Improving efficiency of a mine compressed air system

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ABSTRACT

Title: Improving efficiency of a mine compressed air system

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Keywords: Compressed air, energy efficiency, demand side management, deep level gold mine, leak auditing, peak clipping, control philosophies, bypass valves, compressor offloading, delivery pressure set point

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Eskom supplies electricity to South Africa, which experienced a capacity margin shortfall. Energy savings companies (ESCOs) implement demand side management (DSM) initiatives to reduce the power strain on the electricity grid. Mine compressed air is a large electricity consumer. The operating costs associated with using compressed air can be reduced by implementing energy efficiency initiatives.

Most compressed air systems on mines are inefficient. A typical deep level mine consists of a standalone or ring feed network, containing several centrifugal compressors. Compressors deliver air to surface and underground users. These compressors can have inlet guide vane controls that are effective for controlling airflow. Control valves are also installed on surface or underground for pressure control.

Some initiatives affect the inlet guide vane control of the compressors directly. Implementing these initiatives has proven to reduce the power consumption of a compressed air system. The initiatives with the greatest impact on improving energy efficiency of deep level mine compressed air systems were fixing leaks, adjusting delivery pressure set points and reducing pressure on some levels with control valves.

A new efficient approach to leak auditing was developed. Control valves were used during the morning changeover period and different pressure control philosophies were developed. This dissertation discussed how the compressed air system improved when a large leak was fixed. The compressed air system was adjusted for improved cost savings.

This study also investigated other initiatives available for improving the energy efficiency of a deep level mine compressed air system, such as replacing and selecting compressors, replacing compressor inlet air filters and offloading compressors. Control philosophies were developed to maximise the power savings associated with offloading a compressor. The control philosophies can be implemented to maximise the cost savings when offloading compressors.

Implementation of the initiatives achieved a power reduction of 1.35 MW, which relates to an estimated annual electricity cost saving of R8 million. Leak auditing, adjusting delivery pressure set points, reducing pressure on some levels, developing control philosophies for control valves and offloading compressors are effective initiatives to implement on mine compressed air systems. It was proven that these initiatives reduce compressed air power consumption and operating costs.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

ABBREVIATIONS:

Abbreviation:	**Description:**
DSM	Demand side management
DVC	Digital valve controller
ESCO	Energy savings company
PID	Proportional-Integral-Derivative
PLC	Programmable logic controller
SCADA	Supervisory control and data acquisition
TOU	Time-of-Use

UNITS:

Unit:	**Description:**
CFM	cubic feet per minute
h	hour
K	kelvin
kg/m^3	kilogram per cubic metre
kHz	kilohertz
kJ/(kg·K)	kilojoule per kilogram per kelvin
kPa	kilopascal
kW	kilowatt
kWh	kilowatt-hour
m	metre
mm	millimetre
m/s	metre per second
m/s^2	metre per second squared
MW	megawatt
m^3/h	cubic metre per hour
R	rand
R/kWh	rand per kilowatt-hour
s	second

SYMBOLS:

Symbol:	**Description:**
A	Area of leak
C	Specific heat capacity of compressed air
d	Diameter
f	Friction factor
g	Gravitational acceleration
h	Depth or vertical distance from surface
k	Specific heat ratio of compressed air
L	Length of vertical pipeline
$\dot{m}$	Mass flow of compressed air
P	Pressure
R	Gas constant of air
T	Temperature of air
v	Airflow velocity
W	Electric power
Z	Altitude
η	Efficiency
ρ	Density of air
ΔP	Pressure impact due to auto compression

TERMINOLOGY:

Term	Description
Actuator	The mechanical device on a valve used to change the position of the valve opening.
Demand Side Management (DSM)	A process where electric utilities collaborate with consumers to achieve predictable and sustainable changes in electricity demand. These changes are effected through a permanent reduction in demand levels (energy efficiency) and time-related reductions in demand levels (load management).
Electricity demand	The amount of electricity required by all electric equipment operating simultaneously in a building, area or city.
Maintenance ratio	It is the ratio between the cumulative number of man-hours spent on maintenance, and the cumulative operating hours of the system.
Off-peak period	A time-of-use (TOU) period of relatively low system demand.
Orifice	A small opening in an object where flow goes through.
Peak period	A TOU period of relatively high system demand.
Positioner	An instrument on a valve actuator used for position control.
Standard period	A TOU period of relatively mid-system demand.
TOU tariff	A tariff with energy charges that changes during different TOU periods and seasons.
Transmitter	Instrument used to measure flow rate or pressure.

CHAPTER 1: INTRODUCTION

1.1 Introduction

South Africa's electricity demand has increased by 9.4 % for Eskom's 2016/17 tariff period [1] and Eskom has a maintenance backlog [2]. As a result, Eskom's electricity reserve margin fell under the international reserve margin of 15% in 2008 [3]. Energy savings companies (ESCOs) implemented demand side management (DSM) initiatives to reduce the electricity strain during Eskom's evening peak period.

Eskom has a Megaflex tariff for high electricity consumers, such as mines, which has two different time-of-use (TOU) seasons, namely low-demand and high-demand [4], [5]. The mining industry is a large electricity consumer in South Africa which gold mines is the largest electricity consumer in the mining industry [6]. From the different electricity consumers within the mining industry, compressed air consumes 17% of the mining industry's total electricity consumption [7].

ESCOs will usually implement three different DSM initiatives, namely, energy efficiency, load shifting and peak clipping to reduce a high energy consumer's electricity consumption. Improving the energy efficiency of a gold mine's compressed air system has the largest energy savings impact. This will decrease the power consumption of the compressors and reduce the client's operating costs.

1.2 Overview of the South African electricity supply

Eskom is the state-owned electricity supplier in South Africa, which generates and transmits 95% of South Africa's electrical energy [8]. The other 5% is generated by privately owned electricity suppliers. Eskom is in a difficult situation in terms of power delivery, because of the unpredictable economic situation, human population growth and increasingly high electricity demand [9].

The country experienced an electricity demand reserve margin shortfall of over 10% in 2008 [10]. The international norm for an electricity reserve margin is 15% [3]. Figure 1 shows that South Africa's peak electricity demand for the period from 2006 to 2012 was above the reserve margin [11]. Eskom had to increase their electricity demand reserve margin.

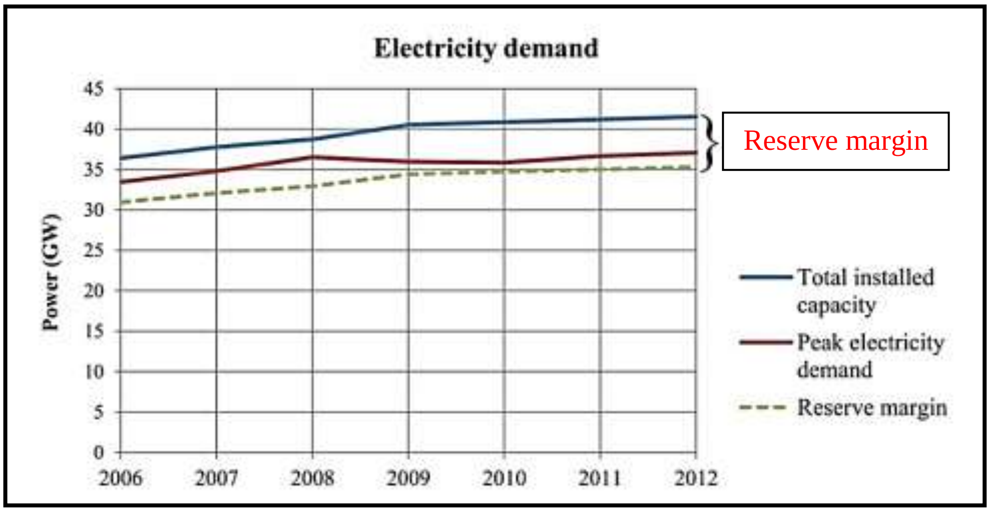


Figure 1: Peak electricity demand in relation to electricity reserve margin [11]

Eskom urgently requested South Africans to reduce electricity demand by 3 000 MW because of the high energy demand and unsustainable maintenance backlog [2]. Eskom's ideal annual maintenance ratio is 10% with only 7% of the planned maintenance being done during 2011. Eskom stated that because of the low reserve margin and increasing demand, it is difficult to shut units down for maintenance, thus increasing the risk that units will trip [12].

Extensive maintenance work was taking place in South Africa in 2015, but the country was still prone to power cuts. Although Medupi Unit 6 which was successfully synchronised to the national power grid, the power system remains constrained due to the reserve margin that remain low [13], [14]. Thus, ESCOs implement DSM initiatives to help prevent the electricity demand shortfall in South Africa [15]. The initiatives are also beneficial to clients as these initiatives reduce the operating costs on their services.

1.3 Overview of DSM initiatives

With the electricity shortages and load shedding taking place in South Africa, the national energy regulator (Nersa) approved a 9.4 % electricity tariff increase for the 2016/17 Eskom electricity tariff period that Eskom requires to avert load shedding [1]. Implementing DSM initiatives is then a short-term solution to reduce peak loads with immediate results and will save the client money by reducing their operational costs [16].

Eskom's peak demand period for high electricity consumers, such as mines, is between 18:00 and 20:00 in the low-demand season and between 17:00 and 19:00 in the high-demand season as (seen in Figure 2 [4], [5]). These are the periods where DSM initiatives are currently limiting the electrical load.

The 2016/2017 Megaflex tariff has two different time-of-use (TOU) seasons; low-demand and high-demand. The high-demand season period is from June to August and the low-demand season from

September to May with different TOU tariffs as seen in Figure 3. Low-demand season's evening peak period is from 18:00–20:00; high-demand season's evening peak period is period from 17:00–19:00.

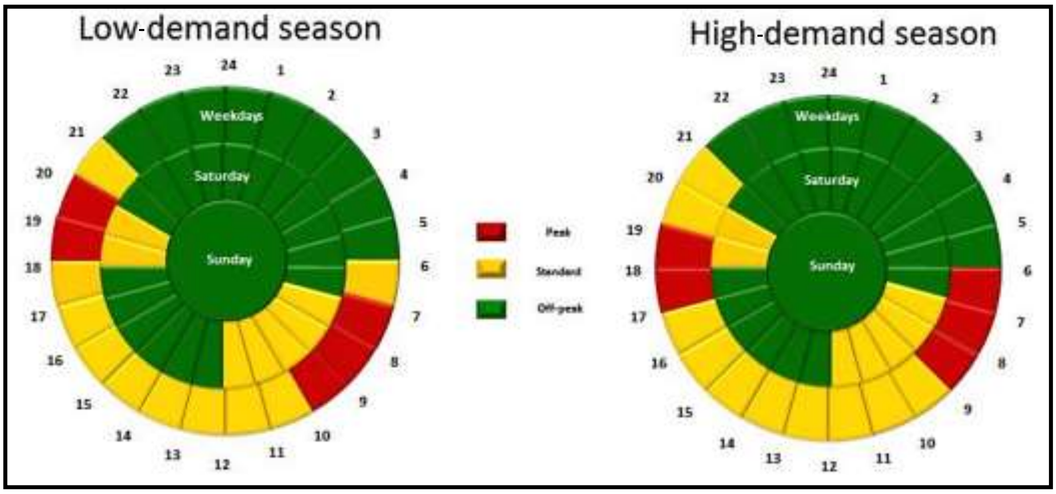


Figure 2: Eskom Megaflex tariff schedule of standard prices 2016/2017 [5]

Figure 3 indicates the active energy charges for different transmission zones from the centre of Gauteng as seen in Figure 4 [5]. Each season has its own peak, standard and off-peak tariffs. The tariffs change within the different transmission zones, but DSM initiative projects are mainly concerned with peak periods, which are significantly more expensive than standard and off-peak periods.

Transmission zone	Voltage	Active energy charge [c/kWh]												Transmission network charges [R/kVA/m]	
		High demand season [Jun - Aug]						Low demand season [Sep - May]							
		Peak		Standard		Off Peak		Peak		Standard		Off Peak			
			VAT incl		VAT incl		VAT incl		VAT incl		VAT incl		VAT incl		VAT incl
≤ 300km	< 500V	248.94	283.79	75.74	86.34	41.35	47.14	81.52	92.93	56.25	64.13	35.86	40.88	R 7.12	R 8.12
	≥ 500V & < 66kV	245.03	279.33	74.23	84.62	40.31	45.95	79.93	91.12	55.02	62.72	34.90	39.79	R 6.51	R 7.42
	≥ 66kV & ≤ 132kV	237.28	270.50	71.87	81.93	39.04	44.51	77.41	88.25	53.27	60.73	33.80	38.53	R 6.34	R 7.23
	> 132kV*	223.63	254.94	67.74	77.22	36.79	41.94	72.96	83.17	50.20	57.23	31.86	36.32	R 8.01	R 9.13
> 300km and ≤ 600km	< 500V	250.97	286.11	76.04	86.69	41.29	47.07	81.87	93.33	56.36	64.25	35.76	40.77	R 7.18	R 8.19
	≥ 500V & < 66kV	247.48	282.13	74.97	85.47	40.71	46.41	80.74	92.04	55.56	63.34	35.25	40.19	R 6.57	R 7.49
	≥ 66kV & ≤ 132kV	239.61	273.16	72.58	82.74	39.41	44.93	78.16	89.10	53.79	61.32	34.12	38.90	R 6.39	R 7.28
	> 132kV*	225.86	257.48	68.43	78.01	37.14	42.34	73.67	83.98	50.70	57.80	32.16	36.66	R 8.09	R 9.22
> 600km and ≤ 900km	< 500V	253.47	288.96	76.78	87.53	41.68	47.52	82.69	94.27	56.91	64.88	36.09	41.14	R 7.27	R 8.29
	≥ 500V & < 66kV	249.96	284.95	75.73	86.33	41.12	46.88	81.54	92.96	56.12	63.98	35.60	40.58	R 6.63	R 7.56
	≥ 66kV & ≤ 132kV	242.05	275.94	73.33	83.60	39.81	45.38	78.95	90.00	54.34	61.95	34.47	39.30	R 6.43	R 7.33
	> 132kV*	228.14	260.08	69.10	78.77	37.54	42.80	74.42	84.84	51.22	58.39	32.50	37.05	R 8.20	R 9.35
> 900km	< 500V	256.02	291.86	77.58	88.44	42.12	48.02	83.53	95.22	57.48	65.53	36.48	41.59	R 7.29	R 8.31
	≥ 500V & < 66kV	252.45	287.79	76.47	87.18	41.51	47.32	82.34	93.87	56.66	64.59	35.95	40.98	R 6.71	R 7.65
	≥ 66kV & ≤ 132kV	244.48	278.71	74.06	84.43	40.21	45.84	79.74	90.90	54.89	62.57	34.82	39.69	R 6.48	R 7.39
	> 132kV*	230.37	262.62	69.82	79.59	37.93	43.24	75.19	85.72	51.76	59.01	32.86	37.46	R 8.26	R 9.42

Figure 3: Eskom's TOU tariff table [5]

Figure 4 indicates Eskom's transmission zones for loads for the TOU tariff table shown in Figure 3. Each zone has a different tariff during the high- and low-demand seasons, which are indicated by dotted circles. Most gold mines are in the first two transmission zones. ESCOs are incentivised to implement projects to control the electrical loads during the afternoon peak period [4], [17].

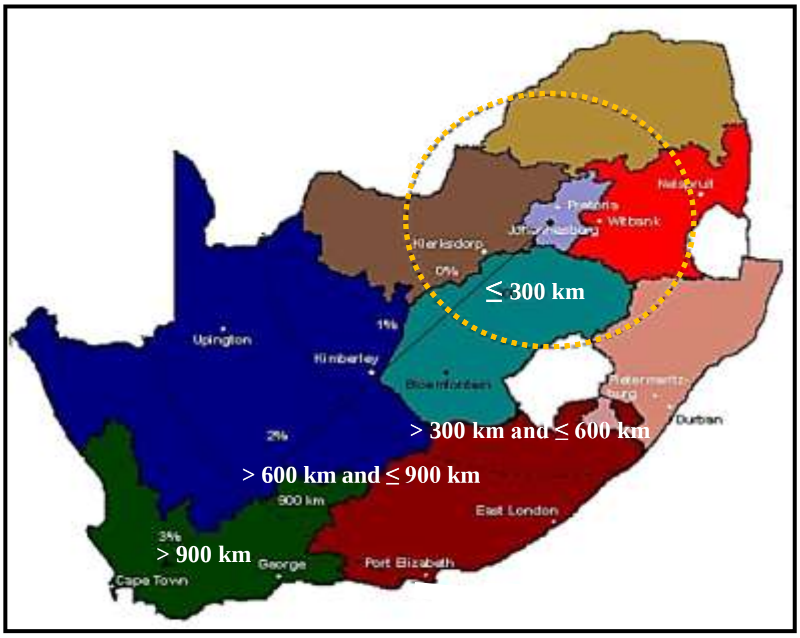


Figure 4: Eskom's transmission zones [5]

By implementing DSM initiatives, the peak period demand on Eskom's electricity supply grid is relieved, but large power savings through implementing energy efficiency control strategies are also realised [18]. This provides opportunities for high electricity consumers to save money during Eskom's peak and other periods, thus reducing their daily operating costs.

1.4 South African mining industry

To achieve energy savings, ESCOs need to identify large electricity consumers in South Africa where DSM initiatives can be applied. The mining industry is a large electricity consumer, consuming 13.8% of Eskom's annual output (as seen in Figure 5) [6]. Compressed air consumes 17% of the mining industry's total electricity [7]. Nersa approved a 9.4 % electricity tariff increase for the 2016/17 Eskom electricity tariff period that Eskom requires to avert load shedding [1], [14].

A number of organisations presented arguments strongly opposing Eskom's tariff hike. Mines have warned Eskom about the possibility of 40 000 job losses due to the unreliable and high electricity tariffs [19]. This is a threat to the electricity users which also leads to disinvestments [19]. Therefore ESCOs have the opportunity to further identify initiatives in for example the gold mining industry to reduce their compressed air operational costs.

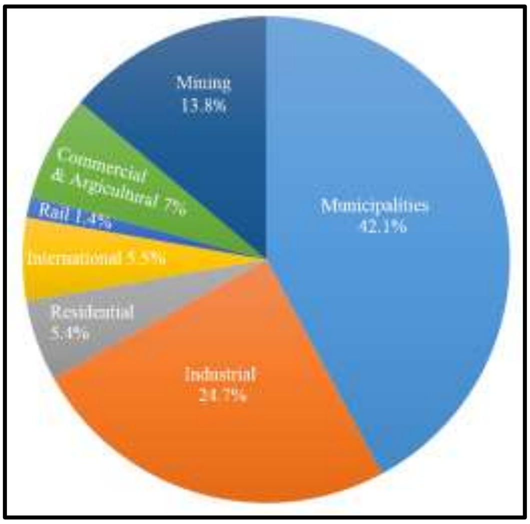


Figure 5: 2015 Eskom electricity sales volumes by customer type [6]

The different energy consumers within the mining sector can be seen in Figure 6, of which compressed air consumes 17% of the mining industry's total electricity [7]. This gives ESCOs the opportunity to investigate the compressed air systems on mines to implement DSM initiatives to reduce their operating costs.

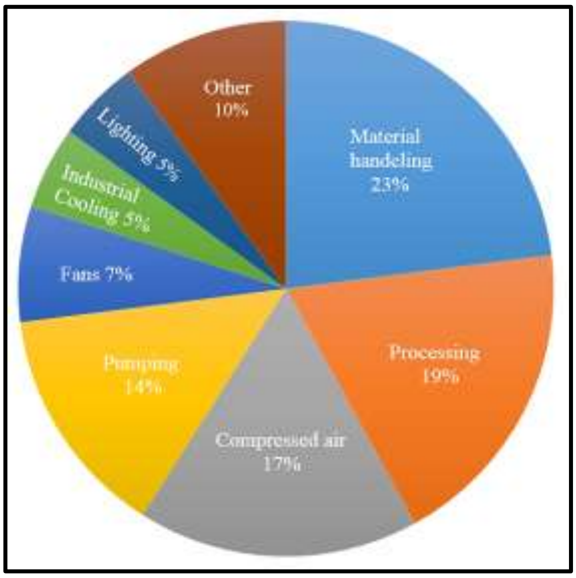


Figure 6: Mining sector's electricity volumes by process type [7]

ESCOs will usually implement three different DSM initiative options, namely, energy efficiency, load shifting and peak clipping [20]. These DSM initiatives can be seen in Figure 7.

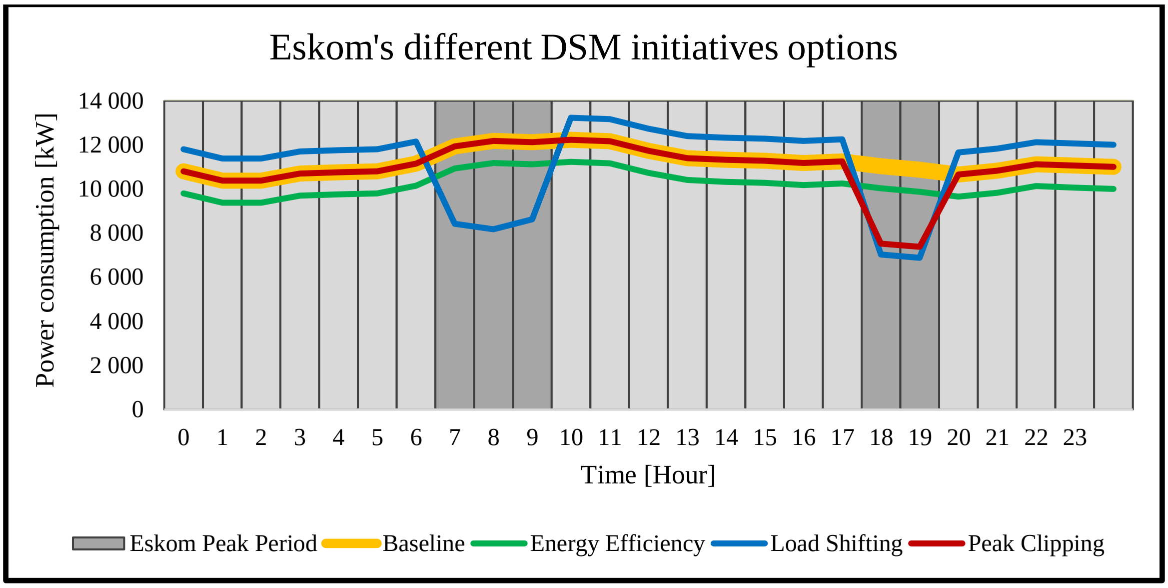


Figure 7: Eskom's different DSM initiative options

The goal of an energy efficiency project is to reduce electricity consumption throughout the whole day, thus they have the largest impact on energy savings. It is usually implemented on compressed air and water pumping systems. For example, in a gold mine's cooling auxiliary system, a variable speed drive is installed to control the frequency of a pump, which reduces the power consumption of the pump when running on a lower frequency. For these energy efficiency projects, infrastructure may be required to obtain complete control over the system [21].

Load-shifting projects are usually implemented on mine dewatering systems. A mine's dewatering system consists of large pumps and large storage dams on various levels. During the off-peak period, pumps are scheduled to pump water out of the dams and prepare the dams to be empty as possible before the peak period starts. During the peak period, fewer pumps are used, while the dam levels slowly increase. The same amount of water will still be pumped, but the load will be shifted to the off-peak periods to lower the power consumption in the evening peak period. Shifting the load out of the evening peak period reduces the operating costs of the pumps [21].

Peak-clipping projects are usually implemented on compressed air systems and fridge plants to reduce electricity usage during the evening peak period. During these projects, machines are switched off and infrastructure is used to reduce the power consumption during the evening peak period. In compressed air systems, infrastructure is usually installed on the mining levels to reduce airflow during the evening peak period. All the compressors cannot be switched off, because compressed air is still required to pressurise refuge bays on the mining levels [22].

DSM initiatives on deep level gold mining compressed air systems

South Africa has some of the world's deepest gold mines [23], where compressed air is a major electricity consumer [22]. Compressed air is easy to produce and to handle, but it is not the most efficient system for a mine's production process [24]. Inefficient control of air, inefficient compressor control and air leaks contribute to the inefficiency of the compressed air system [24], [25].

Production, hoisting and gold plant operations consume compressed air at a gold mine. Gold plant operations in some mines are independent from the mine's compressed air system with their own standalone compressors. During the drilling shift, the most air is consumed by drilling machines.

Blasting takes place during the afternoon shift – minimum compressed air is required at the working areas and refuge bays. During the night shift, higher pressure is required for the loaders and other equipment for cleaning and loading of ore and waste. The ore and waste are then hoisted to surface via the shaft [26].

A typical schedule of compressed air requirements on a gold mine can be seen in Figure 8 that indicates a typical actual pressure profile versus a proposed pressure profile. The figure also indicates the blasting period between 17:00 and 21:00, which requires low pressures for the refuge bays. This offers an opportunity where ESCOs can improve evening peak period cost savings. The typical air pressure requirement schedule gives an ESCO the opportunity to investigate the mine's compressed air system to improve the overall efficiency thereof.

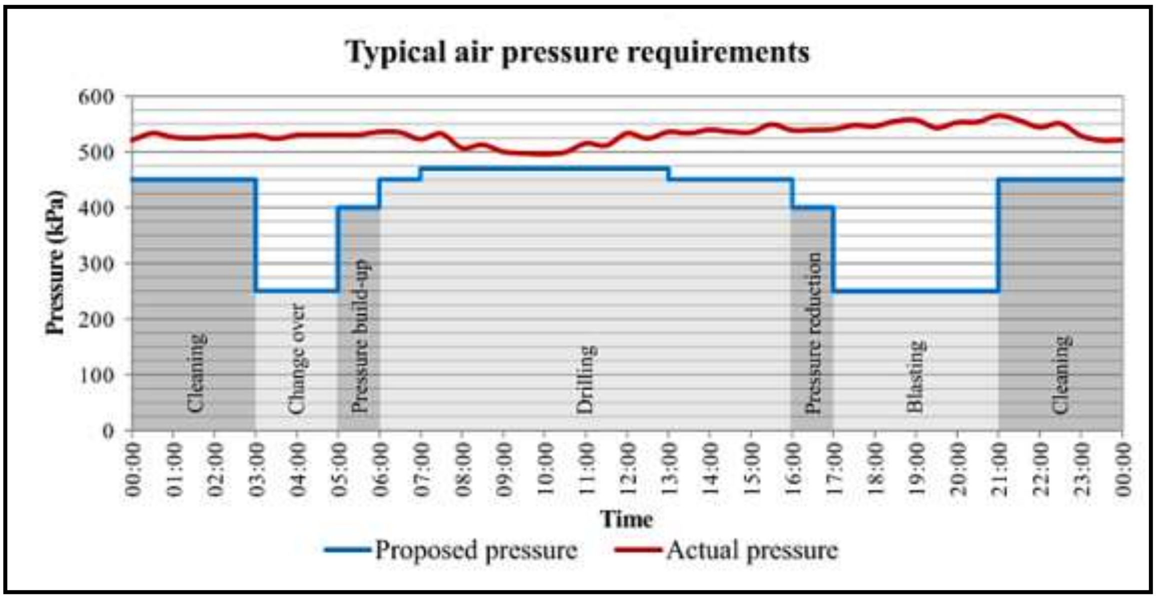


Figure 8: Typical schedule of a gold mine's air pressure requirements [11]

1.5 Problem statement and objectives

With increasing Eskom electricity tariffs [1], deep level mines have the need to reduce operating costs on their compressed air systems as they consume a large amount of the mines' total electricity consumption. There is a need to identify existing DSM initiatives and strategies which can be implemented to improve the energy efficiency of the compressed air systems to reduce the operating costs of the compressors.

A deep level mine compressed air system will be analysed, interventions will be identified which solutions will be designed, implemented and tested. Thus, the goal of this study is to improve the energy efficiency of a mine's compressed air system to reduce its annual operating costs.

1.6 Dissertation overview

Chapter 1: Introduction

In this chapter, background on Eskom as South Africa's electrical energy supplier is provided. ESCOs implement DSM initiatives to reduce power consumption during the evening peak period. ESCOs have the opportunity to improve the energy efficiency on the compressed air systems on deep level mines. A problem statement and objectives of the study are formulated.

Chapter 2: DSM on compressed air systems

In this chapter, a compressed air network of a typical deep level mine is discussed. The study focuses mainly on standalone compressed air systems with inlet guide vane control. Existing DSM initiatives for reducing electricity costs on compressed air systems are discussed where the need for the study is formulated.

Chapter 3: Identifying interventions for improving cost savings

In this chapter, an inefficient deep level mine was identified and explained. Different interventions were explained on how to improve the energy efficiency of the compressed air system. Some of the interventions were simulated to predict the possible saving when implementing the proposed intervention. Control philosophies were developed for some of the interventions.

Chapter 4: Practical implementation of interventions

In this chapter, the interventions identified in Chapter 3 are implemented, results and annual cost savings of the optimised compressed air system are determined and presented.

Chapter 5: Conclusion and recommendations

In this chapter, an overall conclusion is provided for the whole study as well as recommendations for further studies.

1.7 Conclusion

Eskom is a state-owned electricity supplier in South Africa that generates and transmits 95% of South Africa’s electrical energy. With the electricity shortages and load shedding taking place in South Africa, the national energy regulator (Nersa) approved a 9.4 % electricity tariff increase for the 2016/17 Eskom electricity tariff period that Eskom requires to avert load shedding.

ESCOs implement DSM initiatives to help prevent the electricity demand shortfall in South Africa. The initiatives are also beneficial to clients as they reduce clients’ operating costs. In the mining industry, various processes consume electricity, of which compressed air consumes 17% of the total electricity. This gives ESCOs the opportunity to investigate the compressed air systems on mines to implement DSM initiatives to reduce their operating costs.

With the increasing electricity tariffs of Eskom, deep level mines have the need to reduce the operating costs on their compressed air systems, because these systems consume a large amount of their total electricity consumption. There is a need to identify existing DSM initiatives that can be implemented to improve the efficiency of the compressed air system and reduce the operating costs of a deep level mine compressed air system.

CHAPTER 2: DSM ON COMPRESSED AIR SYSTEMS

2.1 Introduction

This chapter examines the background on deep level mine compressed air systems. Network and compressor types are explained, of which this study will mainly focus on standalone and centrifugal compressors. Compressed air systems are large energy consumers on mines as they supply compressed air and pressure to end users, which are important for production. A mine has a typical mining schedule with different pressure requirements throughout the day.

Due to compressed air systems being expensive to operate, the need arises to reduce operating costs. Implemented DSM initiatives on compressed air systems exist and their contributions can be used to improve the efficiency of an inefficient mine, which will be presented as a case study in Chapter 3 and Chapter 4. This specific mine has inlet guide vanes installed on the compressors as well as bypass pressure control valves on the mining levels as part of a previous project.

