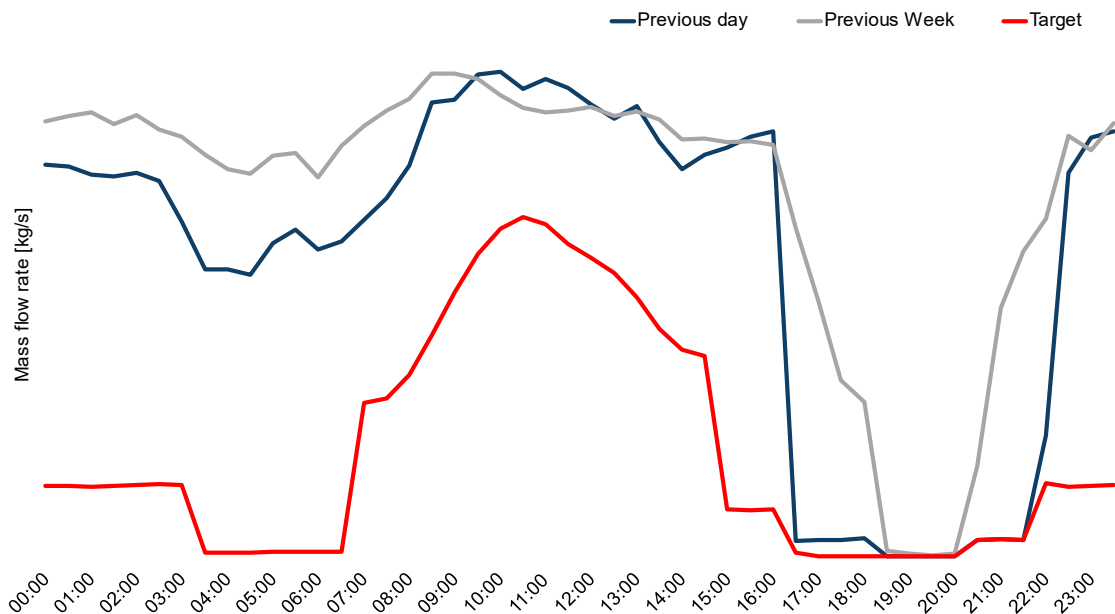


Figure 27: 24-hour profiles of an underground working area for use in continual monitoring and reporting

- A table illustrating (as seen in Table 19):
 - The day's actual, target and historical (average previous week) compressed air consumption.
 - The day's actual, target, and historical estimated annual cost.
 - Estimated consumption wastage and annual cost.

Table 19: Metrics associated with compressed air consumption in Figure 27

Metric	Average compressed air consumption	Estimated annual cost
Previous day	XXX XXX	RX XXX XXX
Previous week	XXX XXX	RX XXX XXX
Target	XXX XXX	RX XXX XXX
Wastage	XXX XXX	RX XXX XXX

2.3.2 Performance overview report

The performance overview report must be developed for a mineshaft for weekly use and should include the following:

- An intensity analysis of the mineshaft's performance compared with the performance of other mineshafts in the mining group, based on the past week's performance (as shown in Table 20).

Table 20: Example of an intensity comparison of different shafts (from data illustrated in Figure 24)

Business unit	Weekly compressed air consumption	Weekly production	Intensity	Ranking (worst to best)
Shaft 1	X XXX XXX	XX XXX	XXX	1
Shaft 2	X XXX XXX	XX XXX	XXX	2
Shaft 3	X XXX XXX	XX XXX	XXX	3
Shaft 4	X XXX XXX	XX XXX	XXX	5
Shaft 5	X XXX XXX	XX XXX	XXX	6
Shaft 6	X XXX XXX	XX XXX	XXX	7
Shaft M	X XXX XXX	XX XXX	XXX	9

- An overview of the performance of a mineshaft's underground sections in the form of a table (as seen in Table 21), which should include:
 - The previous week's actual, target, and wasted compressed air consumption.
 - Estimated annual cost of wastage (as determined by the theoretical target/zero-wastage baseline).
 - Sections ordered from worst to best performance for prioritisation.

Table 21: Example of consumption and wastage comparison of levels at a mineshaft

Level	Weekly compressed air consumption	Target	Wastage	Estimated annual wastage cost
1	XXX XXX	XXX XXX	XXX XXX	RX XXX XXX
2	XXX XXX	XXX XXX	XXX XXX	RX XXX XXX
3	XXX XXX	XXX XXX	XXX XXX	RX XXX XXX
4	XXX XXX	XXX XXX	XXX XXX	RX XXX XXX
5	XXX XXX	XXX XXX	XXX XXX	RX XXX XXX
6	XXX XXX	XXX XXX	XXX XXX	RX XXX XXX
7	XXX XXX	XXX XXX	XXX XXX	RX XXX XXX
N	XXX XXX	XXX XXX	XXX XXX	RX XXX XXX
Total	XXX XXX	XXX XXX	XXX XXX	RX XXX XXX

2.3.3 Control valve performance report

The control valve performance report must be developed for all valves in the mining group. The report will be used on a daily basis to track when the surface and underground valves were closed during the blasting period and to monitor the performance of the control valves. The report should include the following:

- A table of all the valves indicating (as seen in Table 22):
 - Average mass flow rate during the blasting period.

- Average mass flow rate of the blasting period to the maximum daily flow rate as a percentage.
- The time when the valve was closed and when the mineshaft blasted explosives.
- Estimated annual cost if the valve was operated for an entire year on a specific day.

Table 22: Example of a valve closure report for use in monitoring the blasting period

Valve	Average mass flow rate [kg/s]	Average mass flow rate % of maximum daily mass flow rate	Valve closing time	Blasting time	Estimated annual blasting period cost
Shaft 1	X XXX	XX%	Did not close	HH:MM	RX XXX XXX
Shaft 2	X XXX	XX%	HH:MM	HH:MM	RX XXX XXX
Shaft 3	X XXX	XX%	HH:MM	HH:MM	RX XXX XXX
Shaft 4	X XXX	XX%	HH:MM	HH:MM	RX XXX XXX
Total	X XXX				RX XXX XXX

- 24-hour profile of (as seen in Figure 28):
 - Mass flow rate.
 - Pressure (upstream and downstream pressure).
 - Pressure or mass flow rate set point (depending on control philosophy).
- 24-hour profile of (as seen in Figure 29):
 - Valve position and controller output.
 - Control mode.

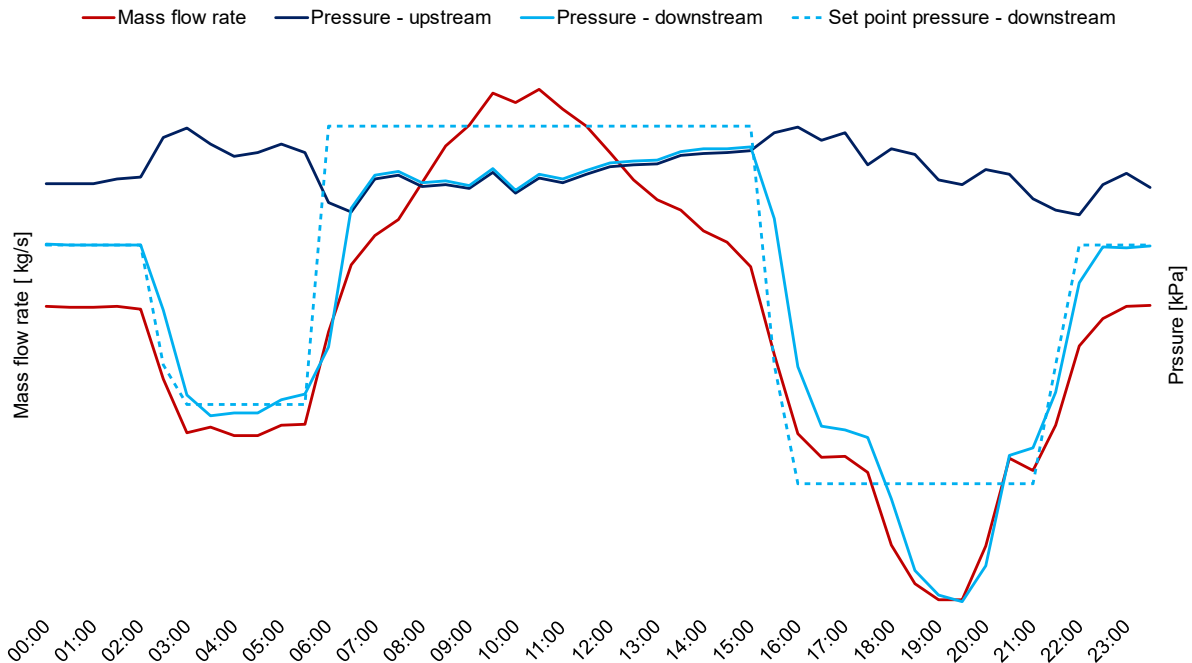


Figure 28: Example of a control valve monitoring view for mass flow rate and pressure

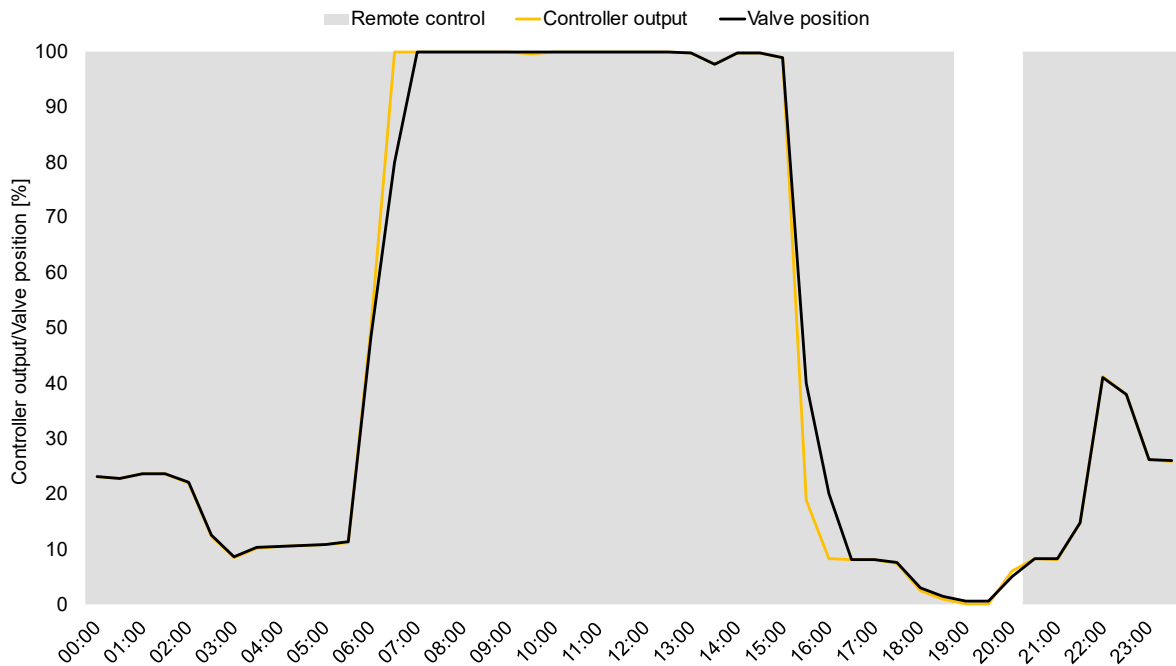


Figure 29: Example of a control valve monitoring view for valve position, controller output and control mode

In summary, the specifications of three reports, namely, the performance overview, section performance, and control valve performance were discussed. Performance indicators and different techniques for analysing compressed air consumption behaviour and control valves were included in the reports for daily and weekly use. These reports showcase the compressed air consumption and control valve performance for use in monitoring and reporting. The following section details a simple procedure for continual monitoring and reporting.

2.4 Continual monitoring and reporting

The previous three sections detailed the data requirements, analysis techniques, and report development, which are all required for continual monitoring and reporting. This section explains a simple procedure for use in a practical setting and provides an overview of the whole solution. The procedure entails monitoring daily and weekly reports to identify inefficiencies. Any insights gained must be shared with the relevant personnel to realise improvements.

The procedure starts by analysing the performance overview report to determine which mineshaft the mining group should focus their efforts on. This is done by using the intensity analysis and verifying it with the theoretical target/zero-wastage baseline. Once confirmed, the remainder of the procedure uses each of the developed reports to gain insight into the behaviour of the demand side of the previous day. This is illustrated in Figure 30 as a flow diagram and explained below.

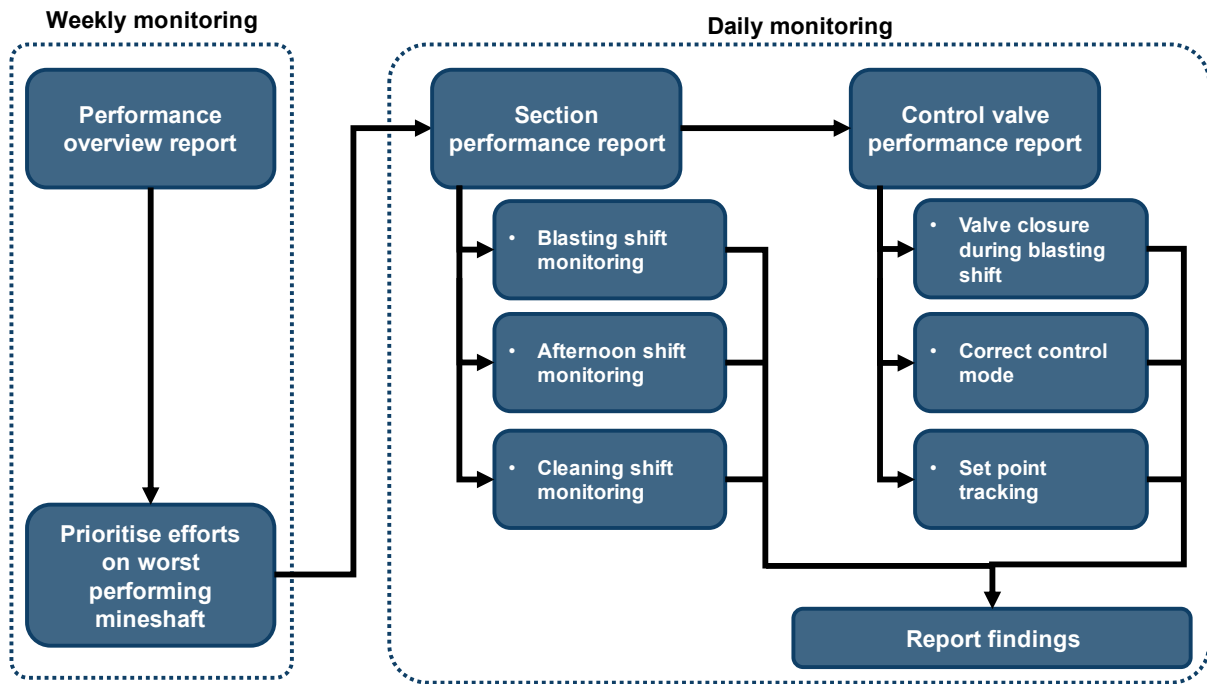


Figure 30: Procedure for continual monitoring and reporting

The procedure considers the daily consumption chart contained in the section performance report (Figure 22). If the previous day's consumption exceeds the upper control limit, prompt action must be taken to identify the shift during which the inefficiency could have occurred. The 24-hour profile of the previous day is used to determine further steps.

The blasting period must be scrutinised first because no personnel are allowed underground during this period, and it is simple to have a control valve closed for the duration of this period. The control valve must also be scrutinised to determine whether the valve is controlling correctly, which can be identified by using the control valve performance report. Typically, one person, such as an engineer, will be assigned the task of managing a section's control valve, which simplifies reporting of any related inefficiencies. Once it has been confirmed that the control valve was closed for the duration of the blasting period and is in working condition, the next step is to scrutinise the other two periods, namely the cleaning and drilling shifts.

It is arbitrary which shift is scrutinised first. Towards the end of the drilling shift, as mining personnel finish their work for the day and exit the working areas, they must close the crosscut valve(s) leading into their respective working areas. The section performance report, containing the daily 24-hour profile of a specific section, can be used to determine whether the compressed air crosscut valves were closed. One person, typically a shift boss, is responsible for a section's (half-level) mining crew. This fact assists with keeping the correct personnel accountable to ensure improved compressed air efficiency.

During the cleaning shift, typical inefficiencies, such as ventilating with compressed air, may become evident, as shown by Van Gruting [39]. This can also be clearly illustrated using the section performance report. The ventilation department personnel should be notified of these insights, and they must investigate further to assist with identifying remedying steps.

With the procedure for continual monitoring and reporting in place, the final step is closing the loop and rectifying inefficiencies. This involves setting actionable steps and commitment dates with responsible personnel, as discussed in the succeeding section.

2.5 Acting on inefficiencies

The final part of this solution is to act upon identified inefficiencies. This study provides a general outline of the necessary steps required to ensure improvement, which include identifying the responsible personnel, developing an action plan, and tracking the progress frequently, as illustrated in Figure 31.

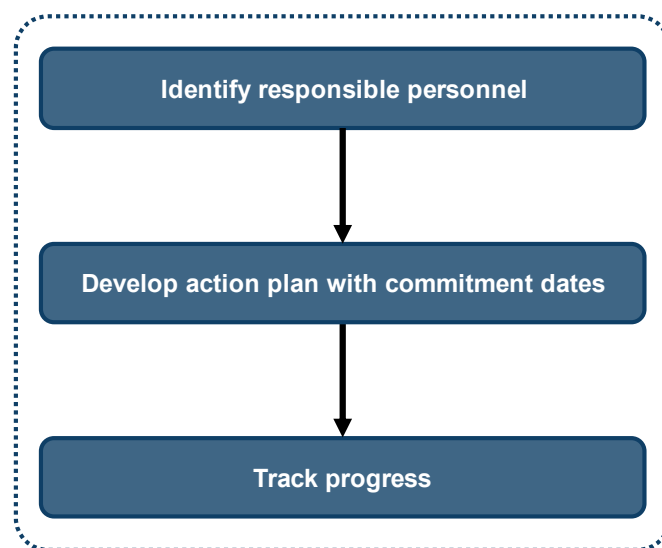


Figure 31: Necessary steps to ensure that inefficiencies are resolved

Identifying the responsible personnel is done by discussing the inefficiency with the relevant manager or engineer responsible for the section. Different departments may be involved depending on the section or type of inefficiency. For instance, if there is a leak in an underground work area, it will be the responsibility of the mining department. On the other hand, if there is a problem with a control valve on the surface, it will be the responsibility of the engineering department.

After identifying an inefficiency and discussing it with the relevant personnel, it is imperative to agree on actionable steps and commitment dates in the form of an action plan report. This will

assist with tracking progress and ensuring accountability. An action plan usually includes a brief description and photo of the issue, the responsible person, the date on which the inefficiencies were identified, the deadline committed by the responsible person to rectify the inefficiency, and the actual date on which the issue was resolved. This is illustrated in the example action plan in Figure 32.

Shaft	Section	Problem	Action	Photo	Responsible Person	Completion date	Status	Signature
Shaft A	Level 2 Crosscut 6	Open 2" hose from manifold	Remove 2" hose if it is not being used – take temperature and report to ventilation.					
Shaft A	Level 2 Crosscut 7	4" pipe torn	Replace 4" pipe with new one.					
Shaft A	Level 2 Crosscut 7	Puncture hole in 32" hose	Remove 32 mm hose and replace with new hose.					
Shaft A	Level 2 Crosscut 8	Puncture hole in 32" hose	Remove 32 mm hose and replace with new hose.					

Figure 32: Example of an action plan used to track progress and ensure accountability for compressed air inefficiencies

The final part of this outline is to track the progress frequently. Progress tracking may be as frequent as hourly depending on the severity of the inefficiency (measured by the financial or production/service delivery impact). As the final step of the solution, it is important that timely feedback on the progress be given to the relevant manager or engineer. This ensures that the responsible personnel will prioritise issues and be kept accountable for resolving the inefficiency. In the next section, an overview of the developed solution is provided.

2.6 Solution overview

The developed solution begins with evaluating and validating the data typically required for monitoring a compressed air network. Subsequently, various analysis techniques for compressed air consumption and control equipment performance were discussed to understand the demand-side behaviour. Reports were created, outlining these analysis techniques, along with a simple procedure that can be used in practical settings. The final step of the solution entails addressing inefficiencies, which consists of identifying responsible personnel, developing an action plan, and tracking progress frequently. The development of the solution is illustrated in Figure 33.

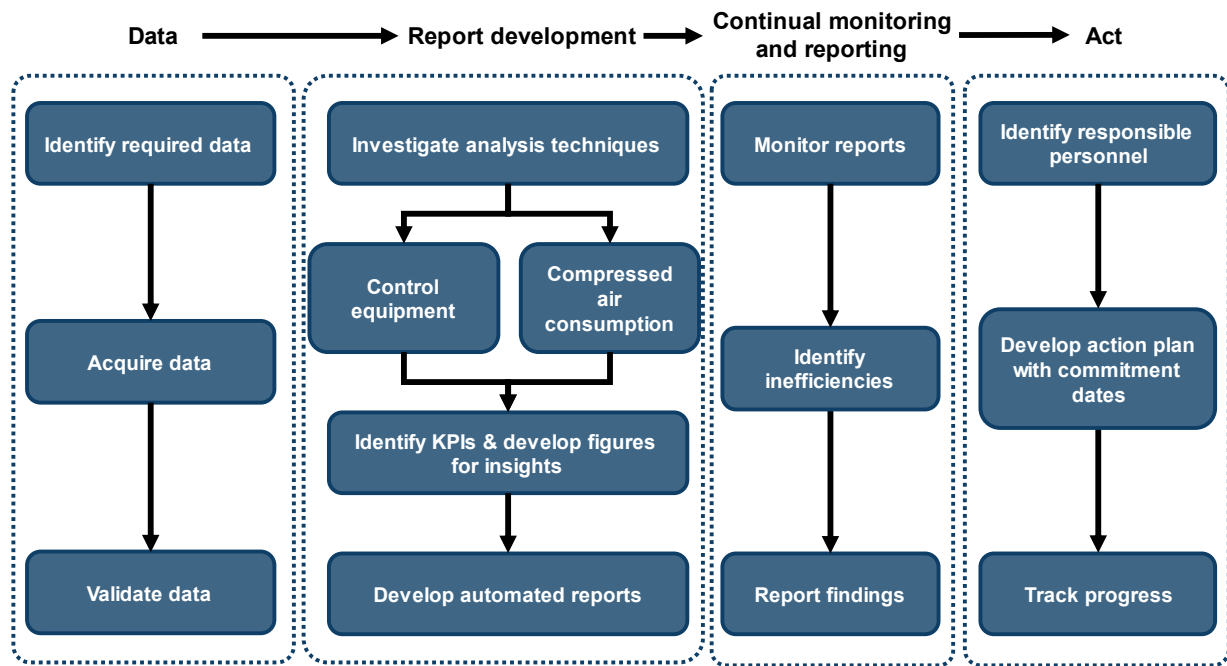


Figure 33: Development of solution overview

This solution is built on data, analysis techniques, monitoring and reporting, and acting on inefficiencies. It contributes to a comprehensive DSM strategy to promote efficiency and performance improvement. The next chapter will detail case studies where this solution was implemented to explore use cases and the benefits achieved to complete the fifth and final secondary objective.

CHAPTER 3: RESULTS AND DISCUSSION

This chapter presents the results of applying the solution developed in Chapter 2. The solution was developed with the aim of addressing the first four secondary objectives stated in Section 1.3.4. The fifth and final secondary objective is to implement the solution on case study mineshafts, which forms the central theme of this chapter. The case studies were selected to show how the developed solution may be applied both reactively and proactively. To address identified inefficiencies in each of the case studies, the developed solution consists of:

1. Acquiring and validating data.
2. Developing reports.
3. Monitoring and reporting continually.
4. Acting on inefficiencies.

Three case studies are presented to validate the solution developed for improving compressed air network performance through continual monitoring and reporting:

- Case Study A: Control valve philosophy change.
- Case Study B: Blasting period valve closure.
- Case Study C: Underground ventilation controls improvement.

Case Study A considers using the developed control valve performance report to monitor the control valve performance at mineshafts. In this case study, a malfunctioning mass flowmeter was identified and reported, and an alternative control philosophy was implemented to allow for continued control. Case Study B discusses an initiative using the same developed report as in Case Study A to drive the closure of control valves during the blasting period. Finally, Case Study C considers a proactive approach to implementing the developed solution in an underground setting to improve ventilation controls. After discussing the three case studies, the report specifications are analysed and the impact of implementing the solution is evaluated to verify and validate the solution.

3.1 Case Study A: Control valve control philosophy change

3.1.1 Background

The mining group in this case study has nine mineshafts, each equipped with a control valve on the surface. The control valves aim to improve the efficiency of the compressed air network by providing only the required pressure throughout the operational cycle. The standard control

philosophy for the control valve equipment entails using both a pressure transmitter and a mass flowmeter to control a 24-hour predetermined set point profile.

This case study focuses on Mineshaft A, where a malfunctioning mass flowmeter was identified, reported and acted upon using the solution developed in Chapter 2. A simple schematic of Mineshaft A is illustrated in Figure 34. The infrastructure includes two pressure transmitters, a flowmeter, and an actuated control valve. Mass flowmeters are also installed on each half-level in Mineshaft A.

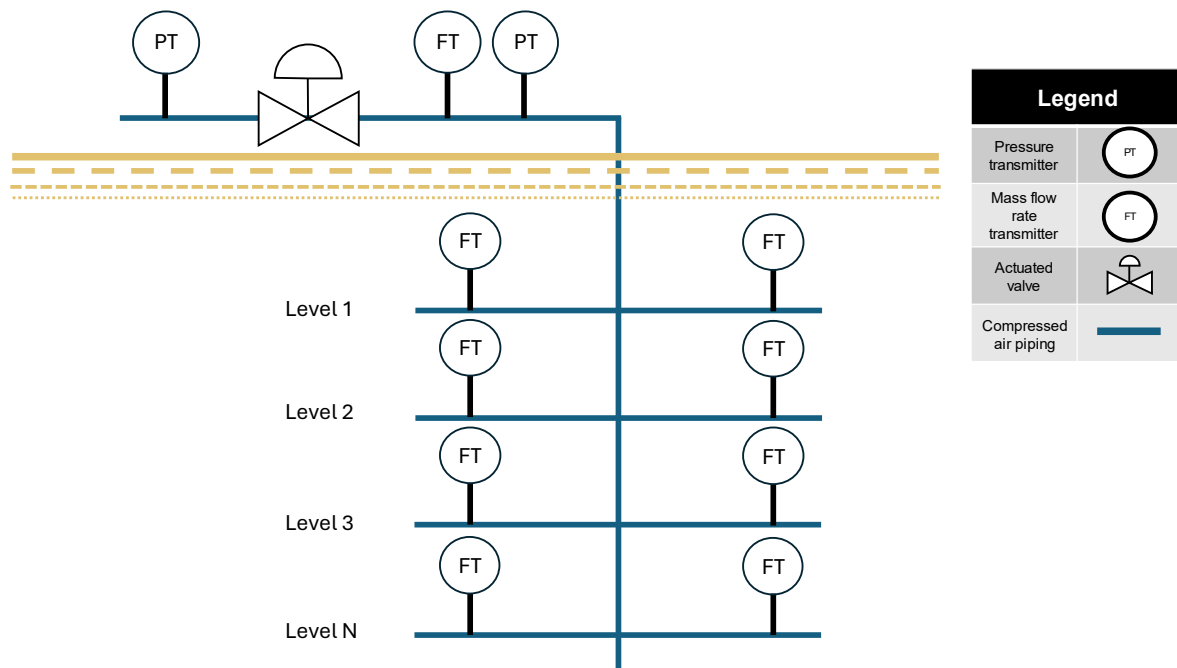


Figure 34: Simple schematic of the compressed air network configuration at Mineshaft A

Before the problem is explained, it is necessary to gain an understanding of the control philosophy of the control valves. In this study, pressure control refers to the actuator of the control valve adjusting the position of the control element until it reaches the predetermined downstream pressure set point. The same is meant for flow control but with a mass flow rate set point. The control philosophy at this mining group uses a combination of pressure and flow control.