There is a need to improve the efficiency of a mine compressed air system. This chapter presents strategies that can be implemented to improve the performance and efficiency of a compressed air system. It is explained how inlet guide vanes function on compressors and how they reduce the electricity consumption of compressors. Initiatives that affect inlet guide vanes are explained, as well as how to use these guide vanes to their full potential.

Existing DSM initiatives prove that energy savings, and resultantly cost savings, are possible by implementing infrastructure, controlling compressor delivery pressure set points, fixing leaks and reducing pressure losses in the pipe network. These initiatives contribute to improving the efficiency of a compressed air system. By managing the supply and demand, operating costs can be reduced.

2.2 Compressed air network of a typical deep level gold mine

A typical gold mine consists of a compressor house, containing several compressors, and a gold plant as seen in Figure 9. Compressors are connected to an intricate pipe network that supplies pressure and air through pipelines to end users' equipment as well as to the gold processing plant. In some cases, these gold plants have their own compressors, making them independent from the mine. Some levels have open/close manual valves and master programmable logic controllers (PLCs) for control and monitoring purposes on each level. It is critical to the compressed air system that these intricate systems are controlled properly [22], [27].

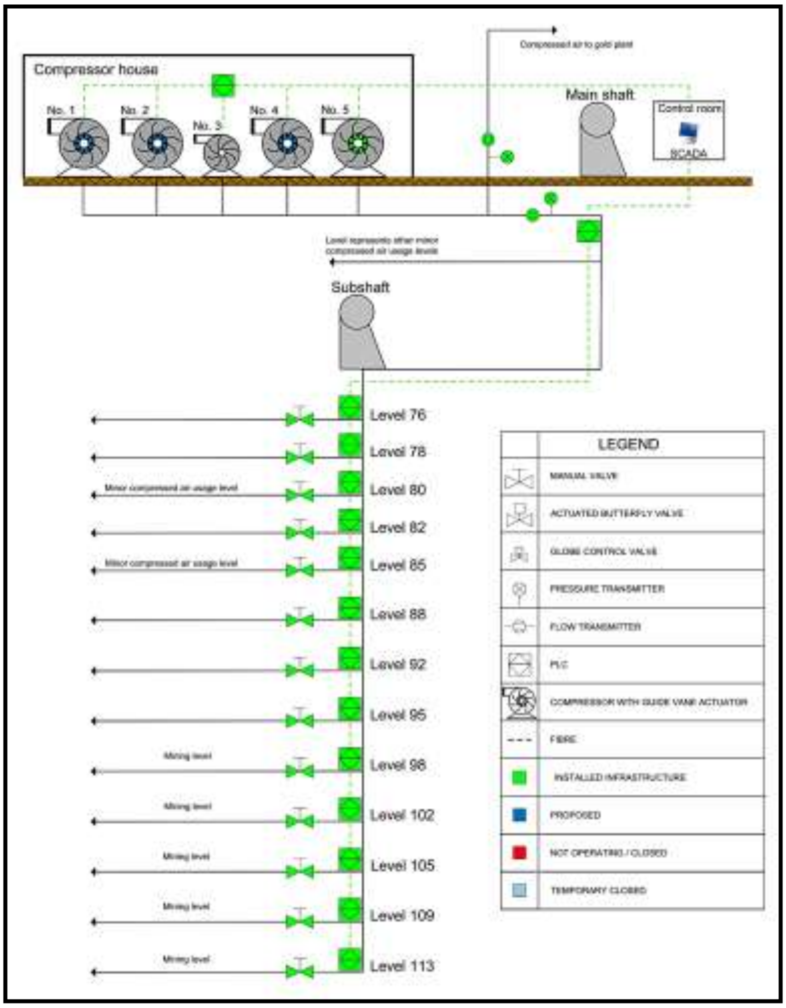


Figure 9: A typical gold mine compressed air network

There are two different types of compressed air network, namely, standalone or ring feed networks, which will be discussed in the sub-sections that follow.

Standalone compressed air systems

In a standalone compressed air system, a single compressor house contains multiple compressors with a common manifold. The compressors discharge compressed air into one pipeline and distribute it to surface users, and down the shaft to underground users [as seen in Figure 10(a)]. This is a simpler system than a compressed air ring and requires less compressed air.

The standalone network has various advantages, for example, changes in airflow and pressure can be detected quickly in the compressed air power consumption. The delivery pressure set point of the compressor house is equal to the highest pressure required in the compressed air network. It is costly to deliver high pressures while other mining sections require lower pressures. When maintenance is required on the compressed air network, the compressor house must be shut down, resulting in production losses [28], [29], [30].

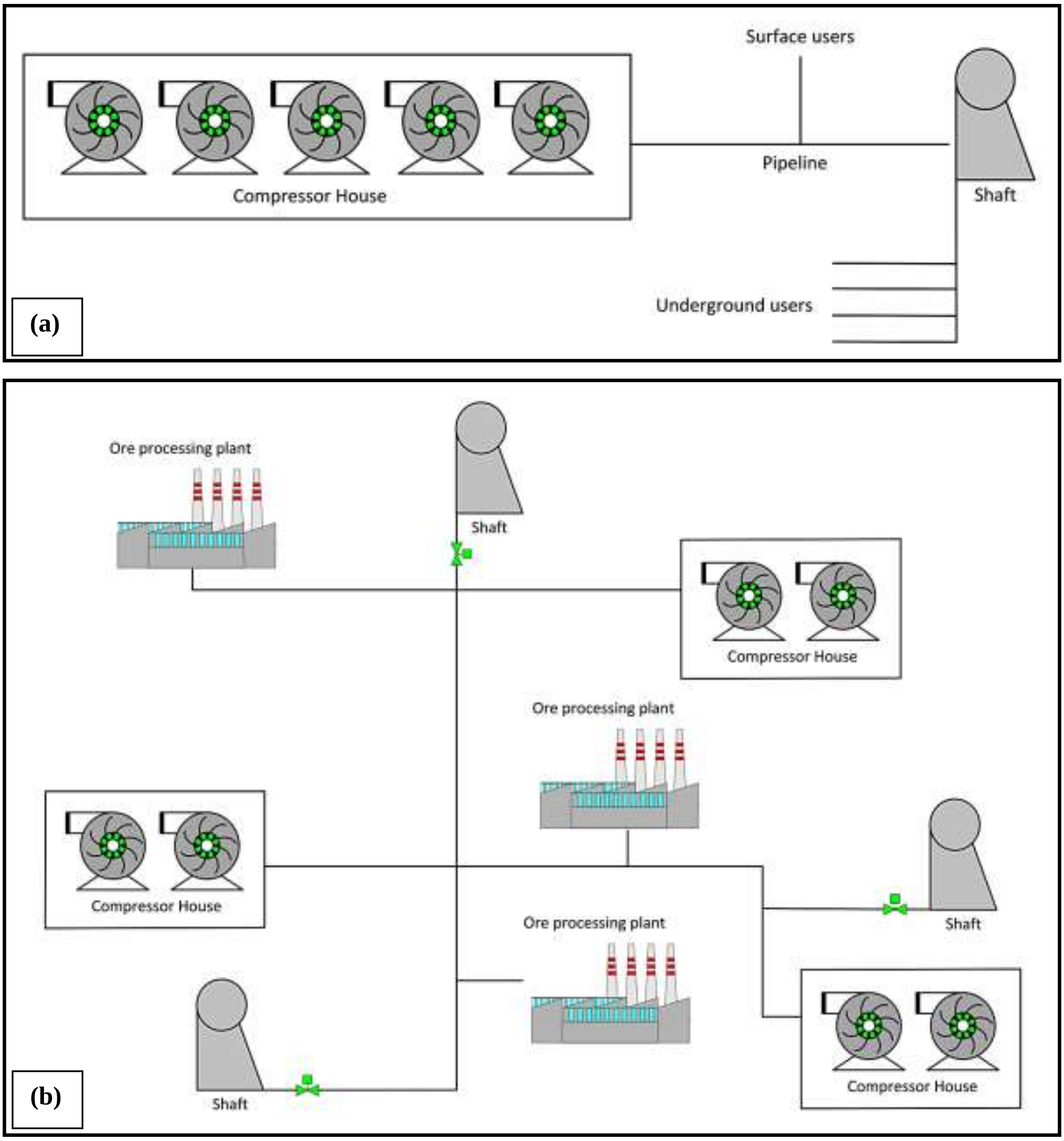


Figure 10: Standalone (a) versus ring feed compressed air network (b)

Ring feed compressed air systems

A ring feed compressed air system consists mainly of several compressor houses that distribute compressed air into a surface pipe network that supplies more than one shaft and end user at the same time [as seen in Figure 10(b)]. Control valves are normally installed before the shaft to control the amount of pressure to end users. The system has to deliver higher volumes of compressed air than the standalone system does, because of the long distances of the pipe network [29], [30], [31].

2.3 Centrifugal compressor background

There are two different types of compressor available, namely, positive displacement and dynamic compressors [32]. Most gold mines use centrifugal-type dynamic compressors that are mechanically simple, which makes them easier to operate and maintain [22]. A centrifugal compressor has continuously flowing air by means of impellers that rotate at a very high speed. A centrifugal force is generated to accelerate and decelerate captured air [33]. This kinetic energy is converted to pressure as the velocity is reduced in a diffuser and casing [27].

A motor rotates the centrifugal compressor. A compressor may have more stages for higher compression ratios, which is then known as a multistage compressor. A multistage compressor contains several impellers in series that form different stages within the casing (as seen in Figure 11). Air enters the suction port and is then compressed through each stage, which delivers very high compression ratios. Multistage compressors are used mostly in the mining industry to meet high pressure requirements [22], [27], [32].

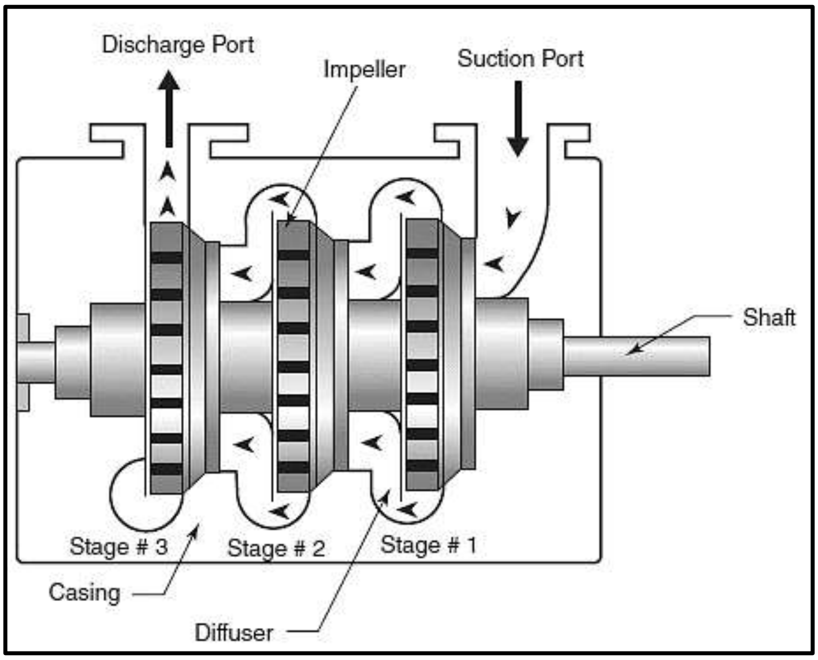


Figure 11: Multistage centrifugal compressor [34]

Inlet guide vanes are usually installed on the suction port at the first stage of the compressor to control the delivery airflow (as seen in Figure 12)[28], [35]. Each compressor is provided with a capacity control system to operate the motor within power limits and to maintain the desired airflow [32]. Airflow and pressure are controlled by adjusting the inlet guide vanes. By closing them, the airflow is reduced, thus reducing the power required to deliver the lower airflow [33], [35].

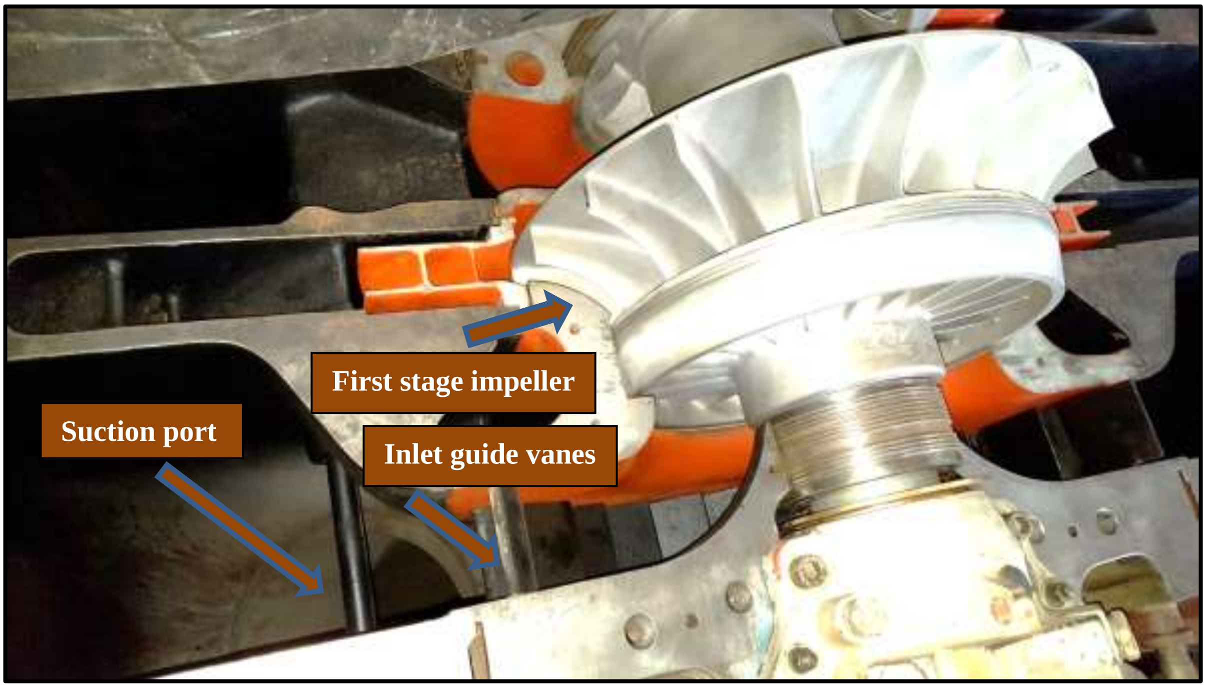


Figure 12: Inlet guide vanes of a centrifugal compressor

Inlet guide vanes are excellent for controlling airflow during fluctuations in airflow demand. They tend to follow the system demand profile and are good at avoiding compressor blow-off [35]. Inlet guide vanes and compressor valves are controlled by a Moore controller that delivers and sustains the correct compressor discharge pressure. The inlet guide vanes will be explained in more detail in Section 2.5.2.

Flow in a compressor may reverse when the system airflow decreases sufficiently [32], [36]. This also occurs when the compressor cannot deliver enough energy in terms of compressed air to the system to overcome the resistance or backpressure in the system [30], [36]. It can also happen when the downstream demand changes and when it does not match a compressor's current operating point [37], [38].

When a compressor's daily operation is not monitored adequately, excessive maintenance may be required. It causes the running costs to increase, which results in more frequent compressor overhauls with expensive equipment repairs. Unwanted production downtime can occur, which influences potential income. Then antisurge and capacity control units became known, which are the main elements of compressor control. They sustain a safe compressor minimum flow by manipulating a blow-off or recycle valve [36].

These compressor control units were designed by Moore – a company with over 27 years' experience with controlling and protecting compressors. The Moore controller (Figure 13) was designed to ensure maximum compressor runtime with improved servicing capabilities. It protects compressors against surging with a well-proven control algorithm while simultaneously optimising compressor efficiency [39].

It has been proven that surge mostly occurs during start-up or shutdown of a compressor [39]. The Moore controller ultimately reduced the possibility of surge by automating these sequences and controlling the sequences in a repeatable and controllable manner [39]. The Moore controller uses suction, discharge pressures and temperatures, and flow through the compressor to ensure that the compressor operates in the safe operating regions to prevent surge [37], [38], [40].

Figure 13: Moore controller

2.4 Typical energy management initiatives for compressed air networks

An ESCO will typically install their own server on a mine, which will contain an energy management system to automate the compressed air system. The energy management system will be connected to the mine’s supervisory control and data acquisition (SCADA) system for controlling a specific project and recording its data [41], [42], [43]. On-site equipment is connected to the SCADA system. Information can be retrieved via SCADA tags as the mine has an instrumentation structure in place, which is the source of communication between electronic equipment and the SCADA system.

PLCs are typically installed on-site, which work alongside the SCADA system. The energy management system is connected to the SCADA system, gaining access to the mine’s data. A layout of the compressed air system is developed in the energy management system that indicates the actual infrastructure of the compressed air network. Relevant SCADA tags of the infrastructure are connected to the developed platform.

Tags are used to display actual data, such as pressures, flow rates and compressor power consumption. Tags are also used to log data of the compressed air system for control purposes. The energy management system can control the delivery pressure of the compressor house via set points and control valves to deliver a desired downstream pressure [41], [42], [43], [44]. In the next section, existing DSM initiatives to reduce electricity costs on compressed air systems are discussed.

2.5 Existing DSM initiatives on mine compressed air systems

2.5.1 Preamble

Reducing electricity costs on deep level mine compressed air systems is possible because existing DSM initiatives have proven to reduce mines' compressed air electricity consumption. Savings as large as 3.4 MW have been achieved during the evening peak period, which resulted in an average monthly financial saving of R340 000 [28], [29], [44], [45]. Thus, it is important to understand and acquire the contributors to the existing DSM initiatives for improving the cost savings of a mine's inefficient compressed air system.

Deep level mines have different compressed air requirements throughout a production day. A typical compressed air requirement schedule can be seen in Figure 14 where mineworkers start to change over from 03:00. It can take them up to three hours to reach their working areas in the stopes where drilling takes place. This is due to the large numbers of workers traveling down the shaft in enclosed cages and the distance to the working areas. Some mines have sub-shafts that prolong the time it takes for miners to reach their destinations.

Drilling takes place in stopes and commences when workers arrive at the stopes where they drill 1.8 m deep holes into the rock. The stopes are located deep within the mine where the ore is located. The blasting shift commences thereafter and explosives are placed inside the drilled holes. During the blasting period, no one is underground and no labour activities take place. The explosives are then wired to a blasting box. Appointed mine personnel activate the blasting box, after which the explosives will be detonated from surface. All mine employees must be evacuated before the mine detonates the explosives during the blasting period [29].

During the blasting period, the compressed air requirements are less than during other periods of the day. Pressure is only required for refuge bays and agitation. Sweeping and cleaning commence after the blasting shift as well as the next mining shift. Table 1 indicates the operating pressure requirements and schedule of the compressed air users.

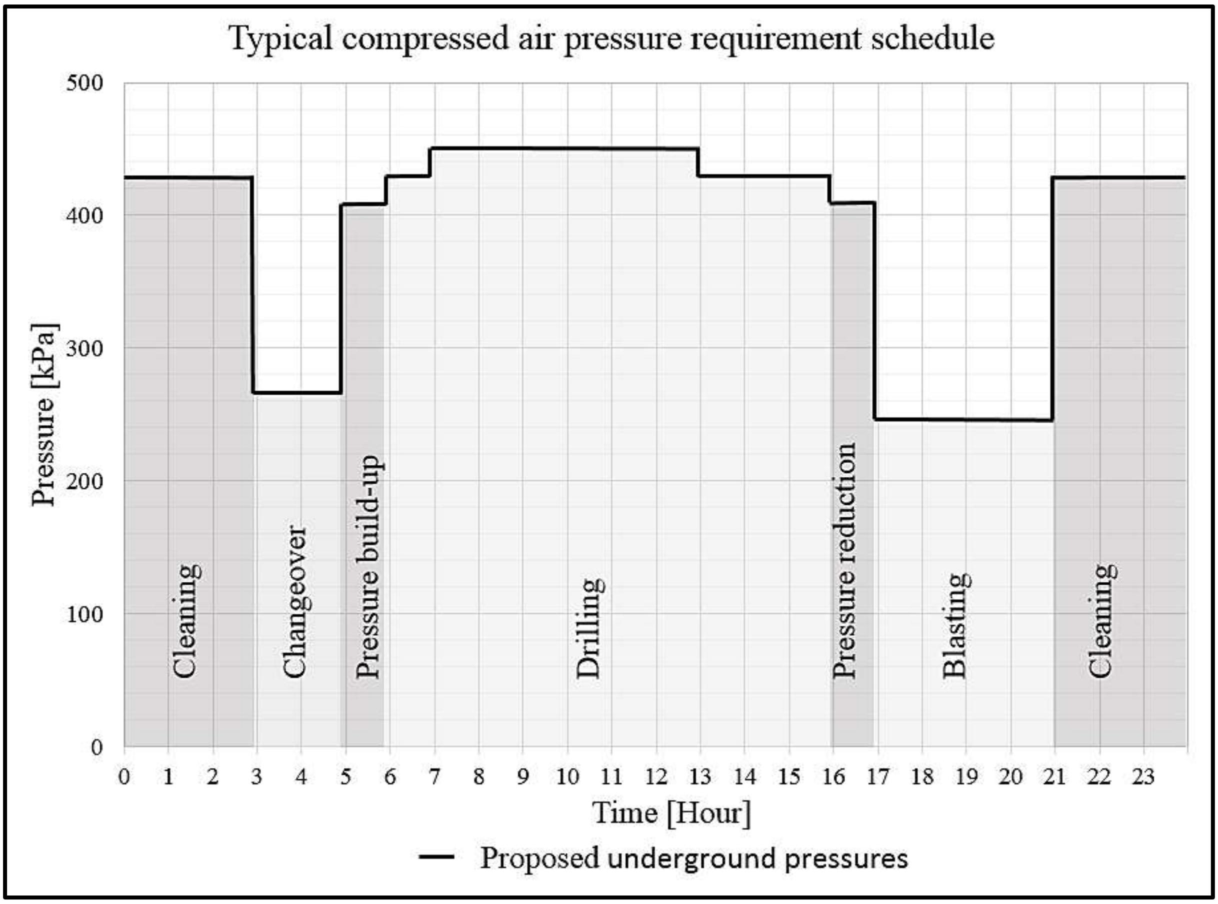


Figure 14: Typical compressed air requirement daily schedule [11]

Table 1: Typical compressed air users and pressure requirement schedule [29]

Type	Application	Consumption rate [m^3/h]	Operating pressure [kPa]	Period
Pneumatic rock drills	Drilling shift	190–320	400–620	07:00–14:00
Pneumatic loaders	Sweeping and cleaning	348	400–490	21:00–14:00
Pneumatic cylinders	Sweeping and cleaning	11	400–500	21:00–14:00
Refuge bays	All	Site-specific	200–300	Continuous
Agitation	All	Site-specific	400	Continuous

Now that the background of a typical gold mine production schedule and pressure requirements have been explained, different strategies that were implemented for reducing the operating cost can be discussed. Each strategy can aid as a guidance for adjusting a system for improved cost savings.

2.5.2 Inlet guide vanes

2.5.2.1 Preamble

Most gold mines use multistage centrifugal compressors to supply compressed air to their end users. Inlet guide vanes can be installed on the suction port at the first stage of the compressor to control the supply or delivery of compressed air into the compressor [28], [35]. They reduce the power required to deliver a lower airflow [35]. Inlet guide vanes are more efficient than throttling airflow with a valve to reduce the power consumption of compressors [35].

Inlet guide vanes have a greater impact on system performance when they are adjusted correctly [46]. At full load, inlet guide vanes offer no benefits to the system. Inlet guide vanes are excellent for flow control during fluctuations of system resistance or backpressure. When vanes are programmed to keep a delivery pressure, the vanes will follow the backpressure and are good at avoiding compressor blow-off [35]. Inlet guide vanes and compressor valves are controlled by a Moore controller to deliver and sustain the correct compressor delivery pressure.

The inlet guide vane’s angle is dependent on the compressor’s delivery pressure set point and the compressed air demand. If the demand for compressed air decreases, pressure builds up in the pipe manifold causing backpressure. The pressure build-up eventually reaches a point above the pressure set point where the internal guide vane angles close slowly to sustain the desired pressure set point [28]. If the demand for compressed air increases, pressure in the manifold pipeline reduces.

The pressure eventually reaches a point lower than the delivery pressure set point. The inlet guide vane angles open slowly to increase the compressor’s power consumption as seen in Figure 15. This increase the airflow to match the delivery pressure to the set point. Therefore, the inlet guide vanes ultimately try to match the compressor delivery pressure set point and react to changes in the compressed air demand [28]. Thus, inlet guide vanes have a direct effect on the energy consumption of a compressor [44].

Inlet guide vanes can also solve cycling issues on compressors without inlet guide vane control. A compressor only supplies its maximum pressure. A compressor was cycled on a specific mine due to match the mine’s pressure demand. This caused unnecessary wear and tear on the compressor. Inlet guide vanes vary a compressor’s supply airflow and they can also be used to place a compressor into a standby (offload) state [47]. Compressor offloading is discussed in Section 2.5.3.

The following sub-sections explain techniques that can be used to gain maximum energy savings through inlet guide vane control. These techniques influence inlet guide vanes directly, which greatly improves the efficiency of an inefficient compressed air system. Qin and McKane state that compressed air systems that have not been maintained properly have a 20–50% energy savings potential [48].

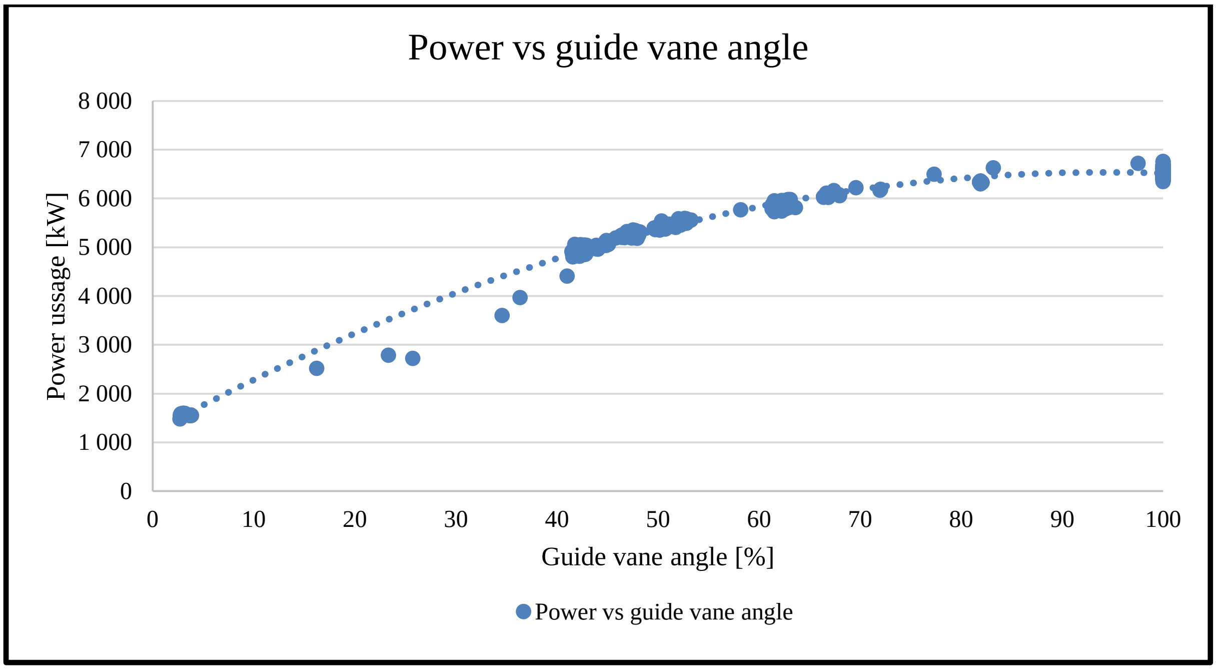


Figure 15: Power vs guide vane angle[1]

2.5.2.2 Compressor house delivery pressure set point control

Compressors deliver compressed air to their consumers with or without inlet guide vanes. Compressors with inlet guide vanes must have the correct delivery pressure set point schedule to deliver the right airflow and pressure to their consumers at the right time. The supply pressure schedule should be adjusted to the maximum pressure and flow required by the mine. But, in some cases, these set points were not monitored and adjusted frequently to match the supply and demand, causing the compressed air system to be overpressurised [29], [44], [49].

Overpressurised compressed air systems offer opportunities to improve their efficiency by supplying the demand [48]. The delivery pressure set point of compressors can be adjusted to the typical pressure requirement schedule as seen in Figure 14. This is a good guide showing what the delivery pressure set point profile needs to be.

To gain additional energy savings through compressor delivery pressure set point control, the set points need to be adjusted. In most cases, set points must be adjusted lower, thus reducing the electricity consumed by compressors [44]. The complete compressed air system should be monitored and adjusted optimally. It is important to do so to safely and effectively to help lower system pressure [47].

The supply pressure of a compressed air network can be improved by reducing leaks [47], [50]. Cutback on inlet guide vane angles occurs when repaired leaks recover airflow losses in the system, resulting in

[1] Drawn using historic operational data for a centrifugal compressor to indicate the approximate relation of guide vane position vs power consumption.

a reduction in compressor power output. Further information about leak management is discussed in the following section.

It is important to know that there may be surface pressure requirements that the delivery pressure of the compressors may have to satisfy. A gold plant typically needs higher pressures than what the compressor house can deliver. Pressure to the underground mining levels increase with auto compression and the compressor delivery pressure can be reduced. Auto compression of compressed air makes it possible to have lower surface pressures, while still having high underground pressures [29].

2.5.2.3 Auto compression and pressure losses

A compressed air pipeline is orientated horizontally on surface and rotates vertically underground, feeding compressed air to various levels at various depths (vertical distance from surface). Compressed air is compressed by its own weight, resulting in an increase in pressure called auto compression (as seen in Figure 16, which friction losses are taken into consideration). It causes the pressure underground to be higher than the pressure on surface. The auto compression impact can be determined at any depth using Equation 1 or Equation 2 [29]. The density of compressed air can be calculated using Equation 3 [51].

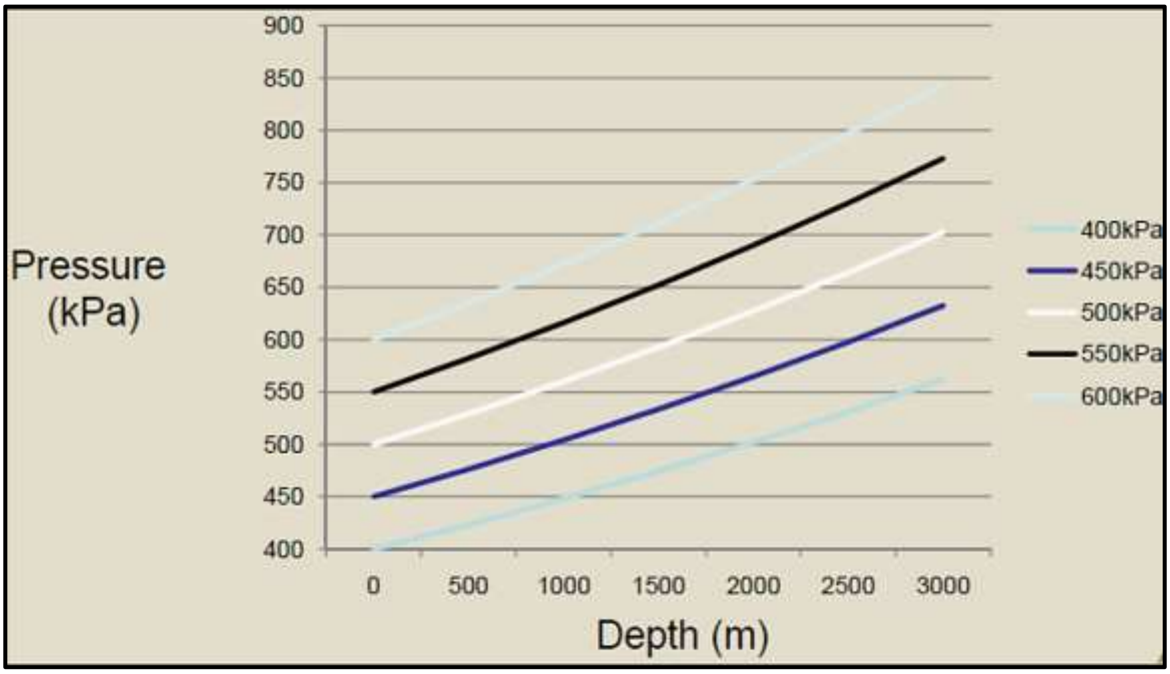


Figure 16: Increase of compressed air pressure due to auto compression [51], [52]

Equation 1: Calculating the impact of auto compression at various depths [29].

$$\Delta P = \rho g h \qquad (1)$$

- $\Delta P =$ Pressure impact due to auto compression [kPa]
- $\rho =$ Density of air $[\mathrm{kg/m^3}]$
- $g =$ Gravitational acceleration (9.81) $[\mathrm{m/s^2}]$
- $h =$ Depth or vertical distance form surface [m]

Or

Equation 2: Calculating the pressure gain at constant airflow rates [51], [53].

$$P_2 = P_1 \left[1 - \frac{g(Z_1 - Z_2)}{T_1 C_p}\right]^{\frac{1}{k}} \qquad (2)$$

- $P_2 =$ Final pressure [kPa]
- $P_1 =$ Initial pressure [kPa]
- $g =$ Gravitational acceleration (9.81) $[\mathrm{m/s^2}]$
- $Z_1 =$ Initial altitude [m]
- $Z_2 =$ Final altitude [m]
- $T_1 =$ Compressed air temperature [K]
- $C_p =$ Specific heat capacity of compressed air $[\mathrm{kJ/(kg \cdot K)}]$
- $k =$ Specific heat ratio of compressed air (1.4) [–]

Equation 3: Calculating air density [51].

$$\rho = \frac{P_{abs}}{RT} \qquad (3)$$

- $\rho =$ Density of air $[\mathrm{kg/m^3}]$
- $P_{abs} =$ Absolute air pressure [kPa]
- $R =$ Gas constant of air (0.278) $[\mathrm{kJ/(kg \cdot K)}]$
- $T =$ Temperature of air [K]

The positive effect that auto compression has on the compressed air system is that the surface compressor delivery pressure can be at a lower pressure. Friction- and airflow losses in the compressed air pipeline network can influence auto compression and the delivery pressure of compressors negatively. It reduces the total amount of pressure increase through auto compression. This increases the required delivery pressure of compressors and decreases electricity savings [29].

Darcy–Weisbach [54] developed an equation (Equation 4) to calculate the pressure gained through auto compression, considering the effect of pressure losses in compressed air pipelines. Equation 1 is used to compile Equation 2, which determines the pressure gain caused by auto compression while considering the effect of friction losses. It is important to reduce pressure losses in compressed air pipelines [29].

Equation 4: Calculating the impact of auto compression at various depths [29].

$$\Delta P_{Total} = \rho g(h - f\,\frac{Lv^2}{d2g}) \tag{4}$$

- $\Delta P_{Total} =$ Pressure impact due to auto compression [kPa]
- $f =$ Friction factor (Moody chart) [–]
- $L =$ Length of vertical pipeline [m]
- $v =$ Airflow velocity [m/s]
- $d =$ Pipe inner diameter [m]

There are various factors that contribute to unnecessary pressure losses in the compressed air network [55]. Older pipes corrode in the inside of the walls due to the moisture content in compressed air. Corrosion increases the pipe wall roughness (friction coefficient) causing pressure losses [24], [55], [56]. When demand increases, airflow increases, increasing the pipe friction losses, which reduce the effect of auto compression as seen in Figure 17. There are other factors that contribute to pressure losses, which can also be investigated [51]:

- Pipe diameter;
- Leaks;
- Bends in pipe sections;
- Sudden increase in airflow;
- Chocked pipelines.

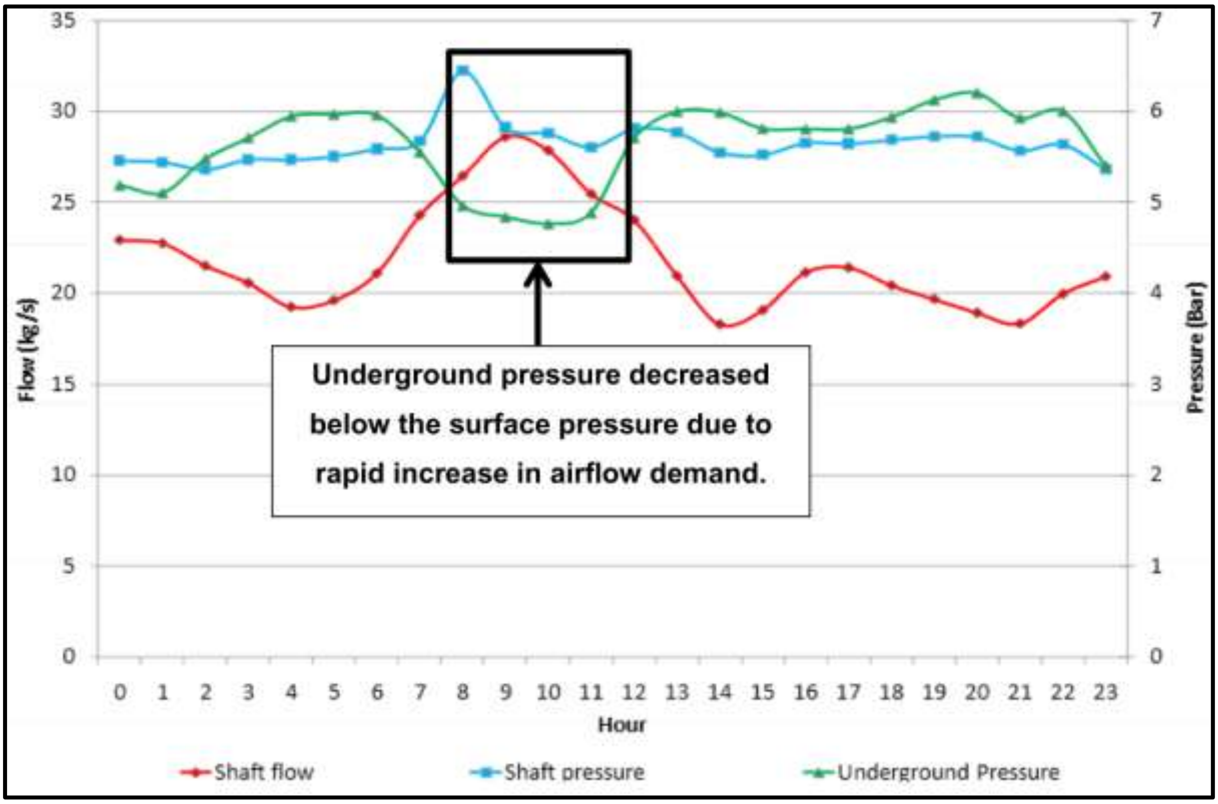


Figure 17: Negative effect of increased airflow on auto compression [51], [52]

The potential pressure gains of a mine's compressed air network can be calculated, because auto compression has a positive impact on surface compressor delivery pressure control. It is important to investigate and rectify areas that cause large pressure losses in compressed air pipelines. It may be necessary to replace pipes with small diameters with larger pipes, improve areas that choke airflow, or reduce leaks for optimal pressure distribution to the compressed air networks. The following section discusses the effects of leaks on a compressed air network.

2.5.2.4 Reducing system leaks

On a compressed air pipe network, leaks waste compressed air [29]. Reducing compressed air leaks is the most effective improvement strategy to carry out in a compressed air network system. This is the first step in improving the efficiency of a compressed air system. Leak detection and repairs are financially feasible because it is very expensive to replace pneumatic equipment with alternative less energy intensive equipment [50].

Compressed air leaks have been estimated to waste as much as 30% of a compressor's output, which result in large energy losses [28], [44]. Common areas where leaks are found are at open ends, clamps, flanges, hose connections, pressure regulators, shut-off valves and fittings [28], [44]. Detecting compressed air leaks is the most difficult process to do since leaks can be found anywhere on a large underground pipe network [57].

The potential for large energy savings is usually on the underground pipe network. Large energy losses also occur at closed sections. This is when sections are closed without closing off the compressed air supply [45]. Compressed air leaks cause unnecessary pressure drop in the system [57]. Pressure drop can cause pneumatic equipment to function less efficiently, which can affect production. Additional compressed air is required to overcome pressure losses in the system [44].

A mine will typically fund the expenses required to fix identified leaks. The scale, severity and potential cost savings of identified leaks should not be overestimated during leak auditing. This is because the mine funds the expenses to fix the leaks to recover compressed air wastage, and expect compressed air power consumption to be reduced. It may disappoint the mine when they have fixed leaks and the potential saving was not achieved.

Overestimating the scale, severity and potential cost savings occurs when an inexperienced employee overestimates the actual volume or flow rate of the leaks. Some situations will make it difficult to predict the actual flow rates of leaks. Figure 18 shows that leaks are not perfectly round holes – they are long and tortuous-shaped [58], [59]. Formulas for calculating savings can be found in Annexure A.

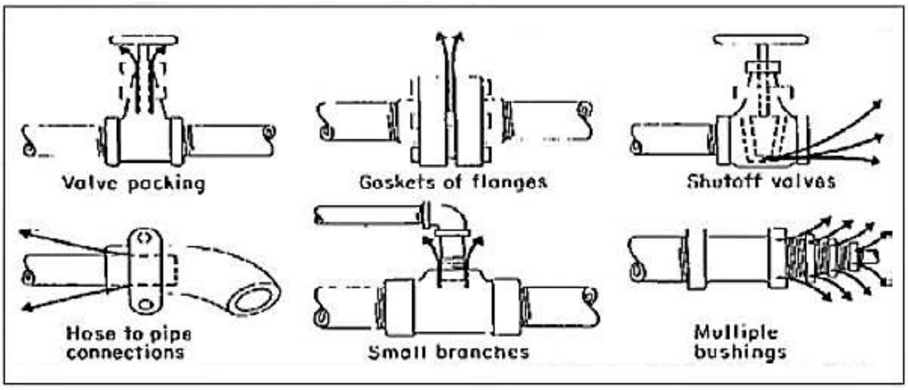
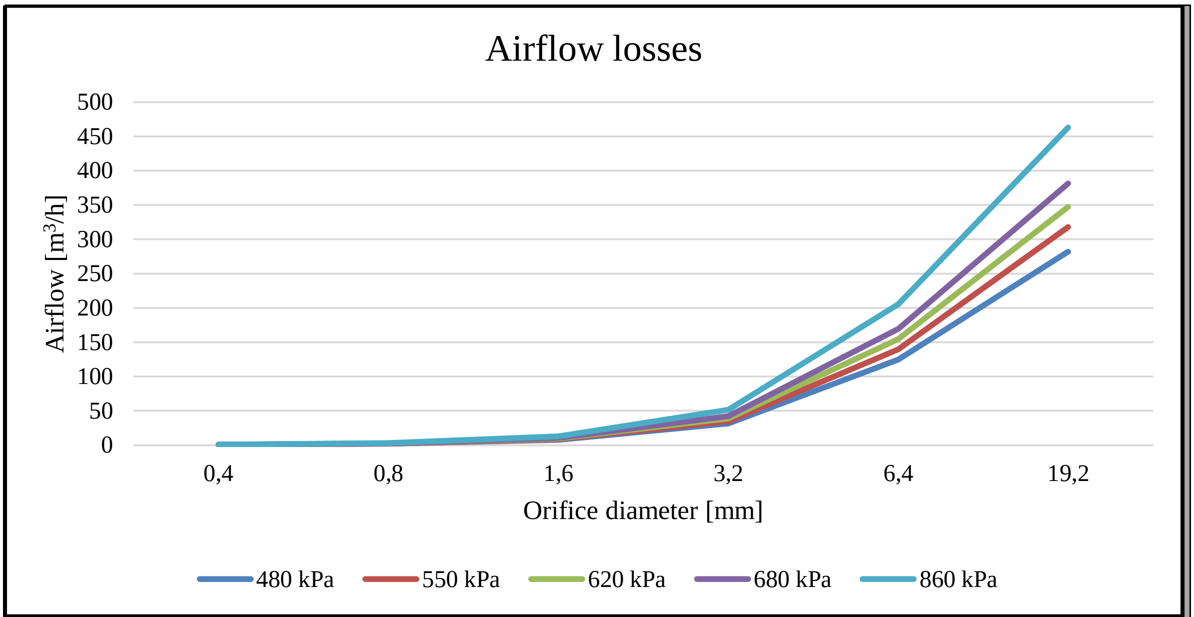


Figure 18: Types of leak where it is difficult to accurately predict actual flow rates [58]

Orifice charts offer a quick guide to calculate the airflow of a specific leak size; for example, knowing an assumed system uses 0.1 kW of power per m^3/h airflow at a tariff of R1/kWh. If a leak size is 6.4 mm in orifice diameter with a pressure of 4.8 bar, the estimated leak flow rate will be 125 m^3/h. The power consumption of the leak is 12.5 kWh, wasting R12.50 per hour in operating cost. As a result, the annual effect of this particular leak will be R109 500 [59].



Leakage [m³/h]						
Pressure [kPa]	**Orifice diameter [mm]**					
	0.4	**0.8**	**1.6**	**3.2**	**6.4**	**19.2**
480	0.4872	1.9488	7.8288	31.2816	124.992	281.904
550	0.5376	2.1168	8.8032	34.8768	139.608	318.000
620	0.6048	2.4528	9.6096	38.8080	154.560	347.088
680	0.6720	2.6040	10.6008	42.3696	169.512	381.360
860	0.8064	3.2592	12.8688	51.4920	205.296	462.840

Figure 19: Compressed airflow through various orifice sizes at different pressures [25]

The assumed leak size, pressure and calculated airflow of a particular leak can affect the accuracy of calculating the cost wastage; it may rarely be correct [59]. The orifice chart usually leads to overestimating leak values [58]. The potential savings depend on how the compressed air system reduces power input when airflow reduces. It depends on how the compressors are controlled, thus if centrifugal compressors do not have inlet guide vane control, the recovered air will just be blown off into the atmosphere by the blow-off valve, while the power input and energy consumption remain the same [59].

Compressor blow-off is prevented by inlet guide vane control. When airflow decreases and backpressure increases on the compressor manifold pipe, the compressed air system will decrease the inlet guide vane angle to deliver a reduced airflow at the same pressure. This will result in additional cost savings. Thus, the additional savings achieved by fixing leaks depend on how well the compressed air system reduces power input during airflow reduction and improved system pressure [59]. It is important to optimise the compressed air system to make leak reduction savings more evident [59].

Leak detection methods

It is difficult to detect leaks on a compressed air pipe network through visual inspection, thus it is mainly done through noise. A sharp noise is caused by the pressurised system and the flow through the leak or orifice (opening), comprising various frequencies. Depending on the size of the orifice or the leak type, the leak sounds will differ. Spotting leaks by walking pipelines can be difficult due to load surrounding noises. This is a time-consuming process [50].

Some smaller leaks can be silent compared with the hissing noises of larger leaks. This is due to higher frequencies that the human ear cannot detect. Common frequencies for compressed air leaks range from 38 kHz to 42 kHz. Ultrasonic leak detectors are used to detect leaks that the human ear cannot detect. These detectors are sensitive to the frequencies of silent leaks and allow the operator to hear the hissing sound through a set of headphones. This helps to pinpoint the location of a leak [60].

Detected leaks need to be recorded and rectified to realise potential energy efficiency savings [26]. It is therefore crucial that the leak information is transferred to the responsible mine employees so that the leaks can be fixed. Various methods are available to collect or record detected leaks – either traditionally using pen and paper or using technology [50]. A common leak detection process is discussed in the next sub-section.

Common leak detection process

Leaks will commonly be detected and the location must be noted. Pictures of the leaks should be taken and the severity and priority must be noted. This is important, because some leaks can only be fixed during non-production periods and should be scheduled to be fixed during that time.

All data collected from the leak detection process should be reported to the relevant employees for fixing. It is important for the responsible employees to fix the leaks. The potential cost savings of leaks can determine their priorities. When leaks are fixed, they should be recorded as fixed with a date in the leak detection report (as seen in Table 2). This is a good way for controlling leak status during management meetings to ensure high priority work gets done.

Table 2: Typical leak report table containing critical information

Level	Location	Leak size (mm)	Fixed	Description	Figure	Priority (H-M-L)
197	s5	50	2016/06/24	Orange pipe left open	Figure 19(a)	H
197	s7	10	No	Flange leak	Figure 19(b)	M

Figure 20: Typical compressed air leaks:
Orange pipe left open (a) and flange leak (b)

2.5.2.5 Control valves

Surface and underground control background

Control valves can be used on the surface compressed air mainline pipe and on the underground compressed air pipelines on the mining levels. Their purpose is to reduce the pressure of overpressurised pipelines by supplying the right amount of pressure (demand side control) to end users. While reducing the pressure in the downstream pipeline, pressure will build up in the upstream pipeline. The inlet guide vanes will react and decrease their angles and lower the power output of the compressors to match the new pressures [57].

Some mines installed control valves on the surface compressed air mainline pipe to regulate the downstream pressure [26], [29], [57]. The effect of auto compression on the depth of the underground mining levels makes it possible to have lower compressor delivery pressures. These control valves are also used to lower the pressure during Eskom's evening period (see Figure 21). Surface control valves are used mainly when there are not control valves installed on the mining levels and when they do not affect hoisting and gold plant operations [26].

Control valves can also be installed on underground mining levels. The compressed air savings strategy is to reduce the downstream pressure on the mining levels, only supplying the required pressures at the right time. The pressure can be reduced on the levels because auto compression increases the pressures, thus energy is wasted due to the pressure oversupply. Controlling the pressure on various levels according to demand gives scope to improve the efficiency of the compressed air system. The control strategy on the control valves is discussed in the next sub-section.

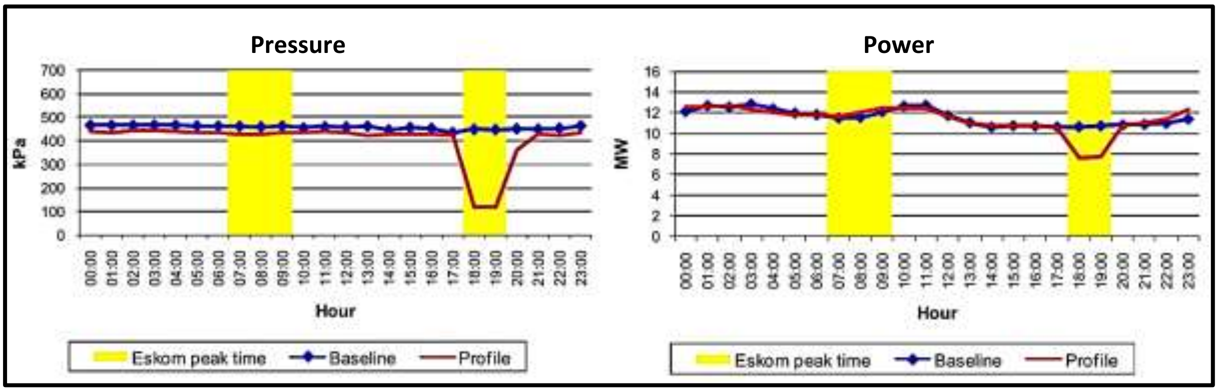


Figure 21: Surface pressure and power reduction during Eskom's evening peak period [26]

Valve control strategy

The function of control valves is to control and sustain a specific downstream pressure through valve position control (a typical setup is shown in Figure 26). The actual pressure on the pipeline is measured by pressure transmitters. The downstream pressure serves as a process variable; the desired downstream pressure as a set point. The valve position is then controlled according to the pressure difference between the process variable and the set point [29].

Proportional-integral-derivative (PID) control is used to calculate the pressure difference. It writes new valve positions to constantly reduce the pressure difference trying to match the set point. These control valves require an actuator and a positioner [also known as a digital valve controller (DVC)]. The actuator is fitted on the valve; the positioner on the actuator. The positioner measures the valve position and changes the valve position via the actuator to match the pressure set point [29]. There are different types of actuator and valve available, which are discussed in the following sub-sections.

Actuator selection

Compressed air pressure control on a pipeline requires a valve and an actuator. Actuators are used to automate the opening and closing of valves. The most commonly used actuator is a manual actuator, because it is the cheapest and requires a person to manually manipulate the valve to open/close or partially open applications. There are also pneumatic, electric and hydraulic actuators. The actuators mostly used in mining industry are electric and pneumatic actuators (see Figure 22). Pneumatic actuators are less expensive than electric and hydraulic actuators [61].

Electric actuators can be used where large forces are required to change the valve position and where no air supply is available [29]. An electric actuator requires electricity and is more expensive than pneumatic actuators with the same performance. The pneumatic actuator is the most popular type, operated by a diaphragm that uses supply pressure from a positioner [61]. This supply pressure pushes down on the diaphragm, opening the valve.

Figure 22: Electric- (a) and pneumatic actuated globe control valve (b) with positioner (c) [62], [63]

Electric actuators require a positioner that regulates the electric current to move the valve to a position that matches the set point. Pneumatically operated valves require a positioner that requires an input signal from a process signal, converting it to valve travel and different valve positions [61]. A typical positioner, as seen in Figure 22(c), is connected on the moving part of the actuator to measure the valve position. The positioner receives a desired pressure set point signal that is given through a PLC and gives inputs to the actuator to move the valve to match the desired set point [29].

Thus, positioners are required for automated valve control applications. They allow for precise positioning accuracy and faster response to process upsets [61]. It is also very important for process variability reduction that the positioner must be a high gain device, as explained in the Control Valve Handbook by Emerson [61]. The positioner and actuator must be placed on a specific valve type. It is therefore important to select the correct valve, which must suit the control requirements and the financial expenses of the valve.

Control valve type selection

The type and sizing of a valve can have a large influence on the performance of a control valve assembly in the system [61]. The valves must be correctly sized to control the type of medium (air) under all circumstances for ultimate performance. Oversized valves are detrimental to the process automation and can result in unnecessary expenses [61]. Undersized valves can choke the system causing large pressure drops, which limit the pressure control functionalities. The different types of control valve used in the industry are displayed in Figure 23 [29], [64].

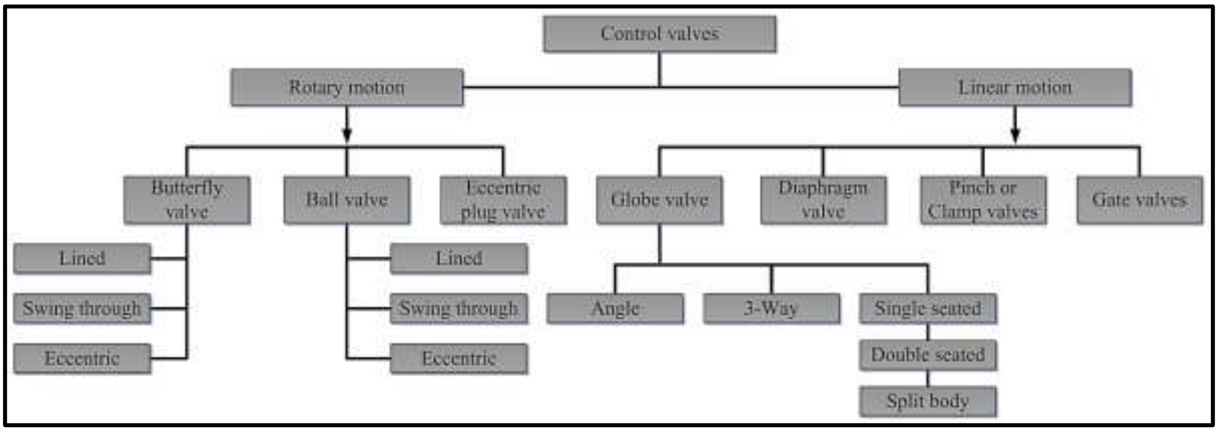


Figure 23: Control valves used in the industry [29]

Rotary motion butterfly valves and linear motion globe valves are popular control valves used on gold mine compressed air systems. These control valves can be categorised under different types of inherent flow characteristics based on the flow through the valve and the valve position as seen in Figure 24. A butterfly valve only has one specific flow characteristic curve while a globe valve has three (as seen in Figure 24). A globe valve has fast opening, linear and equal percentage flow characteristics curves, because of the three different cage trims [29], [61], [64], [65], [66].

Single-seated globe valves are mostly used in industry due to their different flow characteristics [61], [67]. It is a high-quality control valve with different internal cage trims (fast opening, linear or equal percentage), which could be used to obtain a specific flow characteristic. Unfortunately, a globe valve can be five times more expensive than a butterfly valve to obtain certain airflow control [67]. Butterfly valves are significantly cheaper, but their flexibility is limited because they provide a near similar flow characteristic as the equal percentage flow characteristic of the globe valve. According to Emerson, the equal percentage inherent flow characteristics curve is the most common flow characteristics curve for pressure control applications [61].

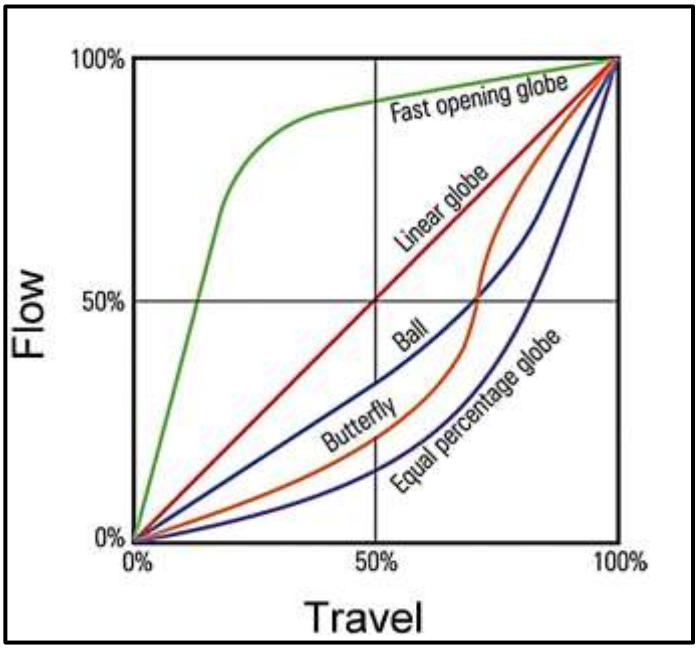


Figure 24: Inherent flow characteristic curves of control valves [66]

Butterfly valves are used mostly in fully opened/closed, and throttling applications. In a fully open position, butterfly valves cause a small pressure drop over the valve [61]. Valve damage may occur when it controls and operates outside of its design control parameters, which is usually at a small percentage opening [67]. The new Fisher™ Control-Disk™ valve introduces a solution to accurate butterfly valve control. It has an equal percentage inherent flow characteristics curve, which is similar to expensive butterfly valves for control applications [18], [68], [69].

Figure 25: Fisher™ Control-Disk™ butterfly valve [68]

It is important to choose the correct valve type [29], [64]. Globe valves are expensive but quality. High performing butterfly valves are new more economical technology, which deliver equal percentage inherent flow characteristics. The larger the valve, the costlier it becomes, thus in some situations a bypass pipeline configuration is used to control downstream pressure. Usual mining level pipeline diameters range between 250 mm and 350 mm. Thus, it is also important to select the right valve size to achieve the required control outcome.

Control valve configuration selection

There are two types of control valve configuration to control downstream pressure, namely, inline and bypassed. Inline valve control usually consists of an actuated butterfly valve due to the large diameter pipe (as seen in Figure 26). A large globe valve would be as much as five times more expensive than a butterfly valve [67]. During the drilling shift, the valve position will be 100% open; during other periods of the day the valve position can be throttled to match the downstream pressure set point. A manual butterfly valve is placed before the control valve to shut the compressed air supply to the mining levels off [57].

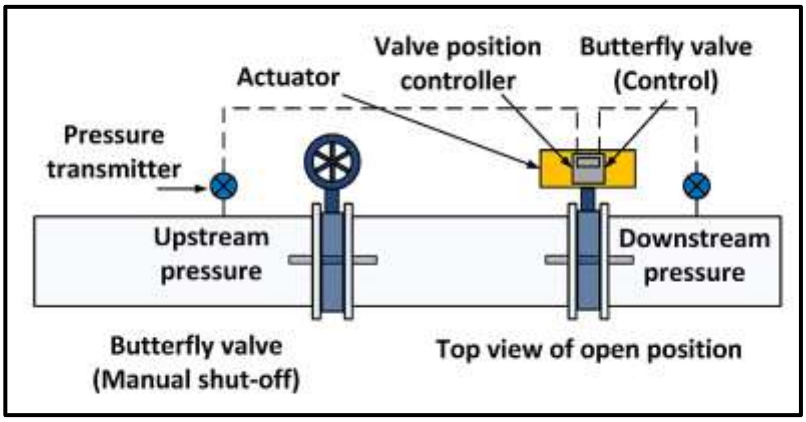


Figure 26: Typical mainline downstream pressure control setup

The bypass valve configuration (as seen in Figure 27) is used to control low downstream pressures. This is to ensure that valves operate within their design control parameters by controlling on the bypass and inline valve. All the valves are opened fully during the drilling shift and no control is allowed on the valves. During lower pressure demand periods, the downstream pressures can be lowered. The bypass valve configuration is normally used to reduce downstream pressures during Eskom's evening peak period. The pressures are normally reduced to match the pressure requirements of the refuge bays [18], [67], [69].