Figure 35 illustrates a two-hour period during which a set point change occurred at 05:00. Before the set point change, pressure control was initiated to track the downstream pressure set point. The requirement to switch from pressure control to flow control is that the downstream pressure (in blue) should exceed the pressure set point (in dotted blue) plus a default margin (in dotted violet). This occurs as soon as the set point is changed, whereafter the valve decreases its position to reach the mass flow rate set point (in dotted red) while in flow control. The condition for switching from flow control to pressure control again is that the downstream pressure must drop below the pressure set point.

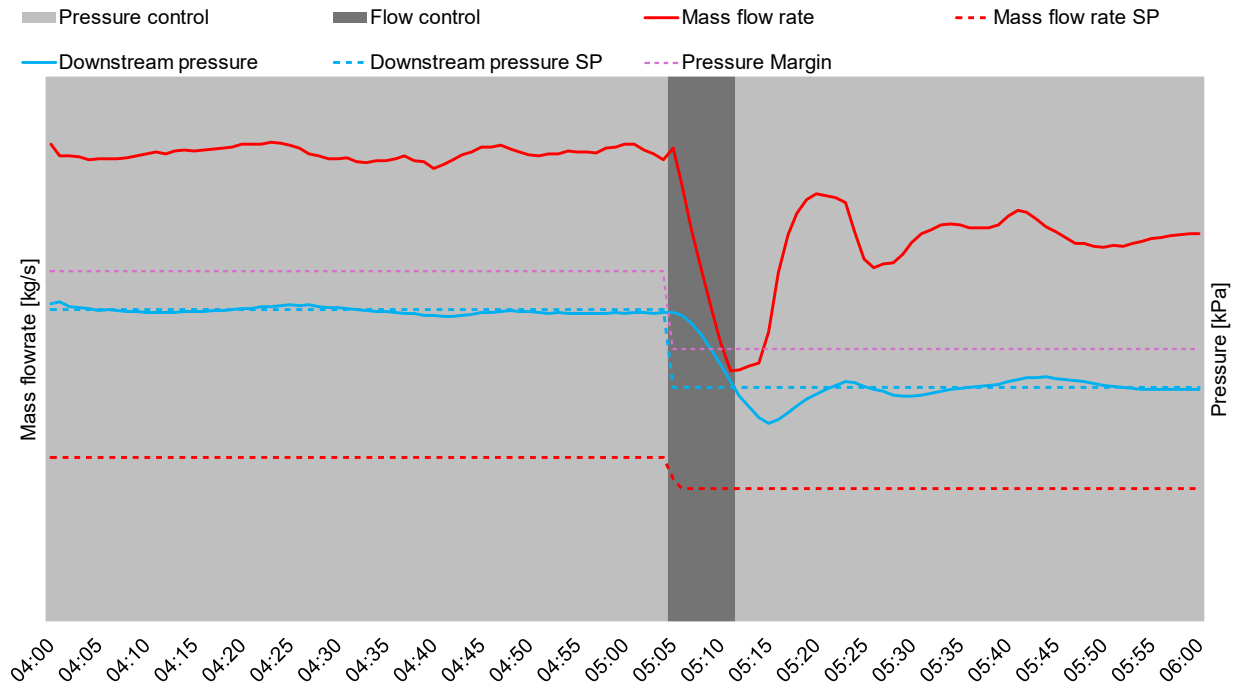


Figure 35: Profile illustrating the control philosophy of the compressed air control valves on the mineshafts in Case Study A

Pressure control is typically initiated throughout most of the 24-hour period of the operational cycle, whereas flow control is only initiated during set point changes. It is argued that using both pressure and flow control unnecessarily complicates the control philosophy. At this mining group, the reason for implementing both pressure and flow control was the challenge of finetuning the pressure control PID system within a limited time frame to ensure proper control during set point changes. Flow control was added as a solution with the specific purpose of controlling during set point changes.

With the background on the control philosophy of the control valve equipment provided, the developed solution was implemented on a mineshaft where the mass flowmeter instrument had malfunctioned. Without a working mass flowmeter, the control valve could not control according to its predetermined set point profile, increasing compressor operational costs. This was identified with continual monitoring and reported to the appropriate personnel. An action plan was developed to ensure swift corrective action was taken. The following section details the acquisition and validation of the data, which is the first step in the solution.

3.1.2 Data acquisition and validation

The required data for this case study is listed in Table 23. The data was acquired from the instrumentation department of the mining group such as explained in section 2.1.1.1. This section validates the process and control variable data for the control valve performance report's

development. The validation procedure follows six steps to ensure a complete and accurate data set. A total of eight variables were validated daily for the control valve performance report.

Table 23: Data required for daily monitoring and reporting on control valve equipment performance

Variable	Unit	Sensor range		System boundary	
		Lower	Upper	Lower	Upper
Upstream pressure	kPa	0	1 000	0	700
Downstream pressure	kPa	0	1 000	0	700
Mass flow rate	kg/s	0	45	0	35
Downstream pressure set point	kPa	0	1 000	0	700
Mass flow rate set point	kg/s	0	1 000	0	700
Control valve position	%	0	100	0	100
PLC controller output	%	0	100	0	100
Mode (pressure or flow control)	Binary	0	1	0	1

The validation procedure, as illustrated in Appendix B, was implemented daily on the data set listed in Table 23. The results for each of the validation steps are briefly discussed in conjunction with Table 23.

3.1.2.1 Constant value check

The data listed in Table 23 was subject to a check that flagged repeating constant values. This check was implemented for compressed air upstream pressure, downstream pressure, and mass flow rate. Throughout the implementation period, no repeating constant values were observed except for the compressed air mass flow rate and downstream pressure during the blasting period. This was expected due to the closure of the control valve.

Repeating constant values were expected for the other variables, such as the set points, control valve position, controller output, and control mode. These values coincided with the limits (0% and 100%) of these values. The set point profiles were also expected to have constant values for the simplicity of the control philosophy.

3.1.2.2 Unit check

The units of the different variables were discussed with the mining group's instrumentation department to ensure consistency. Only the compressed air mass flow rate needed to be converted to SI units. The units of all variables are listed in Table 23.

3.1.2.3 Sensor ranges and system boundary check

The various sensor ranges and system boundaries were discussed with the mining group's instrumentation department to flag potential outliers in the data. The sensor ranges differed from the system boundaries as the sensor can detect values that the system itself may not be able to achieve. For example, the compressed air mass flow rate could be measured at a higher rate than what the system is capable of producing. The sensor ranges and system boundaries are listed in Table 23.

3.1.2.4 Redundant sensors

In Mineshaft A, mass flowmeters were installed on all half-levels. The sum of these mass flowmeters can be used as a redundant total mass flow measurement. However, this poses a risk because if multiple flowmeters malfunction, it could jeopardise control of the control valve. Mass flowmeters should only be used as a redundancy check to verify the mass flow measurement of the surface mass flowmeter.

3.1.2.5 Data correlation

The upstream and downstream pressure must correlate with the mass flow rate through the valve. In the case of a reduction in valve position, a reduction in mass flow rate and downstream pressure will be measured, whereas the upstream pressure will increase. If any of these measurements do not correlate with the others, it indicates the presence of erroneous data that must be excluded from the data set and investigated.

These checks were continually implemented in the developed control valve performance report, which monitored and reported the performance of the control equipment. The following section discusses the developed control valve performance report.

3.1.3 Report development

A daily control valve performance report was developed for the mining group as specified in Section 2.3.3. An example is attached in Appendix G. The developed report is used for both Case Studies A and B, with excerpts from the daily control valve report discussed below. This report aims to monitor control valve performance and address the high compressed air consumption during blasting, which coincides with the Eskom evening peak tariff period.

The overview table in Table 24 shows the average compressed air consumption in kg/s and the compressed air consumption as a percentage of the daily maximum for each mineshaft. The control valve closing, the mineshaft blasting times, and the estimated annual missed opportunity

in rands are also illustrated for monitoring the blasting period. The annual missed opportunity is shown to emphasise the cost of inaction.

Table 24: Example of daily valve closing – overview from Appendix G

Valve	Average mass flow rate [kg/s]	% of maximum daily mass flow rate	Valve closing time	Blasting time	Estimated annual blasting period cost
Shaft A	9.38	27%	Did not close	18:10	R5 700 000
Shaft B	3.07	39%	20:00	17:40	R1 900 000
Shaft C	6.31	21%	18:30	18:20	R3 900 000
Shaft D	1.50	11%	18:20	18:10	R1 000 000
Shaft E	4.92	15%	18:20	18:10	R3 100 000
Shaft F	3.27	15%	18:40	18:40	R2 100 000
Shaft G	4.51	11%	17:50	17:50	R2 800 000
Shaft H	15.09	28%	Did not close	18:10	R9 200 000
Shaft I	8.37	20%	18:20	18:30	R5 300 000
Total	56.43				R35 600 000

Furthermore, the report included two specific profiles, a flow and pressure performance chart and a control variable performance chart for each of the mineshafts. The flow and pressure performance chart illustrated in Figure 36 shows the upstream (dark blue) and downstream pressure (light blue), the mass flow rate (red), and the respective set point profiles (dotted red and dotted light blue).

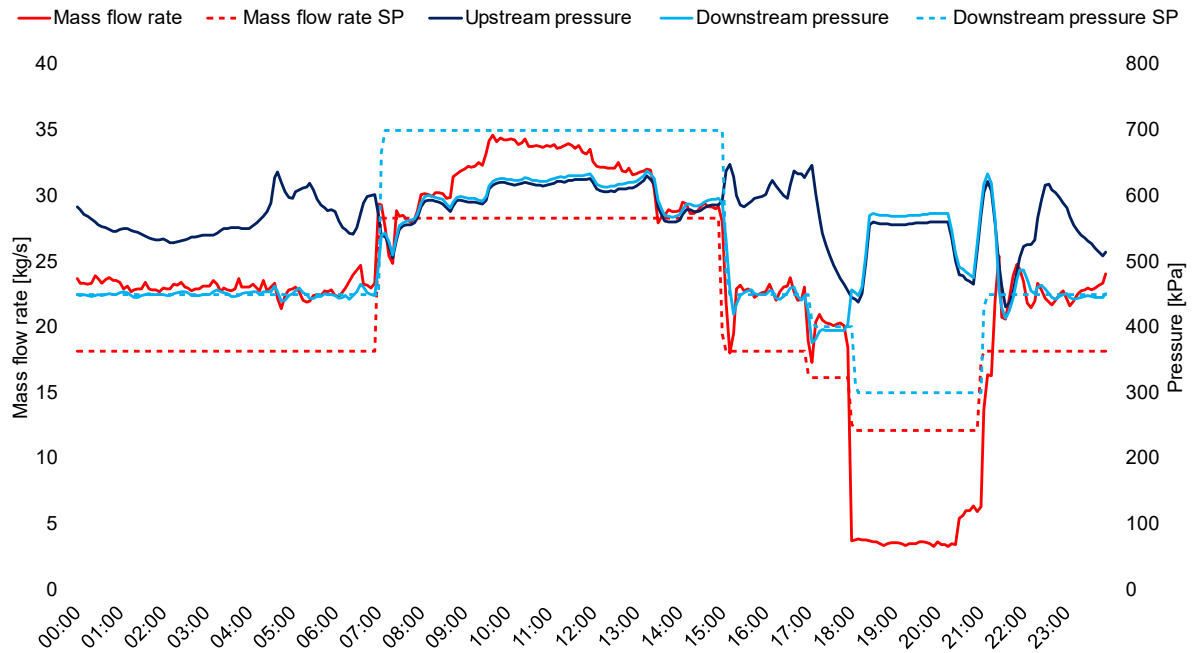


Figure 36: An example of Mineshaft A's flow and pressure performance chart as shown in Appendix G

Figure 37 shows the control variable performance chart, which illustrates the control valve's position, the controller output, and whether pressure or flow control was initiated for a 24-hour period. This performance chart was used to determine whether the control valve was controlled correctly.

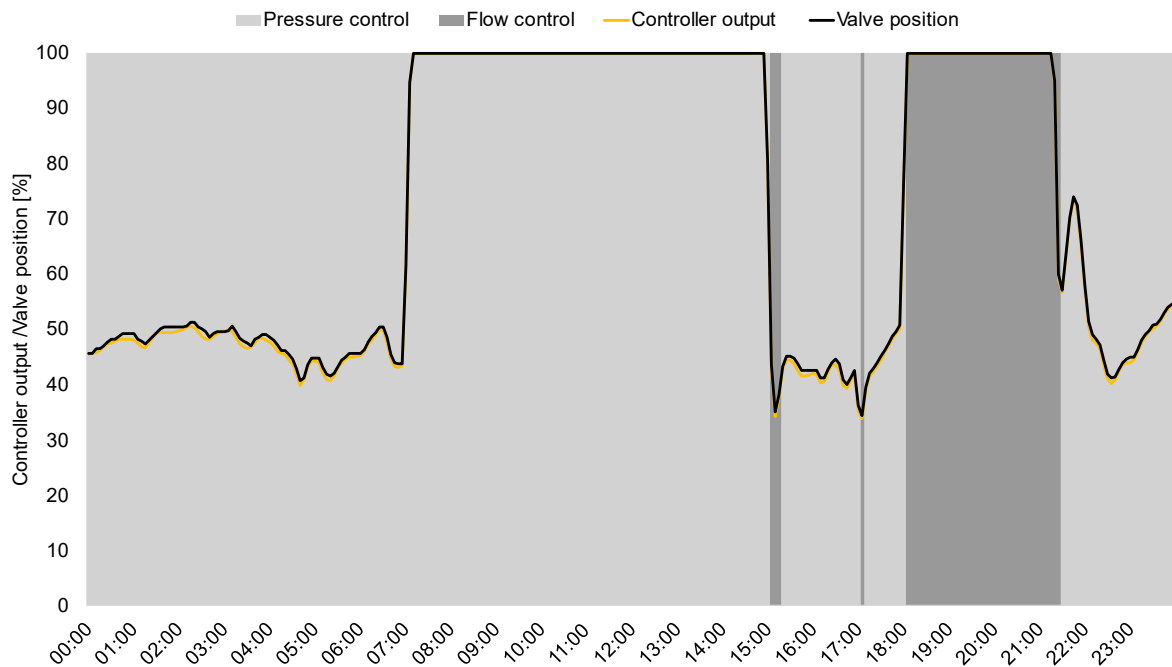


Figure 37: An example of Mineshaft A's control variable chart from Appendix G

3.1.4 Continual monitoring and reporting

The procedure developed in Section 2.4 was used to monitor and report on all surface control valves in the mining group. The control valve performance report was monitored daily to establish whether control valves were controlled correctly. This ensured that any anomalies could be identified and acted upon with immediate effect.

Figure 38 shows a simplified version of the mass flow rate and pressure performance chart with only the mass flow rate and its set point included. An anomaly was observed through routine monitoring during the blasting period from 18:00 to 21:00, as shown in Figure 38. Contrary to the expected 0 kg/s due to the control valve closure, a minimum mass flow rate of 3 kg/s was recorded, which prompted further investigation.

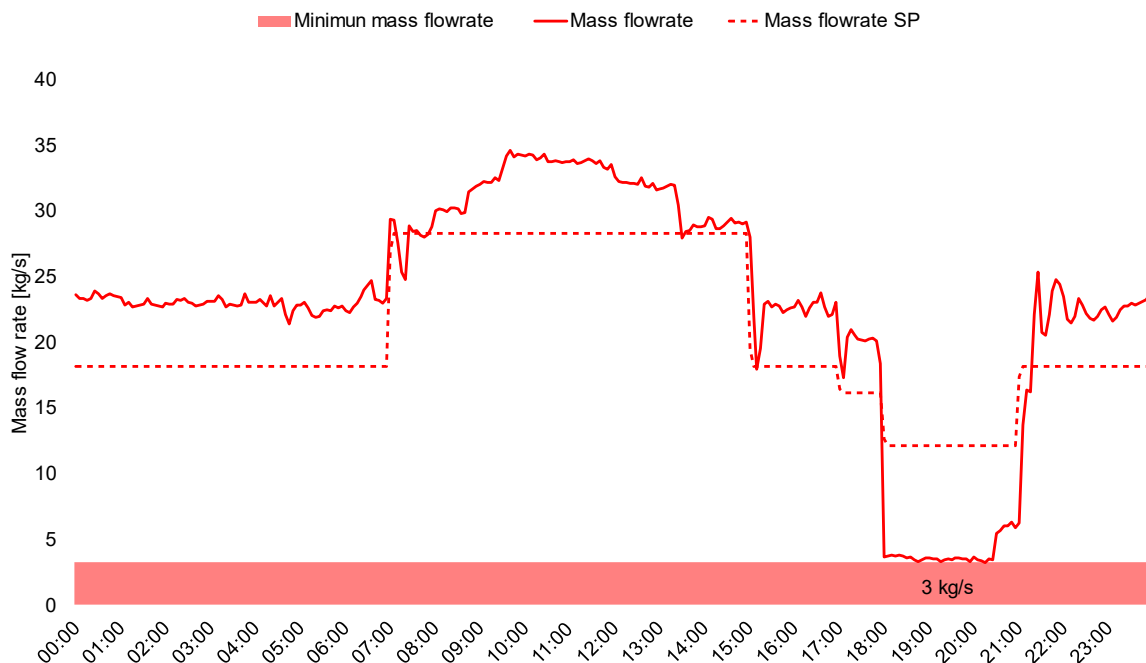


Figure 38: Daily control valve performance – minimum mass flow rate; simplified to illustrate only flow rate variables

Upon investigation, it was determined that the surface mass flowmeter had suffered damage due to rough weather conditions. The next step was to report the issue to the appropriate personnel. In this case, two departments had to be notified – Mineshaft A's engineering department and the central services engineering department.⁸ After discussion with the relevant personnel, i.e. instrumentation technicians and engineer, it was determined that the mass flowmeter's computing circuits had to be replaced.

⁸ This will differ between different mining groups. In this case study, issues such as these have to be reported to the specific shaft's engineering department as well as the central services engineering department.

3.1.5 Acting on inefficiencies

After identifying the responsible personnel as the instrumentation department, a solution to the issue was discussed and agreed upon. The solution was to replace the mass flowmeter's computing circuit with an alternative. Upon replacement, it was observed that the mass flowmeter measurements were much lower than expected, as seen in Figure 39. Comparing the mass flow rate before and after 10:00 showed an evident change, which led to the conclusion that the mass flowmeter was ranged incorrectly. This issue was rectified by contacting the original equipment manufacturer (OEM). The OEM was scheduled to program the appropriate ranges onto the new mass flowmeter's computing circuit, with a lead time of one week. Each of these actions was added to the action plan for progress tracking.

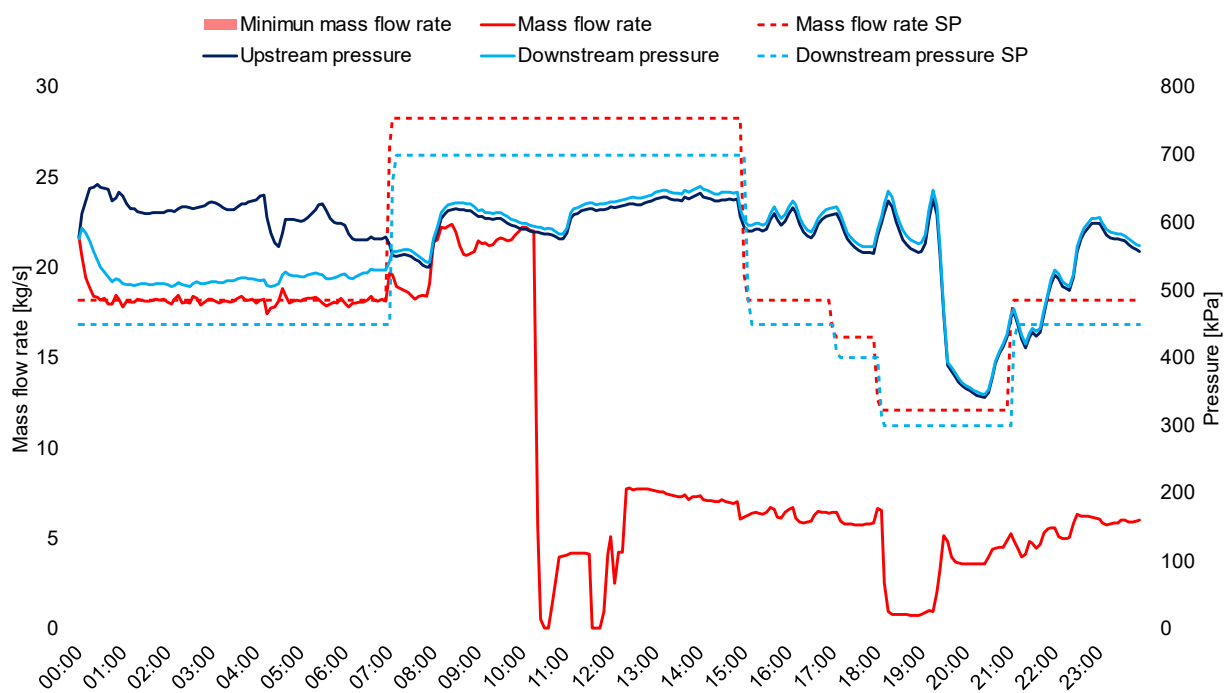


Figure 39: Daily control valve performance – incorrectly ranged mass flowmeter

Due to the incorrectly ranged mass flowmeter, the control valve could not be controlled correctly. Figure 40 clearly illustrates that the control valve performed little to no control after 07:00. This meant that the control valve remained open throughout most of the day, as it could not switch between flow and pressure control.

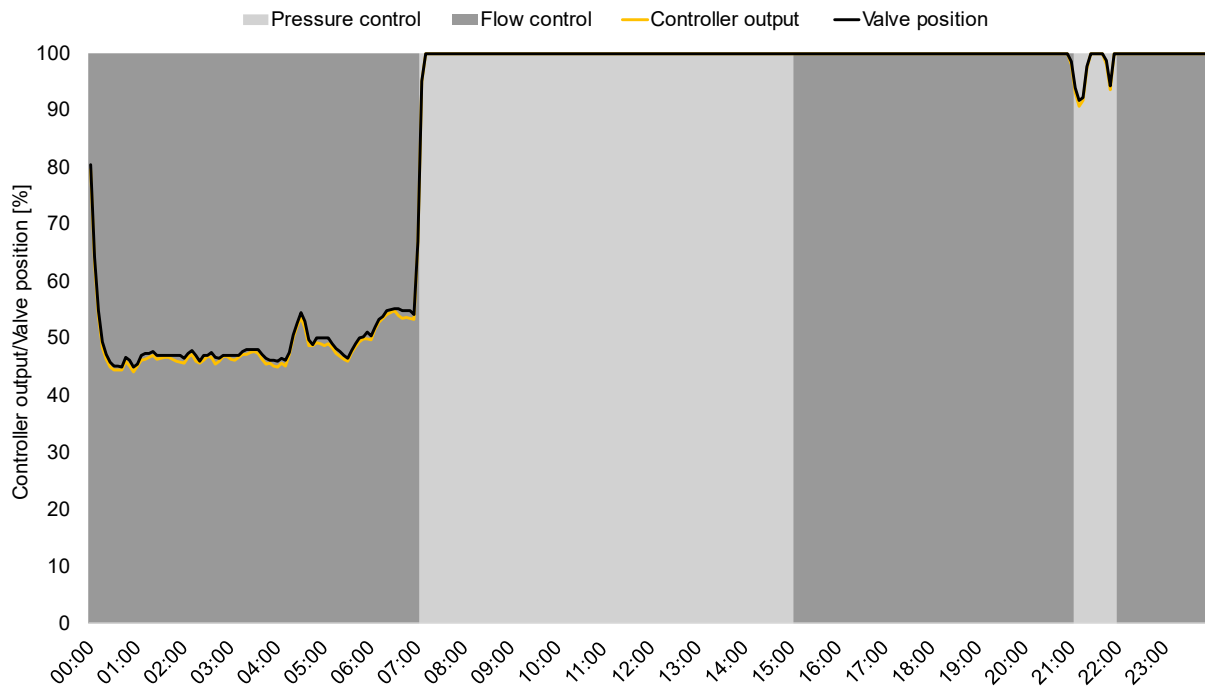


Figure 40: Daily control valve performance – no control

It was determined that the solution entailed a programming change that would alter the control philosophy so that only pressure control would be initiated throughout the 24-hour period. The motivation was to avoid a significant increase in compressor running time, which would ultimately lead to higher electricity consumption and costs. If the solution had not been implemented, the inefficiency would have caused a consumption increase of 116 MWh and a cost increase of R150 000 for five weekdays.

An action plan, shown in Figure 41, was developed for each of the steps discussed in this case study. The action plan described the section as Mineshaft A's Surface, where the mass flowmeter was located. It included a brief description of each of the issues encountered and actions required to rectify them. Photos or images describing the issues were also added, with the responsible personnel identified and commitment dates agreed upon.

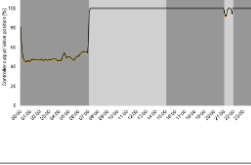
No.	Section	Problem	Action	Photo	Responsible Person	Commitment date	Status	Signature
1	Mineshaft A Surface	Incorrect mass flowmeter measurement.	Replace mass flowmeter computing circuits.		Technician A	YYYY/MM/DD	Complete	Signature technician A
2	Mineshaft A Surface	Incorrectly ranged mass flowmeter.	Arrange OEM to reprogram correct ranges.		OEM	YYYY/MM/DD	Complete	Signature OEM
3	Mineshaft A Surface	No control on control valve	Adapt control philosophy to only initiate pressure control.		Technician B	YYYY/MM/DD	In progress	Signature technician B

Figure 41: Action plan used for tracking actions to address the inefficiency identified in Case Study A

3.1.6 Summary of Case Study A

The solution developed in Chapter 2 was implemented on Mineshaft A's control valve to maintain energy and cost savings. Through continual monitoring and reporting, a problem with the mass flowmeter of Mineshaft A was identified, reported, and acted upon.

The data in Table 23 was subjected to a validation procedure, as shown in Appendix B. This validation procedure was implemented daily as the data set was required for the developed report. The developed report was used to identify the malfunctioning mass flowmeter by considering whether the control valve was closed in the overview table. The 24-hour profile of the mass flow and pressure and the control variable performance charts were used to aid further investigation into identifying and addressing the issue.

Monitoring the control valve performance report daily made it simple for the relevant personnel to identify and report malfunctioning instruments. In this case study, the responsible personnel were the engineering department of Mineshaft A, the central services engineering department, and the OEM. An action plan was developed to track each of the actions and hold the responsible personnel accountable.

If the solution had not been implemented, the impact of this inefficiency would have been an increase of 116 MWh and R150 000 over five weekdays. The following two case studies consider initiative drives to improve the efficiency of the compressed air network at the respective mineshafts.

3.2 Case Study B: Blasting period valve closure

3.2.1 Background

Case Study A utilised daily control valve performance to identify an inefficiency that would have increased operating costs by R150 000 over five weekdays if it had not been addressed. Case Study B takes a holistic view of how this solution was proactively applied to ensure that the surface valves of all nine mineshafts of the mining group were closed throughout the blasting period.

This initiative was motivated by the blasting period (17:00–21:00) aligning with one of the two peak tariff periods of the Eskom time-of-use (TOU) periods in both winter and summer. Reducing compressed air consumption during this period would greatly affect the operating costs of the compressors. The initiative was implemented and results evaluated after a period of 18 months.

Following the same solution method, the data for the nine mineshafts' compressed air required variables were acquired and validated as in Section 3.1.2. The control valve performance report has already been developed in Section 3.1.3 with a sample illustrated in Appendix G. This initiative, however, focused on reducing the blasting period consumption by closing the control valves from the start of the period and keeping them closed until mining personnel proceeded below ground again for the cleaning shift.

3.2.2 Continual monitoring, reporting, and acting on inefficiencies

With the aim established to drive the closure of the control valves throughout the blasting period, the cycle of monitoring and reporting on control valve performance was implemented daily. For initiatives such as these encompassing the entire mineshaft, it is beneficial for the management of the mining group to provide support in motivating mining personnel due to the difficulty of implementing it otherwise. This has also been stated as a requirement for energy management in ISO 50001 [60].

Table 25 shows an example of a typical daily report overview table that illustrates the average consumption, valve closing time, blasting time, and estimated annual cost (this is a duplication of Table 24, illustrated again for convenience). The shafts that must be acted upon are Shaft A and Shaft H. These specific shafts did not close their control valves during the blasting period, and this issue had to be scrutinised to determine whether it could be addressed. Shaft B also had to be investigated further because they closed the control valve towards the end (20:00) of the blasting period while blasting at the start of the period (17:40).