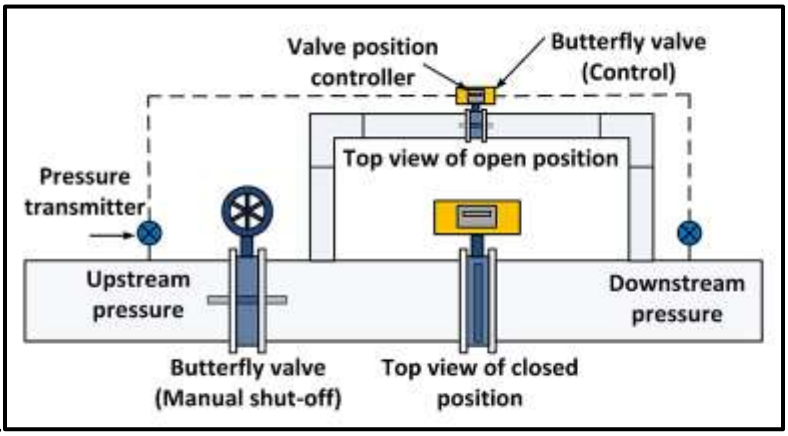


Figure 27: Typical bypass valve configuration for downstream pressure control

Accurate pressure control is very important and the control valves must control according to a typical control philosophy (as indicated in Figure 28). During the control period, the mainline valve closes and the bypass valve opens to match and sustain a downstream pressure set point. If the pressure is high, the bypass valve will try and match the pressure set point by gradually closing the valve. If the pressure is low, the inline valve will open gradually to match the pressure set point [57].

Pressure control on the mining levels through control valves can improve the efficiency of a compressed air network. When downstream pressure is reduced, upstream pressure builds up. This causes the compressors to adjust the inlet guide vane angles to compensate for the reduction in airflow. The compressors reduce the power consumed and electrical cost savings can be achieved. Due to the optimised pressure control, compressors may even be offloaded or stopped to achieve greater efficiency and electrical cost savings [18]. Offloading and selecting compressors will be explained in the following sections.

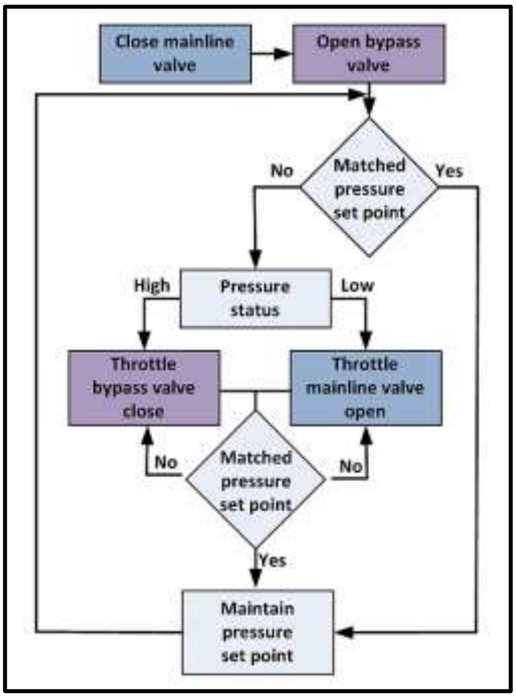


Figure 28: Pressure control functional diagram of bypass valve control figuration [57]

2.5.3 Other energy efficiency initiatives

Compressor offloading

Another function of inlet guide vane control is offloading compressors [47]. Compressors are usually offloaded when the demand is lower for a given period [45], or when the inlet guide vanes of the compressors are operating at their minimum guide vane positions. A compressor is therefore offloaded until the need arises for compressed airflow [31]. A compressor that continuously operates at an offloaded state can be switched off [57].

An offloaded compressor operates under no-load and minimum guide vane position during the offloaded state. It is separated from the compressed air mainline by an isolation valve [47]. A fully offloaded compressor's power consumption with inlet guide vane control will be 20–30% lower than at full load [35]. An offloaded compressor influences the inlet guide vane positions of other compressors, therefore increasing their power consumption to compensate for the offloaded compressor [22].

Compressor selection

A gold mine typically has two or more compressors that deliver compressed air to compressed air systems. These compressors may have different installed capacities and different efficiencies [67]. The most efficient compressors must run as these compressors consume less electricity to deliver the same amount of compressed air. The less efficient compressors, which are switched off, must be on standby for emergencies [57].

Compressor replacement

Sulzer is the most common compressor type used in the gold mining industry in South Africa. Due to the age of the mines, these compressor are as old as 37 years [51]. Their efficiencies decrease and maintenance costs increase over time. These compressors could be maintained or revamped. Mitsubishi Heavy Industries studied the effects of improving and revamping a compressor. They found the following results of revamping (replacing) a compressor against improving it through maintenance [70]:

- The upfront capital expenses are slightly higher;
- Production increased;
- Energy efficiencies increased;
- Capacity increased by 20%.

Compressor suction air filter replacement

A compressor typically sucks atmospheric air into the compressor, then discharges the compressed air to the compressed air network. Atmospheric air may contain particles which will damage a compressor, increase the maintenance and decrease the efficiency. The compressor's internal components are protected by an inlet air filter that filters the particles, letting clean air through to the compressor intake [27].

There is a pressure drop across the air filter, which increases the power consumption of the compressor as seen in Table 3. With an increase in pressure drop, the power consumption increases for the same amount of pressure output. Differential pressure gauges should be placed across filters to monitor the pressure drop. The pressure difference across the filters should be kept at a minimum by frequently cleaning dirty filters, replacing dirty filters or replacing stock filters with new technology filters, which have lower pressure drops over the filters [27].

Table 3: Effect of pressure drop over the filter on power consumption

Pressure drop across air filter [kPa]	Increase in power consumption [%]
0.00	0.0
19.6	1.6
39.2	3.2
58.8	4.7
78.5	7.0

2.6 Literature analysis

2.6.1 Preamble

Various sources were used in the previous section to provide background on existing initiatives that were implemented on compressed air systems for energy efficiency improvements. Only the most efficient strategies, which had a significant impact on the compressed air network and system, were discussed. It is important to provide a clear overview of the energy efficiency strategies. Some sources that did similar work to this study, will now be discussed.

2.6.2 Compressor house set point control

Booysen [22], Bredenkamp [51] and Schroeder [57] investigated various energy efficiency strategies on compressed air systems. One of the identified strategies is to control the delivery pressure set point of the compressor house.

Auto compression and pressure losses

Auto compression and pressure losses are other factors that play a role in compressor house delivery pressure set point control. De Coning [45] says that the pressure underground increases due to auto compression and it has the potential to lower the compressor house discharge pressure. Bredenkamp [51] mentions that pressure losses occur due to long pipe sections and leaks; however, he did not rectify pressure-reducing areas. The pressure recovered, possible compressor house set point adjustments and power savings that occurred after the issues were fixed were not indicated. There is a need to indicate the effect that recovered pressure has on the compressed air network.

Reducing system leaks

Van Tonder's [50] main focus was sustaining a compressed air DSM project by managing air leakages. He used a device to effectively note and manage identified leaks; however, mine personnel preferred the traditional pen and paper technique. There is a need to develop an effective approach to leak detection using the old traditional technique that can use historical data to determine levels with high airflow to increase the efficiency of the leak audit process.

2.6.3 Control valves

Heyns [69] discusses challenges faced during implementation of a bypass valve configuration for downstream pressure control. The mainline valves were leaking when closed and bypass pipes were too small. The system was limited due to the large pressure drops during the control period of the bypass valve. However, such a system can still be useful in other periods of the day with low-pressure requirements on the levels. Optimum bypass valve strategies can be proposed that will have small pressure drops or large pressure drops in the same system. This optimised system may help the mine to continue with drilling when the pressure drops because a compressor tripped.

2.6.4 Compressor offload

Booysen [22] says that inlet guide vanes are used for small pressure fluctuations and compressor offloading is used for larger pressure fluctuations. Booysen [22] demonstrates the influence offloading a compressor has on the power consumption and the control strategy. A compressor may be offloaded when the inlet guide vanes are at maximum reduction. During compressor offloading, the output of the other compressors will increase to compensate for the offloaded compressor. However, Booysen did not mention how to prevent the other compressors from increasing power output during the offloading period. There is therefore a need to conduct an offloading test and present a control strategy that will prevent power output increase of the other compressors during the compressor offloading period.

2.7 Conclusion

Literature shows that it is important to install inlet guide vanes on compressors. Inlet guide vanes control the air input into the compressor, thus controlling the power consumption of the compressor. Inlet guide vanes are sensitive to changes in airflow in the compressed air network. They will reduce power consumption when leaks are fixed and during downstream pressure control on the mining levels through control valves.

Globe or high performing butterfly control valves with equal percentage inherent flow characteristics are required to control pressure applications. The new Fisher™ Control-Disk™ valve can be used instead of a globe valve. It is important to select the correct valve size – selecting oversized valves will be an unnecessary overinvestment; selecting undersized valves will cause a large pressure drop. Bypass valve configuration or inline valve control is used to control downstream pressure of a mine compressed air system.

Pressure drops in the compressed air network can decrease when choking areas or large leaks are fixed. This will increase the effect of auto compression and increase the pressures on the mining levels. Surface delivery pressure control can be adjusted to compensate for the pressure increase. Inlet air filters can be replaced to reduce the pressure drop over the filter to increase the efficiency of compressors. Thus, implementing energy efficiency techniques on a compressed air system will greatly minimise the operating costs of compressors.

CHAPTER 3: IDENTIFYING INTERVENTIONS FOR IMPROVING COST SAVINGS

3.1 Introduction

DSM initiatives on underground compressed air systems reduce the electricity demand and lower the clients' operating costs because of the high electricity tariff in Eskom's evening peak period. Some existing DSM initiatives deteriorate over time. Improving the deteriorated DSM project's current performance and improving overall efficiency of the compressed air system is important for the client to lower their compressed air electricity consumption.

Literature shows that there are various initiatives available for improving energy efficiency on a mine's compressed air system. A critical analysis of an existing deteriorated DSM project is provided on which the intervention will be implemented. Opportunities for intervention are identified and a simulation model is developed to predict the savings of implementing some of the interventions on the compressed air system. The implementation of the interventions is discussed in Chapter 4.

3.2 Background of the existing compressed air DSM project

An existing deteriorated compressed air DSM project on a deep level gold mine is discussed. The project has enough historical data available to aid in investigating and identifying opportunities for the interventions to be implemented to improve the efficiency of the compressed air system. The mine is referred to as Mine X. The existing infrastructure and compressed air network layout can be seen in Figure 29.

There are five compressors in the standalone compressed air system. The installed capacity and flow rates of the compressors can be seen in Table 4. The compressors are connected to a common manifold where the compressed air flows to the gold plant and down the shaft. All five compressors have inlet guide vane control installed. PLCs have been installed on all compressors. Moore controllers are used to control the inlet guide vanes with PID control.

Table 4: Motor installed capacity and radial compressor intake volume on Mine X

Compressor	Motor installed capacity [kW]	Radial compressor intake volume [m³/h]
1	4 800	50 520
2	4 800	50 520
3	2 000	21 237
4	4 800	50 520
5	4 800	50 520
Total	**21 200**	**223 317**

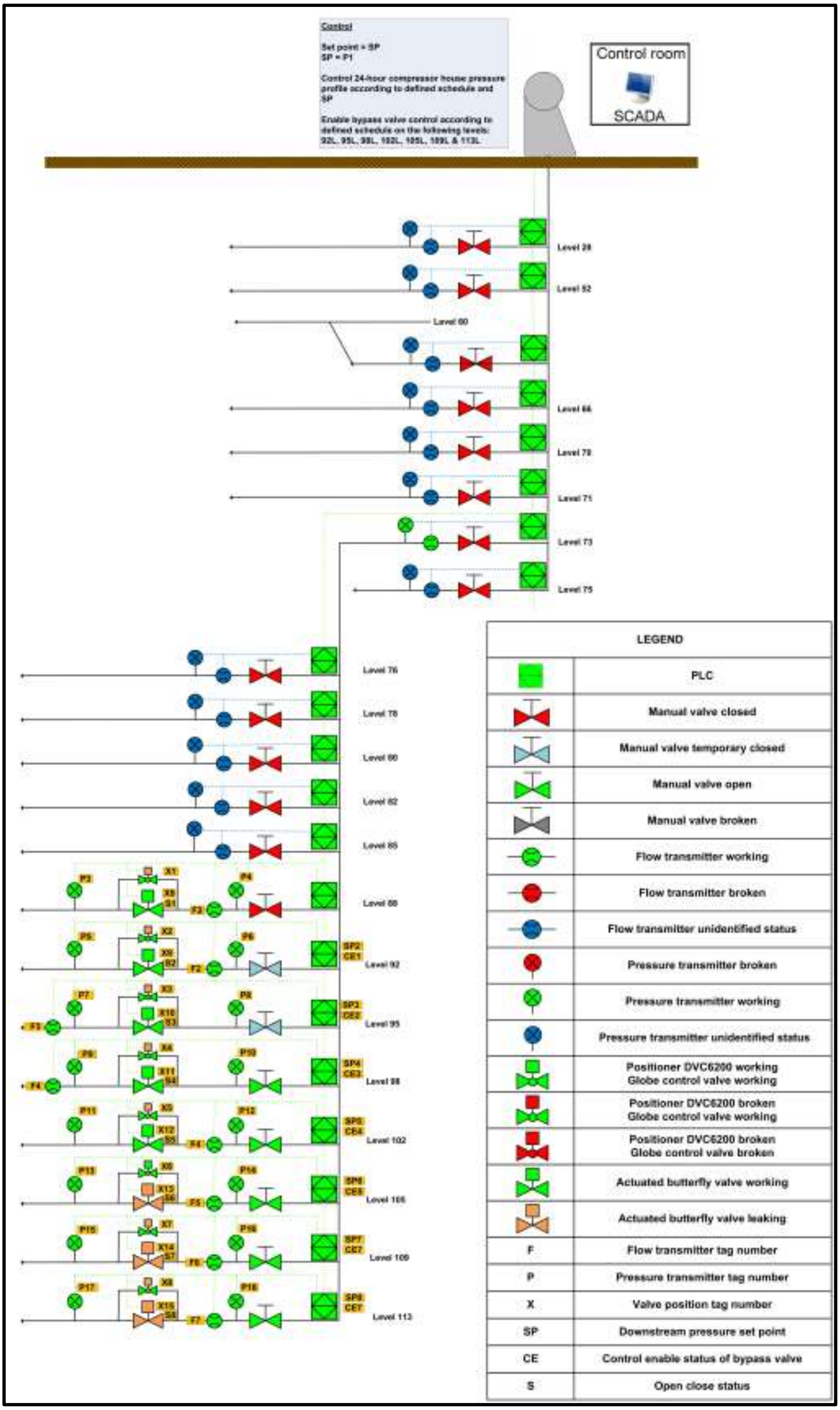


Figure 29: Existing infrastructure and compressed air network layout of Mine X

Their SCADA system does not automatically stop or start any compressor. It is unlikely that any automatic or remote start/stop will be possible due to compressor start-up issues that the mine experienced [69]. Compressor 5 is the only compressor with SCADA offload/ onload capabilities. An energy management system for compressor control is connected to the mine's SCADA system. It controls the delivery pressure of the compressor house and controls the bypass valves of the underground levels to deliver a desired downstream pressure via a set point.

Mine X consists of a main shaft and a sub-shaft, consisting of a 700 mm pipeline situated vertically within the main shaft and sub-shaft. The sub-shaft commences at 73L[2] where the compressed air networks continues in the sub-shaft to 113L. The mine has eight production levels, of which three are closed:

- 88L – closed;
- 92L – closed;
- 95L – temporarily closed;
- 98L – active;
- 102L – active;
- 105L – active;
- 109L – active;
- 113L – active.

The active levels have 350 mm compressed air pipelines with installed manual butterfly shut-off valves on all these mining levels. Electric actuated butterfly valves are installed downstream of the manual valves. These valves are controlled from the mine's SCADA system using the PLCs on the levels. The mine installed 50 mm bypass pipelines (without a globe valve, pneumatic actuator and positioner) as part of their own energy savings initiatives, prior to the bypass pipeline upgrades for better downstream pressure control.

The existing DSM project installed pneumatic actuated globe control valves in parallel with the electric actuated butterfly valves on all the mining levels to reduce the downstream pressures during the control period (as seen in Figure 30). Flow transmitters were installed on all the various levels, including the mining levels. Pressure transmitters were installed before the bypass pipelines to measure upstream pressures and after the bypass pipelines to measure downstream pressures. It is necessary to monitor the pressure difference over the bypassed system for the bypass control valve to control downstream pressures correctly.

[2] 73L refers to Level 73. The same convention will be used throughout for level names.

The bypass control valves were mainly used to reduce the flow and pressure during Eskom's evening peak period. The air consumption on the main shaft is minimal with no major air consumers; no additional valves or sensors were required. The sub-shaft levels from 76L to 85L also used minimal air, while 98L to 113L were major air consumers. The PLCs on all the levels were all within 30 m from the location where the valves were installed. Fibre optic cables were used as a sufficient connection medium on these levels.

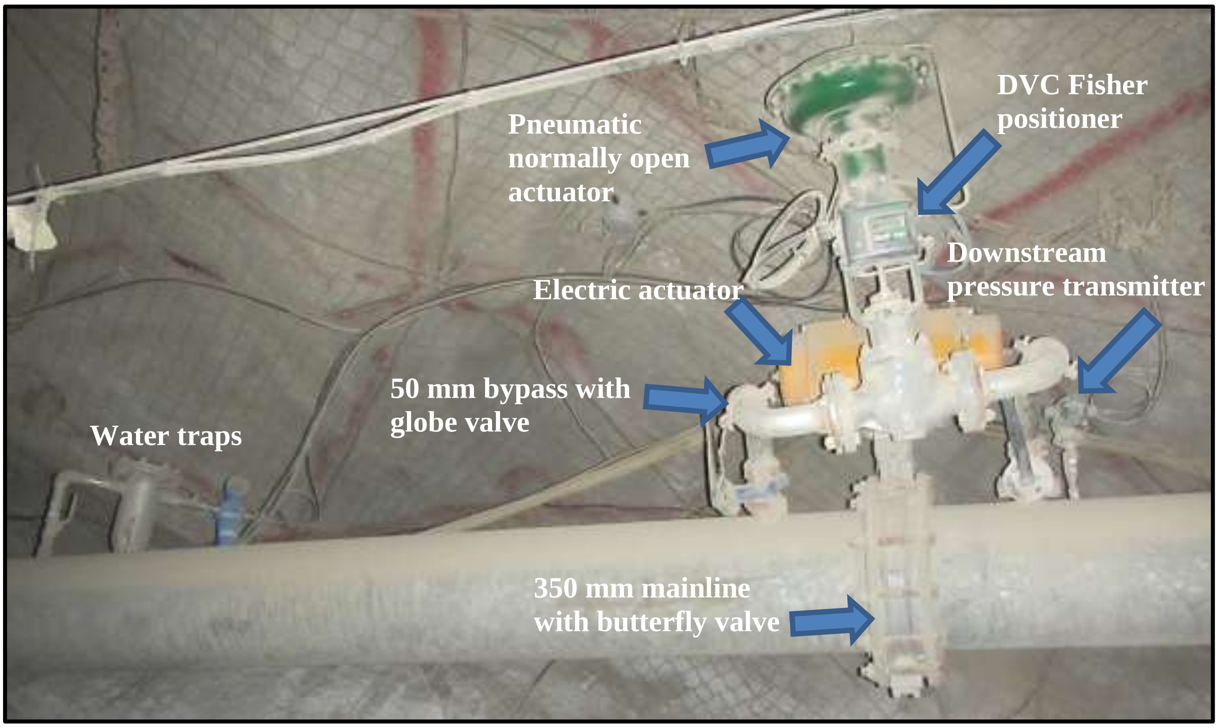


Figure 30: Typical bypass valve configuration on Mine X

Fisher DVC 2000 type positioners were installed on all pneumatic actuators of the bypass control globe valves on the mining levels (as seen in Figure 30). A positioner uses the upstream and downstream pressures to control a valve's position to deliver a required downstream pressure to match the downstream pressure set point received from the PLC. Water traps are used to remove particles and moisture from the compressed air before it enters the positioner to protect it from internal damage.

Figure 31: Fisher DVC 2000 Positioner

The gold plant requires a minimum pressure for agitation purposes, delivered from their own standalone compressors, which is completely independent from the mine's compressed air network. The mine's airflow to the gold plant is closed off with a spade between the flanges on the gold plant pipeline. There are 16 leach agitation tanks and three backfill tanks. Twelve of the leach tanks are air-dependent as air is necessary for some of the chemical reactions. The other four leach tanks have mechanical agitation capabilities but only two of these tanks are mechanically agitated because of mechanical failure.

The compressor house has different pressure requirements throughout the day on the shaft mainline, which vary according to the mine's mining schedule. Blasting takes place at 17:00, thus from 17:00 to 20:00 the mine no longer requires high pressures on the mining levels. The loading boxes situated at shaft bottom are used throughout the day and not during the blasting period. The pressures at the mining levels can be reduced between 17:00 and 20:00 to a minimum pressure of 250 kPa.

The mine has a mimic control room on-site, containing the mine's servers, SCADA system and the ESCO's project server, containing an on-site information management system (OSIMS) for feedback and an energy management system for compressor management. There is a platform that simulate, optimise and control the PLCs through the mine's SCADA tags. The surface platform can be seen in Figure 32. It provides live feedback of the system. Multiple pages are created to display the various underground mining levels of the compressed air network.

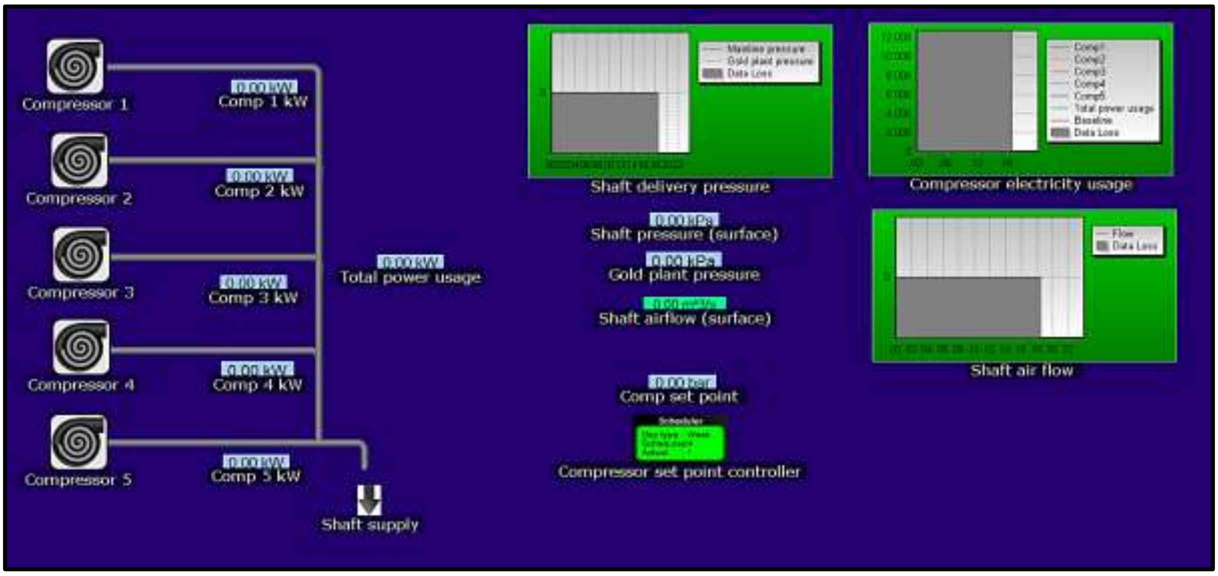


Figure 32: Energy management system for compressor management (surface platform)

The surface platform indicates each individual compressor's active power, shaft airflow, shaft pressure, gold plant pressure, compressor delivery pressure set point controller and graphs. The set point controller controls the delivery pressure of the compressor house on a daily profile (as seen in Table 5), where the schedule is also customisable. The controller uses the control tag of the energy management system to write the desired set point to the compressor house's master PLC. The compressors then open or close the inlet guide vane positions to match the required delivery pressure.

Table 5: Compressor house pressure set point controller (before implementation of interventions)

Time	Pressure set point [kPa]
00:00–07:00	420
07:00–13:00	430
13:00–18:00	420
18:00–20:00	400
20:00–00:00	420

The surface layout of the compressed air system of Mine X can be seen in Figure 33. It shows that the control room and the energy management system are connected to the various infrastructure and the compressor house master PLC. The total power (kW_T), guide vane angles (GV1–5), manifold pressure (P1), mainline pressure (P2) and airflow (F1) data of the compressed air system are logged. The energy management system writes out a set point (SP) to the (P1). The compressors will adjust the inlet guide vanes to match and keep the set point pressure (SP = P1).

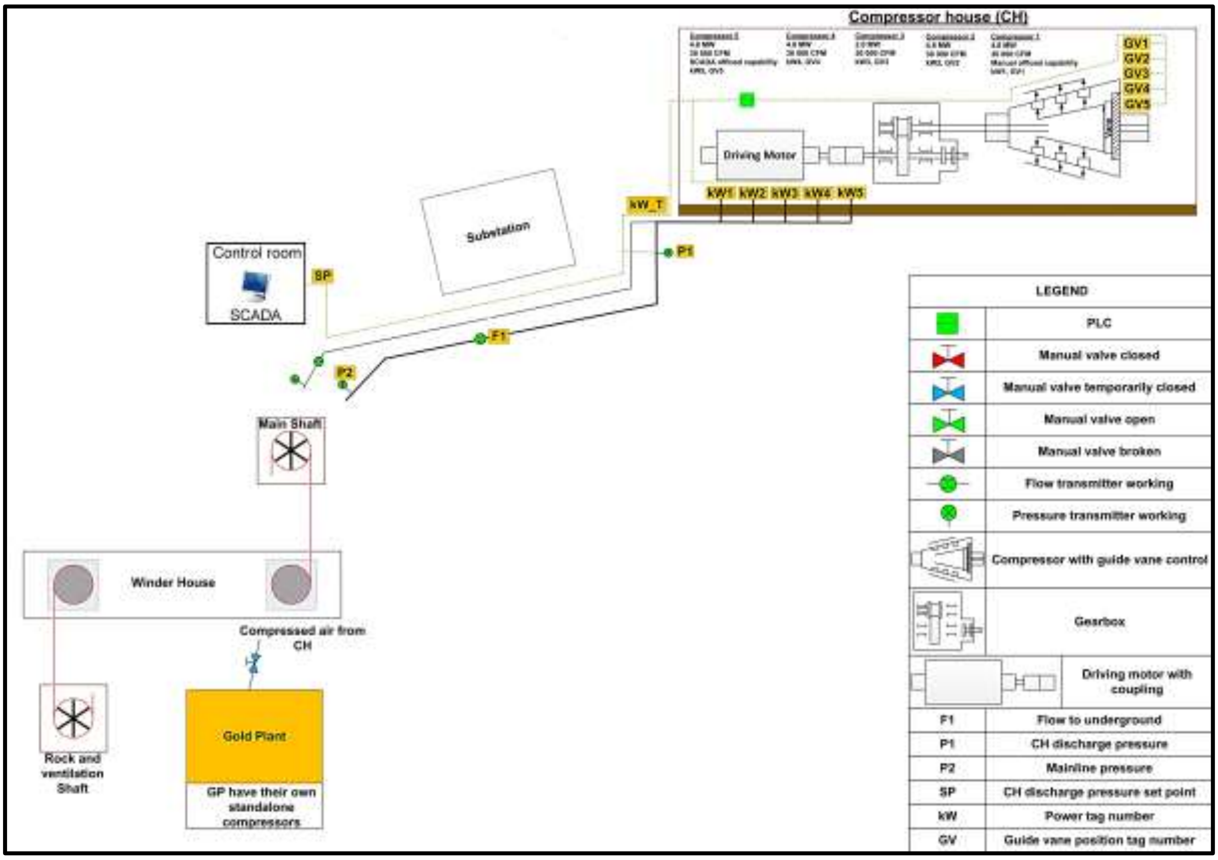


Figure 33: Surface layout of Mine X's compressed air network

The energy management system with a compressor management platform also indicates the mining levels as seen in Figure 34. The upstream and downstream pressure transmitters give live feedback to the operator. It is important to know what the downstream pressures are at the mining levels, because they must meet the level's pressure requirements. A trend tool uses historical flow and pressure profiles and displays them on a daily graph. This is handy for seeing instant changes in the system.

The bypass control valve provides live feedback of the valve's position during the control period. Mine personnel enable automatic control privileges on the bypass valves so that the control system can control the bypass valves. A schedule and set point controller are used where the operator specifies the periods when the bypass system must control according to a specified downstream pressure set point. Background on bypass valve control was mentioned in more detail in Section 2.5.2.4.

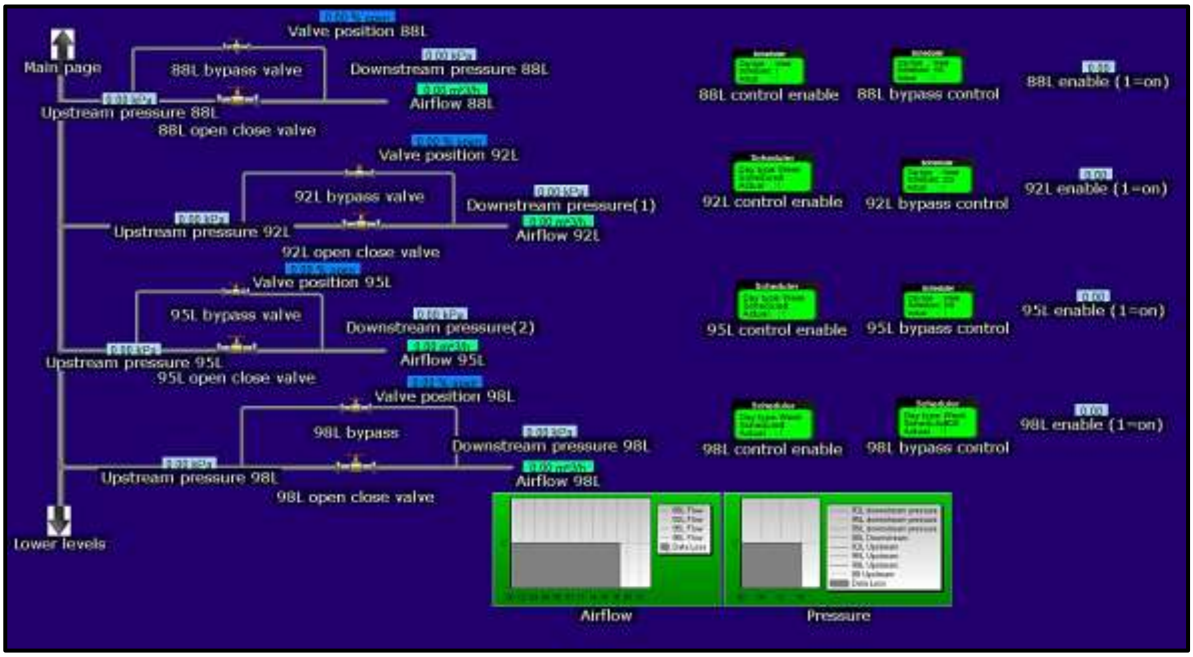


Figure 34: Energy management system for compressor management (mining level platform)

3.3 Critical analysis of the existing DSM project and intervention description

3.3.1 Preamble

To identify areas for improvement, it is beneficial to have a layout of the installed infrastructure on the high air-consuming levels of the existing project. This will help establishing which levels' historical data is required for investigations. Mine X's infrastructure layout was shown in Figure 29. It indicates the bypass control valves, mainline valves, positioners, airflow and pressure transmitters. The pressure transmitter measures the upstream and downstream pressure; the flow transmitter measures the airflow. All transmitters were reported to be in working condition.

Baselines of the downstream pressure for the mining levels, the compressor house delivery pressure set point and total power consumption were developed prior to the case study when adjustments were made. Figure 35 indicates the hourly profile of the delivery pressure set point. The delivery pressure set point was increased in the morning so that there were higher downstream pressures on the mining levels during the drilling period. The delivery pressure set point was reduced in the evening, because during the blasting period there was no need for high pressures on surface and underground.

Figure 35 also indicates that the downstream pressures on the mining levels had the same hourly profile than the delivery pressure set point, except during the morning drilling period. 102L had a faulty tag that caused the pressure profile to be a straight line. During the drilling period, drills use a large amount of compressed air, causing pressure to drop in the compressed air network. The compressors must work harder to supply the required pressures to the mining levels.

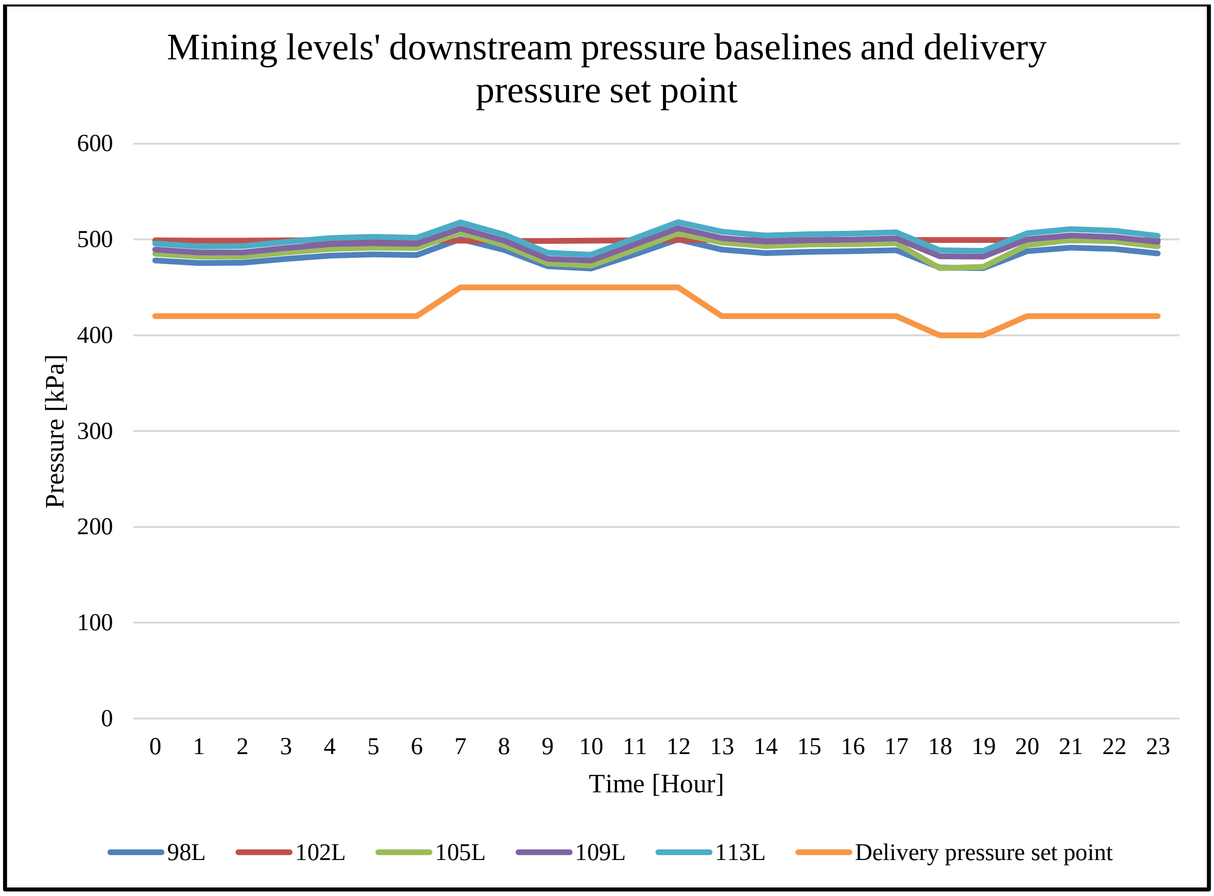


Figure 35: Mining levels’ downstream pressure baselines and delivery pressure set point

The total power consumption baseline before any changes to the system were done can be seen in Figure 36. As the delivery pressure set point (as seen in Figure 35) is increased at 06:00 to supply sufficient pressure to the compressed air network during the drilling period, the power consumption then increases. The compressor house power consumption peaks between 09:00 and 10:00 to match the demand. During the evening peak period when blasting takes place, the delivery pressure set point was reduced which also reduced the compressor house power consumption.

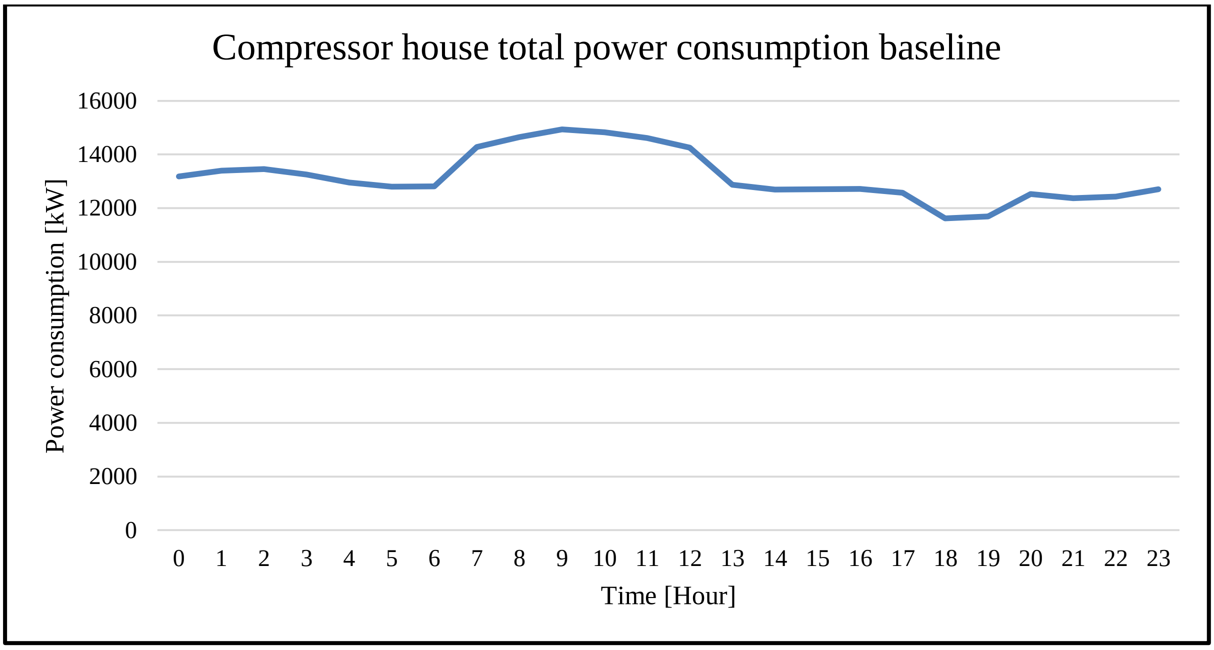


Figure 36: Compressor house total power consumption baseline

There is scope to adjust the compressor house delivery pressure set point to match the demand on the mining levels. Leaks and pressure losses in the compressed air pipe network can be audited and fixed to increase pressure and reduce pressure losses during the drilling shift. The compressor house delivery set point can be reduced and bypass valves can be controlled during the evening peak period and morning changeover period for improved energy efficiency. The interventions identified in Chapter 2 will be used to identify opportunities that can be implemented to improve the efficiency of the compressed air system and maximise cost savings. The baselines will be used to compare the results achieved in Chapter 4.

3.3.2 Intervention 1: Investigating bypass valve automatic control

The existing project’s bypass valves were only operated during the evening peak period. A downstream pressure set point schedule was given and the energy management system enabled the control of the control valves. The mine gives auto control privileges, which must be enabled for the energy management to control the valves. Figure 37 shows a typical pressure profile in red, where auto control privileges were disabled or other issues occurred that prevented the bypass valve from controlling. The profile in green is where the bypass valve controlled between 17:00 and 20:00 and matched the set point during the evening peak period.

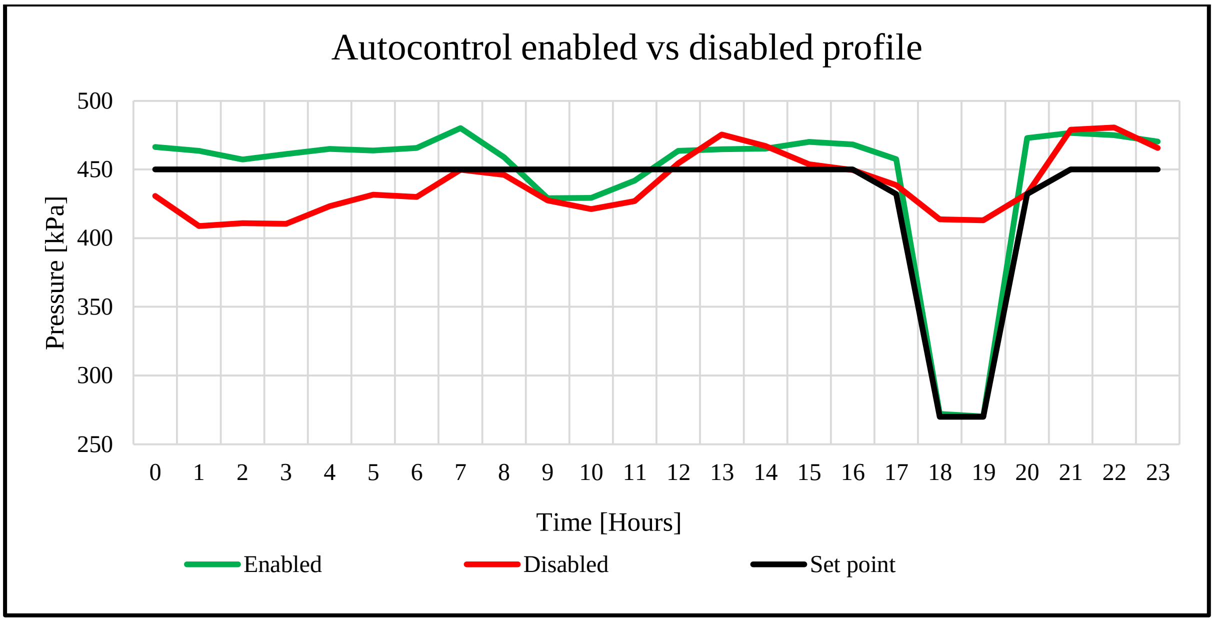


Figure 37: Bypass valve control-enabled versus disabled downstream pressure profiles

An investigation on the available data and infrastructure must be done to identify faults in the infrastructure. The closed levels and levels where automatic valve control was enabled must also be identified. There may be various other reasons for the valves not controlling and maintaining the proposed pressure set point. Areas where valve control issues may occur are listed below:

1. Communication failures between the PLC, positioner and transmitters;
2. Communication failures between the positioner and valve actuator;
3. Communication failures between the PLC and SCADA network;
4. Malfunctioning of the PID control loop executed by the PLC;
5. Set point control; or
6. Mechanical failures of the valves.

Due to historical upstream/downstream pressures and flow rates on the SCADA network and the logged data, the only clear area to focus investigations is at the valve actuator system. The difference in upstream and downstream pressures can be determined to investigate if each level’s bypass valve controlled during the control period, and if the positioners were in working condition. This would be a good indication if the control valves autocontrol privileges were enabled or not. The difference in upstream and downstream pressure when the valve control was enabled must be greater than the difference in pressure when the valve control was not enabled. It is a way to see if the bypass valves controlled, and when there was no historical data available of the autocontrol enabled statuses.

Due to the size of the data, Table 6 summarises the data to indicate the levels’ average upstream and downstream pressures between 19:00 and 20:00. This period is when the valves have stabilised the downstream pressures to match their set points. During the investigation, there was no historical data available for the automatic valve-control-enabled statuses, thus the difference in pressures were determined to indicate levels where there was valve control.

Table 6: Pressure difference and control-enabled statuses

Mining level	Control-enabled status	Upstream pressure [kPa]	Downstream pressure [kPa]	Pressure difference [kPa]
92L	0	437	421	16
	1	454	270	184
95L	0	482	478	3
	1	472	270	202
98L	0	452	441	12
	1	460	319	142
102L	0	482	470	12
	1	499	367	132
105L	0	507	496	11
	1	507	386	121
109L	0	519	503	16
	1	472	361	111
113L	0	536	523	13
	1	521	426	95

The average monthly status is shown by plotting all the automatic valve-control-enabled statuses of the data analysis on a graph (as seen in Figure 38). The controls of all levels were disabled at Month 5 and Month 6 and from Month 10 to Month 14. Some of the levels' bypass valves controlled at Month 7, but they quickly deteriorated to the point where there was no control over any bypass valve.

The control on 113L, indicated in orange in Figure 38, was almost never enabled, giving scope to investigate and audit that level's infrastructure. A technician was instructed to audit the bypass valve configurations by closing the mainline butterfly valve to see if any leakages occurred through the closed valve and to see if the positioners were still operational. The six steps mentioned on the previous page can be used to audit the bypass valve configuration.

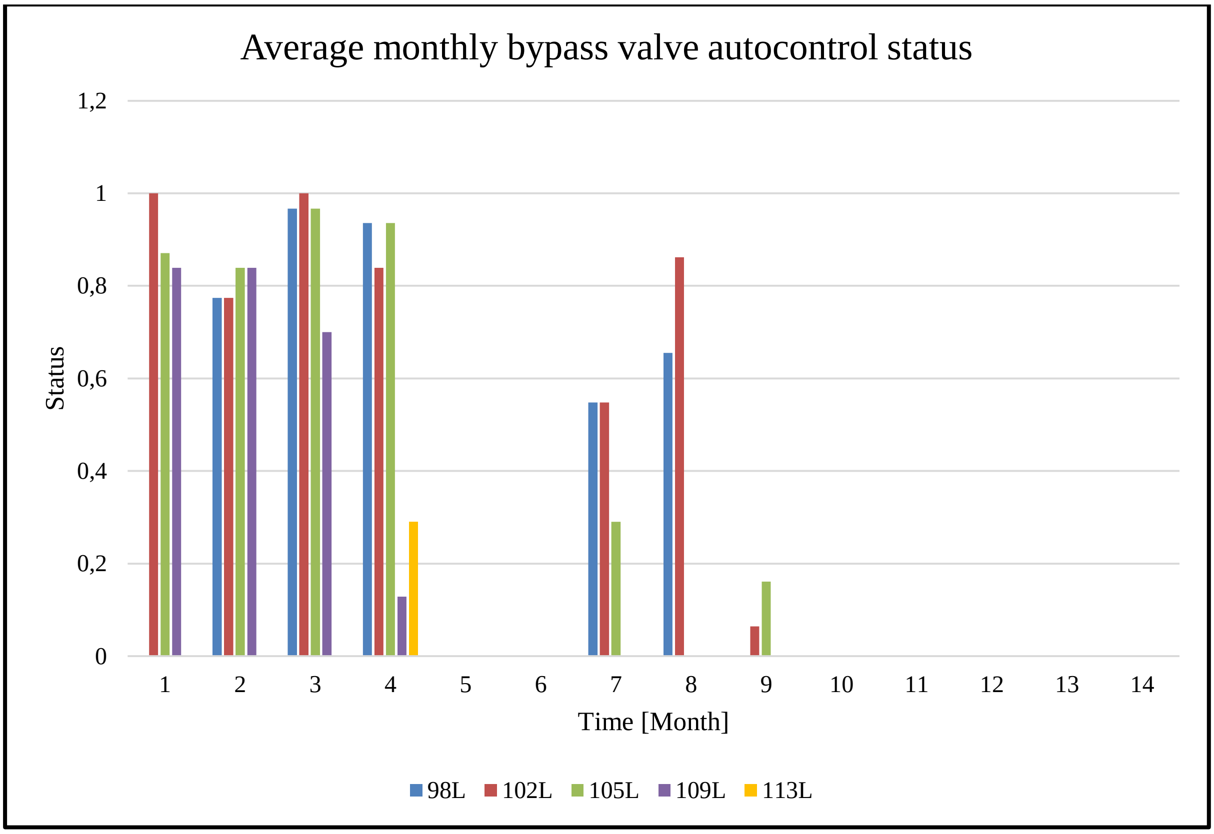


Figure 38: Average monthly bypass valve autocontrol statuses of the mining levels

The technician audited 113L and found that the positioner on the valve actuator did not function and that the butterfly valve on the mainline leaked when closed. The mine audited all the remaining levels and found that their positioners also did not function, except for 105L. All other levels also indicated leakages through the mainline butterfly valve. The faulty positioners were removed to investigate the cause of their failure. The technicians found that the mainboards short-circuited inside the positioners, because moist air leaked through the O-rings, which caused the mainboard electronics to short-circuit and break.

The mine used Fisher DVC 2000 series positioners to control the valve actuators. It can be seen in Figure 39 that the moisture in the air that leaked through the O-ring made blue marks on the mainboard electronic components and at the circle of the O-ring. This type of positioner is not rugged enough and should be replaced with a more rugged Fisher DVC positioner. Mine personnel investigated all the water traps, because their function is to prevent moisture from entering positioners and prevent internal component damage. The mine personnel found that the water traps were broken and that the moisture inside the water traps were not drained frequently.

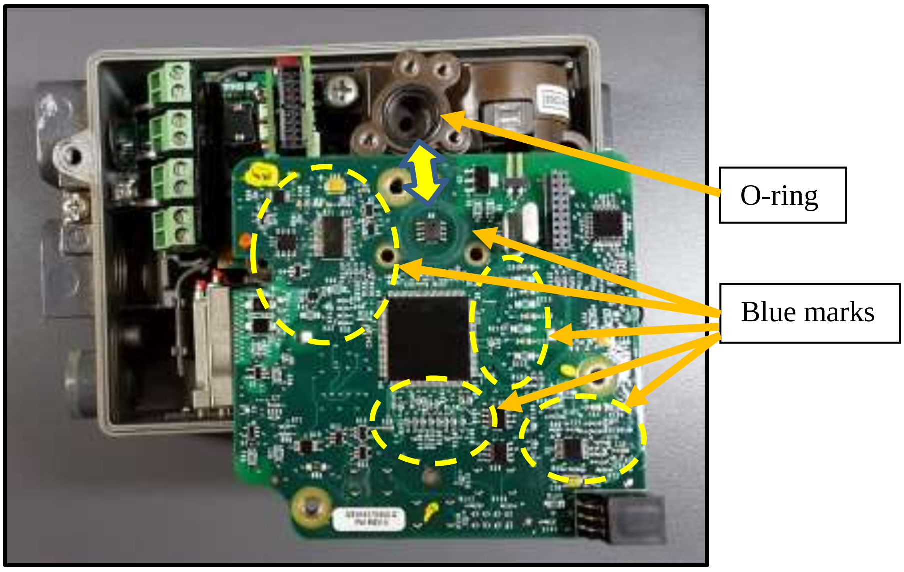


Figure 39: Short-circuited DVC 2000 from 113L

Bypass valve pressure control is an important energy savings initiative to improve the energy efficiency of a mine's compressed air system. It is therefore crucial to have rugged positioners to sustain the control that the energy management system has on the bypass valves. There is a need to identify a more rugged DVC model positioner to replace the currently installed DVC 2000 positioners. When the energy management has control over all the bypass valves, larger energy savings can be achieved during the evening period as well as during the morning changeover period, which will be discussed in Section 3.3.7.

3.3.3 Intervention 2: Compressor house pressure set point control

Mine X consists of a compressor house containing four 4.8 MW compressors and one 2 MW compressor. Standard operation is to use the four big compressors to supply compressed air to the compressed air users, which are drills, actuators, mechanical loaders, loading boxes, agitation and refuge bays. The compressed air users have their own daily pressure requirements (as seen in Section 2.5.2), which are also called the mining schedule, as seen in Figure 40.

The mining schedule indicates that in the periods from 00:00–03:00, 07:00–16:00 and 21:00–00:00 the mine requires high pressure. This is when compressors consume more electricity to supply the required pressure for mining. From 03:00–06:00 and from 17:00–21:00 the mine requires much less pressure. These are potential areas where additional savings can be achieved, but the mine typically neglects those areas and keeps delivering high pressure throughout the whole day as seen in the orange line in Figure 40. This gives scope to modify the compressed air daily set point profile to meet the demand and reduce power consumption.

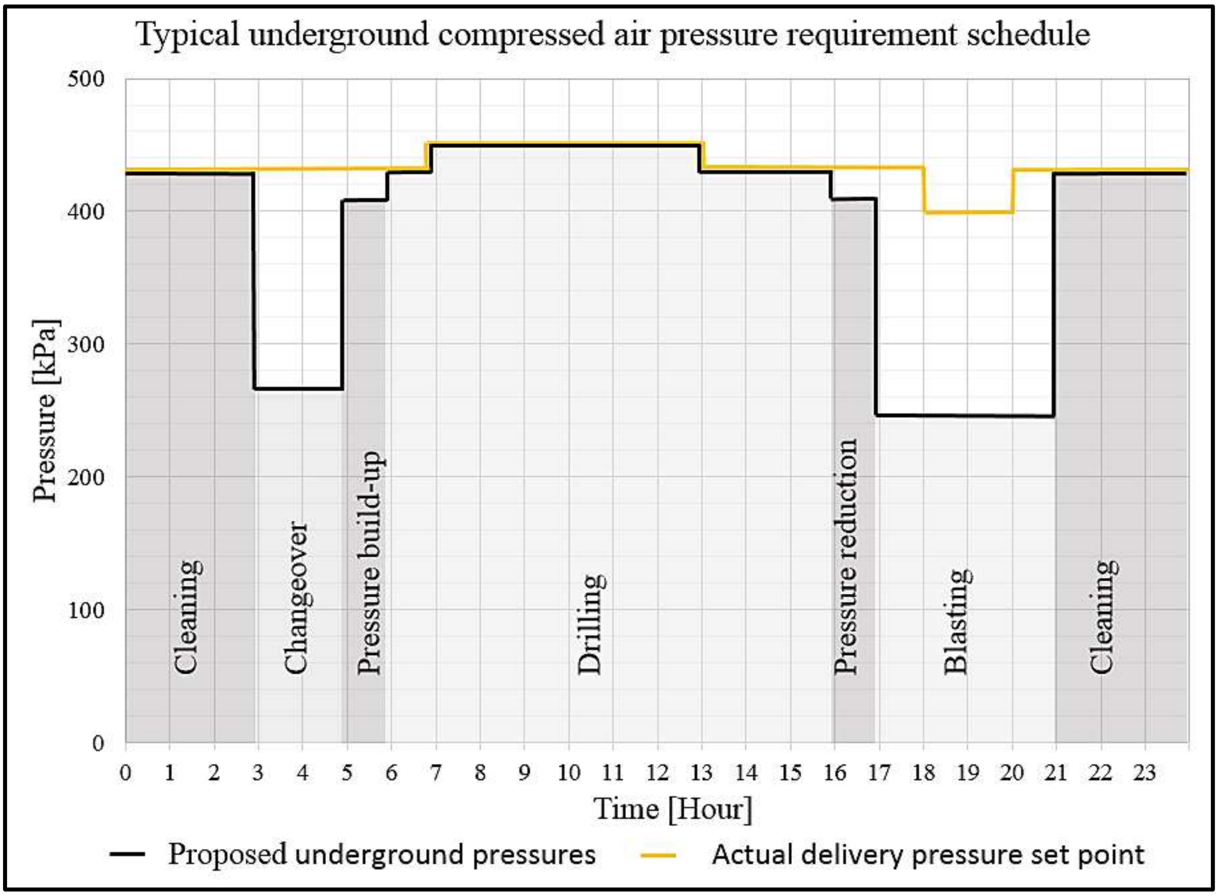


Figure 40: Typical pressure requirements and pressure set point schedule before improvements

All five compressors have guide vanes installed. The compressor house receives a delivery pressure set point from the energy management system that the compressor house delivery pressure must match. The delivery pressure will match the pressure set point by opening or closing each individual compressor's guide vane positions. This will increase or decrease each compressor's delivery airflow into the combined manifold pipeline supplying air to the mining areas. This will also increase or decrease the power consumption of each individual compressor.

The energy management system has a compressor house delivery pressure set point schedule. The delivery pressure set point schedule before the case study started can be seen in Figure 40. This pressure set point schedule is compared with a typical gold mine's mining schedule [11]. The figure indicates that Mine X's pressure set point schedule did not match the required pressures for the periods from 03:00–06:00 and 16:00–21:00. The mine does not adjust the schedule and pressure set point constantly according to their pressure requirements, thus, the mine loses the additional cost savings.

The typical mining schedule is related to the minimum pressure required at the specific mining levels. The surface delivery pressure needs to be 400 kPa, but during the blasting period the set point can be lowered. The delivery pressure set points can be higher during the drilling period to deliver enough pressure on the mining levels to compensate for pressure losses due to the high airflow consumption. The vertical depth of the gold mine increases the pressure on the mining levels by auto compression. Thus, mining levels closer to the surface will have less auto compression than deeper levels.

To determine how the current compressed air system reacts to delivery set point changes, historical data was used to compare raw hourly profiles of the guide vane positions of the compressors to the delivery pressure set point schedule (as seen in Figure 41). The areas before and after the set point has changed from 420 kPa to 400 kPa are indicated as Block A and Block B and after the set point has changed from 400 kPa to 420 kPa are indicated as Block C and Block D.

The average period of the indicated blocks was chosen to be 45 minutes. This is when the guide vane positions were nearly constant so that an average of the power consumption, airflow and delivery pressure can be determined, which is seen in Table 7. The delivery pressure is used in Table 7 is slightly lower than the set point because it is the pressure transmitter reading on surface closest to when the pipe goes underground.

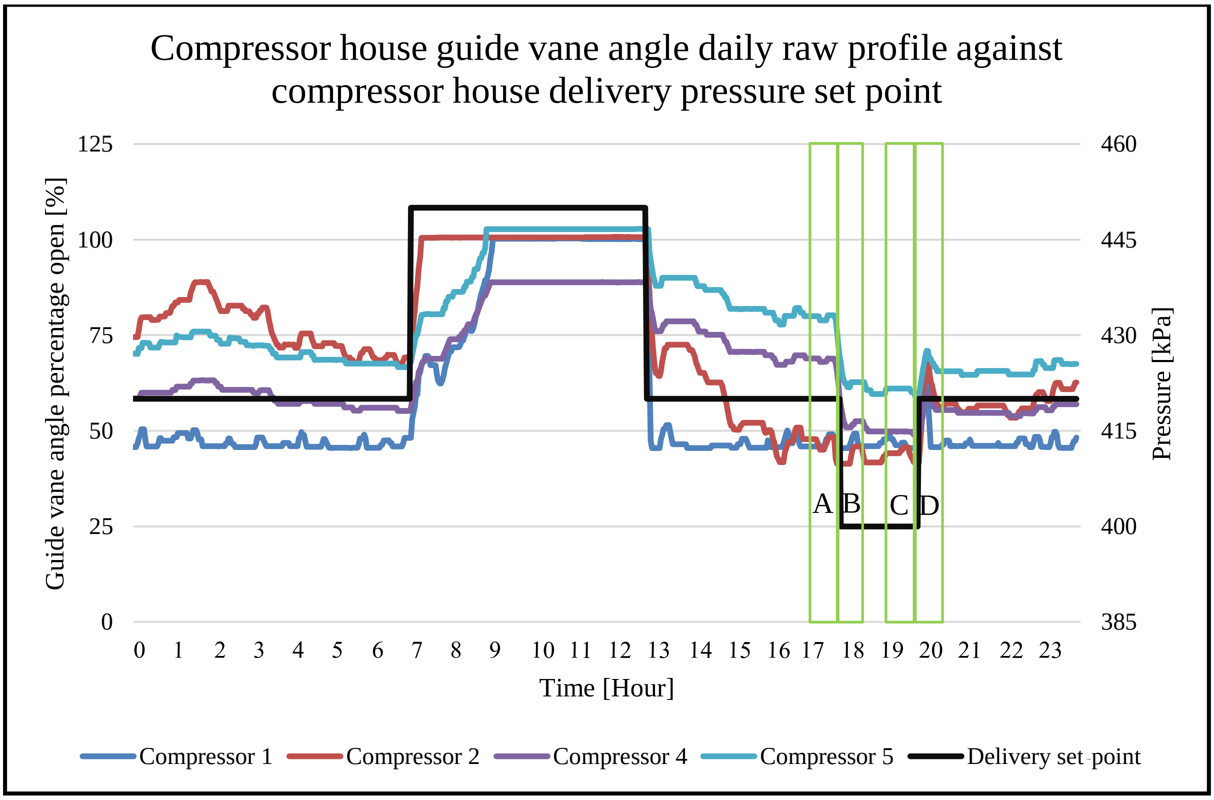


Figure 41: Compressor house guide vane positions raw hourly profile per delivery pressure set point

The 45-minute average values for Block A to Block D for actual power consumption, actual delivery pressure and actual delivery airflow for the period from 18:00 to 20:00 are seen in Table 7. The decrease/ increase columns indicate the reduction in power consumption, delivery pressure and delivery airflow from Block A to Block B for a delivery pressure set point reduction of 20 kPa. It then indicates the increase values when the delivery pressure is back to normal from Block C to Block D.