Table 25: Example of daily valve closing – overview from Appendix G

Valve	Average mass flow rate [kg/s]	% of maximum daily mass flow rate	Valve closing time	Blasting time	Estimated annual blasting period cost
Shaft A	9.38	27%	Did not close	18:10	R5 700 000
Shaft B	3.07	39%	20:00	17:40	R1 900 000
Shaft C	6.31	21%	18:30	18:20	R3 900 000
Shaft D	1.50	11%	18:20	18:10	R1 000 000
Shaft E	4.92	15%	18:20	18:10	R3 100 000
Shaft F	3.27	15%	18:40	18:40	R2 100 000
Shaft G	4.51	11%	17:50	17:50	R2 800 000
Shaft H	15.09	28%	Did not close	18:10	R9 200 000
Shaft I	8.37	20%	18:20	18:30	R5 300 000
Total	56.43				R35 600 000

The mineshaft engineer responsible for the section where the control valve is installed must be contacted and notified of this information. In this case study, all control valves are situated on the surface and fall under the surface engineer's responsibility. It is also essential to provide this information to the engineering manager of the mineshaft. However, the main hindrance to the full implementation of this initiative is the inconsistency of underground personnel in clearing the mineshaft early enough, which is the responsibility of the mine managers and overseers. Therefore, reporting this information to them is crucial.

Throughout the implementation period, the control valve performance report was monitored daily, and inefficiencies were reported to the appropriate personnel on a case-by-case basis. As the most inefficient mineshafts improved through awareness of the costs associated with this initiative, other mineshafts could be targeted to investigate the limitations of closing the control valves earlier.

The implementation of this initiative was evaluated over a period of 18 months. After implementing continual monitoring and reporting of control valve performance and prioritising the closure of control valves during blasting periods, a substantial improvement in compressed air efficiency was observed across all nine mineshafts. The improvement is clearly illustrated in Figure 42, which showcases the average compressed air consumption during the blasting period (17:00–21:00) before and after implementing the performance improvement drive.

During the blasting period, the average mass flow rate was reduced by 21% on all mineshafts except for Mineshaft D. Mineshaft D is a small mineshaft limited by pneumatic pumps fed from the primary compressed air pipeline. An initiative to replace the pneumatic pumps with electrical pumps was still underway during the evaluation of the results. There was a significant

improvement in Mineshaft E due to a project that allowed the underground loading box to be fed by a pipe from the surface. As a result, the reduction in consumption did not include this improvement. If the reduction of Mineshaft E was considered, the overall decrease in compressed air usage for this period would be 28%. An average mass flow rate reduction of 28.2 kg/s was achieved with this initiative. The reduction for each mineshaft is also shown in Table 26.

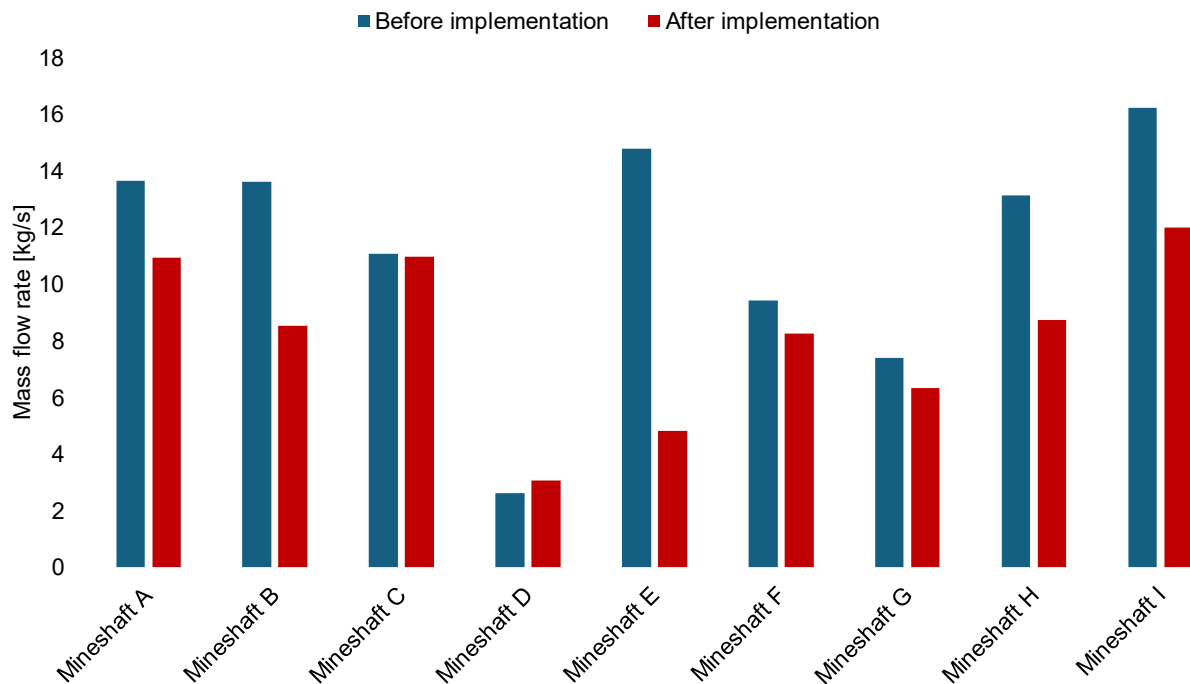


Figure 42: Average compressed air mass flow rate throughout the blasting period, before and after implementation

Table 26: Mass flow rate reduction of each mineshaft before and after implementation

Mineshaft	Before implementation [kg/s]	After implementation [kg/s]	Reduction
A	13.6	10.9	-20%
B	13.6	8.5	-37%
C	11.1	11.0	-1%
D	2.6	3.1	18%
E	14.8	4.8	-67%
F	9.4	8.3	-12%
G	7.4	6.3	-14%
H	13.1	8.7	-33%
I	16.2	12.0	-26%
Total	101.9	73.7	-21%⁹

⁹ Mineshaft E was excluded from this calculation.

The impact of this initiative yielded an annual reduction of 5.6 GWh and R10.6 million. While this impact may be significant, this initiative should aim to ultimately reduce the compressed air consumption to 0 kg/s during the blasting period, which indicates a need for further improvement.

Other solutions that may improve this initiative include tracking whether personnel are still underground to identify which sections clear the mineshaft the latest and focusing efforts on these specific sections or installing control valve equipment as far as possible (on the crosscuts) to reduce consumption even more.

Nonetheless, the solution developed in Chapter 2 was implemented successfully as part of an initiative to drive the closure of control valves during the blasting period at the mining group. The following case study uses the developed solution to implement an improvement initiative on underground ventilation controls with the aim of reducing the mineshaft's compressed air consumption.

3.3 Case Study C: Underground ventilation controls improvement

3.3.1 Background

This case study was implemented on a specific mineshaft from the mining group mentioned in Case Studies A and B. Data on compressed air consumption and production was acquired and validated using the same procedure shown in Section 3.1.2. The mineshafts were prioritised based on two criteria: first, whether mass flowmeters had been installed on each of the half-levels of the said mineshaft, and second, the mineshaft's performance rating on the intensity analysis of the performance overview report.

As part of investigating energy efficiency opportunities in the mining group, data from the three months before the implementation of the demand side performance improvement initiative was gathered and summarised in Table 27, which is adapted from the performance overview report. Table 27 shows the average weekly consumption, as well as the production and intensity of this three-month period for each of the mineshafts on the property of the mining group. The last two columns indicate the mode ranking of the shaft and whether the shaft had mass flowmeters installed on each half-level at that point in time.

From these results, Mineshafts A, B and I (highlighted in blue) were possible options for selecting and prioritising performance improvement initiatives. Another critical factor was whether mass flowmeters were installed on each half-level underground, which was also the case for these three mineshafts. Mineshaft B was selected instead of Mineshaft A or Mineshaft I due to the mode ranking and the fact that a case study had already been conducted on Mineshaft A. The

performance of Mineshaft B was discussed with its managerial personnel, who had provided permission to conduct investigations to determine possible performance improvement initiatives.

Table 27: Compressed air consumption performance from the performance overview report (three months before implementation)

Mineshaft	Consumption [kg]	Production [tonnes]	Intensity [kg/000 tonne]	Mode ranking	Half-level mass flowmeters
A	3 860	14 933	270	9	Yes
B	3 818	19 583	197	8	Yes
C	4 792	38 595	125	5	No
D	658	8 138	81	1	No
E	6 279	32 404	209	7	No
F	455	5 450	85	1	No
G	1 968	21 335	93	3	No
H	4 153	35 796	117	4	No
I	4 719	25 274	189	6	Yes

After approval from Mineshaft B's management, the investigations determined that ventilation controls were not implemented according to the mining group's standards in most working areas. Mineshaft B's management approved the initiative to improve underground ventilation controls. The following sections detail the data validation, report development, continual monitoring and reporting, and acting on and verifying results.

3.3.2 Data acquisition and validation

For this case study, only the compressed air consumption for each section and the total compressed air consumption and production data of the entire shaft were required. The compressed air mass flow rate was obtained from the instrumentation department, whereas production data was acquired from the survey department. The data set with its units, sensor ranges, and system boundaries are listed in Table 28. A discussion on the validation of the data in this data set follows.

Table 28: Data required for daily monitoring of surface and section compressed air performance

Variable	Unit	Sensor range		System boundary	
		Lower	Upper	Lower	Upper
Shaft mass flow rate	kg/s	0.0	45.0	0.0	35.0
Section mass flow rate	kg/s	0.0	7.2	0.0	7.2
Shaft production	tonne	N/A		N/A	

3.3.2.1 Constant value check

Throughout the period of implementation of the solution, the data listed in Table 28 was subject to a check that flagged repeating constant values in the data. It was evident that no repeating constant values were flagged during the implementation period.

3.3.2.2 Unit check

The units of the different variables were discussed with the instrumentation department and survey department to ensure consistency. It was only necessary to convert the compressed air mass flow rate to SI units. The units of all variables are listed in Table 28.

3.3.2.3 Sensor ranges and system boundary check

The different sensor ranges and system boundaries were also discussed with the mining group's instrumentation department to determine the upper and lower limits of the sensor ranges. The sensor ranges may exceed the system boundaries, since the sensor can detect values, such as the compressed air mass flow rate, that the system is unlikely to achieve.

The survey department measures and calculates production data manually based on the progress of the mining crew in a given section since the last measurement. Therefore, there are no checks on the sensor range or system boundaries for this variable. The sensor ranges and system boundaries are also listed in Table 28.

3.3.2.4 Redundant sensors

While it is possible to use the underground mass flowmeters on Mineshaft B as redundant sensors that are correlated with the surface, it is not recommended, especially if multiple mass flowmeters malfunction.

3.3.2.5 Data correlation

As mentioned earlier, in order to have redundancy, the surface mass flowmeter can be correlated with the underground half-level mass flowmeters. This step is only necessary if a single mass flowmeter, such as the surface mass flowmeter, malfunctions. These checks were continually implemented in the developed reports (Appendix H and Appendix I) that were used to monitor and report the compressed air network's consumption, thereby validating the data set.

The following section details a case-specific use of continual monitoring and reporting with trusted and accurate data sets on a demand-side improvement initiative, namely to improve ventilation controls underground.

3.3.3 Report development

Mineshaft B comprises a vertical and decline section as per data obtained from the instrumentation and mine planning departments. A simplified schematic is shown in Figure 43.

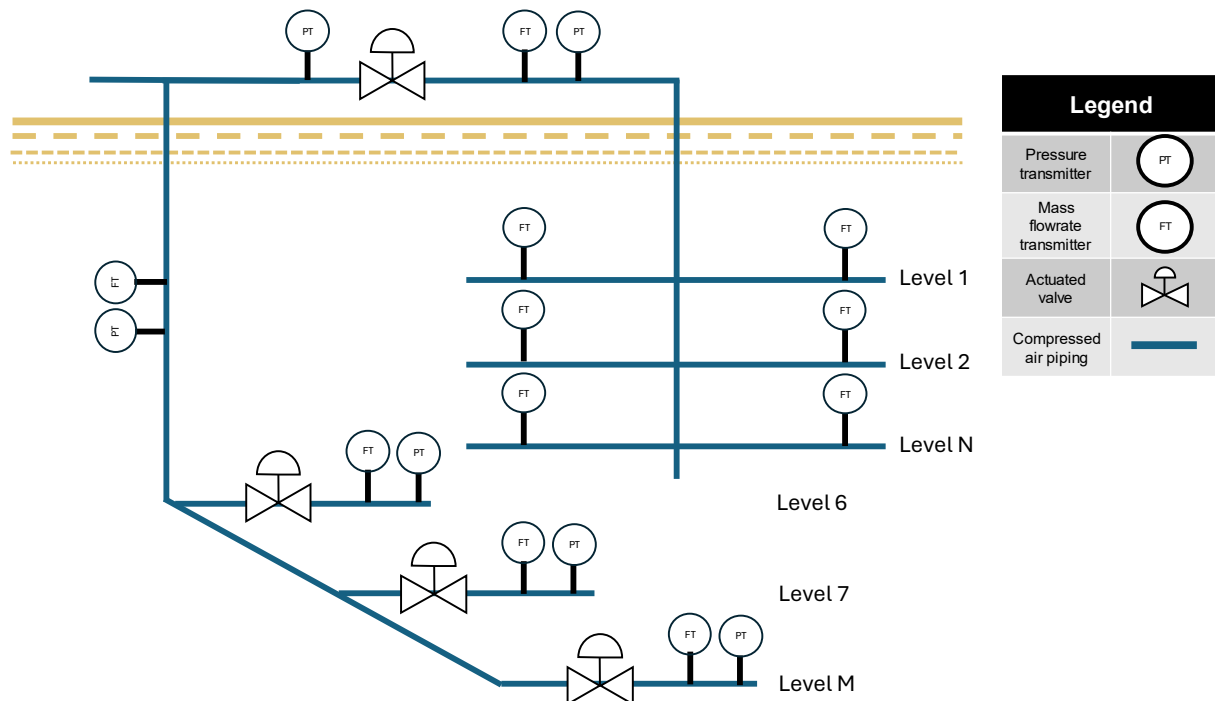


Figure 43: Illustration of the instrumentation and control equipment configuration of Mineshaft B

The vertical section consists of six active levels (nine active half-levels) while the decline section consists of four active levels (eleven active half-levels). A mass flowmeter was installed on each of the half-levels. Control valves and downstream pressure transmitters were installed at each level of the decline section.

For this case study, two reports were developed for Mineshaft B (refer to Appendix H and Appendix I) according to the specifications set out in Sections 2.3.1 and 2.3.2. For the performance overview report, Table 29 and Figure 45 illustrate an overview table and bubble chart showing Mineshaft B's performance in comparison to the other nine mineshafts of the mining group. These illustrations are helpful when discussing the current performance of the entire mineshaft with the relevant personnel.

Table 29: Excerpt from the performance overview report in Appendix H

Mineshaft	Compressed air consumption ['000 kg/week]	Production ['000 tonne/week]	Intensity [kg/tonne]	Ranking (worst to best)
Mineshaft A	9 238 617	12 175	759	1
Mineshaft E	14 126 434	25 470	555	2
Mineshaft B	8 778 952	16 164	543	3
Mineshaft I	15 279 294	29 741	514	4
Mineshaft C	13 824 898	35 602	388	5
Mineshaft H	11 224 995	37 838	297	6
Mineshaft F	1 561 271	5 610	278	7
Mineshaft G	6 937 178	25 638	271	8
Mineshaft D	2 035 204	8 388	243	9

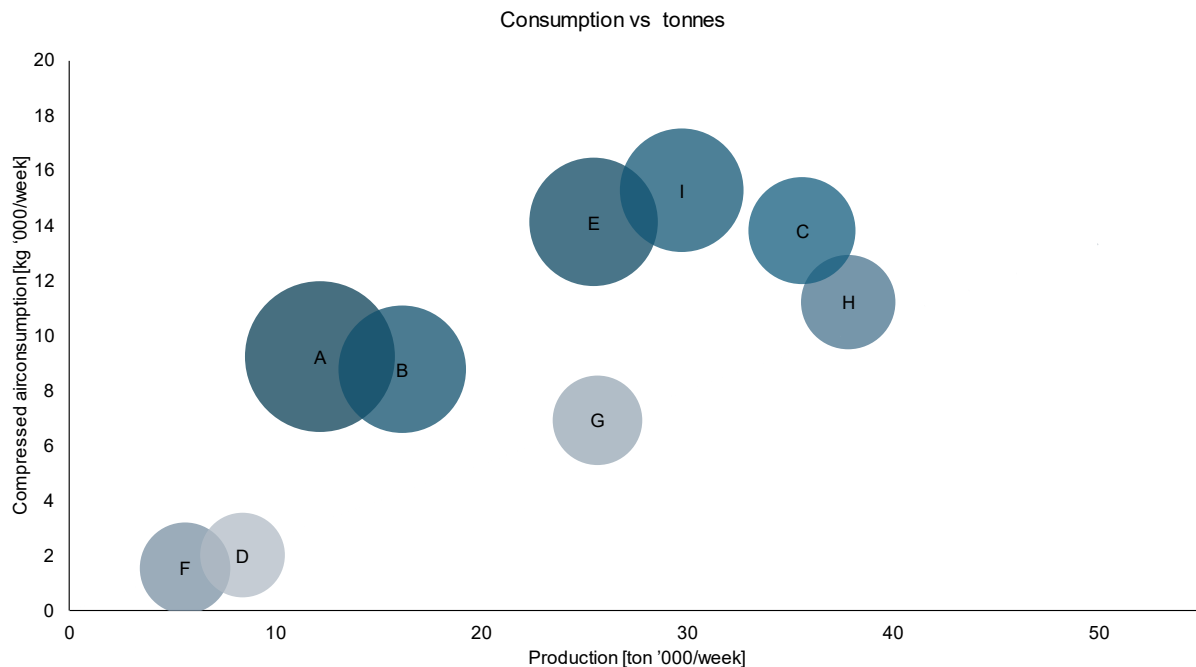


Figure 44: Mineshaft overview chart – excerpt from performance overview report in Appendix H

Table 30, which was also included in the developed report, demonstrates the performance of all sections on the vertical section of the mineshaft. This shows the actual and target compressed air consumption of each half-level prioritised according to the estimated compressed air wastage costs. The estimated daily and annual costs of the wastage are also listed to provide an estimate of the opportunity available per half-level.

Table 30: Section performance overview table – excerpt from performance overview report in Appendix H

Half-level	Compressed air consumption ['000 kg/week]			Estimated wastage cost [R'000]	
	Actual	Target	Wastage	Daily	Annual
Vertical Section	866	280	586	138	22 942
Level 3 North	199	44	155	35	5 893
Level 2 North	167	37	130	30	5 023
Level 4 North	160	40	120	30	4 980
Level 5 North	139	55	83	19	3 201
Level 1 North	122	52	70	16	2 597
Level 6 North	72	44	28	8	1 219
Level 6 South	0	0	0	0	0
Level 5 South	7	7	0	0	0
Level 3 South	0	0	0	0	0

For the section performance report, the daily total consumption and an average 24-hour profile were included in the developed report for each section. Excerpts from the report showcasing the consumption and performance of Level 1 North are shown in Figure 45 and Figure 46. The daily consumption for Level 1 North indicates whether further investigation was required on this half-level; in this case, other half-levels had to be prioritised due to their adequate performance. However, it should be noted that there was an opportunity for improvement during the cleaning shift from 00:00 to 04:00 when the actual is compared with the target.

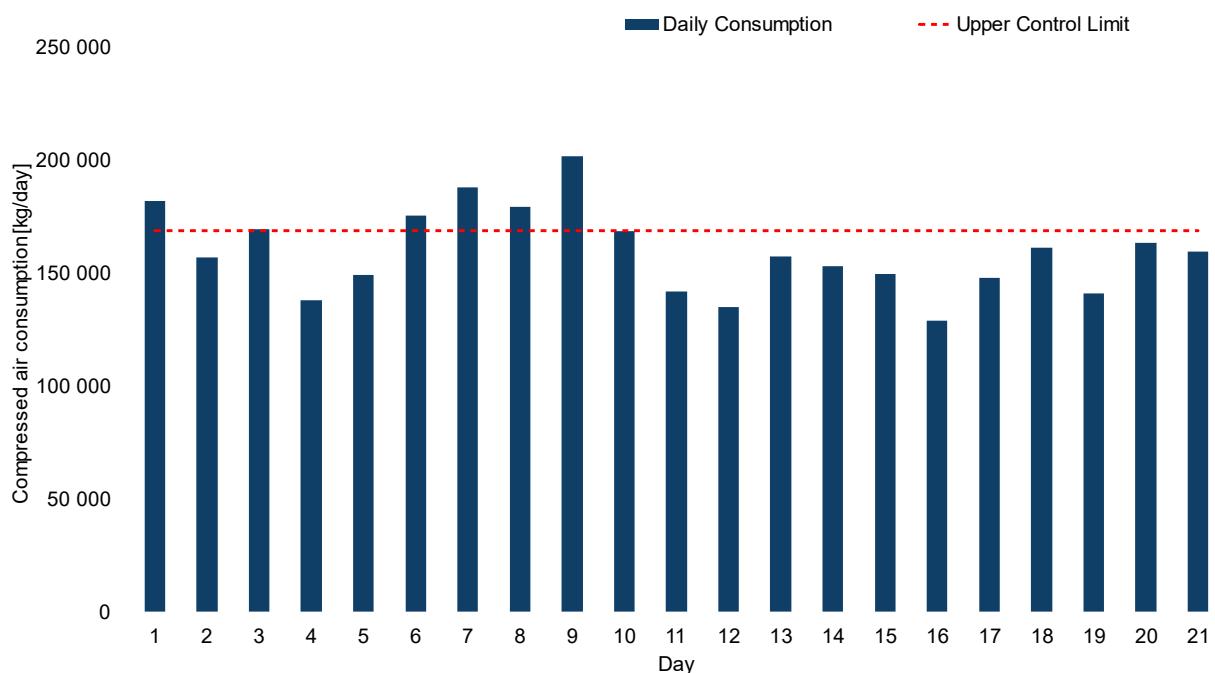


Figure 45: Daily consumption of Level 1 North – excerpt from section performance report in Appendix I

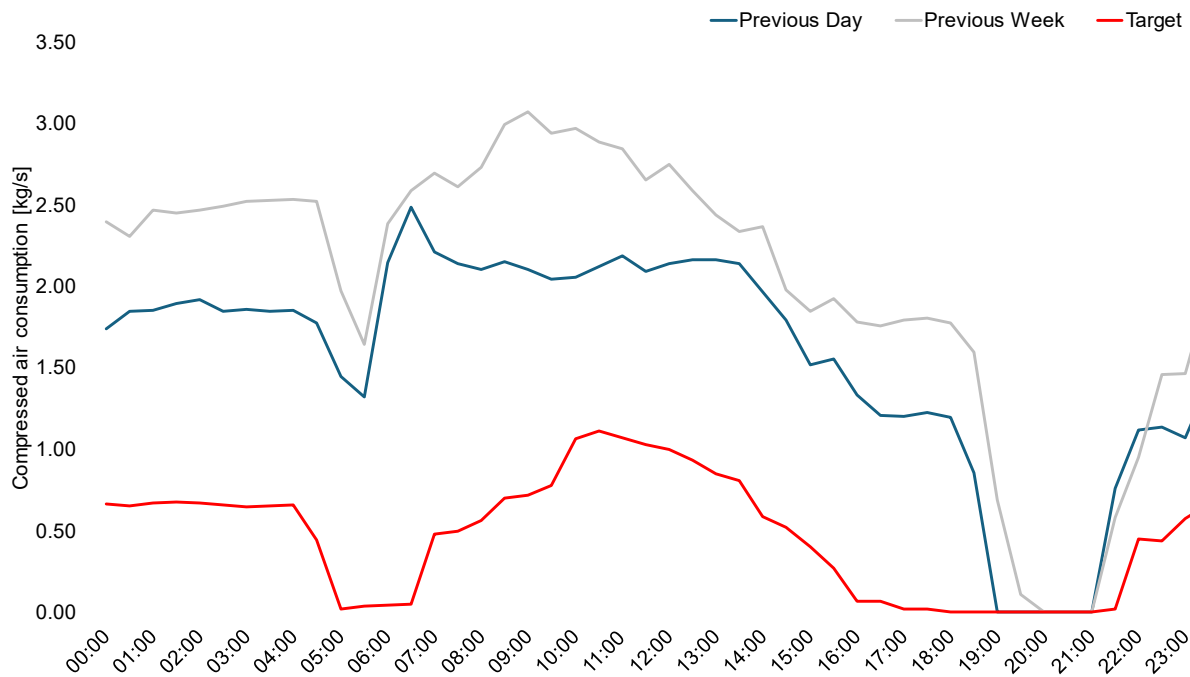


Figure 46: 24-Hour profile of Level 1 North from section performance report in Appendix I

A summary of the information contained in the two figures above is listed in Table 31. This information is used in discussions aimed at improving the performance of the specific section's compressed air network.

Table 31: A summary table of Level 1 North performance from the section performance report in Appendix I

Metric	Average compressed air consumption [kg/day]	Estimated annual cost [R]
Previous day	37.54	1 660 526
Previous week	48.86	2 161 616
Target	11.14	492 745
Wastage	26.40	1 167 781

With the information captured in Figure 44 to Figure 46 and Table 29 to Table 31, effective monitoring of the performance of a mineshaft and its respective underground sections can occur. These reports are helpful for discussions related to the performance of the respective mineshafts and their underground sections.

3.3.4 Continual monitoring and reporting

The underground investigation conducted on Mineshaft B concluded that ventilating using compressed air was a common practice. Reducing the number of times this practice occurs would have the highest impact on compressed air performance at this specific mineshaft. Hence, an initiative was started to identify and improve underground ventilation controls in the areas with the highest consumption.

Following the procedure developed for continual monitoring and reporting in Section 2.4, specific sections were targeted to address ventilation controls. This was done based on the excess compressed air consumption compared with the theoretical target during the cleaning shift period, as seen in Figure 47. In this instance, a significant difference exists between the theoretical target and the actual compressed air consumption for this specific section. Based on this finding, half-levels were prioritised and acted upon, similar to Du Plooy's [44] method. A sample of the vertical section's performance overview report is illustrated in Table 32.

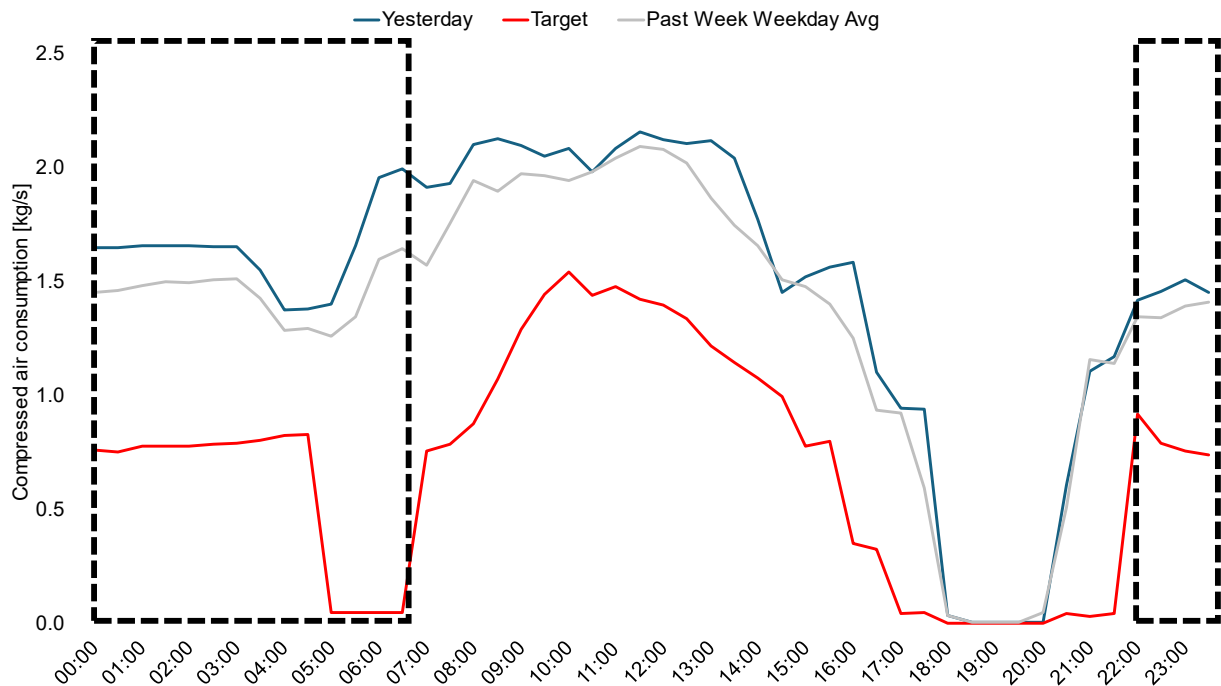


Figure 47: Excess compressed air consumption, likely attributable to ventilation with compressed air, can be seen in the 24-hour profile

Table 32: Sample of Mineshaft B's Vertical Section performance overview report

Half-level	Compressed air consumption ['000 kg/week]			Estimated wastage cost [R'000]	
	Actual	Target	Wastage	Daily	Annual
Vertical Section	866	280	586	138	22 942
Level 3 North	199	44	155	35	5 893
Level 2 North	167	37	130	30	5 023
Level 4 North	160	40	120	30	4 980
Level 5 North	139	55	83	19	3 201
Level 1 North	122	52	70	16	2 597
Level 6 North	72	44	28	8	1 219
Level 6 South	0	0	0	0	0
Level 5 South	7	7	0	0	0
Level 3 South	0	0	0	0	0

Level 3 North, which consumed the most excess compressed air during the cleaning shift, was selected for a step test. On this half-level, Zietsman's [11] step-testing method was used to determine the crosscuts with the most inefficient compressed air consumption by conducting the step test during non-production periods. Sample results from the step test are illustrated in Table 33.