Table 7: Results of decreasing and increasing the delivery pressure set point by 20 kPa

Evening peak period 18:00 to 20:00	Power consumption [kW]		Delivery pressure [kPa]		Delivery airflow [m^3/h]	
	Actual	Decrease/ Increase	Actual	Decrease/ Increase	Actual	Decrease/ Increase
A	12 024	–736	416	-20	114 415	–7 758
B	11 288		396		106 657	
C	11 284	767	396	22	106 671	7 017
D	12 051		418		113 688	

The typical power consumption of the compressed air system on the indicated delivery pressure set point schedule can be seen in Table 8. It also indicates the actual delivery pressure at the specific hour and the actual delivery pressure and set point difference. The delivery pressure difference to set point value is used to predict the actual delivery pressure for the proposed delivery pressure set point schedule, which is seen in Section 3.4.2 for simulation purposes. The airflow of the adjustments in Table 8 reduced by 6 161 m^3/h from 17:00 to 18:00 which is used in the simulation model. The proposed schedule is adjusted to the new high-demand evening peak period, which is changed from 18:00–20:00 to 17:00–19:00. The simulation and predicted savings of changing the evening peak period set points are found in Section 3.4.2.

Table 8: Delivery pressure set point parameters before adjustments

Hour	Power [kW]	Delivery pressure set point [kPa]	Actual delivery pressure [kPa]	Delivery pressure difference to set point [kPa]	Airflow [m^3/h]
15	12 093	420	417	3	114 680
16	11 981	420	416	4	113 394
17	11 959	420	416	4	112 991
18	11 182	400	397	3	106 830
19	11 266	400	397	3	106 886
20	12 090	420	415	5	113 582
21	11 870	420	416	4	112 353

This is done because a test will be conducted to lower the delivery pressure set point during the evening peak period to determine the amount of power reduced during the set point reduction. The test will be discussed in more detail during the simulation is Section 3.4.2 and the results will be compared with the actual test in Section 4.2.3.

3.3.4 Intervention 3: Auto compression and pressure losses

According to the literature analysis in Section 2.5.2.3, underground pressure losses occur due to long pipe sections and large leaks that prevent maximum benefit from auto compression. The listed equations in Section 2.5.2.3 were not used to determine the auto compression pressures at various depths. Figure 16 from an article "Energy savings through auto compression and the air distribution control of a deep level gold mine" [52] which had taken friction losses into consideration was used predict the underground pressures of Mine X at various depths. The depths of the mining levels of Mine X are known and the average surface pressure are also known as 400 kPa.

Thus, 400 kPa in Figure 16 can be used as reference pressure for Table 9 which indicates the vertical distances of the mining levels of Mine X. From Table 9 it can be seen that the actual pressures on the mining levels are 20 % less than the predicted pressures. Table 9 is therefore used as a reference to see what the percentage pressure loss is in Mine X's compressed air network. This leads to the need to identify the area that may cause choking or where a large leak is evident which restricts airflow or wastes a large amount of compressed air.

Table 9: Predicted underground upstream pressures at the mining levels

Mining level	Vertical distance from surface (depth) [m]	Predicted underground pressures for a 400 kPa surface pressure as per Figure 16 [kPa]	Actual pressures [kPa]	Percentage pressure loss [%]
98L	2 982	560	445	20
102L	3 102	570	455	20
105L	3 222	580	462	20
109L	3 342	590	470	20
113L	3 462	600	480	20

Section 4.2.4 will discuss the impact on the compressed air network when a large was fixed.

3.3.5 Intervention 4: Identifying compressed air leaks

Investigations on the underground compressed air pipe networks can be done to identify compressed air leaks. According to research, compressed air leaks cause pressure losses in the pipe network and increases compressor power consumption [51]. This is because leaks are also a compressed air user decreasing compressor efficiency, thus there is a need to approach leak detection efficiently to gain maximum benefit from leak management and repairs.

Efficient approach to leak auditing

Mine X has various flow meters installed on the compressed air network, which is simplified in Figure 42. The compressor house delivery airflow is measured at Point 1, which supplies compressed air to the main shaft and sub-shaft. There is a separate pipeline from the compressor house that supplies air to surface users seen in Point 2. The next airflow meter is situated on 73L (Point 4), which measures the total sub-shaft airflow. The main shaft flow is calculated by subtracting Point 4 from Point 1.

The total sub-shaft airflow is separated into two categories, namely, “other inactive levels (Point 5)” and “active mining levels (Point 6)”. “Other inactive levels” are levels where mining has stopped, areas where mine personnel do not go often, and the vertical shaft pipeline. The flow meters on the active mining levels are operational and all the flows of the mining levels are summed together to get the flow of the active mining levels. The flows of the other inactive levels (Point 5) are then calculated by subtracting the flow of Point 6 from the flow of Point 4. This approach will be implemented to identify the areas where the leak detection investigation will start.

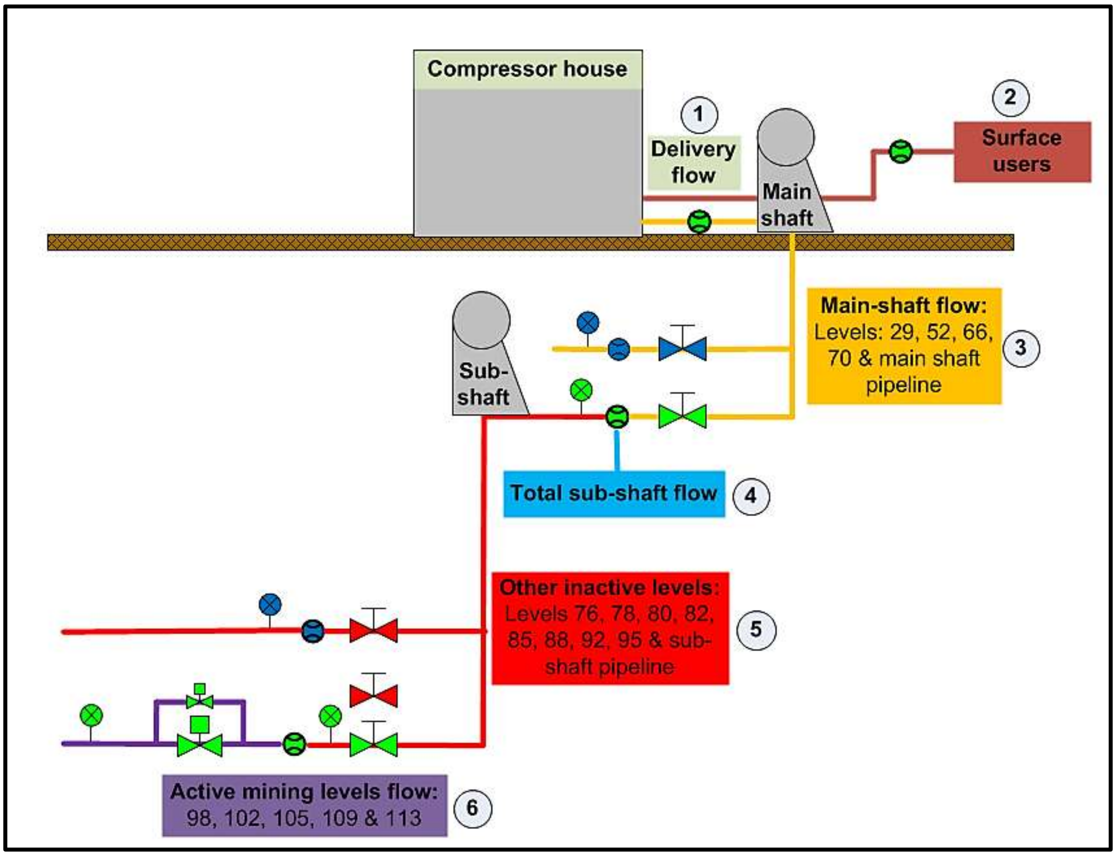


Figure 42: Simplified compressed air distribution network

Approach to identifying the compressed air leaks and reporting to mine personnel

The approach previously discussed will be used to identify the underground levels that require attention. 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 the various levels, shafts, etc.
3. Indicate the underground areas for leak auditing to the responsible mine personnel.

4. Get all documentation and accessories ready (bright flashlight, camera, notebook, 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 traveling down the shaft, note the leaks in the shaft and the level nearby.
8. At the station, audit the mainline and refuge bays.
9. When a leak is identified, take a picture, note the level, location, pipe diameter, leak diameter, priority and what can be done to fix the leak.
10. Develop a report when the leak 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.

This leak auditing process will be implemented and a leak-detection auditing guideline checklist and notes will be developed to ensure that leak detection and reporting to responsible mine personnel are done efficiently. By being involved with the process during the leak repairs, the effect of the fixed leaks on the compressed air system can be noted quickly.

3.3.6 Intervention 5: Optimum valve control philosophies for improved pressure control

Bypass valves are normally used to reduce pressure on the underground mining levels during the evening peak period for evening peak clipping. The off-peak periods are normally neglected, giving scope to control the bypass valves during the morning changeover period between 04:15 and 06:15 for morning peak clipping. This will increase the energy efficiency because during that period it is only necessary to pressurise the refuge bays. This initiative is discussed in Section 3.3.7.

During the drilling period, the mining levels require a minimum pressure of 420 kPa for operating their drilling machinery. A compressor can trip during the drilling period (as seen in Figure 43) causing a large pressure drop in the compressed air network. The pressure drop causes the pressure on the mining levels to be below the minimum operating point, leading to production losses on all mining levels.

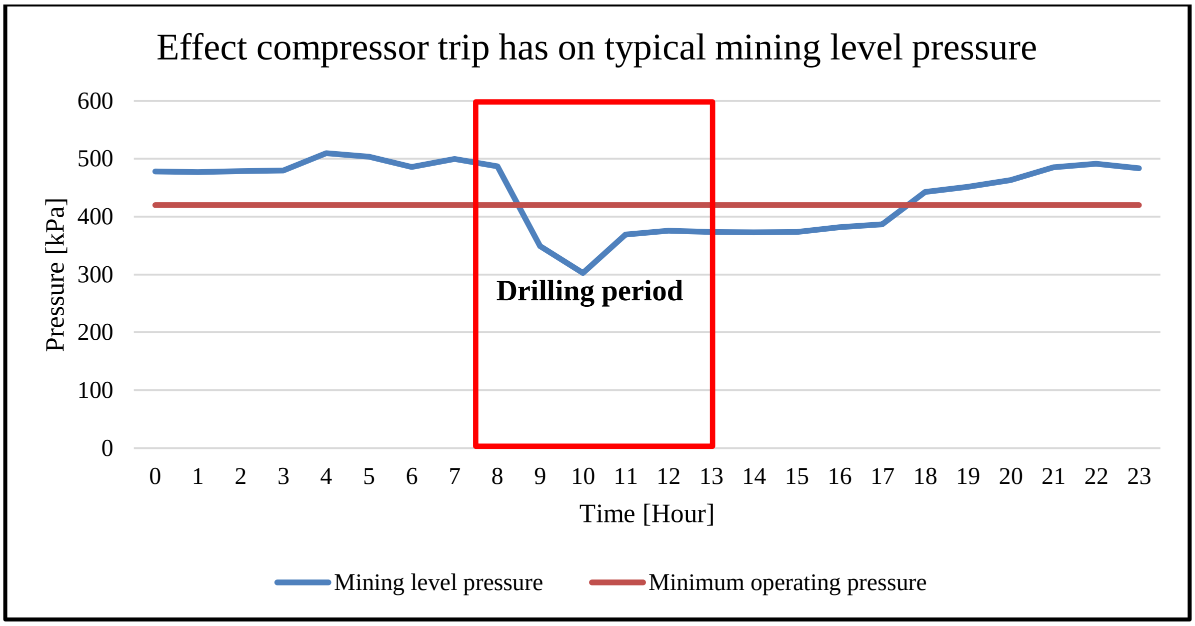


Figure 43: Effect on mining level pressures during compressor trip period

A strategy to increase pressures on some of the mining levels is to use the bypass valves on some levels to redirect the pressures on the required mining levels. The strategy can be implemented to determine its feasibility when a compressor trips during the drilling shift. Different bypass valve pressure control philosophies are developed for improved pressure control in the sub-section that follows.

Maximum pressure drop valve control philosophy

This control philosophy is mainly used as a shut-off valve when a compressor trips during the drilling shift and pressure must be shifted to other mining levels. Firstly, the levels that can be closed when a compressor trips during the drilling shift must be specified (as seen in Figure 44). When a compressor trips, the operator must firstly close the actuated shut-off valve and then monitor the pressure on the open mining levels. When the compressor is back online, the operator should open the shut-off valve.

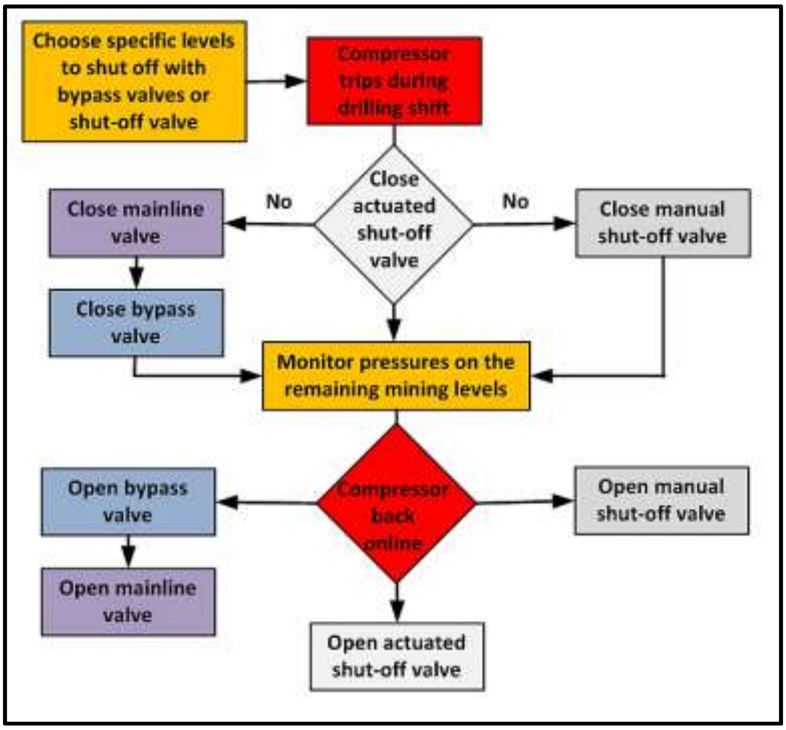


Figure 44: Maximum pressure drop valve control strategy

If there is no actuated shut-off valve, then the bypass valves must be used to shut off the level's airflow. Firstly, close the mainline valve, because with an open bypass valve the pressure on the mainline valve will be less. Then close the bypass valve and continue monitoring the pressures on the open mining levels. When the compressor is back online, open the bypass valve first followed by the mainline valve. The bypass valve system therefore requires full control on both valves to act as a shut-off valve. If there are no actuated shut-off valves or full control on the bypass valves, then the manual valve must be used to shut off the airflow to the level.

Medium pressure drop valve control philosophy

The purpose of this control philosophy is to use the bypass valves to reduce the pressures on the mining levels to supply enough pressure for the refuge bays, which require the lowest pressure. The periods for using this strategy will be during the morning changeover and the evening peak period. The bypass valve pipe diameter must be specified so that when the mainline valve is fully closed and the bypass valve is fully opened, it should deliver a near minimum required downstream pressure.

The control philosophy of the mentioned strategy can be seen in Figure 45. During the mentioned control periods, close the mainline valve and open the bypass valve. If the downstream pressure set point is matched, the pressure can be sustained. If the pressure is higher than the set point, throttle the bypass valves to match the set point. When the pressure is lower than the set point, throttle only the mainline valve. For this bypass valve control strategy, both valve actuators require positioners and control.

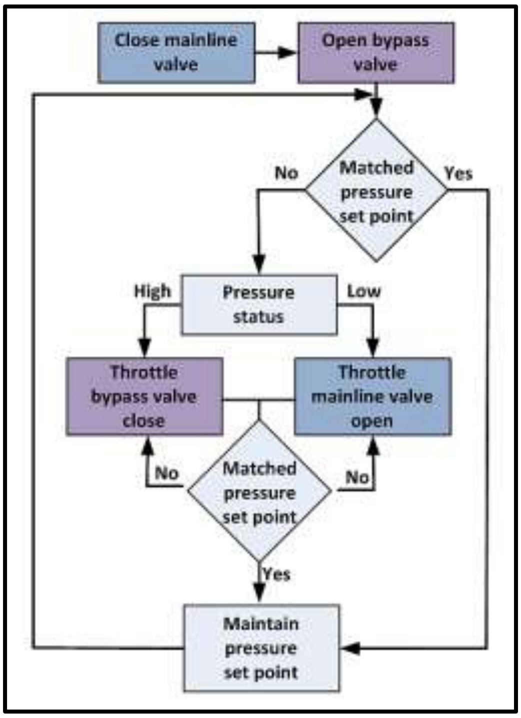


Figure 45: Medium pressure drop valve control strategy

Low pressure drop valve control philosophy

This control philosophy will be useful to reduce the pressure on levels that are overpressurised. For example, the lowest levels of a deep level mine have the highest pressures caused by auto compression. The valves can reduce these levels' downstream pressure to match the demand pressure on the specific level. The control philosophy as seen in Figure 46 indicates that when the downstream pressure is low, no valves must control. When the pressure is high and there is scope to reduce the pressure, the mainline valve can be throttled close and when it reaches the pressure set point, it can be maintained.

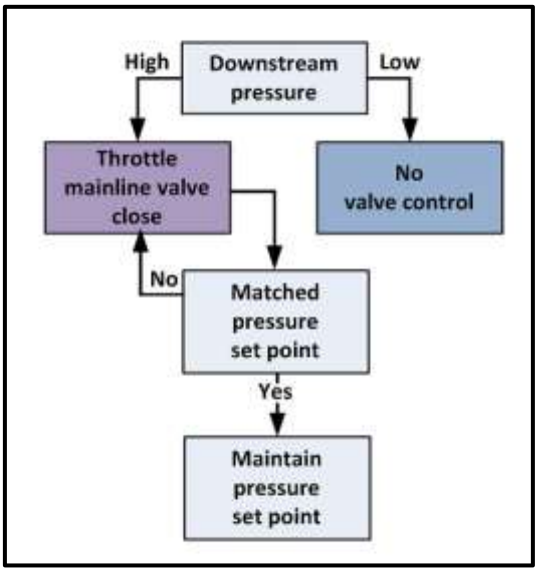


Figure 46: Low pressure drop valve control philosophy

3.3.7 Intervention 6: Control bypass valve during morning changeover period

A typical deep level gold mine has a morning changeover period when nightshift miners come to surface and morning shift miners go down to their working areas. The bypass valves on the mining levels are activated to control to a proposed schedule during the changeover period at Mine X. Historical data of the differential pressure and reduction in airflow for each level's bypass system (when they were the only valves to control) are seen in Table 10. This table is used in Section 0 to develop a simulation to predict the electrical cost savings of this intervention for the period from 04:15 to 06:15.

Table 10: Historical data when control valves controlled alone during evening peak period

Mining level	Pressure before [kPa]	Pressure after [kPa]	Reduced pressure [kPa]	Airflow before [m³/h]	Airflow after [m³/h]	Reduced airflow [m³/h]	Actual power reduction [kW]
98L	463	270	193	9 103	6 372	2 731	616
102L	483	343	140	7 697	5 492	2 205	462
105L	494	438	56	15 450	13 845	1 605	354
109L	453	321	132	8 663	5 995	2 668	495
113L	425	376	49	10 284	7 720	2 564	401

The intervention will be implemented and the results of the actual test will be compared with the simulation results. The compressed air system will be investigated to identify how the upstream and downstream pressures reacted to bypass valve control period. The manifold pressure, guide vane angles and compressor house power consumption will be displayed and discussed to indicate what happens with the compressed air system during bypass valve control.

3.3.8 Intervention 7: Offloading a compressor during evening peak period

As stated in the literature analysis, Section 2.6.4, during compressor offloading the output of other compressors increase to compensate for the offloaded compressor; however, there is not a strategy to prevent other compressors from increasing their power output during the offloading period. A compressor offloading test will be conducted during the evening peak period and the delivery pressure set point will be adjusted during the test.

The results will be explained in detail on how the compressed air system reacted. From the results obtained, a simplified strategy will be proposed to prevent other compressors from increasing their power output. There is therefore a need to do offloading tests and present a control strategy during the compressor offloading period that will prevent the power output increase of the other compressors and maximise peak-clipping savings.

3.4 Simulating proposed interventions

3.4.1 Preamble

Simulating a proposed intervention is a useful method for determining the potential cost saving of a compressed air system when an electricity savings initiative is proposed. Various simulation packages are available that can simulate a compressed air network. Parameters in the simulation can be adjusted to predict the effect of the changes. For this study, KYPipe simulation software is used to simulate the compressed air network of Mine X. The simulation software determines the reduction in flow rate, which Equation 6 uses to calculate the electric power [71].

Equation 6: Calculating the electric power consumption of a compressor.

$$W_e = \frac{\left[\dot{m} C_p T_{in} \left(\frac{P_{out}^{\left(\frac{k-1}{k}\right)}}{P_{in}} - 1 \right)\right]}{\eta_c \eta_m} \qquad (6)$$

Where:

- W_e = Electric power [kW]
- $\dot{m}$ = Mass flow of the compressed air [kg/s]
- C_p = Specific heat constant [kJ/kgK]
- T_{in} = Absolute inlet air temperature [K]
- P_{out} = Absolute outlet air pressure [kPa]
- P_{in} = Absolute inlet air pressure [kPa]
- k = Specific heat ratio of compressed air [–]
- η_c = Compressor efficiency [%]
- η_m = Electric motor efficiency [%]

3.4.2 Simulating Intervention 2 for compressor house pressure set point control

The purpose of the simulation is to determine the annual cost saving by reducing the delivery pressure set point for the period 16:00 to 18:00. As discussed in Section 3.3.3 in Intervention 2, a new delivery pressure set point schedule will be proposed for the evening peak period. The simulation parameters from Table 8 for the period 17:00 to 18:00 will be used in the KYPipe simulation model to develop a simulation and calibrate the model to actual values.

This calibrated simulation model uses historic data from Table 8 for the period 17:00 and 18:00. The actual pressure reduced from 415.6 kPa to 397.2 kPa, the airflow reduced with 6 161.2 m^3/h and the power reduced from 11 959 kW to 11 182 kW. The two pressures were then used in the simulation model as seen in Figure 47, which a valve was used to calibrate the model to match the actual reduced airflow. The total power consumption of the compressor house was then calculated for that specific hour by using Equation 6 which delivered the same reduced power of 11 182 kW previously mentioned.

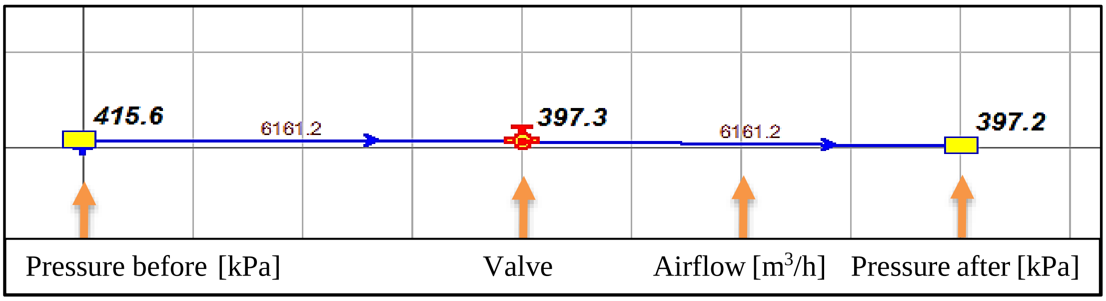


Figure 47: KYPipe simulation for Table 8 from 17:00 to 18:00 for calibration

The calibrated simulation model can now be used to simulate and predict the reduced airflow from the predicted reduced delivery pressures set at the specific hour. Figure 40 indicates that the pressure underground can be reduced to 240 kPa from 17:00 to 21:00, but it does not necessary mean that the surface pressures can be lower too. With consulting with the services engineer, the pressure set point on surface can be reduced to 390 kPa.

The set point was reduced to 390 kPa for the period 16:00 to 18:00. Table 11 indicates the results of the simulation where the reduced power for the period 16:00 to 18:00 resulted in a R650 000 annual cost saving. The other periods had no additional savings because the delivery pressure set point schedule was only adjusted for the period 16:00 to 18:00. The predicted savings compared with the actual results are found in Section 4.2.3.

Table 11: Predicted savings for adjusting the evening peak period pressure set point to 390 kPa

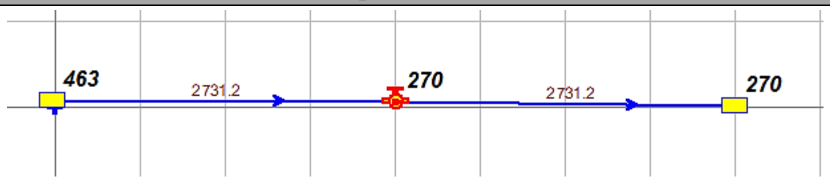
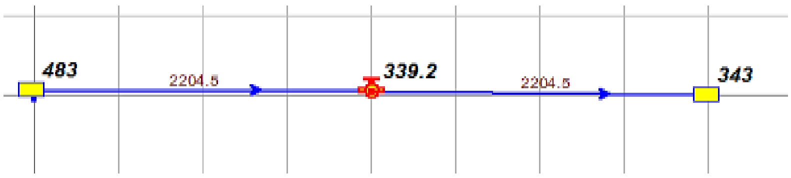
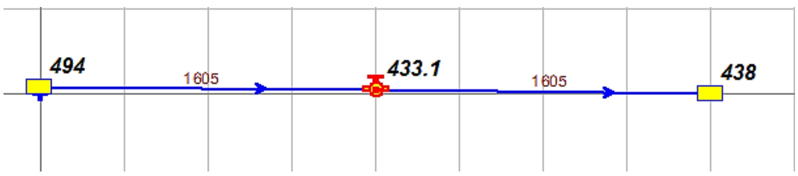
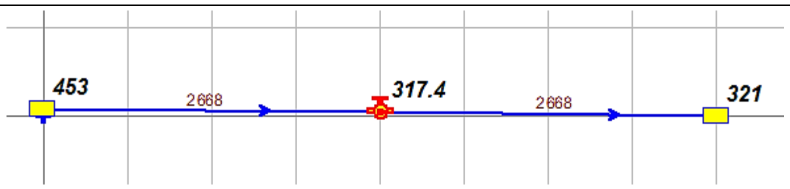
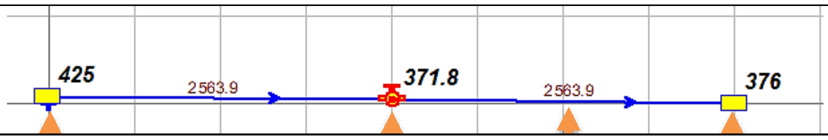
Hour	Before		Simulated			
	Power [kW]	Delivery pressure [kPa]	Reduced delivery pressure [kPa]	Reduced airflow [m³/h]	Reduced power [kW]	Power [kW]
15	12 093	417	417	0	**0**	12 093
16	11 981	416	386	7 760	**1 006**	10 974
17	11 959	416	386	7 756	**1 005**	10 954
18	11 182	397	387	4 486	**583**	10 600
19	11 266	397	397	0	**0**	11 266
20	12 090	415	415	0	**0**	12 090
21	11 870	416	416	0	**0**	11 870

3.4.3 Simulating Intervention 6 for electrical savings during morning changeover period

As discussed in Section 3.3.7, the bypass valves will be used during the morning changeover period from 04:15 to 06:15 at Mine X. The actual pressure before and after from the historic data as seen in Table 10 are used as inputs in the KYPipe simulation model. A valve was used to calibrate the model to match the actual reduced airflow. For example at 98L the actual pressure before was 463 kPa and the pressure reduced to 270 kPa with a flow reduction of 2 731.2 m^3/h.

A valve was used as calibration tool until the valve setting produced the same reduced airflow output. Thus, the simulation model for 98L as seen in Table 12is then calibrated and can predict new reduced airflow values according to pressure before and after inputs. The actual power consumption of the compressors according to the actual airflow can then be calculated for that specific hour by using Equation 6.

Table 12: Historical data from Table 10 used to calibrate the KYPipe simulation model

Mining level	KYPipe simulation model
98L	
102L	
105L	
109L	
113L	 Pressure before [kPa] Valve Airflow [m^3/h] Pressure after [kPa]

Historic data as seen in Section 3.3.7 was used when the bypass valves controlled independently during the evening peak period. The actual power reduction of each level was then determined. The simulated power reduction of each level was determined by using the simulated results obtained in Table 12. The simulated power reduction of each bypass valve when being controlled alone is verified with the actual power reduction as seen in Table 13. The calibrated model compared to the actual results is accurate within an average of 3%.

Table 13: Simulated power reduction vs actual power reduction for accuracy of calibrated model

Mining level	Actual power reduction [kW]	Simulated power reduction [kW]	Accurate within - [%]
98L	616	627	2
102L	462	457	1
105L	354	366	3
109L	495	519	5
113L	401	409	2

A one-day test will be conducted in Section 4.2.7 where multiple valves will be controlled during the same period which the actual results will then be compared to the simulated results as seen in Table 14. The pressures of the day prior to the test were used which the reduced pressures from Table 10 were used to calculate the predicted pressure when the valves controlled. The simulated airflow of each mining level where determined by using the calibrated simulation model which Equation 6 was used to calculate the simulated power reduction of each mining level. The expected annual cost savings for the period from 04:15 to 06:15 for each individual level can be seen in Table 14.

Table 14: Expected reductions and cost savings of morning changeover bypass valve control

Mining level	Pressure before [kPa]	Predicted pressure after [kPa]	Reduced pressure (Table 10) [kPa]	Simulated airflow [m^3/h]	Simulated power reduction [kW]	Expected annual cost savings
98L	468	275	193	2 726	627	R193 000
102L	480	340	140	2 195	455	R140 000
105L	488	432	56	1 594	364	R112 000
109L	460	328	132	2 697	524	R161 000
113L	503	454	49	2 817	471	R145 000

3.5 Conclusion

With the current situation where gold mines aim to improve their compressed air system's efficiency, energy efficiency interventions will be implemented on an inefficient mine. Background on Mine X was provided and interventions were identified in the compressed air system that will be implemented to improve the energy efficiency on the mine's compressed air system.