Table 33: Sample results from step test conducted on Level 3 North

Crosscut	Compressed air consumption [kg/s]	Distribution
Crosscut 1	0.270	11.7%
Crosscut 2	1.150	50.1%
Crosscut 3	0.874	38.0%
Crosscut 4	0.004	0.2%
Half-level Total	2.297	100.0%

This information was reported to both the ventilation and mining departments. Information regarding compressed air improvement initiatives must be shared with the relevant departments frequently. This information includes the results from a step test, as illustrated in Table 33. These findings are especially relevant to the section's mine manager and overseer, who are responsible for its performance. The following section details the steps taken to further identify and address inefficiencies related to ventilating with compressed air.

3.3.5 Acting on inefficiencies

The most inefficient crosscuts, such as Crosscut 2 in Table 33, were audited to determine whether ventilation controls were in place. The audit results were reported to both the mining and ventilation departments. Sample inefficiencies of the ventilation controls identified during an audit are illustrated in the Figure 48 and Figure 49 which are photos taken by the author during separate audits. Figure 48 illustrates the lack of brattices used to guide ventilation air in working areas, whereas Figure 49 shows a broken ventilation duct guiding ventilation air towards the working areas. Depending on the difficulty of rectifying the inefficiencies, weekly or bi-weekly follow-up meetings were held.



Figure 48: Lack of brattices in a centre gully in an underground working area



Figure 49: Broken ventilation ducting guiding ventilation air to the working areas

The inefficiencies identified in this crosscut were included in an action plan that outlined the necessary information for their identification along with the mutually agreed-upon deadline. This action, as illustrated in Figure 50, was discussed with the mining and ventilation departments, and solutions to the identified issues were implemented.

No.	Section	Problem	Action	Photo	Responsible Person	Commitment date	Status	Signature
1	Mineshaft B Level 3 Chrome North X/C 02	No brattices installed in centre gully to guide ventilation air.	Install brattices.		Shift Boss A	YYYY/MM/DD	Complete	Signature Shift Boss A
2	Mineshaft B Level 3 Chrome North X/C 02	Broken ventilation ducting.	Replace ventilation ducting.		Shift Boss A	YYYY/MM/DD	In progress	Signature Shift Boss A

Figure 50: Action plan used for tracking progress on fixing ventilation controls

3.3.6 Summary of Case Study C

The solution developed in Chapter 2 was implemented at Mineshaft B to improve ventilation controls in the underground sections. Through continual monitoring and reporting, substandard ventilation controls were identified, reported, and acted upon continually for 15 months. The impact of this initiative was determined to be roughly 3.7 GWh and R7.2 million in annual operating costs.

The data listed in Table 28 was subjected to the validation procedure shown in Appendix B. This was implemented daily as the data set was required for the two developed reports for this initiative. The developed report was used to identify working areas with high levels of compressed air consumption. These high-consuming half-levels were later subjected to the methods of Du Plooy [44] and Zietsman [11] to identify the highest-consuming crosscuts where an audit of ventilation controls could be conducted.

This case study reported substandard ventilation controls to the mining and ventilation departments of the specific sections and mineshaft. Substandard ventilation controls were also included in an action tracker with deadlines and responsible personnel. The identified issues were followed up weekly or bi-weekly depending on the difficulty of implementing solutions. This solution was implemented continually at Mineshaft B for a period of 15 months.

3.4 Verification and validation

The solution was built on data, continual monitoring and reporting, identifying and acting on inefficiencies in the compressed air network. This solution was implemented in three case studies discussed in the preceding sections.

The first case study was implemented on control valve equipment to address malfunctioning instrumentation. The second case study considered implementing the solution with a focus on closing valves during the blasting period to address consumption during the Eskom evening peak tariff period. The third case study used performance overview and section performance reports as a fundamental part of a DSM initiative to improve ventilation controls. The three developed reports were tested on unique cases and deemed suitable for continual monitoring and reporting.

The following sections detail the verification of the specifications of the developed reports and the validation of the solution in each case study. The verification process involved checking whether the developed reports considered and met the initial design specifications. The validation process entailed measuring the energy and cost impact of each of the initiatives in the case studies.

3.4.1 Verification

A set of specifications for the three different reports were stipulated in Section 2.3. These are listed in Table 34, which describes the specifications for the reports and whether the specifications were met. All the design specifications were implemented in the developed reports.

By using three different reports, it was possible to:

- Determine whether any malfunctioning equipment was used for the control valves.
- Determine the operational energy cost of compressed air during the blasting period.
- Prioritise mineshafts in the mining group based on their performance.
- Prioritise underground half-levels per mineshaft based on their performance.
- Determine periods/shifts of high consumption on specific half-levels.
- Determine the operational energy cost of the wasted compressed air during specific periods/shifts.

Table 34: Specification checklist of the developed reports

Specification	Accomplished
Section performance report	
Historical daily consumption chart with the upper control limit included.	Yes
24-hour profile chart of the actual, historical and target compressed air consumption.	Yes
Table of the daily actual, historical and target compressed air consumption and wastage.	Yes
Performance overview report	
Intensity analysis of the mining group's mineshafts.	Yes
Overview table including:	
• Historical actual, target and wastage compressed air consumption.	Yes
• Estimated annual cost of wastage.	Yes
• Sections ordered from worst to best performance.	Yes
Control valve performance report	
Table of all the valves that includes:	
• Average mass flow rate during the blasting period.	Yes
• Percentage that average blasting period flow rate is of daily maximum flow rate.	Yes
• The time when the valve was closed and when the shaft blasted.	Yes
• Estimated annual cost if the valve was operated for an entire year on a specific day.	Yes
24-hour profile chart including (for each valve):	
• Mass flow rate through the specific valve.	Yes
• Pressure (upstream and downstream).	Yes
• Set point (pressure and mass flow).	Yes
24-hour profile chart including (for each valve):	
• Valve position.	Yes
• Controller output.	Yes
• Control mode.	Yes

This verifies that the specifications listed in Section 2.3 were all implemented in the developed reports.

3.4.2 Validation

The energy and cost impact of implementing the solution in the three case studies are validated below. The validation method varies depending on the specific case study. In essence, it involves comparing the performance after the initiative was implemented with the baseline energy consumption. The Eskom tariffs of 2024/25 were used for all energy-to-cost calculations.

3.4.2.1 Case Study A

Case Study A examined a malfunctioning mass flowmeter, which may have resulted in a significant increase in compressed air consumption because the control valve could not be controlled effectively. To address this problem, an alternative control philosophy was implemented. To assess the impact of the corrective measure, redundant underground mass flowmeters, identified during the data acquisition and validation phase of the solution, were used.

Based on the sum of the readings from underground mass flowmeters, it was estimated that an increase in operating costs of roughly R150 000 for five weekdays would have been incurred if the malfunctioning mass flowmeter was not addressed. A baseline was established by considering the sum of the readings from the underground mass flowmeters when the control was inactive and comparing it with the compressed air consumption when the control was active. The baseline and actual compressed air consumption of Mineshaft A's underground mass flowmeters is shown in Table 35.

Table 35: Compressed air consumption of Mineshaft A before and after control philosophy change per TOU period

TOU period	Mineshaft A compressed air consumption			
	Before [kg]	After [kg]	Difference [kg]	Difference
Peak	73	63	10	-14%
Standard	212	177	35	-17%
Off-Peak	146	121	24	-17%
Total	431	362	69	-16%

Since Mineshaft A is part of a ring network, the compressor energy was estimated using the method discussed in Appendix C, and its results shown in Table 36. It is assumed that a linear decrease in compressed air consumption translates into a corresponding linear decrease in compressor electricity consumption. The calculation was done for a single weekday.

Table 36: Compressed electricity consumption and cost calculation based on Table 35

TOU period	Mineshaft A compressor electricity consumption and cost (per weekday)				
	Before [kWh]	After [kWh]	Difference [kWh]	TOU tariff [R/kWh]	Cost reduction [R]
Peak	24 819	21 440	3 378	1.96	6 626
Standard	71 440	59 646	11 795	1.42	16 728
Off-peak	48 628	40 472	8 157	0.98	7 991
Total	144 888	121 558	23 330		31 345

Case Study A demonstrated that continual monitoring and reporting can identify malfunctioning instrumentation and help mitigate significant energy and cost increases, provided that action is taken in a timely manner. Continual monitoring and reporting pivots on the responsible person's knowledge and experience of the system's characteristics. It is worth noting that the data

validation procedure could have flagged this anomaly; therefore, another possible automated step could be implemented to mitigate this issue. Irrespective of this downside, the act of continual monitoring and reporting helped mitigate a control error, resulting in a savings of approximately 117 MWh and R150 000 over a period of five weekdays.

3.4.2.2 Case Study B

Case Study B examined an initiative that was implemented to reduce the operational energy and cost during the blasting period of the mining group. This case study included a total of nine mineshafts with the objective of improving the control valve closure. Specifically, the study aimed to achieve an earlier closure of the control valves. This initiative was implemented and evaluated over a period of 18 months.

Based on the decrease in Table 26 (21% reduction) and the decrease in compressor energy, the annual energy and cost reduction (weekdays only) was calculated to be 5.6 GWh and R10.6 million. This is shown in Table 37.

Table 37: Energy and cost reduction calculations based on Eskom 2024/25 Tariffs, excluding weekends and holidays

	Before implementation	After implementation	Difference
Daily average energy	31 784 kWh	26 231 kWh	5 553 kWh
Daily cost	R243 375	R200 856	R42 519
Annual energy	31 910 952 kWh	26 335 958 kWh	5 574 993 kWh
Annual cost	R61 087 135	R50 414 925	R10 672 210

Case Study B is an extension of Case Study A, in which a proactive approach was implemented rather than addressing inefficiencies reactively. This led to significant energy and cost reductions of 5.6 GWh and R10.6 million annually. One obstacle that, if removed, will significantly improve this initiative's benefit is ensuring that mining personnel vacate the mineshaft before the start of the Eskom Peak Tariff period. This prerequisite is difficult to fulfil due to the number of mining personnel. The mining industry may benefit from further research in this area.

3.4.2.3 Case Study C

Case Study C was implemented on Mineshaft B, which consists of nine active half-levels on the decline section and eleven active half-levels on the vertical section. Two reports, namely a performance overview report and a section performance report, were developed for Mineshaft B. These reports were used to drive an improvement initiative for the ventilation controls on the twenty underground half-levels.

Continuing the actions of identifying, prioritising, auditing, and rectifying issues with a specific focus on ventilation in the underground working areas over a period of 15 months, a notable reduction in compressed air intensity was seen. This is shown in Figure 51, where the period of pre-implementation and implementation are highlighted. A clear downtrend in intensity is seen, which further supports the validation that the implementation of the initiative was successful.

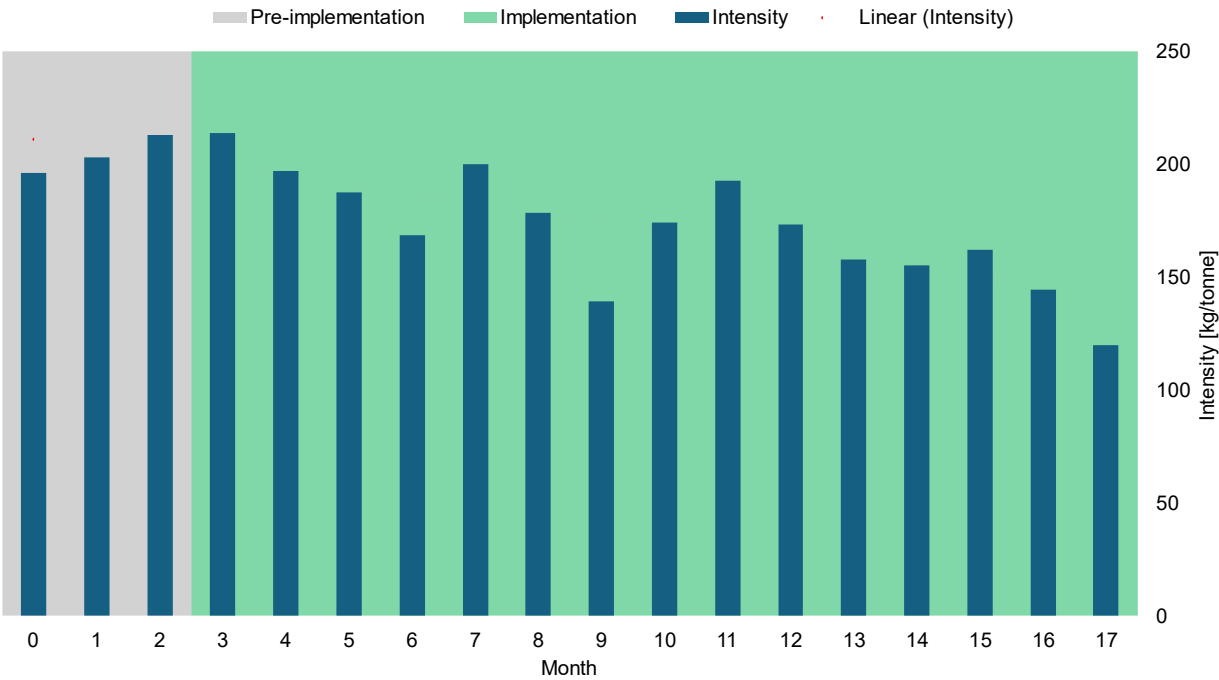


Figure 51: Compressed air consumption intensity of Mineshaft B

The improvement of ventilation controls in underground working areas reduced baseload consumption. This is further illustrated in Figure 52 which displays the pre-and post-implementation 24-hour profiles.

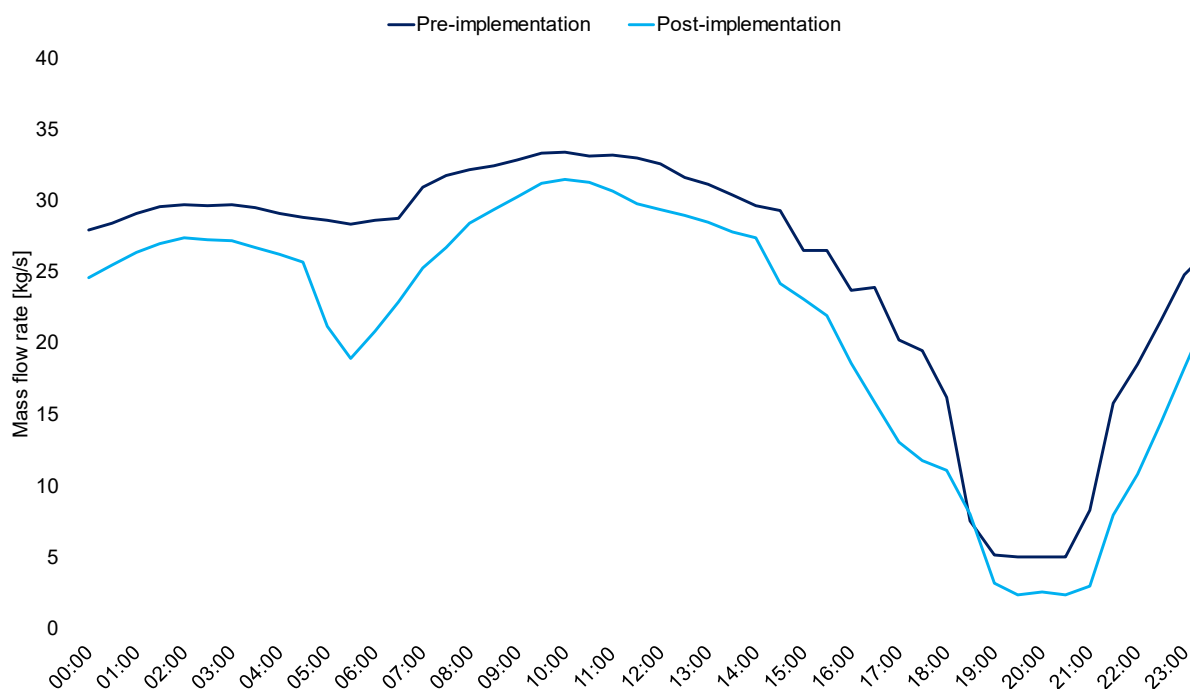


Figure 52: Comparison of Mineshaft B's 24-hour profile, pre-and post-implementation of the demand-side improvement initiative

The performance improvement and cost reduction achieved through this demand-side improvement initiative were calculated using the same method as in Case Study B, as it was part of a ring network. Table 38 shows an improvement in operating costs of roughly 9% per annum.

Table 38: Energy and cost reduction calculations based on Eskom 2024/25 Tariffs, excluding weekends and holidays

	Before implementation	After implementation	Difference
Daily average energy	7 448 kWh	6 828 kWh	620 kWh
Daily cost	R324 439	R295 667	R28 772
Annual energy	44 865 115 kWh	41 131 081 kWh	3 734 034 kWh
Annual cost	R81 848 900	R74 592 587	R7 256 312

After identifying an initiative to improve ventilation controls, continual monitoring and reporting were implemented at Mineshaft B. This resulted in a sustained improvement in both energy and cost, estimated to have an impact of approximately 3.7 GWh and R7.2 million annually. This further validates the use of continual monitoring and reporting as a sustainable tool for implementing and maintaining compressed air improvement initiatives.

After implementing these three case studies, the solution developed was validated using the case study methodology discussed in Section 1.5 and demonstrated in Figure 20. It was concluded that applying continual monitoring and reporting as a tool for improving compressed air network efficiency on PGM mines in South Africa is a suitable and sustainable solution.

CHAPTER 4: CONCLUSION

4.1 Summary

Chapter 1 of this study started with an overview of the use of compressed air in both the industry and the world. This was followed by highlighting the overall energy consumption of compressed air generation of different industries in South Africa. In the PGM mining industry in South Africa, about 21% of energy, which translates to 2.6 TWh, is consumed for compressed air generation. With a possible R1.6 billion that could be saved annually, there is a need for efficiency improvements on this utility.

The first chapter provided additional information on compressed air networks in South African PGM mines. It offered an overview of the supply and demand sides and explained how mismanagement and misappropriation of compressed air networks could be identified. Based on this, a literature review was conducted, which highlighted the need to improve the demand side of compressed air networks in the PGM mining industry through continual monitoring and reporting.

Chapter 2 discussed the development of the solution, which was outlined in the first four secondary objectives. The first secondary objective was to determine, acquire, and validate the required data for the analysis and performance reporting of compressed air networks on PGM mines. This was done by identifying the types of required data and their respective sources and conducting the data validation procedure as set out in Appendix B.

The second secondary objective was to investigate methods and techniques for analysing the performance of compressed air networks. This was done by exploring techniques such as conducting a step test and intensity analysis, and analysing the different variables important to control valve performance.

The third secondary objective was to develop reports that use the investigated methods or techniques. Three different reports were developed in this section: the control valve performance report, the section performance report, and the performance overview report.

The fourth objective was to develop a continual monitoring and reporting procedure that uses the developed reports. This was done by considering a weekly and daily monitoring schedule. The performance overview report should be reviewed weekly, and efforts to improve efficiency should be prioritised for the worst-performing mineshaft. The performance and control valve report for the section must be reviewed on a daily basis to determine any improvement in performance, and to act accordingly.

Chapter 3 addressed the fifth and final secondary objective by implementing the solution on the case study mineshafts. This developed solution was implemented in three case studies. The first two case studies involved continual monitoring and reporting of control valve performance to identify and address inefficiencies quickly. This process drove a performance improvement initiative that included closing control valves during the blasting period. The third case study considered improving ventilation controls to address the misappropriation of compressed air in underground working areas through ventilation.

The example in Case Study A determined that roughly R150 000 could be saved over five weekdays if swift action was taken on malfunctioning instrumentation to ensure the control of a control valve was active. Case Study B achieved a significant energy and cost reduction of approximately 5.6 GWh and R10.6 million annually. However, it was plagued by the consistent limitation of personnel clearing from underground.

Like Case Study B, Case Study C was a performance improvement initiative that focused on improving ventilation controls in underground working areas. The main limitation of this case study is that acquiring actionable information is a tedious and time-consuming process. However, the solution still achieved an energy and cost reduction of approximately 3.7 GWh and R7.3 million annually.

4.2 Study objectives analysis

The secondary objectives devised in Section 1.3.4 were met in this study, with limitations and recommendations identified throughout the implementation. This section discusses the secondary objectives and how they were achieved in this study.

- 1. Determine, acquire and validate the required data for the analysis and performance reporting of compressed air networks on PGM mines.*

In Chapter 2, the required data and where it could be acquired on a typical PGM mine were identified. Furthermore, once the data had been acquired, it was subjected to a validation procedure to confirm a complete and accurate data set for each of the case studies presented in Chapter 3. Thus, the first study objective was satisfied.

- 2. Investigate methods or techniques used for analysing the performance of compressed air networks.*

Chapter 2 fulfilled this objective by discussing performance analysis methods and techniques that can be implemented in the developed reports. The methods and techniques include total daily

compressed air consumption analysis, intensity analysis, step-testing, and theoretical target comparison.

3. Develop reports that utilise the above-mentioned methods or techniques.

The objective was met as Chapter 2 provided three specific use reports for the case studies in Chapter 3. Additionally, for each report, a list of specifications was inferred from the discussion on performance analysis of compressed air networks. The developed reports consider the most important aspects of compressed air network performance (on the demand side) and may be used for various performance improvement initiatives.

4. Develop a procedure for continual monitoring and reporting that utilises developed reports.

The procedure developed in Chapter 2 satisfied this objective. A procedure was developed based on current information about the mining operation cycle, compressed air consumption behaviour, and the reporting hierarchy. This was done successfully with the procedure, including analysing reports, identifying inefficiencies, and reporting them to the correct personnel.

5. Implement the developed solution on case study mineshafts.

The final objective was to implement the solution in multiple case study mineshafts. Chapter 3 met this objective, implementing the solution in three case studies. The three case studies explored the reactive and proactive use of continual monitoring and reporting on compressed air control valve equipment and improved ventilation controls in underground working areas.

4.3 Future recommendations

This study considered the continual monitoring and reporting of compressed air performance with the aim of improving performance. Upon completion of the study, recommendations for future research are made based on the limitations noted in this study. The future recommendations are as follows:

- This study considered only PGM mines. Due to the similar generation, distribution, and consumption of compressed air in South African gold mines, the solution could be adapted to this specific industry and possibly for other utilities in energy-intensive industries.
- The data validation procedure in Appendix B does not take the expected specific process values into account. It is recommended that a check be added to the procedure that flags data according to a specific metric to improve this procedure further. This can be achieved by comparing data with a historical average or upper control limit, much like the approach discussed in Section 2.2.1.

- This study considered improving consumption on the demand side of the compressed air network due to the high operational costs of compressed air generation. It is recommended that the solution be expanded to other high-energy consumers, such as ventilation, refrigeration or water systems.
- From Case Study B, it was noted that personnel often do not clear from underground before the start of the Eskom peak period, especially in winter. Research is recommended to understand and improve the clearing time to avoid unnecessary operation costs associated with compressed air generation. Solutions such as utilising personnel tracking may further improve initiatives such as this.
- From Case Study C, it was noted that acquiring actionable information is still a time-consuming process, even with mass flowmeters at each half-level. Research that involves a less resource-intensive method of acquiring actionable information is recommended.

4.4 Concluding remarks

The PGM mining industry in South Africa needs to find solutions for the inefficient utilisation of compressed air. Solutions employing instrumentation and control equipment have become increasingly viable due to high electricity costs, resulting in favourable payback periods. However, there is limited research on the added value that can be obtained by using the data obtained from implementing these solutions.

This study considered continual monitoring and reporting as a tool to assist with maintaining efficiency initiatives on PGM mineshafts in South Africa. An overview of required data and the analysis thereof was discussed, with reports developed that may be used to interpret the information. A procedure was also developed that utilises all of the above. Finally, the solution was implemented in three case studies to determine the impact. The developed solution provides a framework that may be of value to the management of other utilities, such as water or electricity, and could even be extended to other industries.

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APPENDIX A: POSSIBLE ENERGY REDUCTION IN A COMPRESSED AIR NETWORK IN THE PGM MINING INDUSTRY IN SOUTH AFRICA

The purpose of this appendix is to calculate the impact of a possible energy reduction on compressed air networks in the PGM mining industry in South Africa. Data was compiled from various sources for the calculation [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22]. The steps to calculate the impact are listed in Table 39.

Table 39: Method to calculate the impact of a possible energy reduction on compressed air networks in the PGM industry in South Africa

Step	Action	Assumption	Source
1	Identify PGM mineshafts in South Africa.		[1]
2	Acquire and compile greenhouse gas (GHG) Scope 2 emissions in tons CO ₂ e.	a	[13], [14], [15], [16], [17], [18], [19], [20]
3	Convert GHG Scope 2 emissions to energy.	b	[21]
4	Calculate compressed air generation energy in PGM mining industry by using Figure 53.	c	
5	Scale compressed air generation energy to assumed profile.	d	
6	Calculate the difference in energy consumption before and after 40% reduction in compressed air generation energy.	e & f	[11]
7	Calculate annual estimated cost for one year of sustained reduction with latest Eskom tariffs.		[22]

Assumptions

- It is assumed that the GHG Scope 2 emissions for PGM mining companies are solely attributable to electricity purchased from Eskom.
- GHG Scope 2 emissions are converted to energy with the assumed Grid Factor 2 (million tons CO₂e per MWh generated excluding own consumption) provided by Eskom [21].
- Compressed air contributes to 21.4% of the total electricity consumption in the PGM mining industry. The assumption is based on actual data acquired from mining companies owning a total of 21 mineshafts from 1 January to 31 December 2022.¹⁰
- The average daily compressed air power profile is illustrated in Figure 53. The profile was determined by compiling the energy consumption for compressed air generation and the total

¹⁰ Source: Own compilation.

operation of 21 PGM mineshafts in South Africa from 1 January to 31 December 2022. The data is listed at the end of this appendix as a percentage of one.¹¹

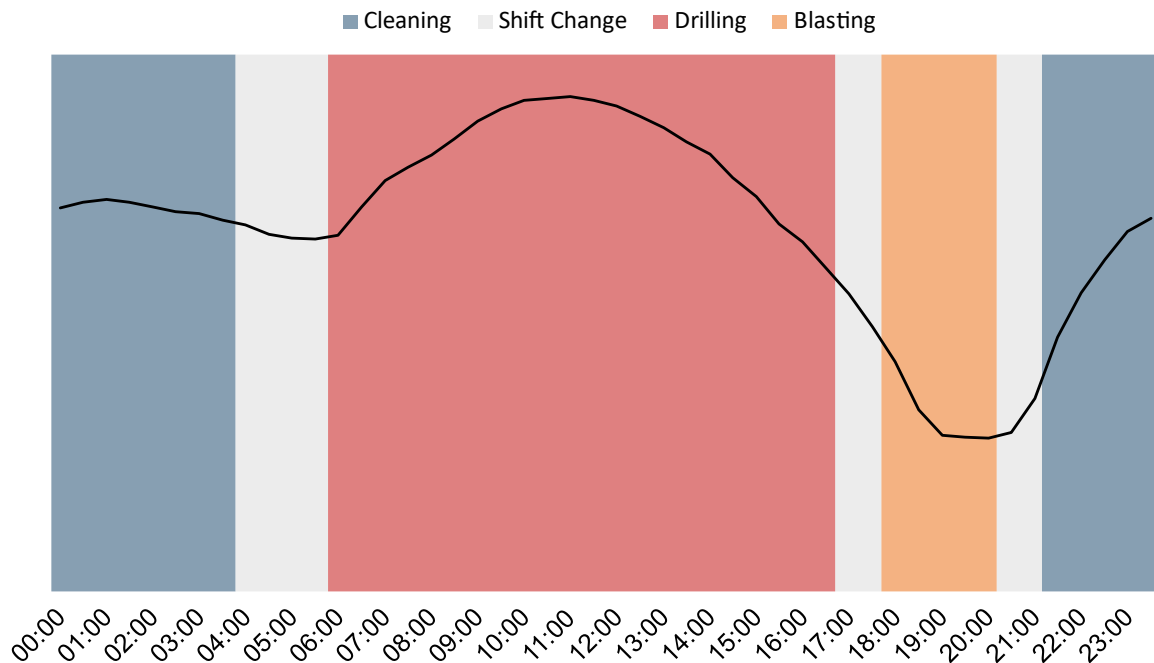


Figure 53: Assumed average daily compressed air power profile (Source: Own compilation)

- e. The compressed air reduction mentioned by Zietsman could be up to 40% outside of the drilling shift (14:00 to 07:00) [11].
- f. The percentage power reduction is equal to percentage flow reduction [11].

Additional notes

- PGM mines and mining companies were identified from the website of the Department of Mineral Resources and Energy [12]. A total of 26 PGM mineshafts were identified.
- Annual integrated and/or sustainability reports from the companies were surveyed to acquire GHG Scope 2 emissions in tons CO₂e. Scope 2 includes emissions from energy purchased and consumed by the reporting company, which is typically Eskom in South Africa [13], [14], [15], [16], [17], [18], [19], [20].
- The annual reports from some mining companies are for different periods, for example 1 July to 30 June. For comparable analysis, all companies' data was converted to calendar years (1 January to 31 December) using interim results.
- Eskom tariffs for 2024/25 were used to calculate cost figures [22].

¹¹ Source: Own compilation.

With the steps and assumptions listed, the calculation follows. Firstly, the electricity consumption of seven different PGM mining companies owning operations in South Africa for 2022 is shown in Table 40.

Table 40: Electricity consumption of PGM mining companies' operations in South Africa

Mining Company	Reference	GHG Scope 2 Emissions 2022	
		CO ₂ e Tons	GWh
African Rainbow Minerals	[15]	584 245	562
Anglo American Platinum	[14]	3 402 000	3 272
Impala Platinum	[16]	3 622 342	3 483
Northam Platinum	[17]	1 466 495	1 410
Royal Bafokeng Platinum	[18]	547 699	527
Sibanye Stillwater Platinum	[19]	2 994 000	2 879
Wesizwe Platinum	[20]	47 563	46
Total		12 664 344	12 179

The total electricity consumption was multiplied by the assumed compressed air generation contribution to total operation electricity consumption (21.4%), which equated to roughly 2 600 GWh for the year. This value was scaled to the daily average power profile illustrated in Figure 53 to acquire a 24-hour power profile. The next step was to apply the reduction mentioned by Zietsman (40%), whereafter costs were calculated with the tariffs provided by Eskom.

In conclusion, if a 40% reduction in compressed air consumption during the non-drilling period were to be achieved on all mineshafts that utilise compressed air in the PGM mining industry for one year, an estimated energy reduction of 214 MW could be attained, which would translate to roughly R1.64 billion per year.

APPENDIX B: DATA VALIDATION PROCEDURE

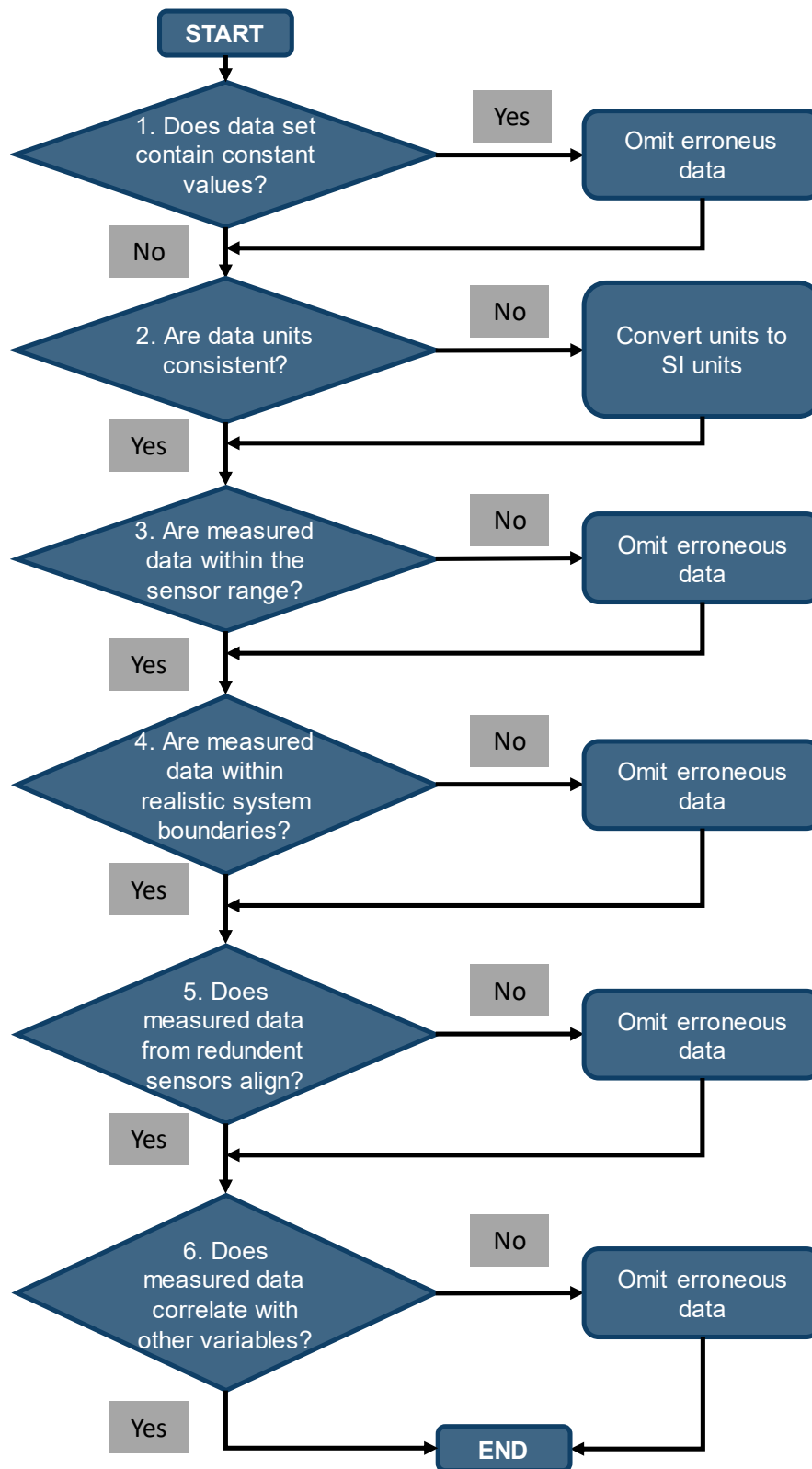


Figure 54: Data validation procedure

APPENDIX C: THE ENERGY AND COST OF COMPRESSED AIR GENERATION

In compressed air networks, multiple factors contribute to the cost of compressed air generation. For this study, only the operating costs related to compressed air generation are taken into account. For this calculation, a simple example of a ring network is considered, as illustrated in Figure 55.

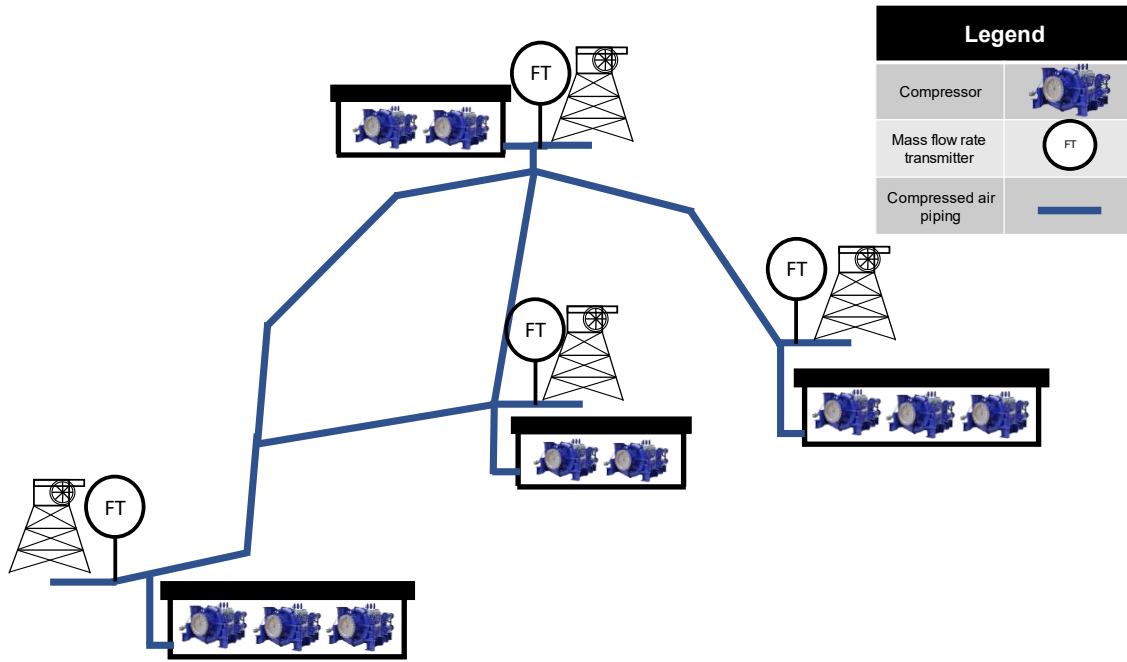


Figure 55: Example of a ring network supply configuration

Four compressor houses supply four mineshafts with compressed air on this ring network. A mass flowmeter measures the mass flow rate to each mineshaft. The measured consumption is aggregated to a monthly total for use in billing purposes. To determine the energy consumption for each mineshaft, the total energy consumed is divided fractionally depending on the amount of compressed air consumed by the specific mineshaft. This calculation accounts for leakages on the ring or end users that are not measured by individual mass flowmeters. To account for this, it is divided equally among each mineshaft on the ring network as calculated with Equation (3):

$$E_{\text{Mineshaft 1}} = \frac{M_{\text{Mineshaft 1}}}{M_{\text{Total}}} \times E_{\text{Total}} \quad (3)$$

where:

- $E_{\text{Mineshaft 1}}$ = Compressed air energy consumed of Mineshaft 1
- E_{Total} = Total compressor energy consumption
- $M_{\text{Mineshaft 1}}$ = Compressed air mass consumed of Mineshaft 1
- M_{Total} = Total mass flow of all mineshafts

Typically, a 24-hour energy consumption profile is obtained from this calculation, which is converted to a cost value by considering the typical TOU tariffs provided by the energy supplier [22]. The TOU periods provided by Eskom are illustrated in Figure 56.

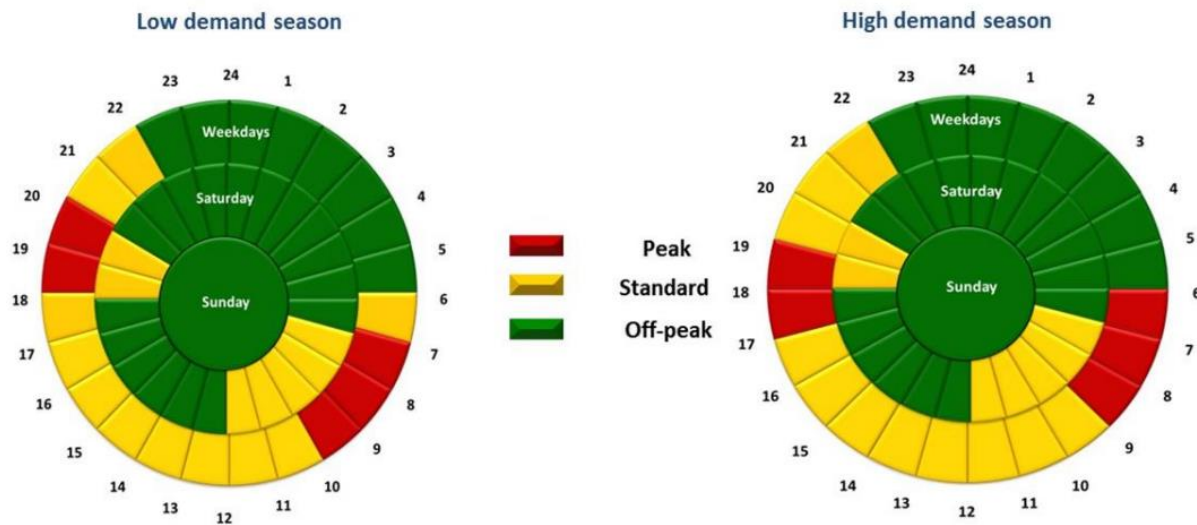


Figure 56: Eskom's defined TOU periods for industrial customers [22]

Most mining companies fall under the Megaflex tariff schedule, with varying costs depending on the mineshaft's supply voltage and distance from power supply as determined by Eskom's transmission zones depicted in Figure 57.

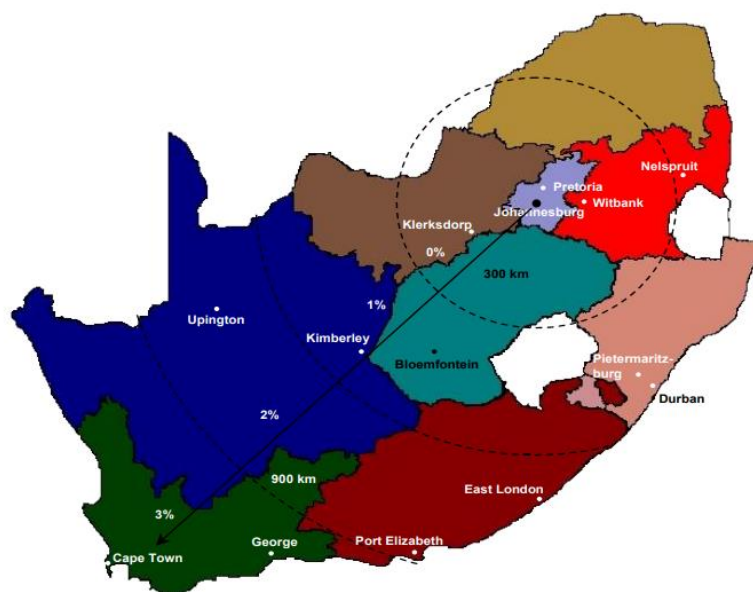
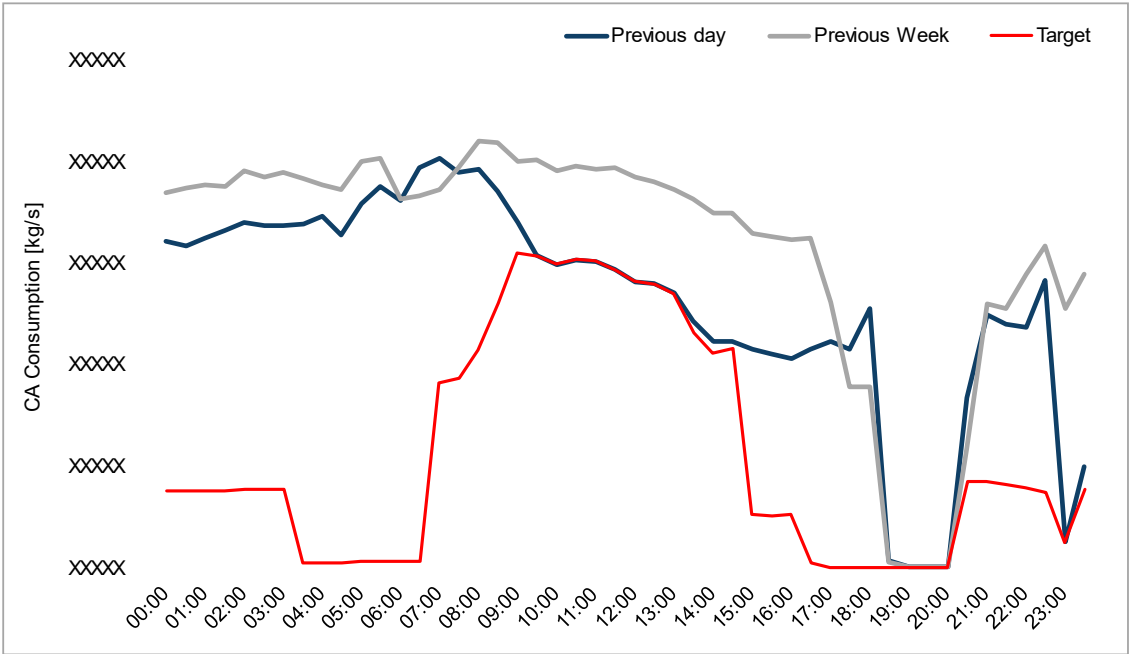
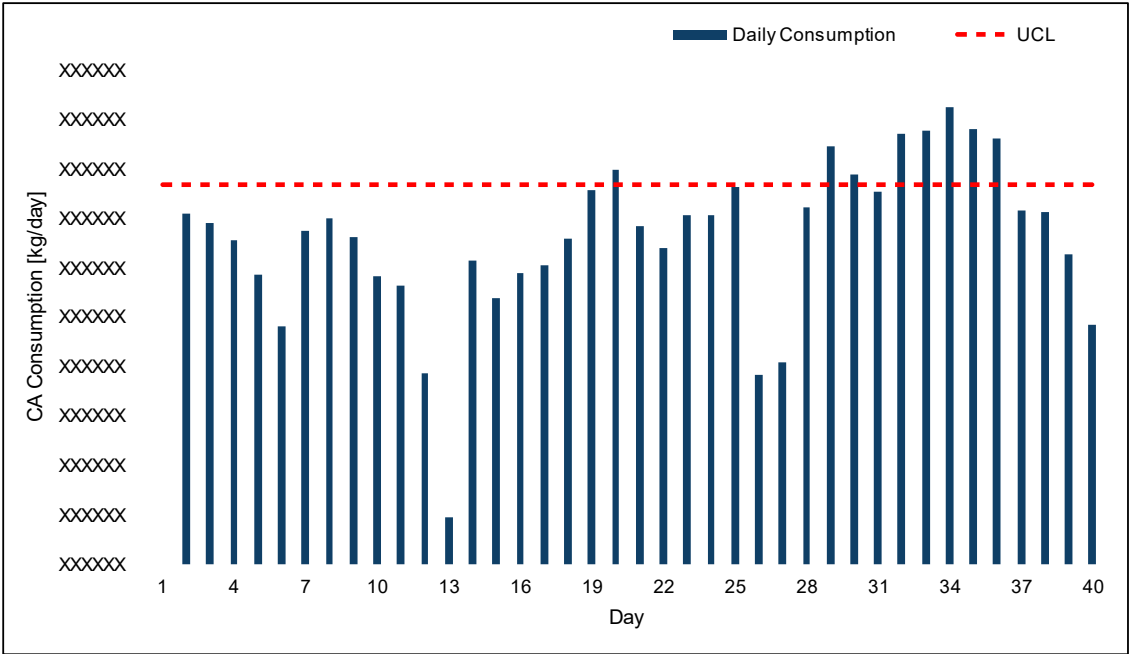


Figure 57: Eskom's transmission zones for loads [22]

APPENDIX D: EXAMPLE OF A SECTION PERFORMANCE REPORT

Mineshaft 1 Section A - CA Performance Report: YYYY/MM/DD

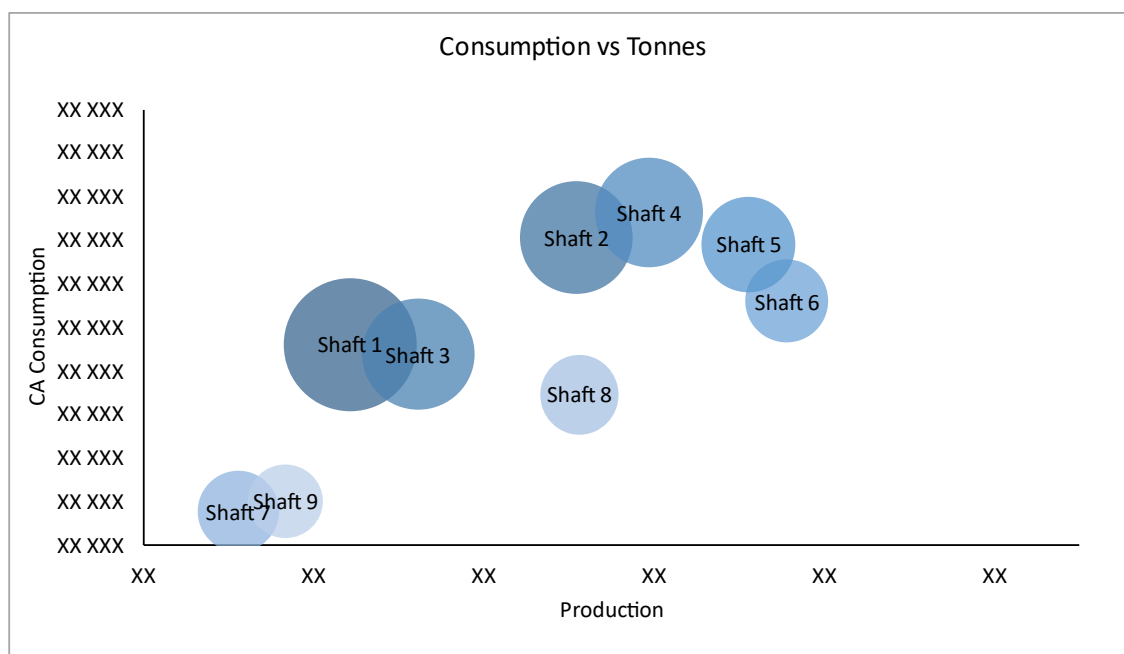


Metric	Average CA consumption	Estimated Annual Cost
Previous Day	XXX XXX	RXX XXX XXX
Previous Week	XXX XXX	RXX XXX XXX
Target	XXX XXX	RXX XXX XXX
Wastage	XXX XXX	RXX XXX XXX

APPENDIX E: EXAMPLE OF A PERFORMANCE OVERVIEW REPORT

Shaft 1 - Performance Overview Report: YYYY/MM/DD

Mineshaft	CA Consumption	Production	Intensity	Ranking (Worst to Best)
Shaft 1	XX XXX XXX	XX XXX	XXX	1
Shaft 2	XX XXX XXX	XX XXX	XXX	2
Shaft 3	XX XXX XXX	XX XXX	XXX	3
Shaft 4	XX XXX XXX	XX XXX	XXX	4
Shaft 5	XX XXX XXX	XX XXX	XXX	5
Shaft 6	XX XXX XXX	XX XXX	XXX	6
shaft 7	XX XXX XXX	XX XXX	XXX	7
Shaft 8	XX XXX XXX	XX XXX	XXX	8
Shaft 9	XX XXX XXX	XX XXX	XXX	9



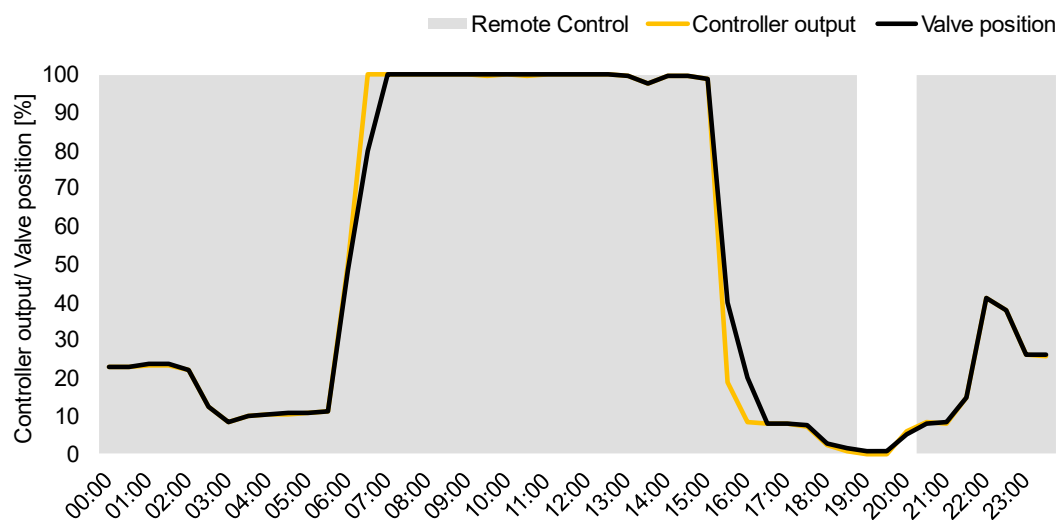
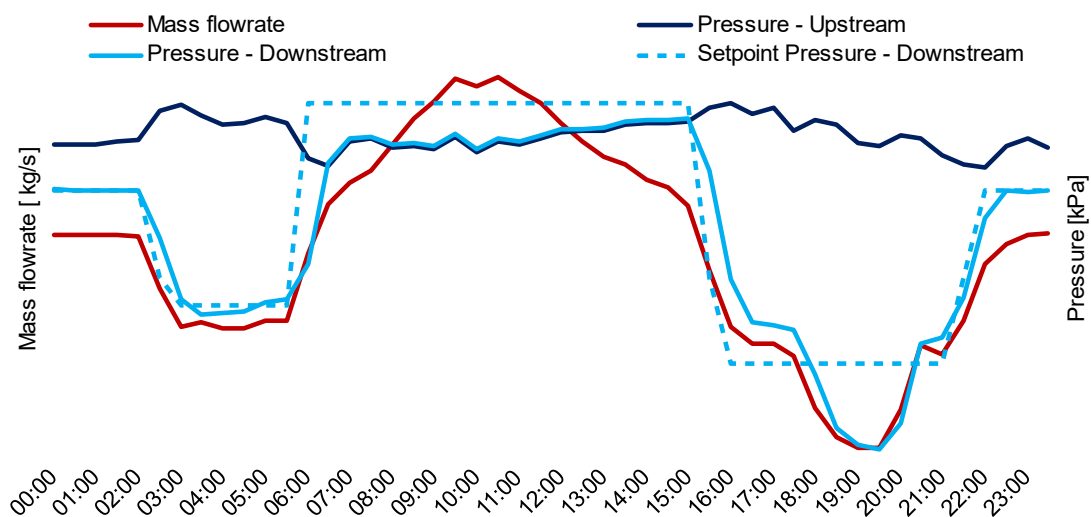
Level	Weekly CA consumption	Target	Wastage	Estimated annual wastage cost
1	XXX XXX	XXX XXX	XXX XXX	R XX XXX XXX
2	XXX XXX	XXX XXX	XXX XXX	R XX XXX XXX
3	XXX XXX	XXX XXX	XXX XXX	R XX XXX XXX
4	XXX XXX	XXX XXX	XXX XXX	R XX XXX XXX
5	XXX XXX	XXX XXX	XXX XXX	R XX XXX XXX
6	XXX XXX	XXX XXX	XXX XXX	R XX XXX XXX
7	XXX XXX	XXX XXX	XXX XXX	R XX XXX XXX
8	XXX XXX	XXX XXX	XXX XXX	R XX XXX XXX
9	XXX XXX	XXX XXX	XXX XXX	R XX XXX XXX
10	XXX XXX	XXX XXX	XXX XXX	R XX XXX XXX

APPENDIX F: EXAMPLE OF A CONTROL VALVE PERFORMANCE REPORT

Control Valve Performance Report: YYYY/MM/DD

Valve	Average mass flowrate	% of maximum daily mass flowrate	Valve closing time	Blasting time	Estimated annual blasting shift cost
Shaft 1	XX XXX	XX%	Did not close.	XX:XX	RX XXX XXX
Shaft 2	XX XXX	XX%	XX:XX	XX:XX	RX XXX XXX
Shaft 3	XX XXX	XX%	XX:XX	XX:XX	RX XXX XXX
Shaft 4	XX XXX	XX%	XX:XX	XX:XX	RX XXX XXX
Total	XX XXX				RX XXX XXX