There is a need to identify a more rugged DVC model positioner to replace the currently installed DVC 2000 positioner. When the energy management controls all the bypass valves, larger energy savings can be achieved during the evening period as well as during the morning changeover period.

An intervention was identified to lower the compressor house delivery pressure set point an additional two hours earlier before the evening peak period. The intervention was simulated and achieved an additional R650 000 annual cost saving. The other periods will have no additional savings because the delivery pressure set point schedule was adjusted from 16:00 to 18:00. It was also identified that the actual pressures on the mining levels are not near the predicted pressures. Therefore, there is a need to audit the underground levels to fix leaks and reduce pressure losses in the compressed air system to increase the pressure and potentially adjust compressor delivery pressure set points further.

During the drilling period, mining levels require a minimum pressure of 420 kPa to operate their drilling machinery. A compressor can trip during the drilling period, causing a large pressure drop in the compressed air network. In turn, this causes the pressure drop on the mining levels to be below minimum operating point, leading to production losses on all mining levels. A strategy was proposed to use the bypass valves to shift pressure to the required levels. Thus, optimum pressure control philosophies on valves were proposed.

It was identified that during the morning changeover period there was scope to use the bypass valves on the levels to increase the energy efficiency on the compressed air system. A simulation was developed and verified. The simulation was used to predict the annual cost savings of each individual bypass valve on the various mining levels.

As stated in the literature, during compressor offloading, the output of other compressors will increase to compensate for the offloaded compressor. However, there is not a strategy to prevent other compressors from increasing power output during the offloading period. A compressor offloading test will be conducted during the evening peak period. The results will be explained in detail on how the compressed air system reacted during the compressor offloading period.

From the results obtained, a simplified strategy will be proposed to prevent other compressors from increasing their power output. There is therefore a need to do offloading tests and present a control strategy during the compressor offloading period that will prevent other compressors from increasing their power output, thus maximising peak clipping savings.

There were many interventions identified in the compressed air system of Mine X. More rugged positioners are required for sustained control on bypass valves. Compressor house delivery pressure set points can be reduced and the bypass valves can be controlled during the morning changeover period to increase the energy efficiency of the compressed air system. Optimum pressure control philosophies on valves were developed and control philosophies for increasing compressor offloading will be developed.

CHAPTER 4: PRACTICAL IMPLEMENTATION OF INTERVENTIONS

4.1 Introduction

Chapter 2 discussed the background on centrifugal compressors on deep level gold mines and interventions of improving energy efficiency on compressor power consumption. Mine X with inefficient compressor power consumption was identified. In Chapter 3, opportunities were identified that will be implemented and discussed in greater detail in this chapter.

4.2 Implementation of interventions

4.2.1 Preamble

In this section the identified opportunities in Chapter 3 will be implemented and discussed.

4.2.2 Intervention 1: Investigating bypass valve autocontrol

In Section 3.3.2, historical data was used to identify the control status of the mining level's bypass valves of Mine X. The investigation revealed that the positioners on the bypass pneumatic actuators have deteriorated and broken over time. The DVC 2000 model positioner short-circuited due to moisture in the air that leaked through the internal O-ring, damaging the main circuit board as seen in Figure 48. This was caused by faulty water traps. The positioners breaking made the bypass valves stationary. A more rugged positioner is required to regain bypass valve control.

Figure 48: Faulty DVC 2000 positioner – internal design

The design of the faulty DVC 2000 positioner was investigated to determine its ruggedness. The internal design of the DVC 2000 indicates that the main circuit board had an open electronic circuit design as seen in Figure 48. The O-ring was the only component that prevented moisture in the air from leaking through and damaging the circuit board. As water traps were not drained frequently, these positioners broke over time due to circuit board shortages. A more rugged positioner was suggested; namely, the DVC 6200 positioner, which can be seen in Figure 49.

Figure 49: Fisher DVC 6200 positioner

The mining level's faulty positioners were replaced with the proposed positioners. The faulty water traps were also replaced with new ones (as seen in Figure 50) to ensure that the bypass valve control was sustainable. It is important to drain all water traps frequently to prolong the service life of the pneumatic equipment.

Figure 50: New water trap installed on the pneumatic actuator

The next intervention covers the impact that changing the compressor house delivery pressure set point has on the efficiency of the compressed air system. The bypass valve control intervention is discussed in Section 4.2.6, because of a delay in replacing the positioners and water traps.

4.2.3 Intervention 2: Compressor house set point control

Background on Mine X's current set point schedule was provided in Section 3.3.3, which also indicated that there was room for set point adjustments. Historical data was analysed in Section 3.3.3 and then simulated in KYPipe in Section 3.4.2 to predict the savings of a proposed set point schedule as seen in Table 15.

Table 15: Predicted savings for adjusting the evening peak period delivery pressure set point

Hour	Before			Simulated				
	Power [kW]	Set point before [kPa]	Delivery pressure [kPa]	Proposed set point [kPa]	Reduced delivery pressure [kPa]	Reduced flow [m^3/h]	Simulated power reduction [kW]	Reduced power [kW]
15	12 093	420	417	420	417	0	0	12 093
16	11 981	420	416	390	386	7 760	1 006	10 974
17	11 959	420	416	390	386	7 756	1 005	10 954
18	11 182	400	397	390	387	4 486	583	10 600
19	11 266	400	397	400	397	0	0	11 266
20	12 090	420	415	420	415	0	0	12 090
21	11 870	420	416	420	416	0	0	11 870

The intervention was implemented. The simulated and actual results of the test day are compared in Table 16. The accuracy of the simulation is an average of 83%, which is the ratio of the simulation vs actual results. It indicates that the average actual power reductions is 17 % less than simulated as determined in Table 16. The reasons for the inaccuracy of the simulated results vs actual results may be because of the data method used to develop the simulation to predict the test outcome and the period of data used may be far from the actual test day.

Table 16: Simulation and actual results comparison

Hour	Power [kW]	Simulated reduced delivery pressure [kPa]	Actual reduced delivery pressure [kPa]	Simulated power reduction [kW]	Actual power reduction [kW]	Accuracy of simulation vs. actual results
15	12 093	417	416	0	0.0	0.00
16	11 981	386	391	1 006	1 000	1.01
17	11 959	386	387	1 005	1 046	0.96
18	11 182	387	387	583	315	1.85
19	11 266	397	401	0	0.0	0.00
20	12 090	415	414	0	0.0	0.00
21	11 870	416	416	0	0.0	0.00

Thus the annual cost savings of the actual test was R540 000, saving an average 780 kW compared with the annual cost savings of R650 000 predicted by the simulation, saving an average of 860 kW. The baseline, simulated and actual power profiles are seen in Figure 51, which indicates that the profiles are almost the same and indicates that the power is reduced two hours earlier to improve the efficiency of the compressed air system.

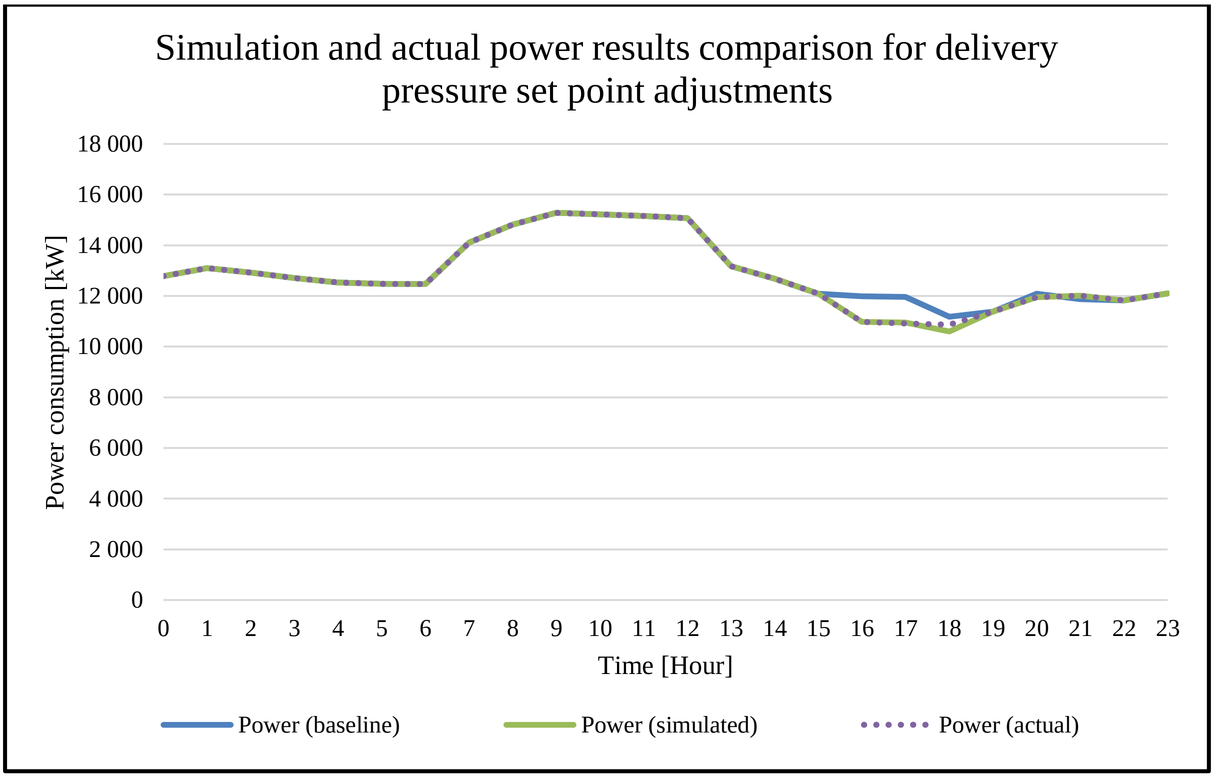


Figure 51: Comparing simulated and actual results for delivery pressure set point adjustments

4.2.4 Intervention 3: Auto compression and pressure losses

The predicted upstream pressures and actual upstream pressures at the mining levels were compared in Section 3.3.4 in Table 9. It indicated that the actual upstream pressures on the mining levels were much lower than what they should have been. During the literature analysis, few case studies were found that indicated the effect pressure loss has on a compressed air system because of friction losses. The low upstream pressures (as seen in Table 17) that Mine X experienced were reported to mine engineers for investigation.

Table 17: Predicted underground upstream pressures at the mining levels

Level	Vertical distance from surface (depth) [m]	Predicted underground pressures for a 400 kPa surface pressure as per Figure 16 [kPa]	Actual upstream pressures [kPa]	Percentage pressure loss [%]
98L	2 982	560	445	20
102L	3 102	570	455	20
105L	3 222	580	462	20
109L	3 342	590	470	20
113L	3 462	600	480	20

During the investigation, mine engineers found a large open-ended leak on a closed level (82L), which they fixed. Baselines of the compressed air system were developed before the intervention was implemented, which is referred to as “Profile A = baseline before (C1-C2-C4-C5)”. C1 is Compressor 1, and C1-C2-C4-C5 is the usual compressor configuration for running all four large compressors.

After fixing the leak, the pressures increased and this period is referred to as “Profile B = C1-C2-C4-C5 after”. Very soon afterwards, the compressor configuration was changed to running three 4.8 MW compressors and the small 2 MW compressor, which is referred to as “Profile C = C1-C2-C3-C5”.

The pressure increase in the compressed air network caused Compressor 3 to start to supply sufficient compressed air to the compressed air network. Compressor 4 was switched off for its five-yearly maintenance. Due to the increased underground pressures, the compressor house delivery pressure was adjusted to nearly match the pressure profile of Profile A, which is referred to as “Profile D = C1-C2-C3-C5 adjusted”. Profile A to Profile D show how the process proceeded after the large leak was fixed. The effects it had on the compressed air system will be discussed below.

Effect on 73L pressures

To indicate how the compressed air system changed after fixing the leak, it is necessary to review the average 73L pressure profile. As seen in Figure 52, the pressure increased with an average of 32 kPa from Profile A to Profile B. The pressure increase, increased the auto compression pressures by 5 % which 15 % off the pressure losses may be caused by unfixed leaks and friction losses due the large pipe network, pipe sizes, etc.

This pressure increase gave the mine scope to change their typical compressor configuration of C1-C2-C4-C5 to C1-C2-C3-C5. Compressor 4 then started with its five-yearly maintenance plan. The change from Profile B to Profile C did not change the pressures significantly. Therefore, the set point was adjusted to Profile D so that the pressure on the mining levels could almost be the same as it was at Profile A, which will be discussed next.

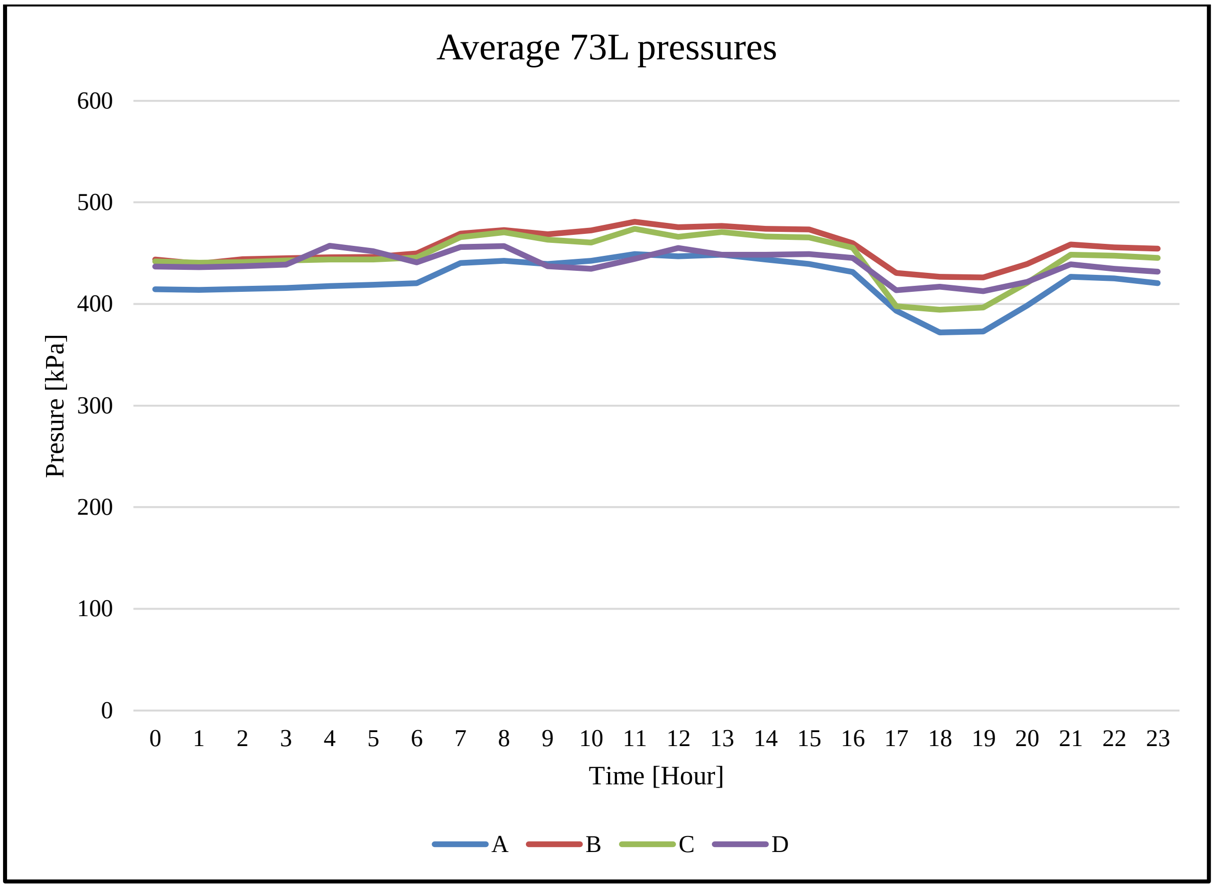


Figure 52: Average 73L pressures of the process steps

Effect on the mining level pressures

As seen in Figure 53, the average upstream pressures increased with an average of 32 kPa on the mining levels from Profile A to Profile B. The pressure profiles of B and C are almost the same and have an average of 32 kPa higher pressure than the profile of A. Due to the higher pressure of the mining levels, the compressor house delivery set point was adjusted lower from 08:00 to 16:00 to get almost the same pressure on the mining levels as Profile A. The adjustment was done because the daily operation of the mine was still functional with the pressure profiles at A. (To see the individual pressure profiles of the mining levels, refer to Annexure B.)

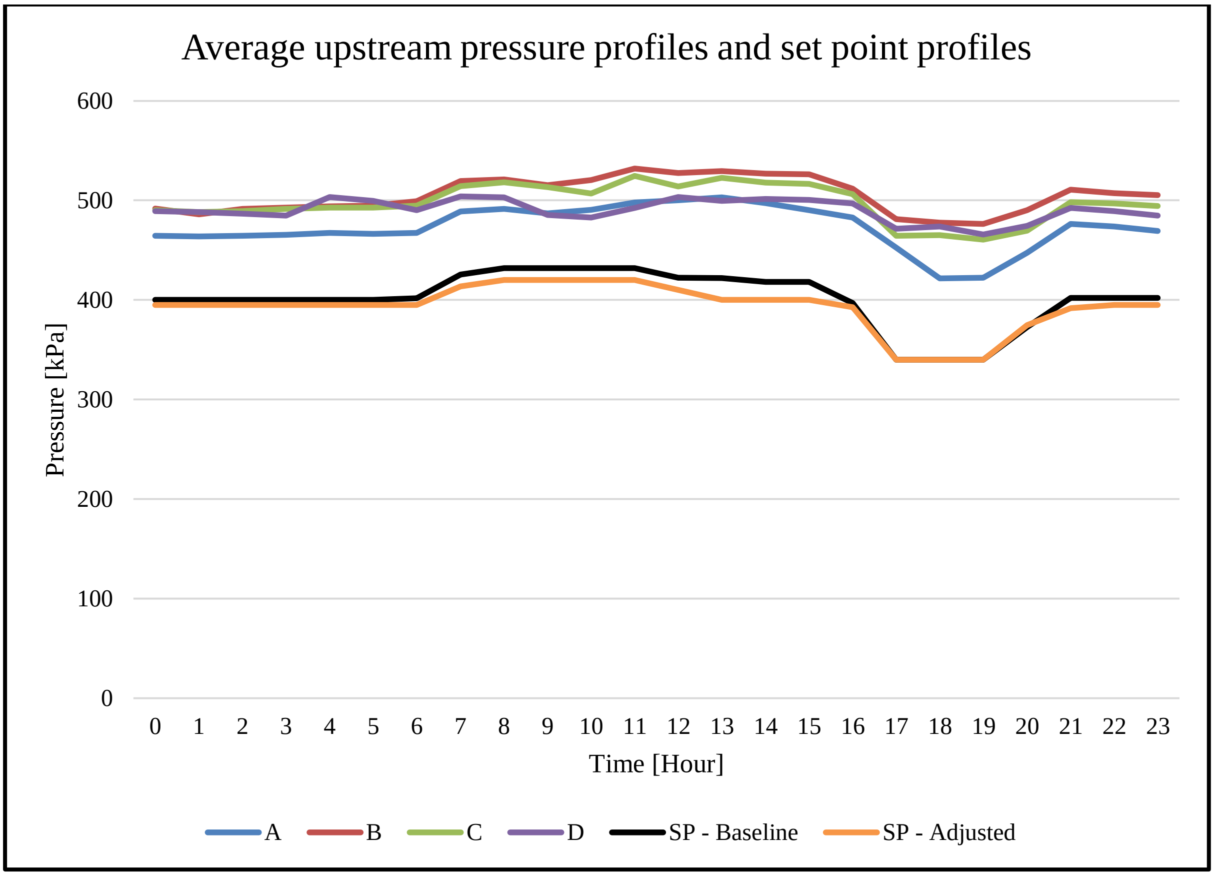


Figure 53: Average upstream pressure profiles of mining levels and pressure set point schedule

Effect on the compressor house delivery pressure

It can be seen from Figure 54 that the pressure profiles of A, B and C almost follow the same profile; Profile D is the exception. The pressure profile of D is lower than the other three profiles for the period from 08:00 to 16:00, because the compressor house set point was adjusted as seen in Figure 53 to deliver almost the same pressure profile on the mining levels as Profile A. The increase in pressure also caused the pressure to be higher during the evening period at the same delivery pressure set point as Profile A during the evening peak period.

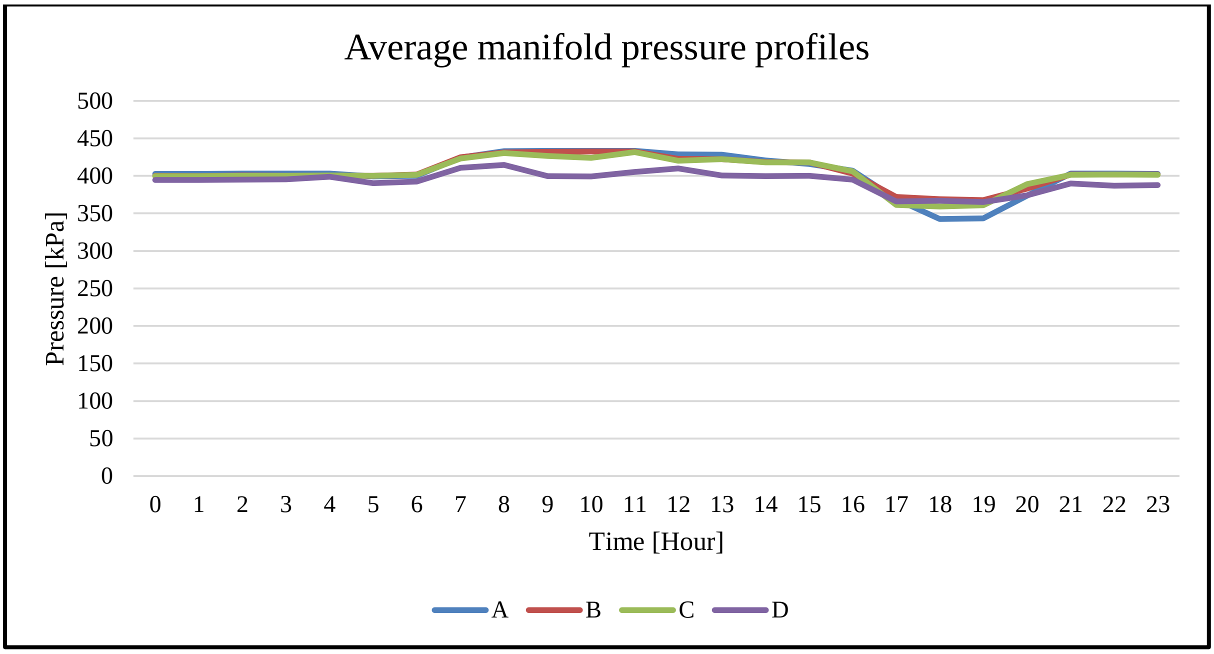


Figure 54: Average compressor house delivery pressure profiles

Effect on 73L airflow

It can be seen from Figure 55 that by fixing the leak at 82L, the airflow of 73L decreased with an average of 21 700 m^3/h from Profile A to Profile B. This is almost the design flow of 21 237 m^3/h for Compressor 3, which is a 2 MW compressor. The airflow profiles of B and C are almost the same. The profile of D indicates the reduction in airflow due to the compressor house set point adjustments.

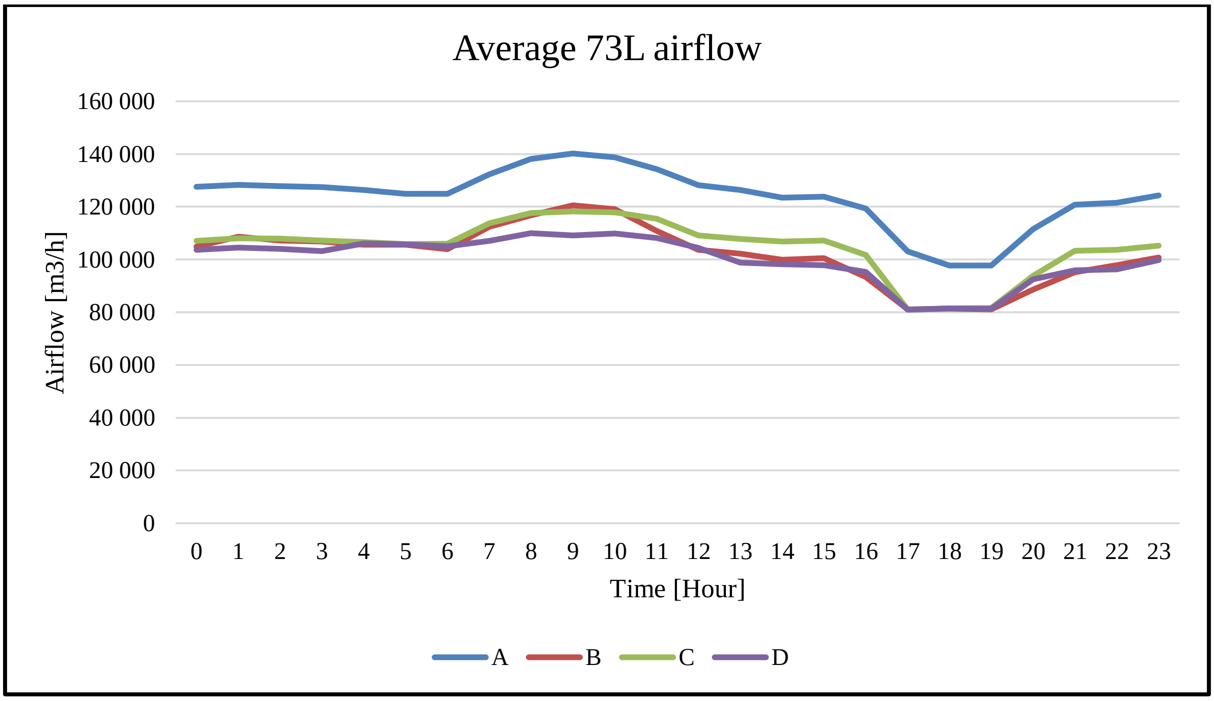


Figure 55: Average 73L airflow

Effect on compressor house total power consumption

As seen in Figure 56, there was an average decrease of 1 727 kW in compressor power consumption from Profile A to Profile B. If this profile was sustained annually, it would realise an annual cost saving of R9.4 million. Unfortunately, the compressor configuration was changed for the maintenance on Compressor 4. It can be seen from Figure 55 that the compressor configurations of Profile B and Profile C have almost the same daily airflow profile, except for the power consumption profile of C being an average of 1 100 kW higher than Profile B.

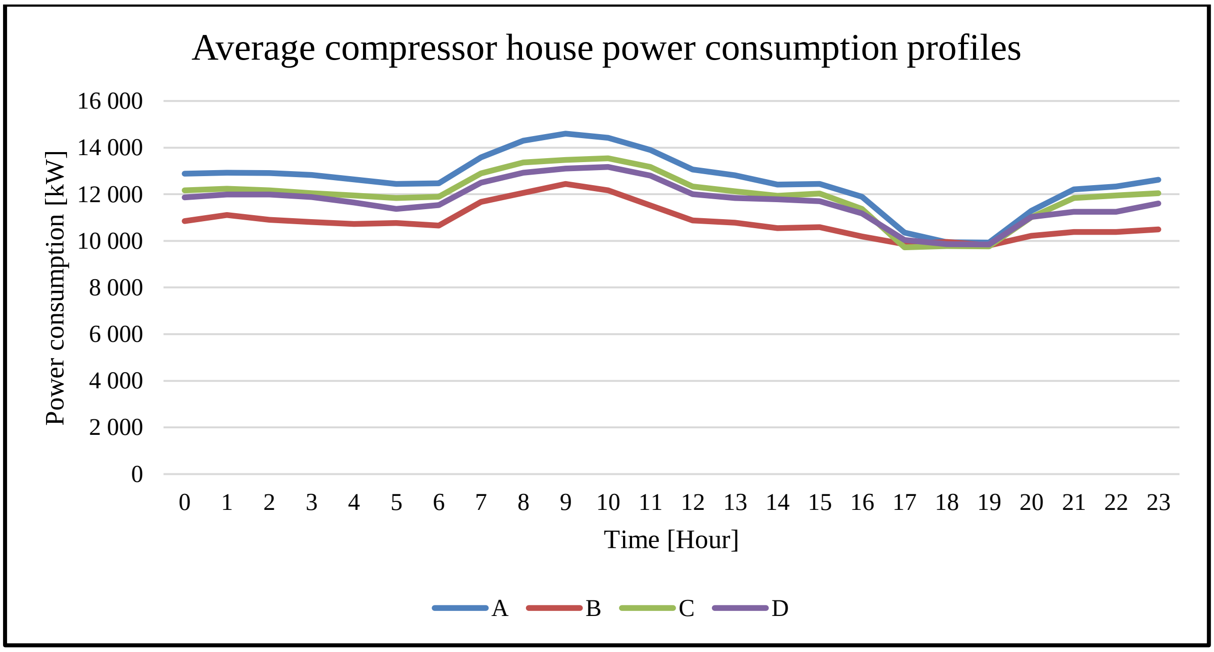


Figure 56: Average compressor house power consumption profiles

If Profile C was sustained for a year, it would realise an annual cost saving of R3.5 million. With the added set point adjustments of Profile D, an additional R1.4 million could be realised. Thus, fixing large leaks that cause pressure losses in the compressed air pipeline can increase compressed air system pressures by 5 % and reduce the power consumption of the compressors. A total saving of 877 kW energy efficiency was achieved, leading to an annual cost saving of R4.9 million while having the same underground pressures as in the past.

4.2.5 Intervention 4: Identifying compressed air leaks

Investigations on the underground compressed air pipe networks can be done by identifying compressed air leaks. According to Section 2.5.2.4, compressed air leaks cause pressure losses in the pipe network and increase compressor power consumption. By fixing leaks (as seen in Section 4.2.4), an annual cost saving of R4.9 million and increase the compressed air system pressures by 32 kPa can be realised.

The approach for efficiently identifying high compressed air consumers and the approach for identifying the compressed air leaks and reporting to mine personnel will be implemented and discussed next.

Efficient approach for leak auditing

In Section 3.3.5, the approach to efficiently identify high airflow areas in the compressed air network was explained. The approach was implemented, displaying the compressed air distribution on surface and in the main shaft in Figure 57. It indicates that the compressor house consumes a daily average of 11 560 kW to produce a daily average of 114 745 m^3/h compressed airflow that costs R166 000 per day. On surface, 4% of air is distributed to surface users; 13% of the airflow is distributed to the main shaft vertical mainline pipe to the levels. The main shaft and surface compressed air consumers therefore consume 17% of the total delivered airflow.