Shaft 1 Valve Performance

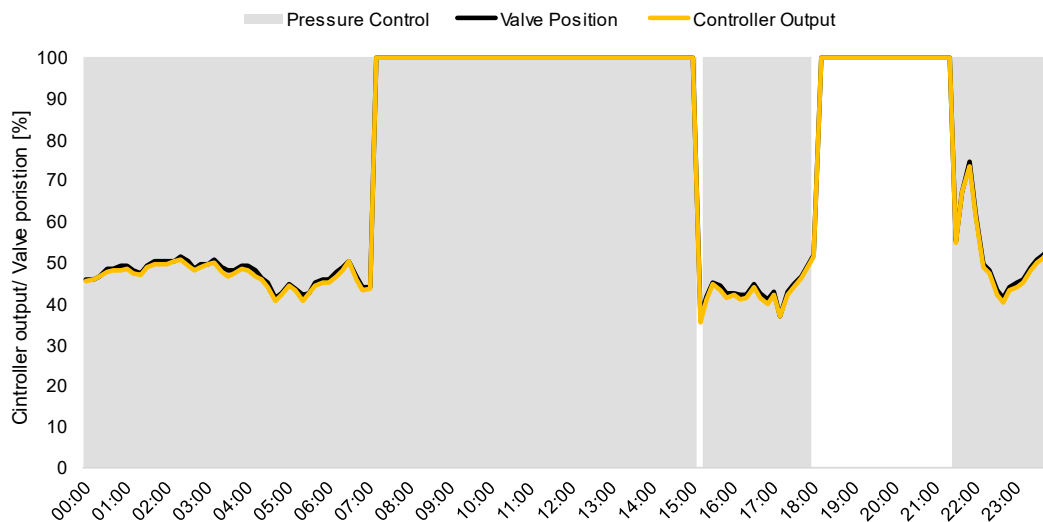
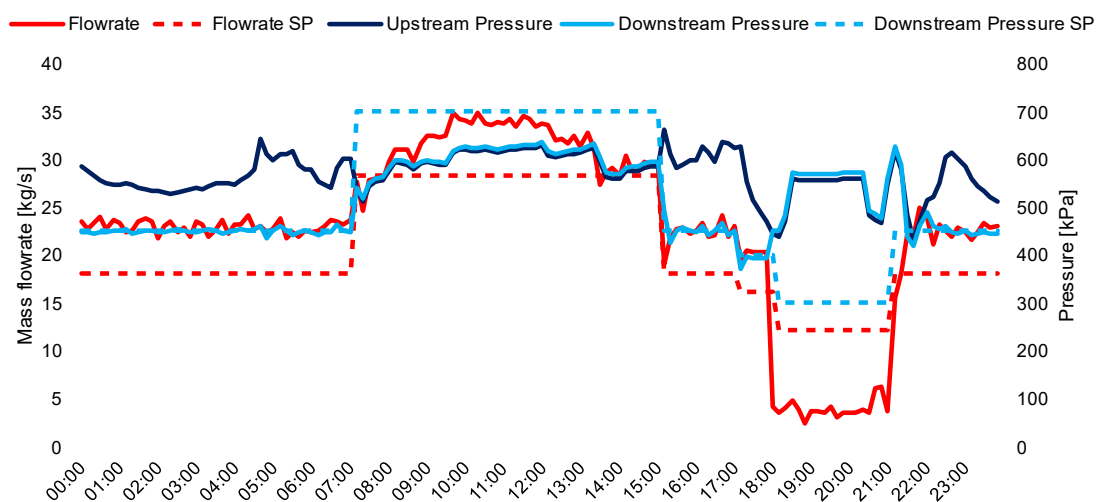


APPENDIX G: MINING GROUP CONTROL VALVE PERFORMANCE SAMPLE REPORT

Control Valve Performance Report: YYYY/MM/DD

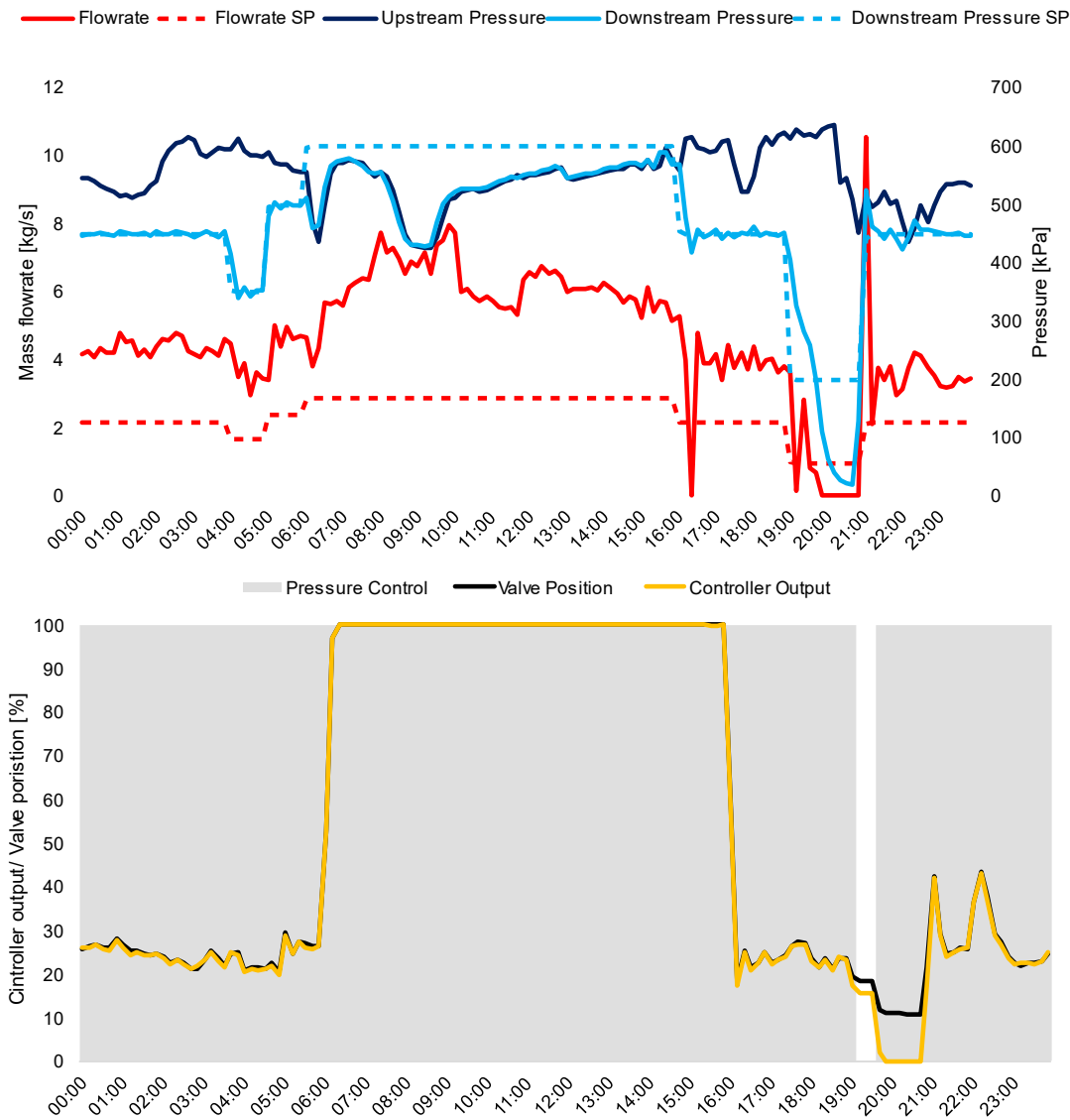
Valve	Average mass flowrate	% of maximum daily mass flowrate	Valve closing time	Blasting time	Estimated annual blasting shift cost
Shaft A	9.38	27%	Did not close.	18:10	R5 700 000
Shaft B	3.07	39%	20:00	17:40	R1 900 000
Shaft C	6.31	21%	18:30	18:20	R3 900 000
Shaft D	1.50	11%	18:20	18:10	R1 000 000
Shaft E	4.92	15%	18:20	18:10	R3 100 000
Shaft F	3.27	15%	18:40	18:40	R2 100 000
Shaft G	4.51	11%	17:50	17:50	R2 800 000
Shaft H	15.09	28%	Did not close.	18:10	R9 200 000
Shaft I	8.37	20%	18:20	18:30	R5 300 000
Total	56.43				R35 600 000

Mineshaft A Control Valve YYYY/MM/DD



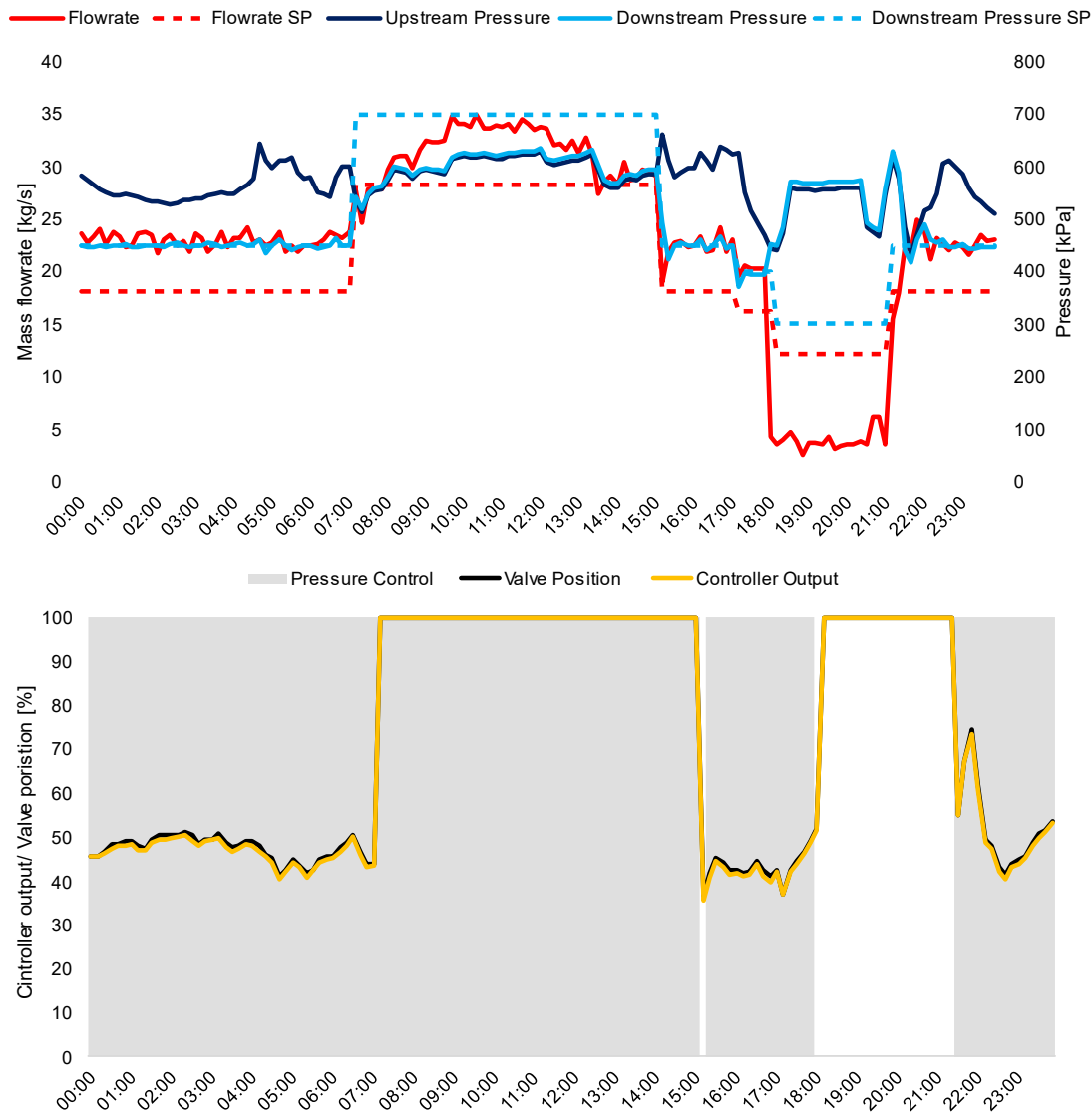
Control Valve Performance Report: YYYY/MM/DD

Mineshaft B Control Valve YYYY/MM/DD



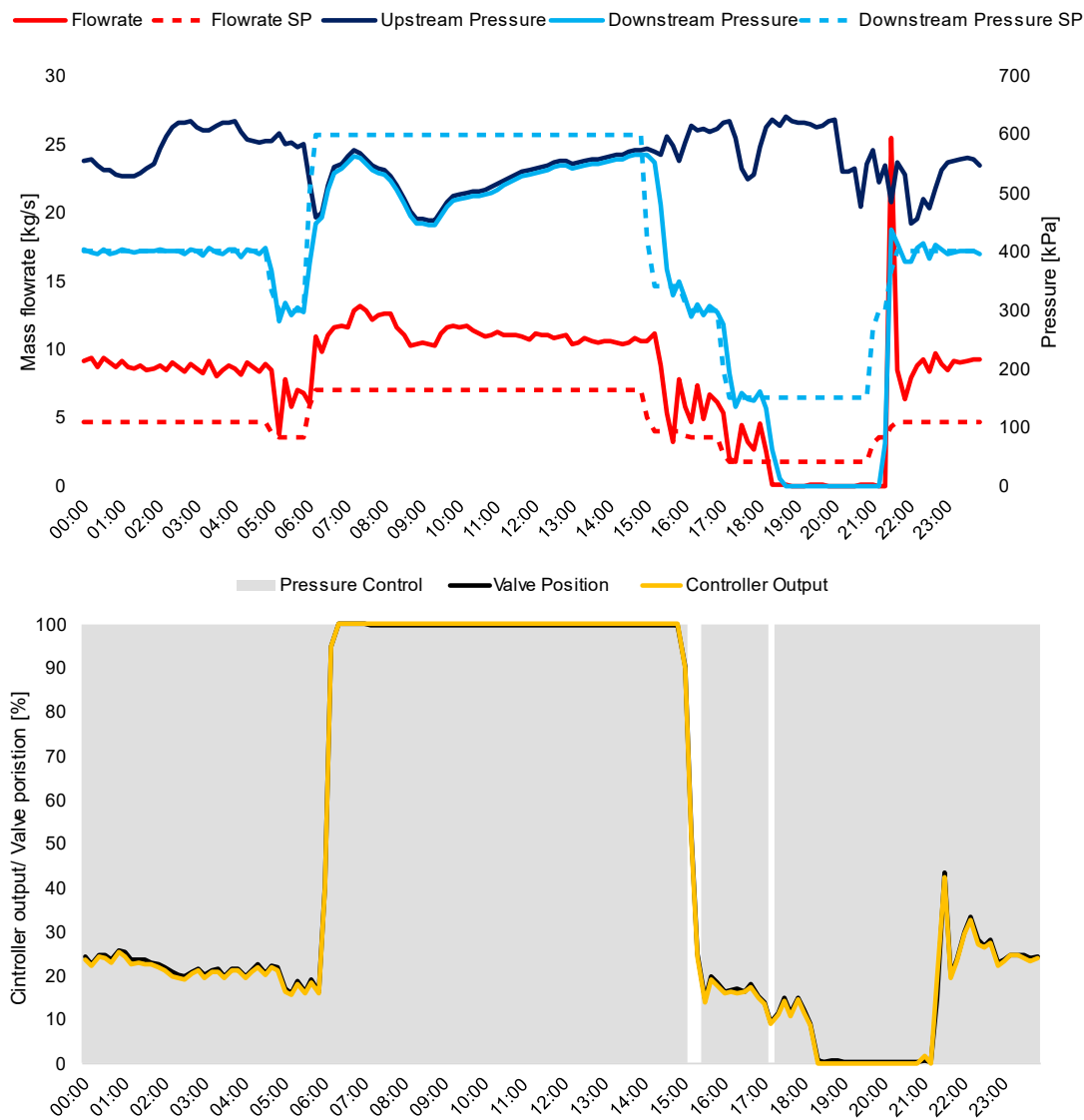
Control Valve Performance Report: YYYY/MM/DD

Mineshaft C Control Valve YYYY/MM/DD



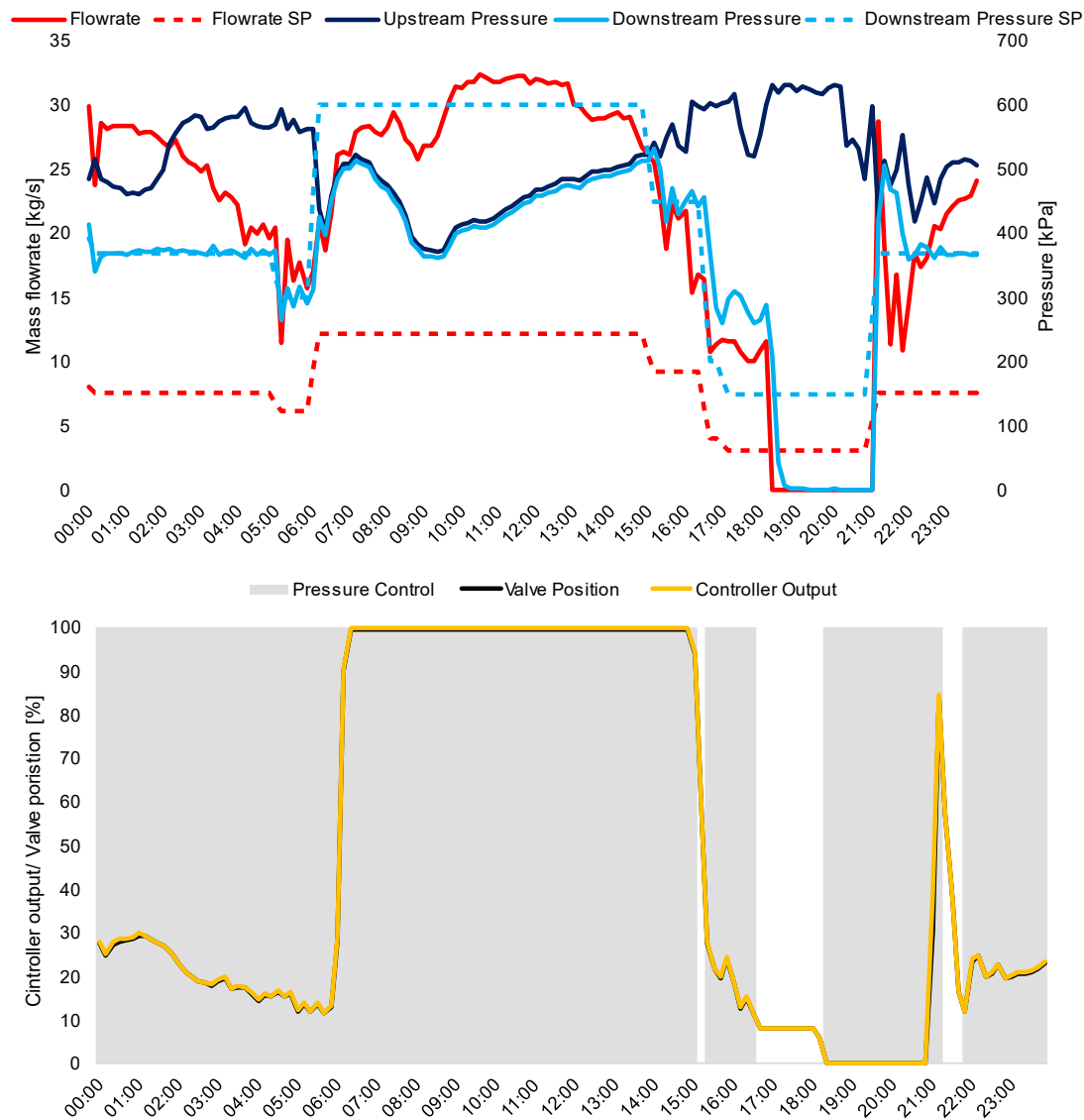
Control Valve Performance Report: YYYY/MM/DD

Mineshaft D Control Valve YYYY/MM/DD



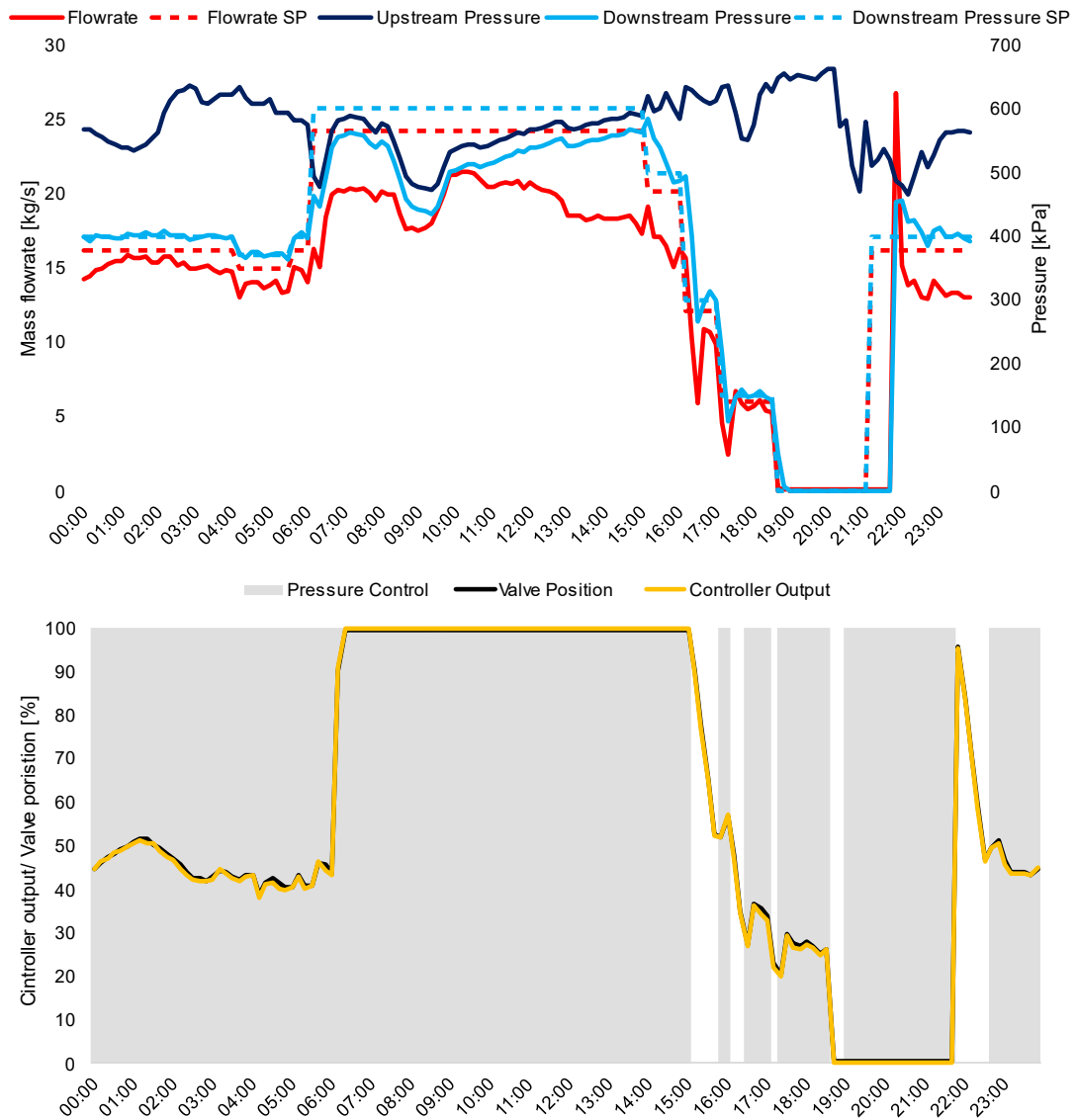
Control Valve Performance Report: YYYY/MM/DD

Mineshaft E Control Valve YYYY/MM/DD



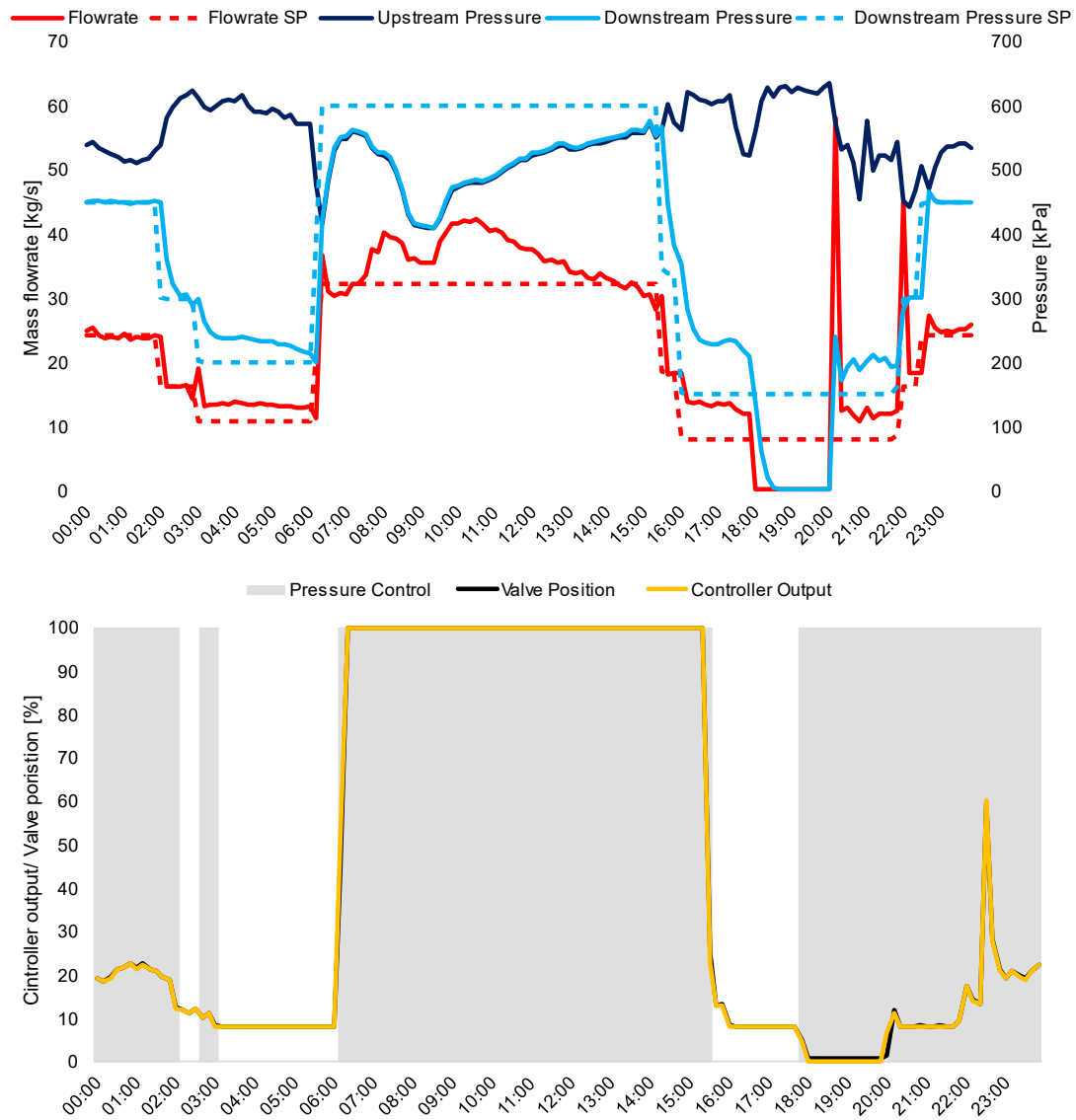
Control Valve Performance Report: YYYY/MM/DD

Mineshaft F Control Valve YYYY/MM/DD



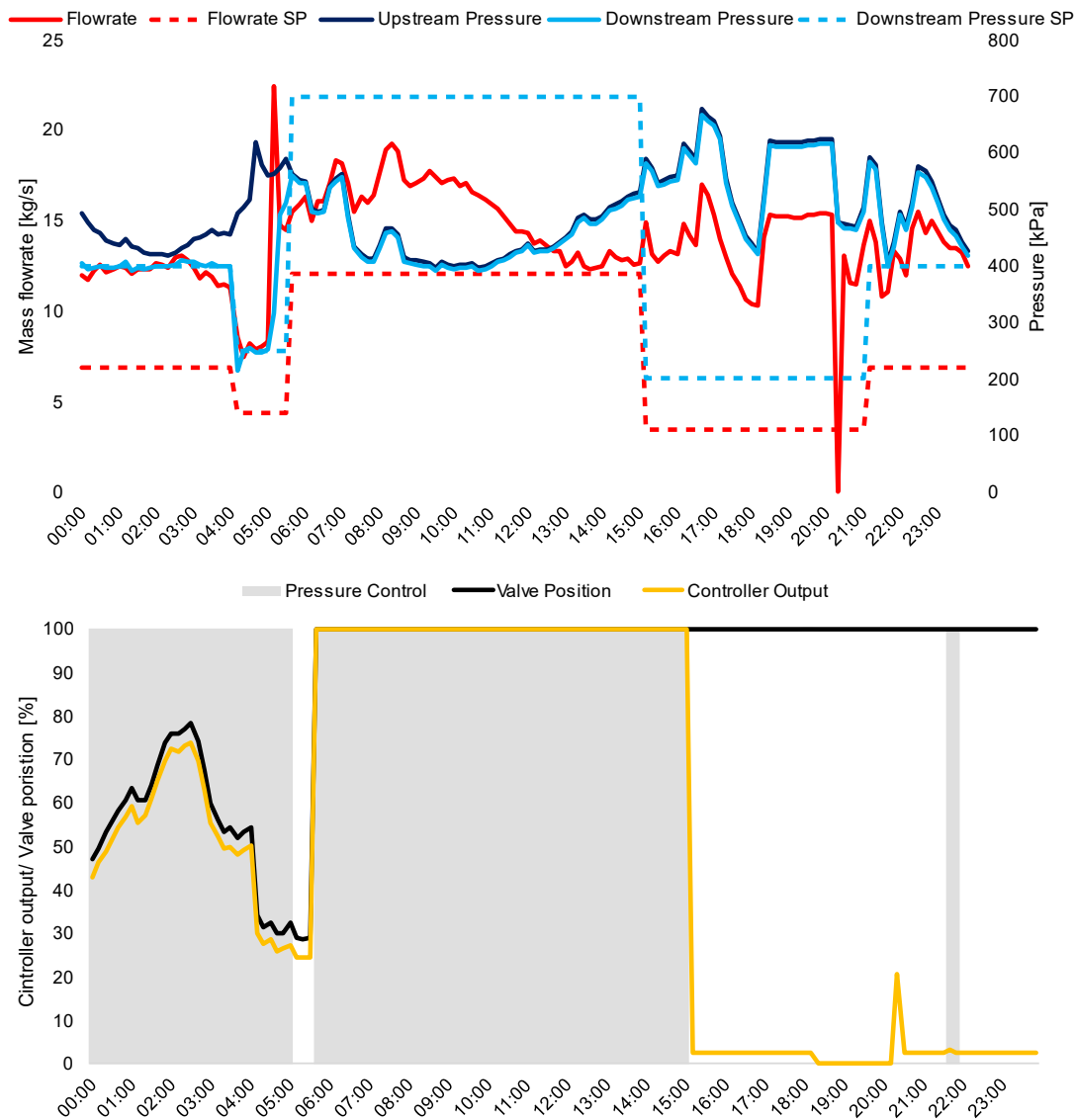
Control Valve Performance Report: YYYY/MM/DD

Mineshaft G Control Valve YYYY/MM/DD



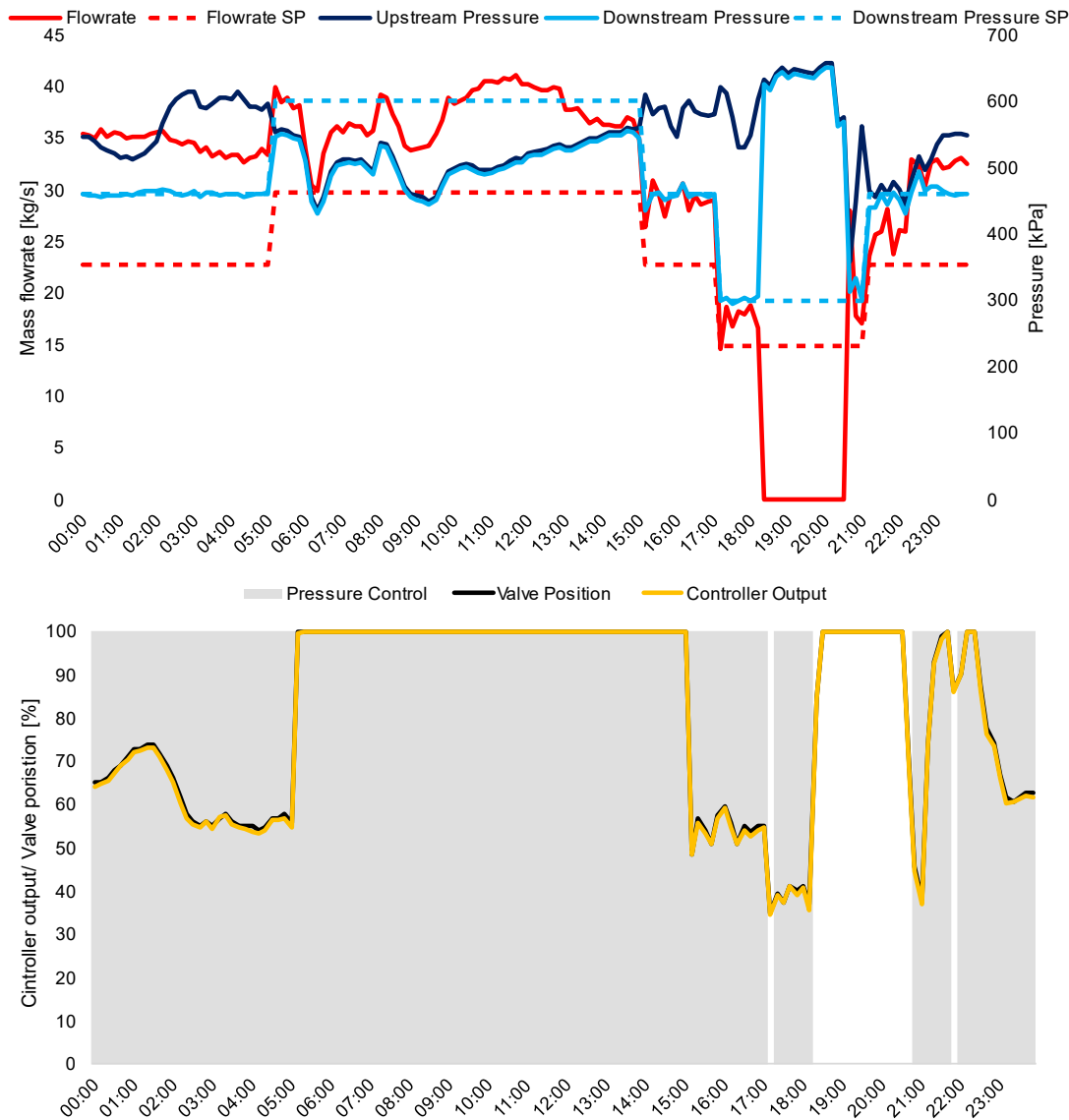
Control Valve Performance Report: YYYY/MM/DD

Mineshaft H Control Valve YYYY/MM/DD



Control Valve Performance Report: YYYY/MM/DD

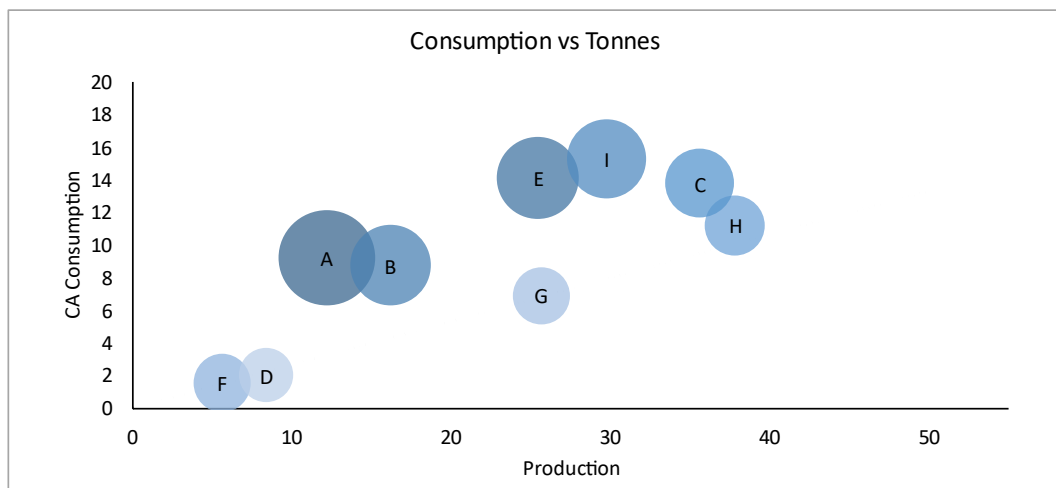
Mineshaft I Control Valve YYYY/MM/DD



APPENDIX H: MINESHAFT B PERFORMANCE OVERVIEW SAMPLE REPORT

Mineshaft B Vertical Section - Performance Overview Report: YYYY/MM/DD

Mineshaft	CA Consumption ['000 kg/week]	Production ['000 tonne/week]	Intensity [kg/tonne]	Ranking (Worst to Best)
Mineshaft A	9 238 617	12 175	759	1
Mineshaft E	14 126 434	25 470	555	2
Mineshaft B	8 778 952	16 164	543	3
Mineshaft I	15 279 294	29 741	514	4
Mineshaft C	13 824 898	35 602	388	5
Mineshaft H	11 224 995	37 838	297	6
Mineshaft F	1 561 271	5 610	278	7
Mineshaft G	6 937 178	25 638	271	8
Mineshaft D	2 035 204	8 388	243	9

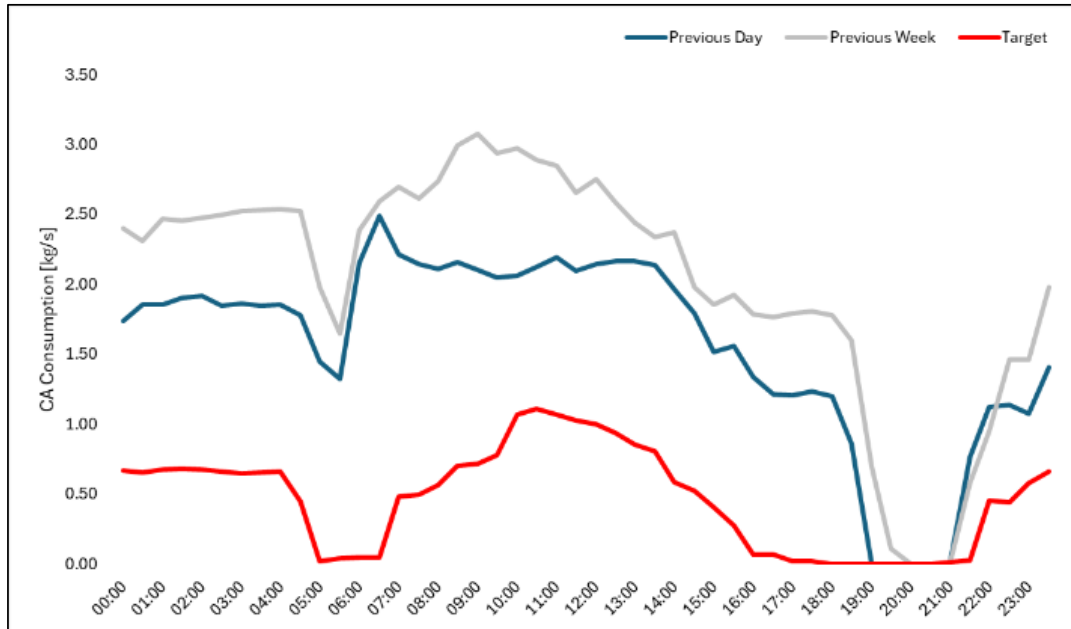
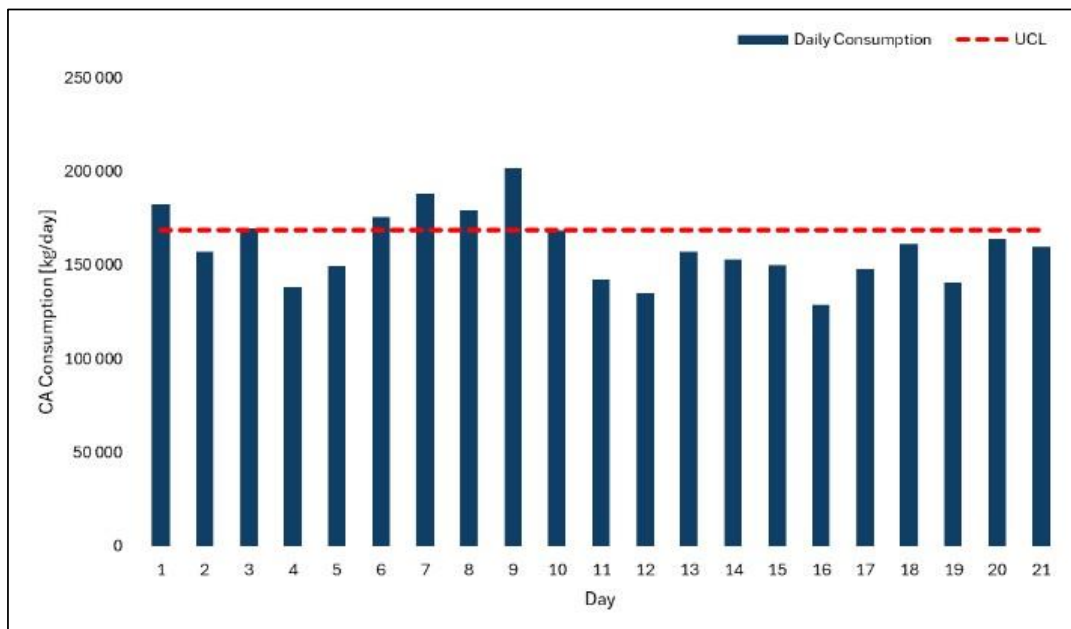


Half-level	CAconsumption ['000 kg/week]			Estimated Wastage Cost [R '000]	
	Actual	Target	Wastage	Daily	Annual
Vertical Section	866	280	586	R138	R22 942
Level 3 North	199	44	155	R35	R5 893
Level 2 North	167	37	130	R30	R5 023
Level 4 North	160	40	120	R30	R4 980
Level 5 North	139	55	83	R19	R3 201
Level 1 North	122	52	70	R16	R2 597
Level 6 North	72	44	28	R8.0	R1 219
Level 6 South	0.4	0.0	0.4	R0.1	R17.0
Level 5 South	7.3	7.1	0.2	R0.1	R12.0
Level 3 South	0.0	0.0	0.0	R0.0	R0.0

W

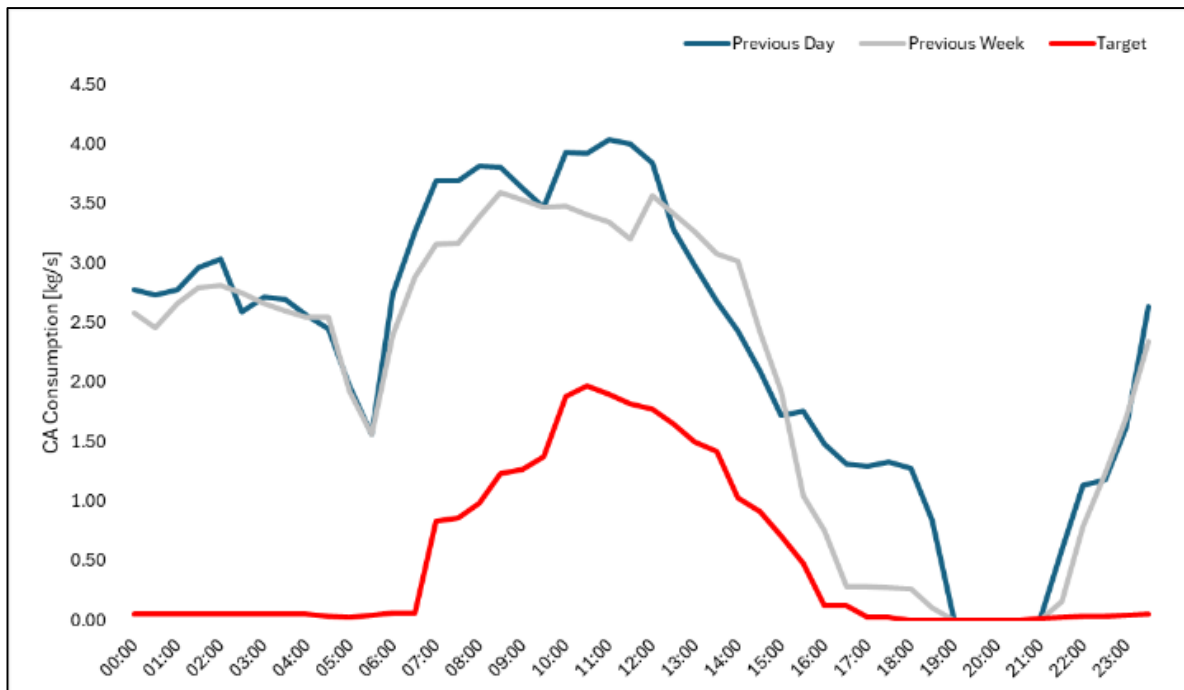
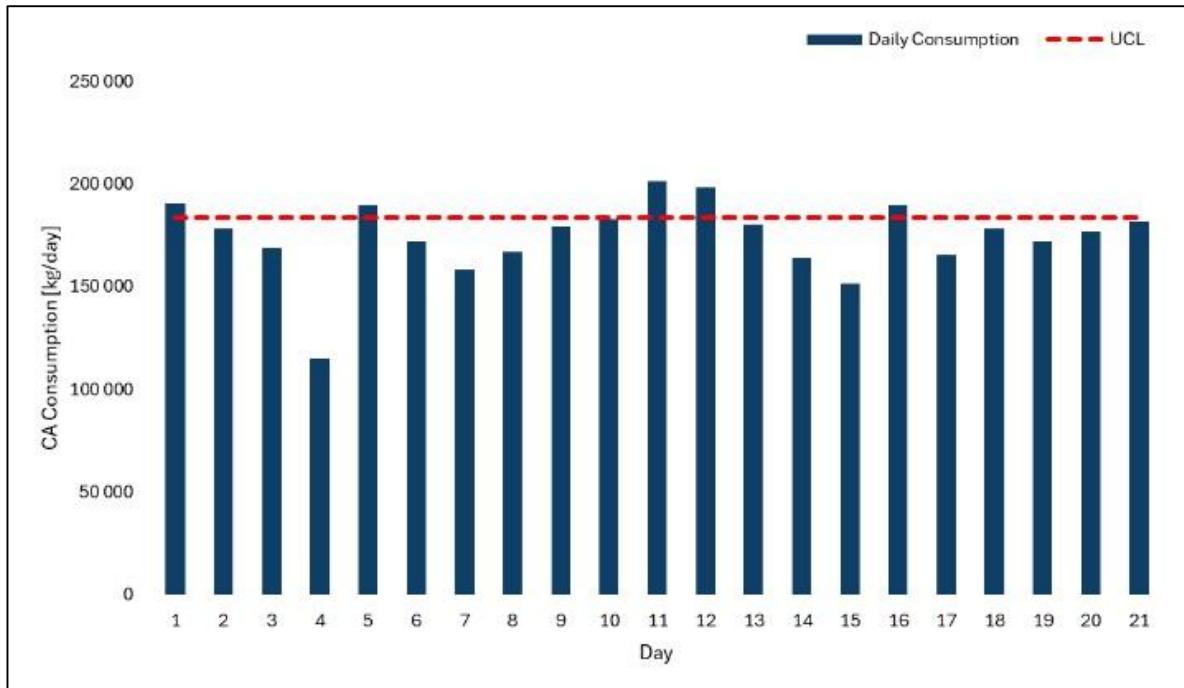
APPENDIX I: MINESHAFT B SECTION PERFORMANCE SAMPLE REPORT

Mineshaft B Level 1 North CA Performance Report: YYYY/MM/DD



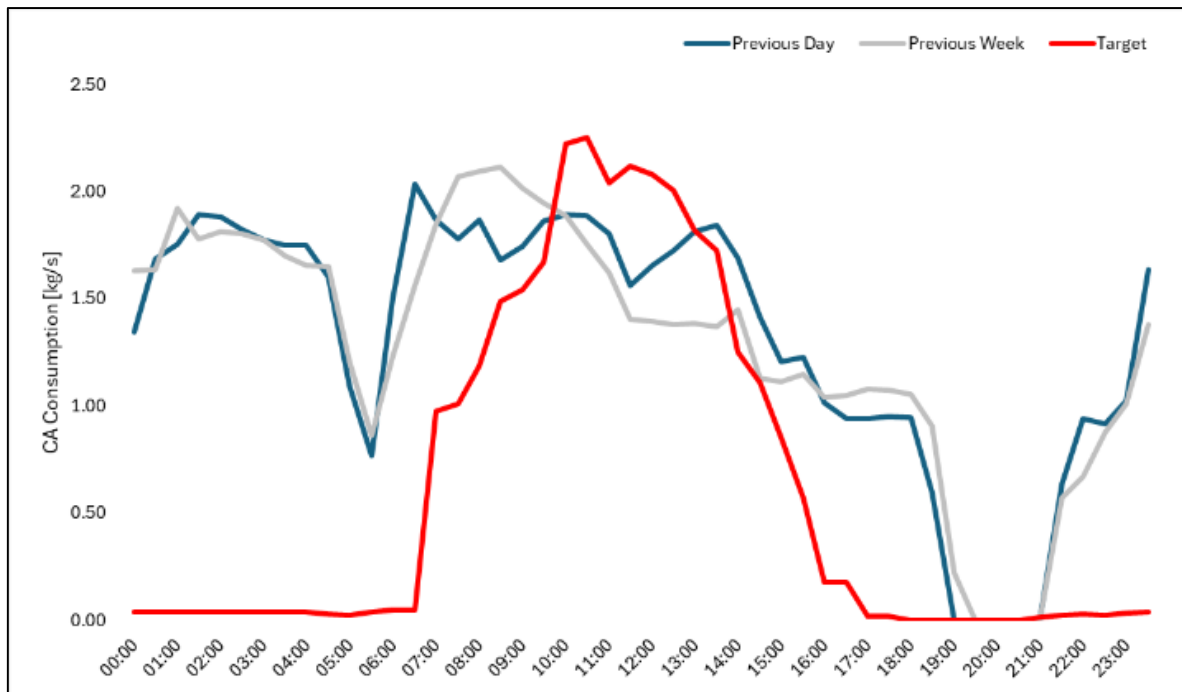
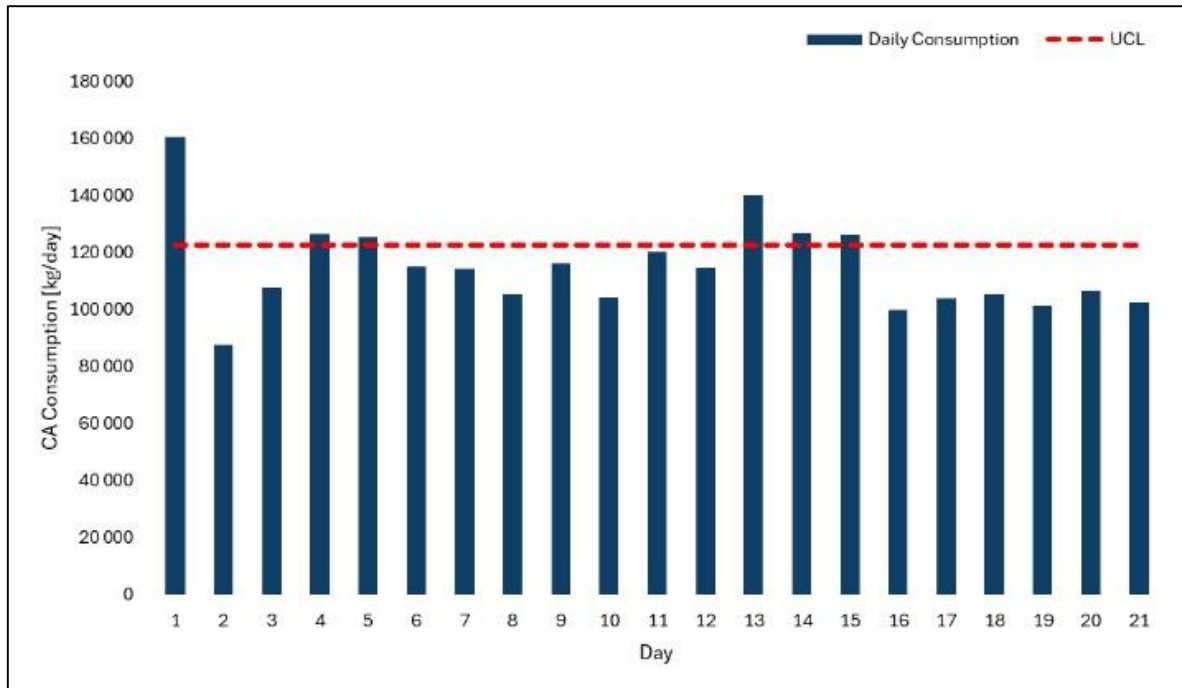
Metric	Average CA consumption [kg/day]	Estimated Annual Cost [R]
Previous Day	37.54	1 660 526
Previous Week	48.86	2 161 616
Target	11.14	493 026
Wastage	26.39	R1 167 500

Mineshaft B Level 2 North CA Performance Report: YYYY/MM/DD



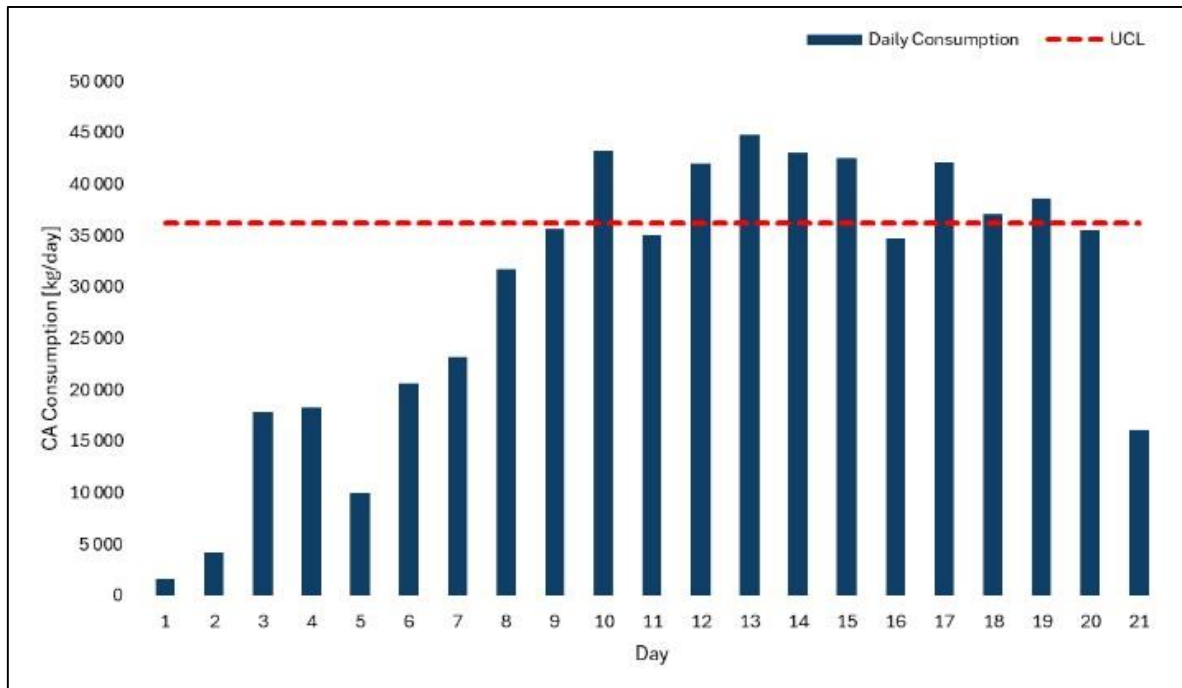
Metric	Average CA consumption [kg/day]	Estimated Annual Cost [R]
Previous Day	55.11	2 438 031
Previous Week	49.38	2 184 262
Target	12.35	546 229
Wastage	42.76	R1 891 803

Mineshaft B Level 3 North CA Performance Report: YYYY/MM/DD



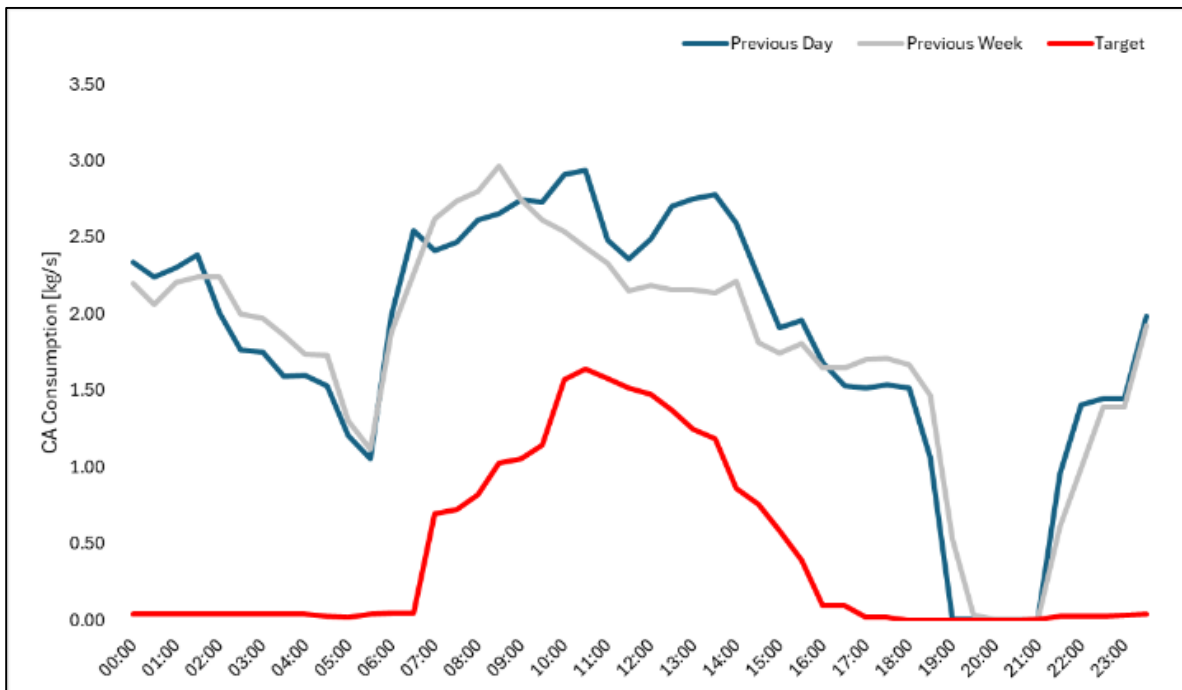
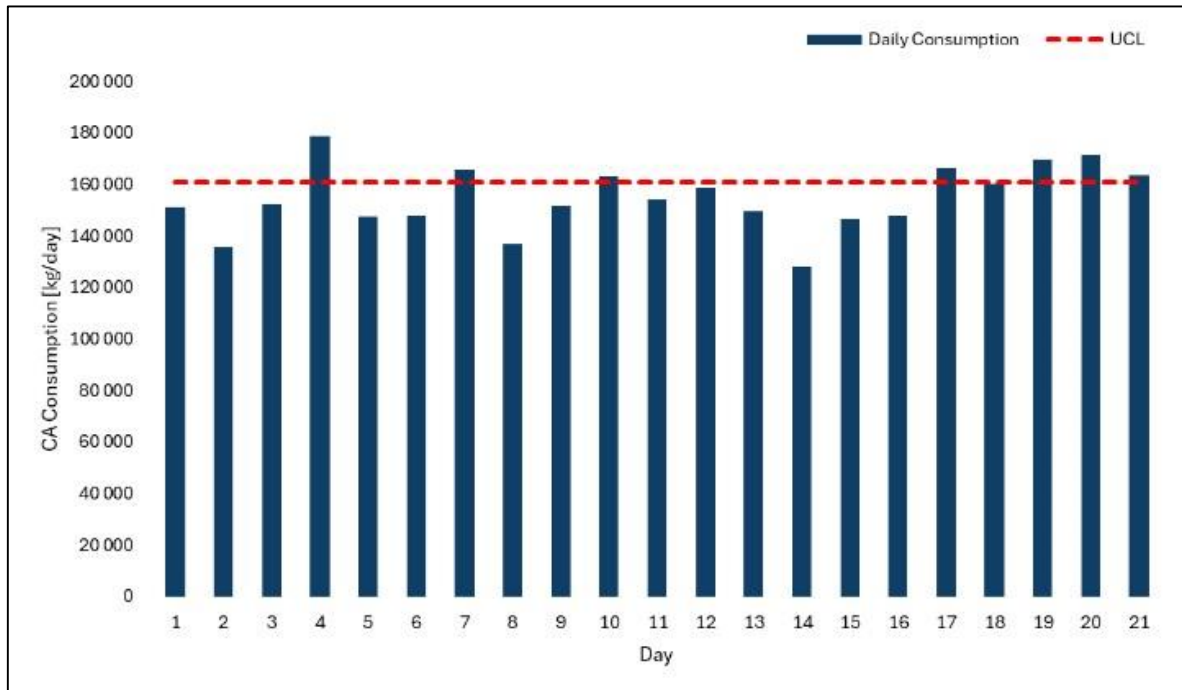
Metric	Average CA consumption [kg/day]	Estimated Annual Cost [R]
Previous Day	31.85	1 408 824
Previous Week	31.12	1 376 505
Target	14.49	641 156
Wastage	17.35	R767 668

Mineshaft B Level 3 South CA Performance Report: YYYY/MM/DD



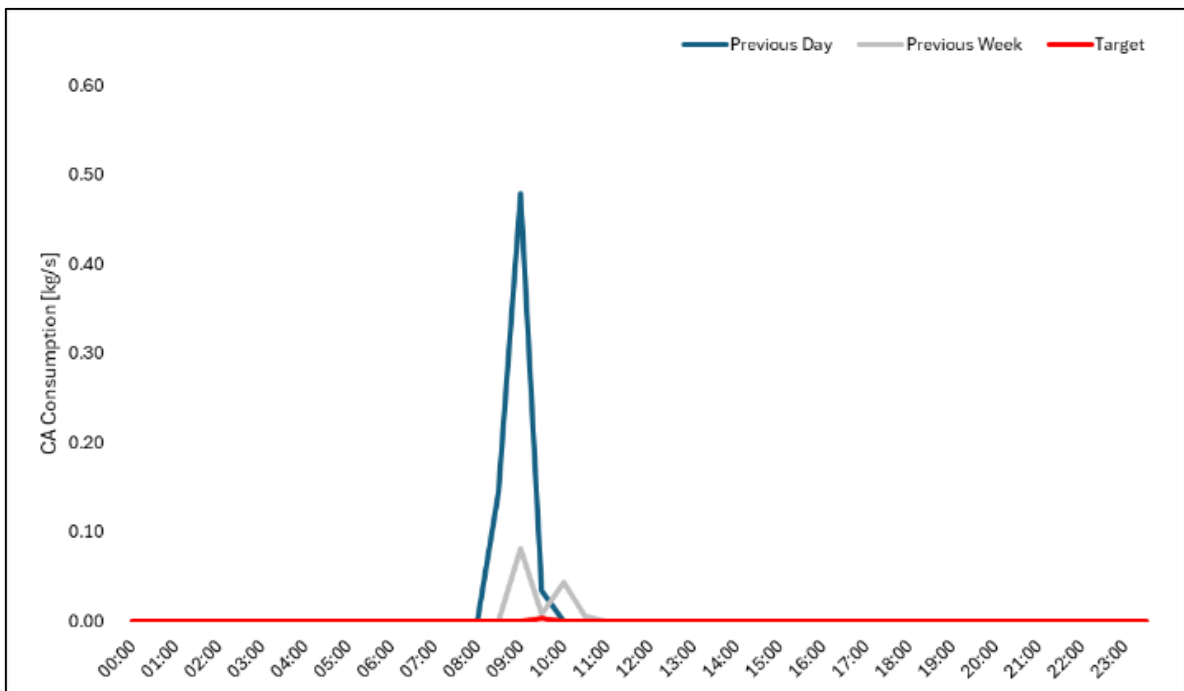
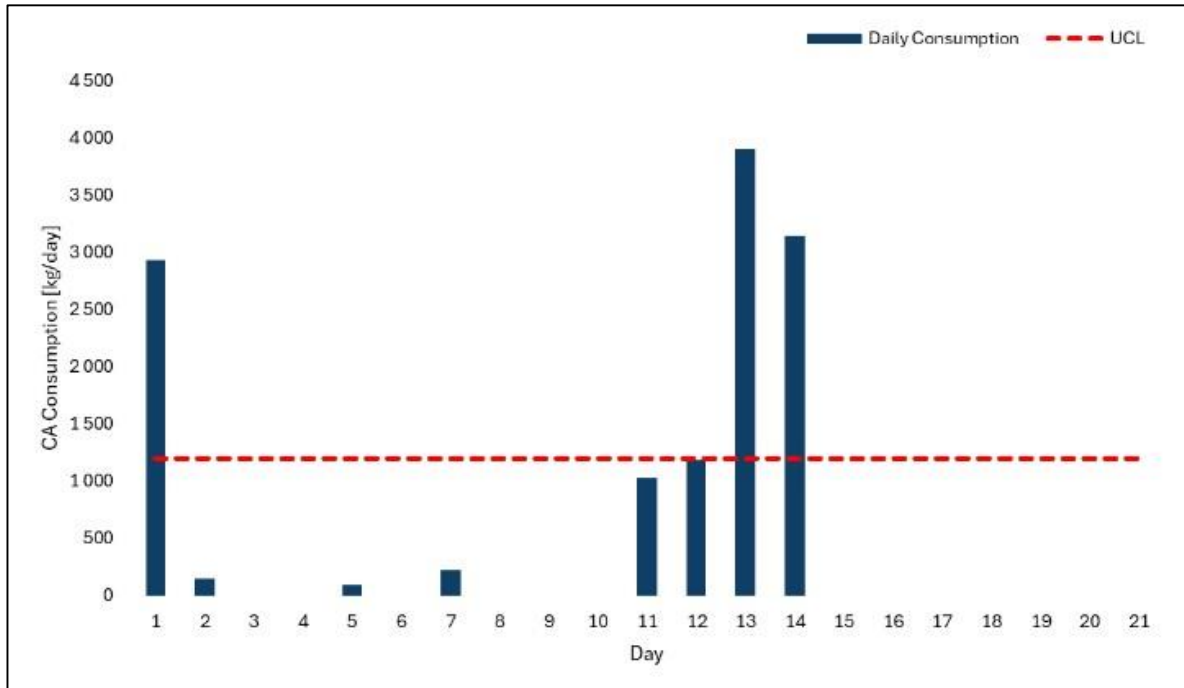
Metric	Average CA consumption [kg/day]	Estimated Annual Cost [R]
Previous Day	11.65	515 516
Previous Week	9.37	414 728
Target	8.95	396 096
Wastage	2.70	R119 420

Mineshaft B Level 4 North CA Performance Report: YYYY/MM/DD



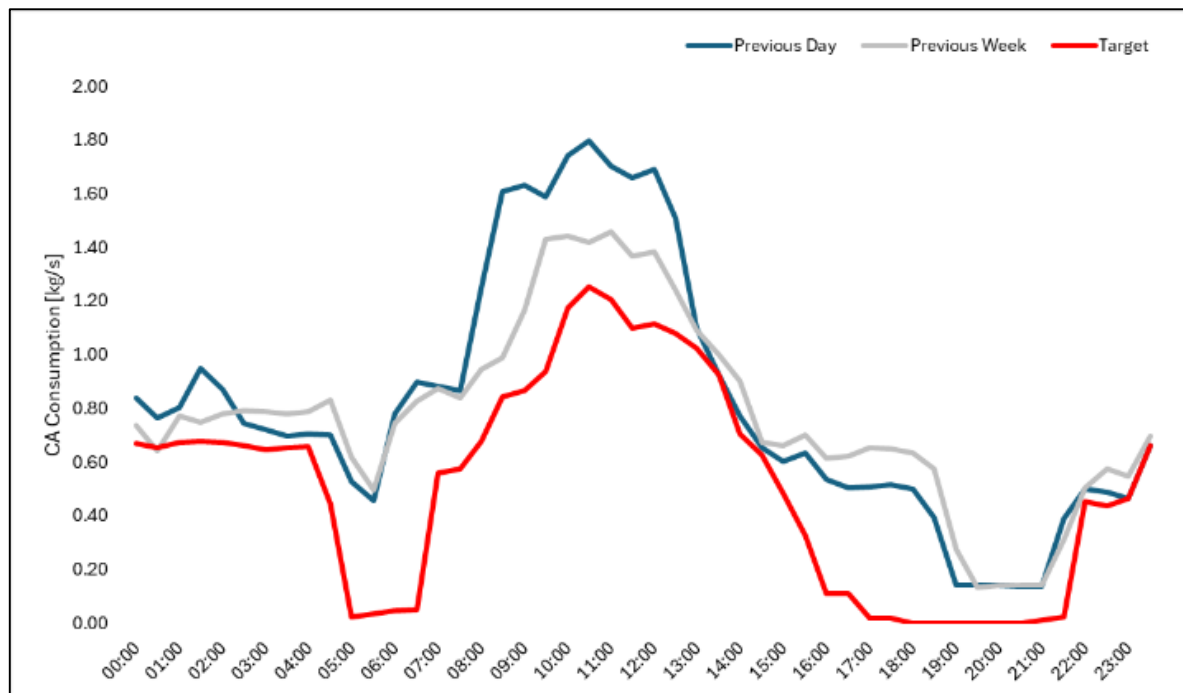
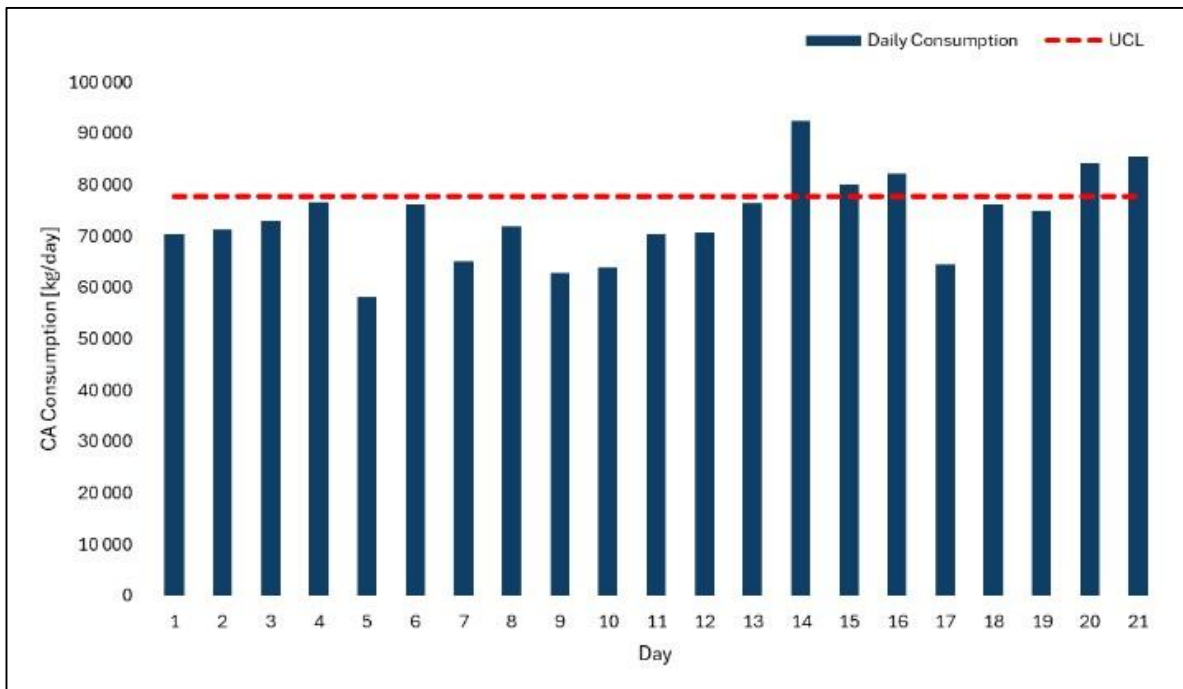
Metric	Average CA consumption [kg/day]	Estimated Annual Cost [R]
Previous Day	44.07	1 949 695
Previous Week	42.84	1 895 312
Target	10.28	454 713
Wastage	33.79	R1 494 982

Mineshaft B Level 5 North CA Performance Report: YYYY/MM/DD



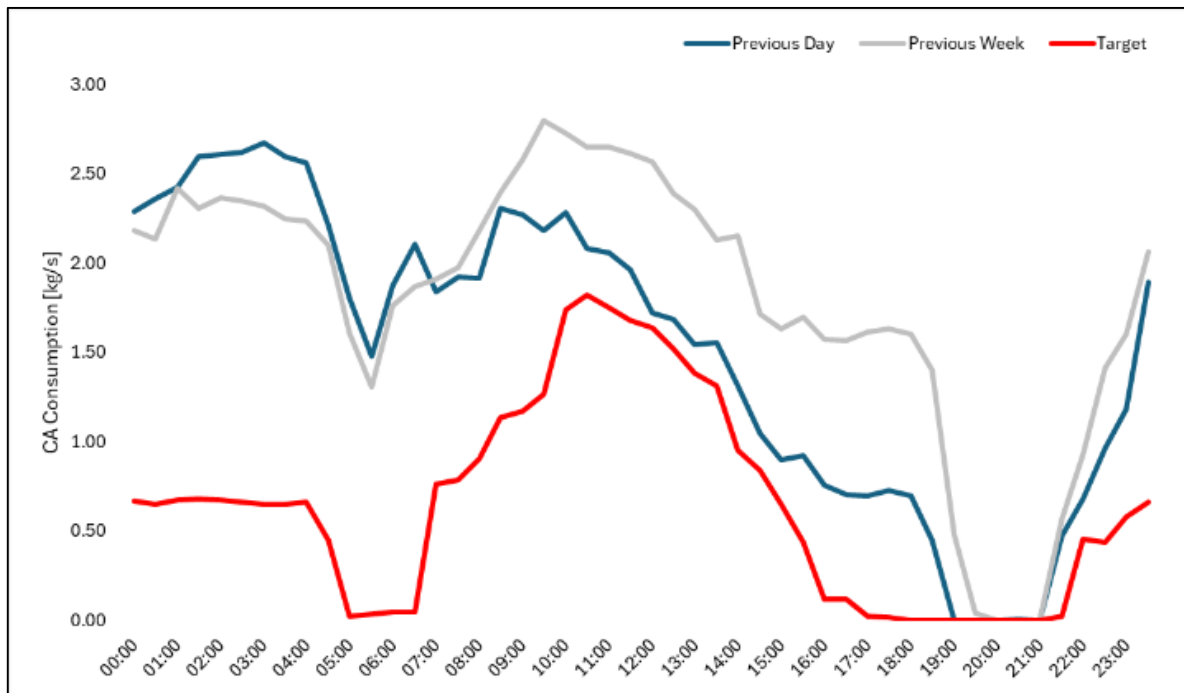
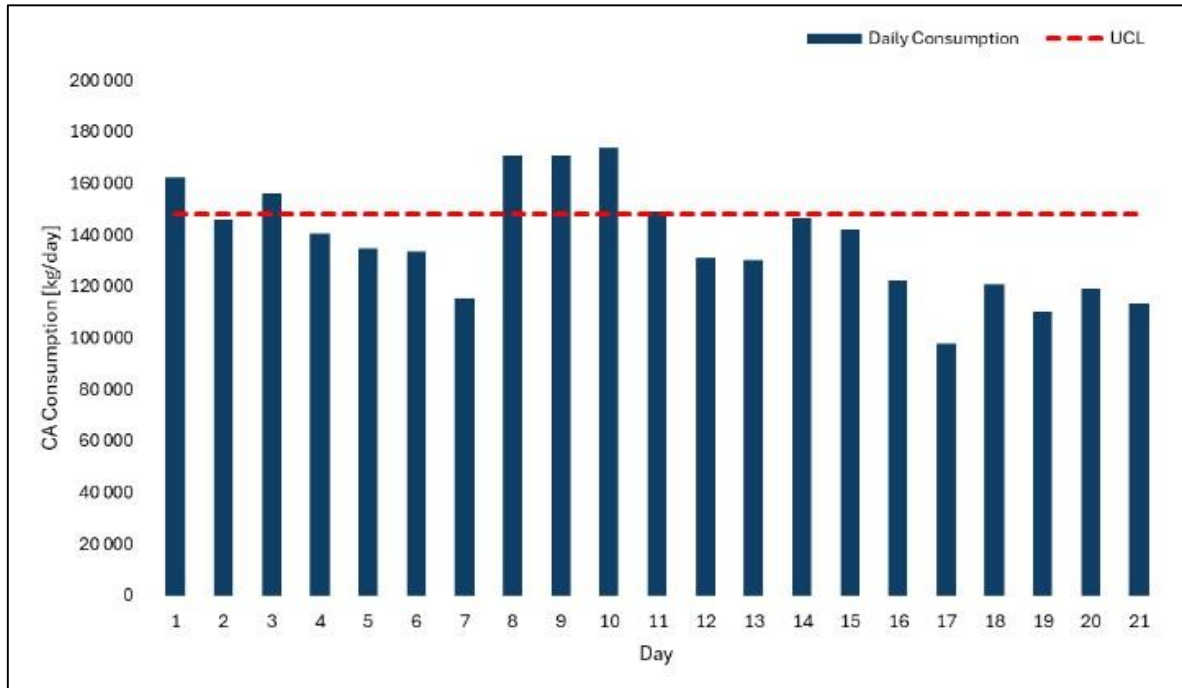
Metric	Average CA consumption [kg/day]	Estimated Annual Cost [R]
Previous Day	0.33	14 535
Previous Week	0.07	3 057
Target	0.00	66
Wastage	0.33	R14 469

Mineshaft B Level 5 South CA Performance Report: YYYY/MM/DD



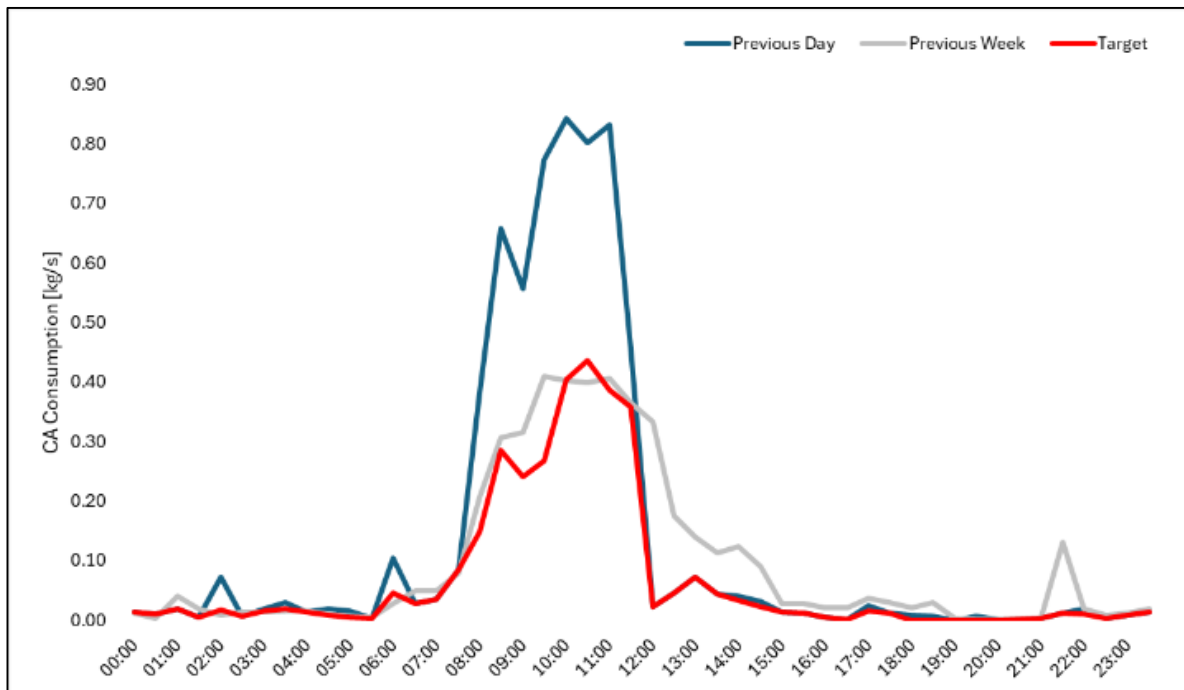
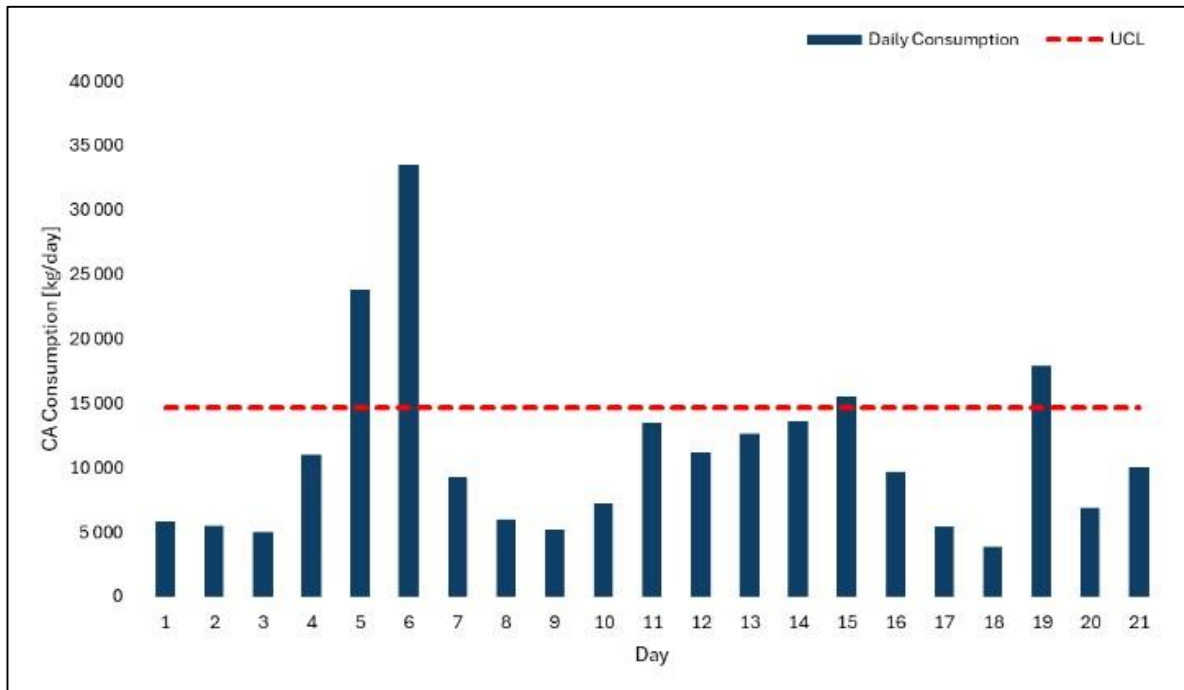
Metric	Average CA consumption [kg/day]	Estimated Annual Cost [R]
Previous Day	19.61	867 527
Previous Week	18.57	821 300
Target	12.17	538 218
Wastage	7.44	R329 309

Mineshaft B Level 6 North CA Performance Report: YYYY/MM/DD



Metric	Average CA consumption [kg/day]	Estimated Annual Cost [R]
Previous Day	36.43	1 611 801
Previous Week	43.35	1 917 759
Target	15.36	679 308
Wastage	21.08	R932 493

Mineshaft B Level 6 South CA Performance Report: YYYY/MM/DD



Metric	Average CA consumption [kg/day]	Estimated Annual Cost [R]
Previous Day	3.09	136 896
Previous Week	2.28	101 057
Target	1.60	70 951
Wastage	1.49	R65 945