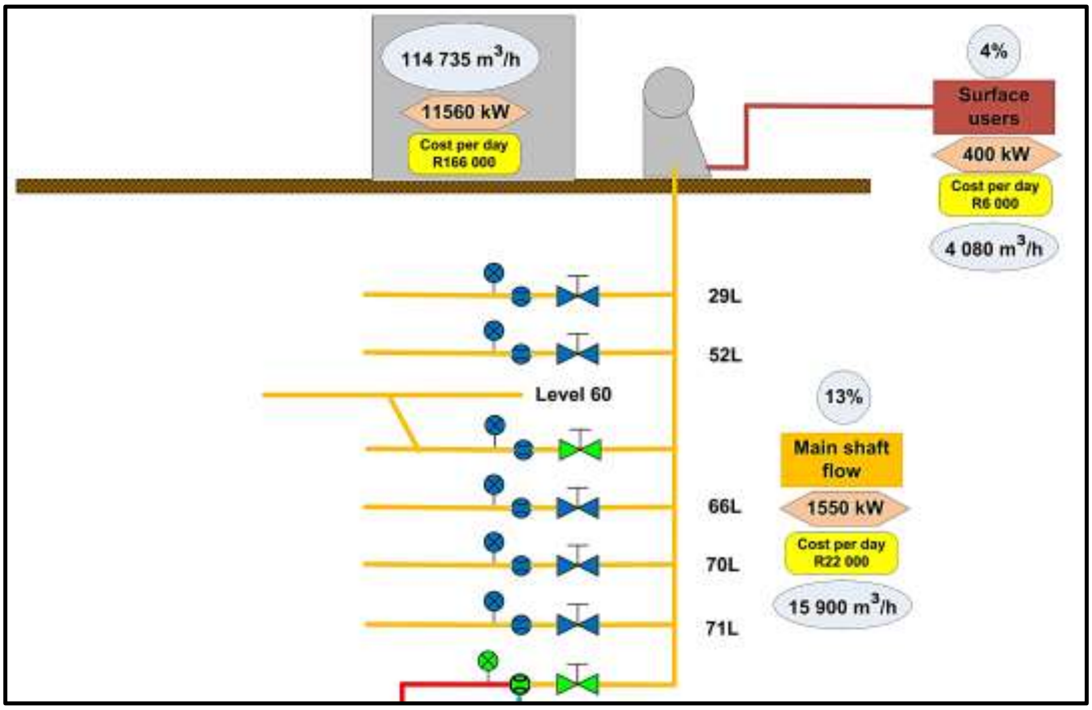


Figure 57: Surface and main shaft compressed air distribution network

The next section was to determine the airflow distribution on the sub-shaft. The daily average airflow measured on 73L was 98 850 m^3/h and the daily total average airflow of the mining levels was 51 245 m^3/h, which was 43% of the total airflow (as seen in Figure 58). The remaining 40% of airflow was at the closed and inactive levels, the vertical pipeline at the sub-shaft and on the mining levels before the airflow meters. If the airflow readings of 88L and 95L are correct, the mine wasted R2.8 million of annual electricity costs for levels that should be closed because they are inactive. This approach narrowed the leak identification process down to firstly focusing on levels from 73L to 98L and the sub-shaft pipe.

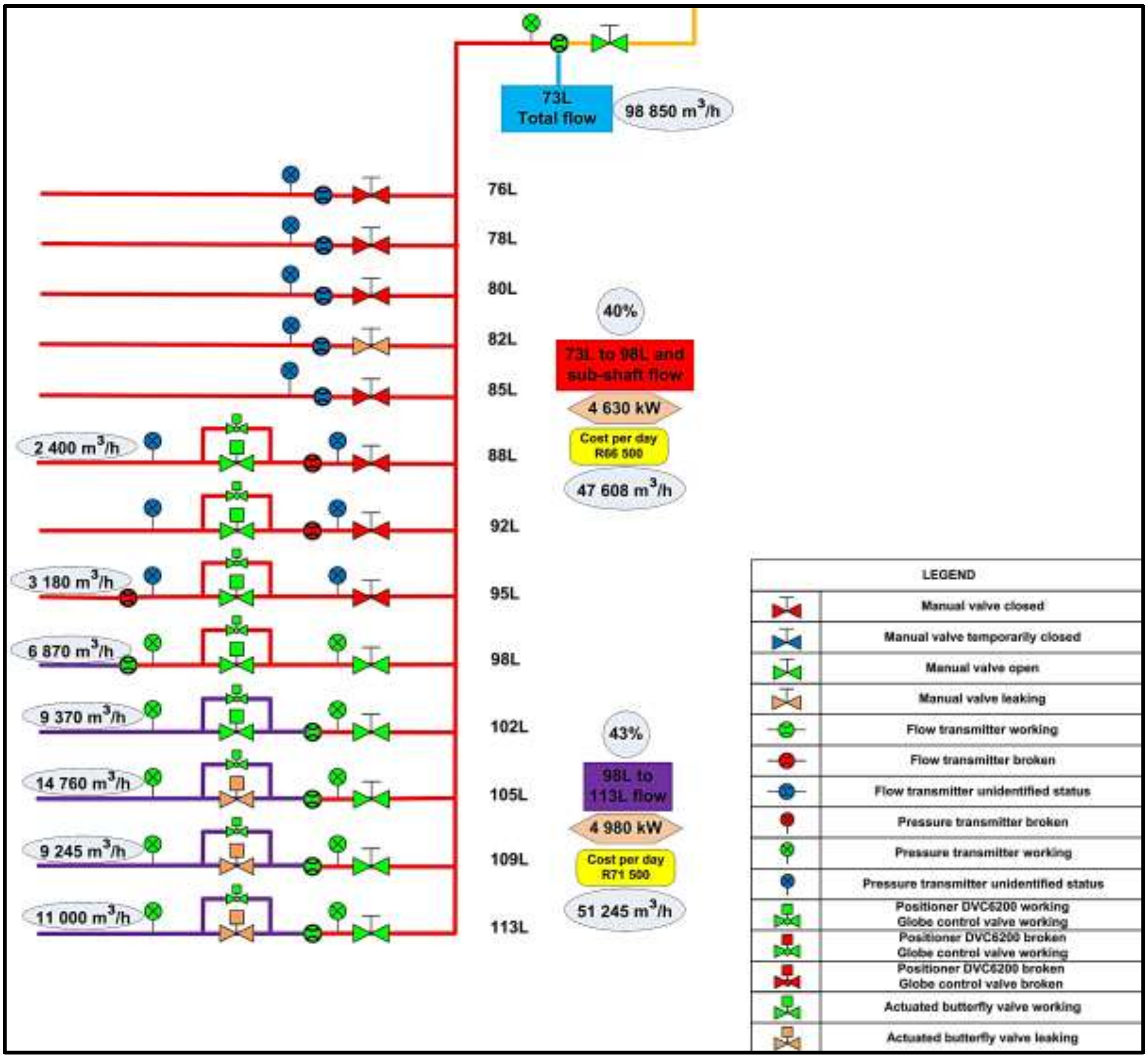


Figure 58: Sub-shaft compressed air distribution network

The approach to identifying the compressed air leaks and reporting to mine personnel is discussed next.

Approach to identifying the compressed air leaks and reporting to mine personnel

The approach to identifying the compressed air leaks were covered in Section 3.3.5 in 11 steps. The first six steps are the approach to leak auditing that will be followed before the day of the actual audit. The last five steps are the approach to the actual leak auditing process. The first six steps were implemented and are discussed below:

1. Compile an underground layout indicating problem levels.
    - The layout was compiled as seen in Figure 57 and Figure 58.
2. Request details from mine personnel regarding heads of the various levels, shafts, etc.
    - The mine personnel who oversee the closed levels and the mining levels are the production engineering team.

- The mine personnel who oversee the shaft are the shaft engineering team.
- The mine person who oversees the compressors is the services engineer.

3. Indicate the underground areas for leak auditing to the responsible mine personnel.
    - The layout as indicated in Step 1 was discussed with both production and shaft engineering teams.
    - Both teams were unaware that so much compressed air was wasted in the closed and inactive sections of the mine.
4. Get all documentation and accessories ready (bright flashlight, camera, notebook, layouts of underground levels).
    - A bright flashlight is necessary to illuminate dark areas, because the standard mining headlight is not bright enough.
    - A camera is required to take pictures of compressed air leaks and everything out of the ordinary. The photos will show the severity of the leaks and will be used in the leak report.
    - A notebook is required to note the level, location, pipe diameter, leak diameter and what can be done to fix the leak.
    - The underground layouts can be found at the mine's surveying section; the drawings can be useful to note the leak's exact location.
5. Organise an underground site visit.
    - After the discussions with the shaft or production engineering team, an underground site visit must be organised. Typically, someone in one of those teams will provide guidance on the levels and in/out the shaft.
6. Study all the levels beforehand.
    - It is important to know the layout beforehand to identify a possible shaft leak at the right level while still in the cage.

Once the pre-auditing checklist was done, the leak auditing process was implemented:

7. While traveling down the shaft, note the leaks in the shaft and the level nearby.
    - While traveling down the main shaft, constant tracking on the levels and listening for shaft compressed air leaks were done and no compressed air leaks were identified.
    - While traveling down the sub-shaft, constant tracking on the levels and listening for shaft compressed air leaks were done. The first stop was at 100L and a large compressed air leak was noted on the mainline pipe flange. The noise was very loud (such as a whistle). Another three shaft leaks between 98L and 95L were identified and noted, which were also noticed due to load whistling noises.

8. At the station, audit the mainline and the refuge bays.
    - The mainline pipe at the stations has a bypass with a large and small valve. These valves were inspected and it was found that the large valves were all closed. The small valves could not be inspected due to the height. One level had a large leak at the bypass small valve.
9. When a leak is identified, take a picture, note the level, location, pipe diameter, leak diameter and what can be done to fix the leak.
    - This process was done according to Step 4.
    - A mobile phone application was used that prompted the user to rename an image after that image was taken. The image was renamed containing all the necessary location and leak data.
10. Develop a leak report when the leak audit is finished.
    - A leak report was developed, which can be seen in Annexure B.
    - A mobile phone camera image title-renaming application was used, which prompted the user to rename new images with leak details. This simplified the development of the report.
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.
    - The leak report was presented to the services engineer, shaft and production engineering teams.

4.2.6 Intervention 5: Optimum valve control philosophies for improved pressure control

As stated in Section 3.3.6, there is an opportunity to increase the pressures on some of the mining levels when a compressor trips during the drilling period. Bypass valves are useful for this initiative to reduce the pressure on some of the levels to redirect the pressure and airflow to the required mining levels. The maximum and medium pressure valve control philosophies developed in Section 3.3.6 were discussed with mine personnel to implement one of these initiatives when a compressor trips during the drilling period to continue mining on some of the mining levels.

The initiatives were approved and mine personnel suggested that a test be conducted on 98L and 113L when a compressor trips. Mine personnel also suggested using the maximum pressure drop-valve control philosophy on the mentioned levels instead of using bypass valves. This is because the current bypass valves close the mainline valve fully and then airflow passes through the bypassed valve, thus reducing the downstream pressure. Thus, closing the airflow fully on 98L and 113L will result in a maximum pressure increase on 102L, 105L and 109L.

On a typical weekday, one of the large compressors tripped at 01:00 causing a large pressure drop on the downstream pressure of the mining levels (as seen in Figure 59). Mine personnel could not get the compressor back online and therefore the initiative was implemented after 07:00. The mainline shut-off valves of 98L and 113L were closed fully and the pressure on those levels reduced to 0 kPa. The pressures of 102L, 105L and 109L increased to above 420 kPa, which is the minimum operating pressure.

Therefore, mining could commence on 102L, 105L and 109L until the compressor was back online. The compressor was back online after 20:00 and the shut-off valves were opened to get the compressed air system back to its usual operating profile. This initiative was therefore proven to be successful as three levels were able to continue with production.

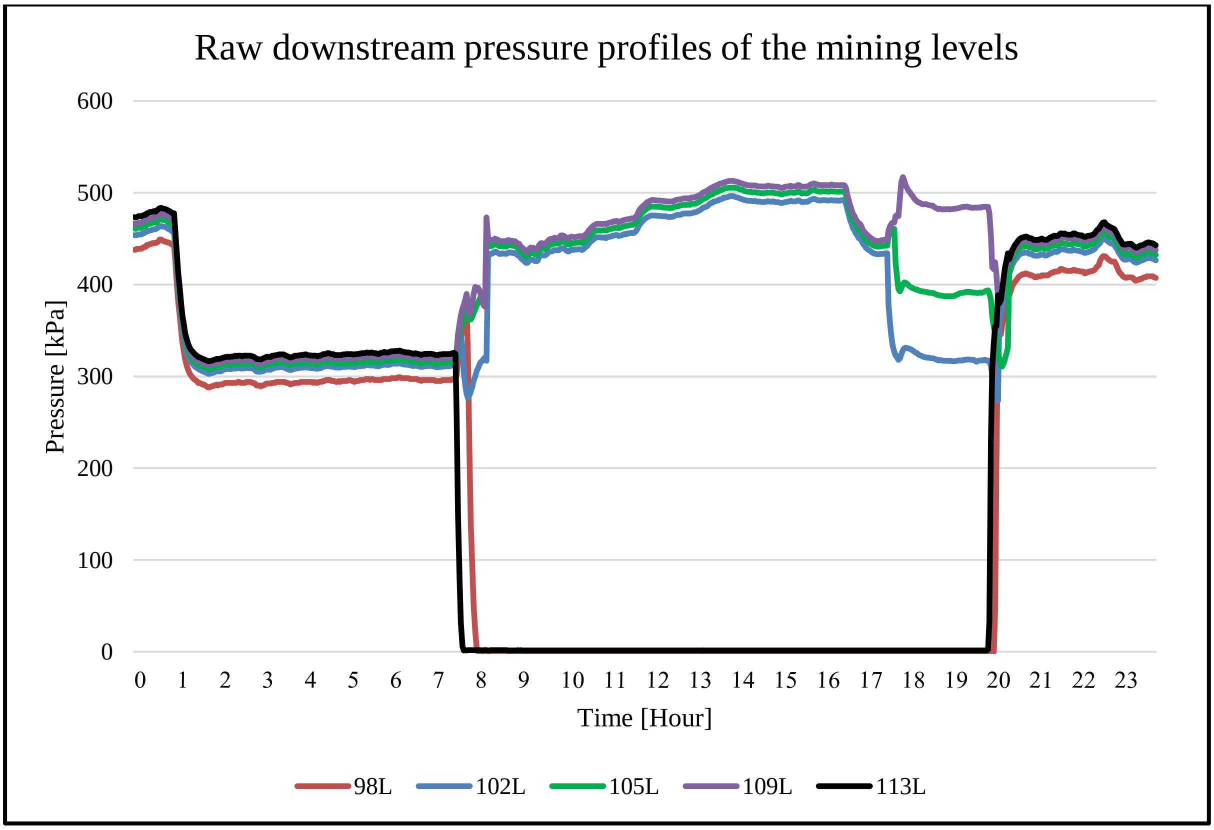


Figure 59: Raw downstream pressure profiles of the mining levels

4.2.7 Intervention 6: Control bypass valve during morning changeover period

As discussed in Section 3.3.7, the bypass valves on the mining levels will be activated to control during the morning changeover period between 04:15 and 06:15. A simulation model was developed to predict the savings when this intervention is implemented. The results of the simulation are seen in Table 18, which will be compared with the actual results that will validate the simulation model. The results are presented in graphs that indicate the compressed air system changes during the control period.

Table 18: Expected power reduction and cost savings for morning changeover bypass valve control

Level	Pressure before [kPa]	Predicted pressure after [kPa]	Pressure reduction [kPa]	Simulated flow reduction [m³/h]	Simulated power reduction [kWh]	Expected annual cost savings
98L	468	275	193	2 726	627	R193 000
102L	480	340	140	2 195	456	R140 000
105L	488	432	56	1 594	364	R112 000
109L	460	328	132	2 697	524	R161 000
113L	503	454	49	2 817	471	R145 000

Implementation of intervention and results

This section discusses the changes to the compressed air system for the controlled period of the bypass valves during the morning changeover period. The bypass valves of 98L, 102L, 105L and 109L are controlled between 04:15 and 06:15. The demonstration of the compressed air system changes will be discussed for 98L as an example.

It can be seen from Figure 60 that when the bypass valves are controlling, the airflow and pressure decrease and stabilise after 15 minutes. The upstream pressure therefore increases when the bypass valves control, because the mainline valve is closed during the bypass valve control period. The increase in upstream pressure builds up pressure in the mainline pipe up to the compressor manifold pipe. As soon as the control on the bypass valves are deactivated, the process reverses.

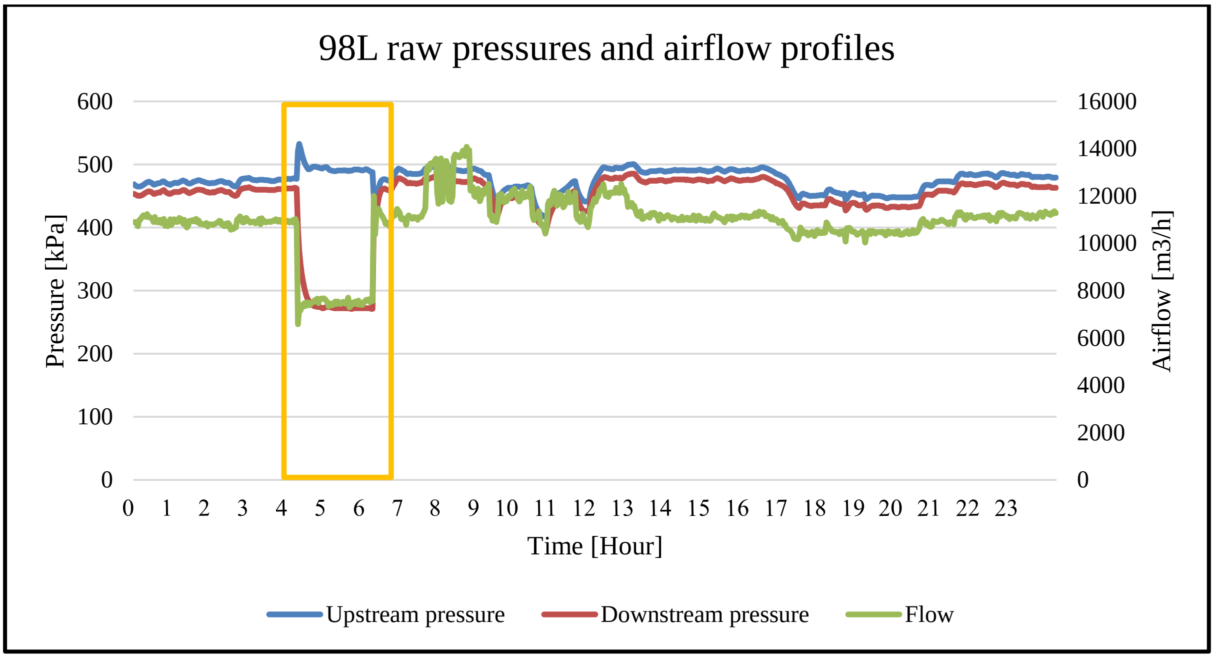


Figure 60: 98L detail pressure and airflow profiles

As discussed earlier, when the bypass valves are controlling, they cause the upstream pressures to increase – leading to a pressure built-up in the mainline pipe, causing the manifold pressure to increase over the set point. The compressor house power output reduces through inlet guide vane control to reduce the overpressurised manifold pressure to match the set point. As soon as all the bypass valves are disabled and the airflow increases, it causes a large pressure drop, causing the compressor house to increase power consumption to increase the manifold pressure to match the set point.

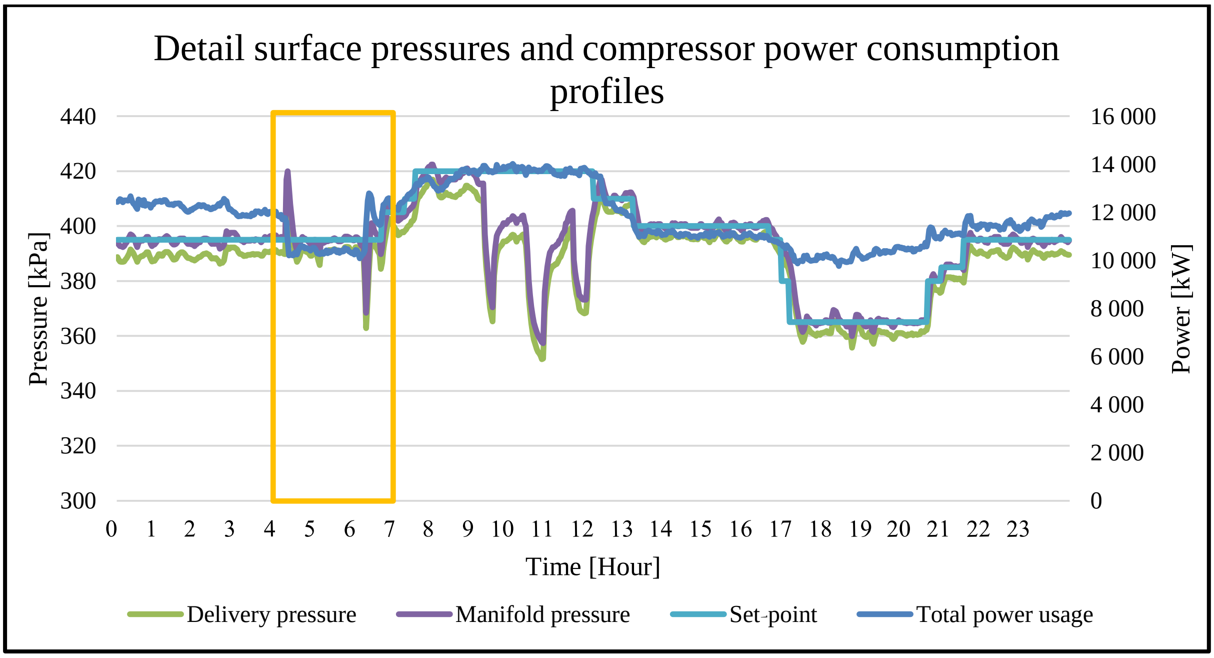


Figure 61: Detail surface pressure and compressor power consumption profiles

It can be seen from Figure 62 how the inlet guide vanes of the compressors changed positions during the bypass valve control period. All the compressor's inlet guide vane positions close and stabilise when the manifold pressure and set point match. When the bypass valves control was disabled and the manifold pressure dropped, the inlet guide vanes of the compressor opened to increase the airflow and build pressure in the mainline to match the manifold pressure with the delivery pressure set point. The inlet guide vanes then opened and closed to stabilise the manifold pressure to the set point.

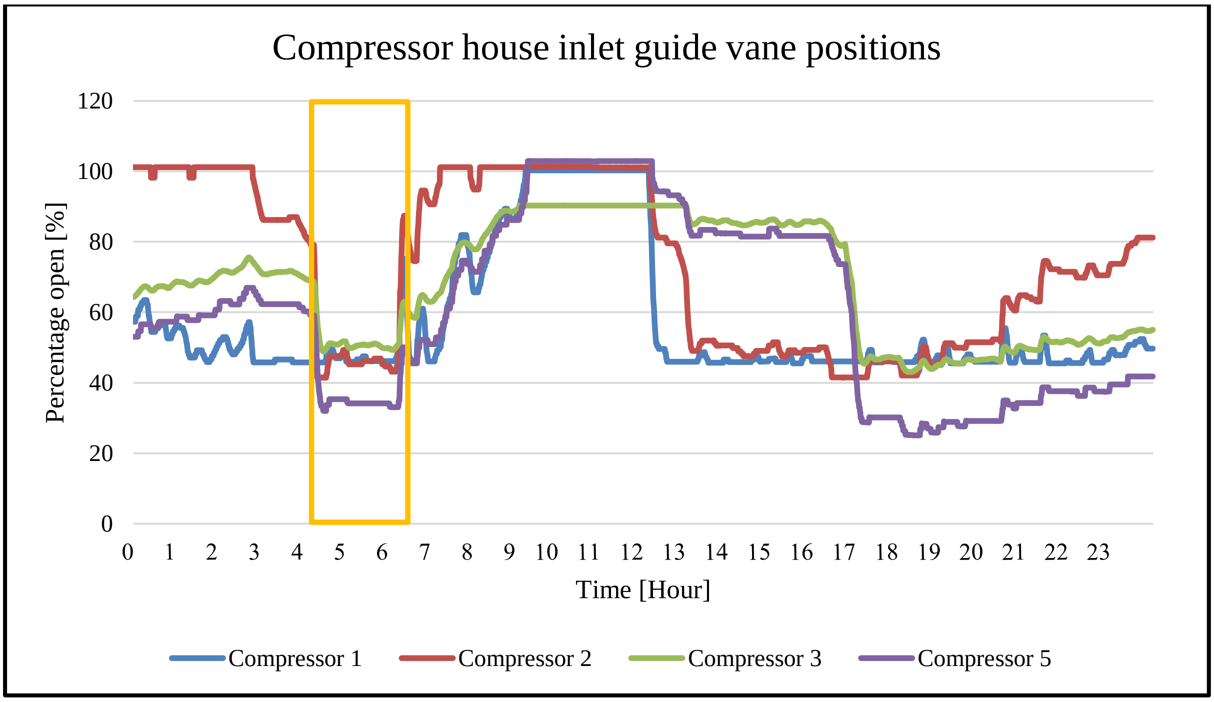


Figure 62: Compressor house inlet guide vane positions detail profiles

The simulation predicted an average power reduction of 1 970 kWh if the bypass valves on 98L, 102L, 105L and 109L controlled. During the actual implementation, an average power reduction of 1 754 kWh was achieved. The accuracy of the simulation and the actual results is 89%. If this profile is sustained for a year at the 2016/2017 tariff, the annual savings would be R540 000.

4.2.8 Intervention 7: Offloading a compressor during evening peak period

Section 3.3.8 stated that other compressors will increase their output to compensate for offloading a compressor; however, there is not a strategy preventing other compressors from increasing power output during the offloading period. A compressor offloading test will be conducted during the evening peak period. The results will be explained in detail on how the compressed air system reacted during the compressor offloading period. From the results obtained, control philosophies will be proposed to prevent other compressors from increasing their power output and maximising the peak-clipping savings.

An offloading test was conducted on the compressed air system of Mine X during Eskom's evening peak period between 18:00 and 20:00. The aim of the test was to offload Compressor 5 in the compressor configuration of C1-C2-C4-C5. The delivery set point was lowered during the test to determine if the delivery pressure set point should be lower for a compressor offloading period. The compressed air system results of the offloading test were compared with typical compressed air system profiles prior to the test, which is referred to as the baseline.

As mentioned, the delivery pressure set points were lowered during the test, therefore the results are divided into Block A–Block E (see Figure 64):

- Block A is when Compressor 5 is offloaded;
- Block B is the first set point drop;
- Block C is the second set point drop;
- Block D is the last set point drop; and
- Block E when the compressor is loaded again.

Therefore, Block B, Block C and Block D will be referred to as the set point drop periods. As seen from Figure 63, Compressor 5 is offloaded, which results in an average power reduction of 800 kW, stabilising at 1 400 kW.

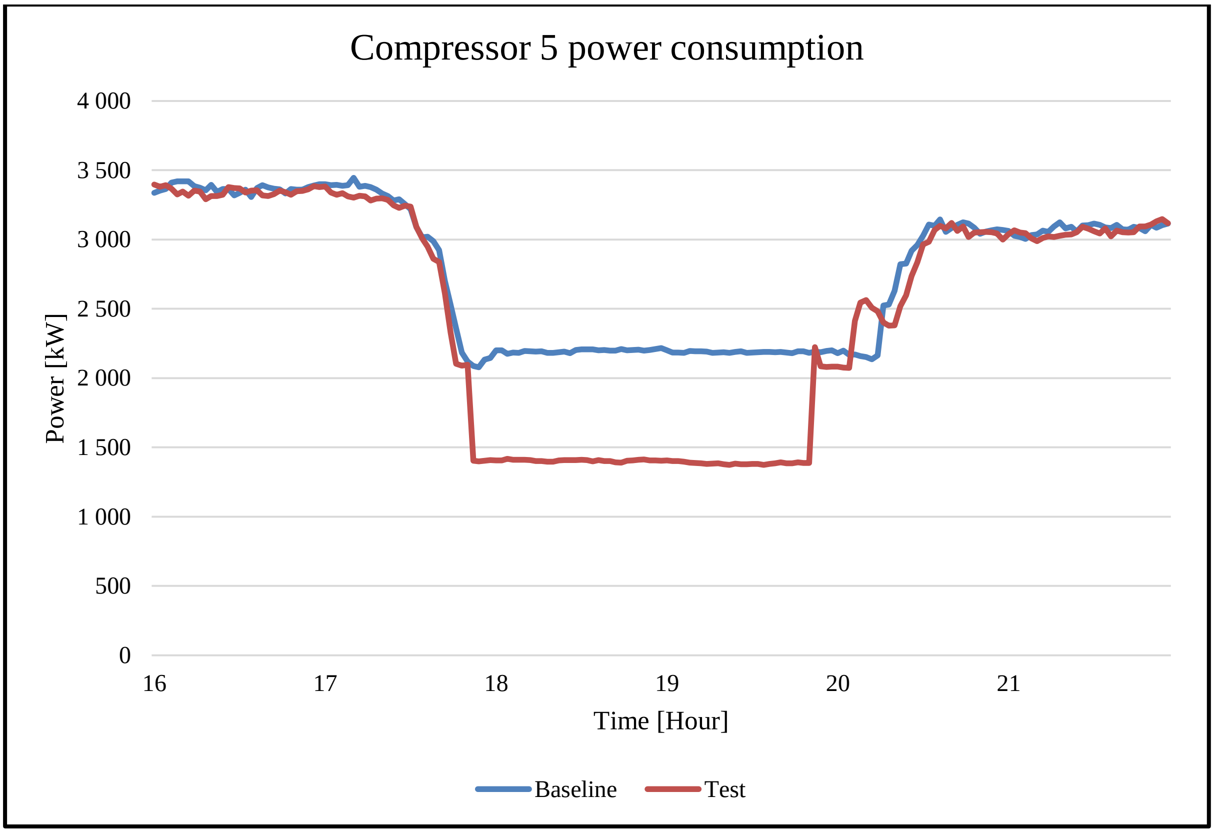


Figure 63: Compressor 5 power consumption during offloading test

The offloaded compressor caused the other compressors to increase their power consumption (as seen in Figure 64**Error! Reference source not found.** in Block A) to compensate for the loss of airflow and pressure. The average baseline power consumption is 9 850 kW; if the set point was not reduced at Block B, the power consumption would likely have remained at 10 400 kW. Thus, offloading the compressor increased the power consumption on the same delivery set point. The delivery set point was then lowered with 40 kPa at Block B to decrease the power consumption.

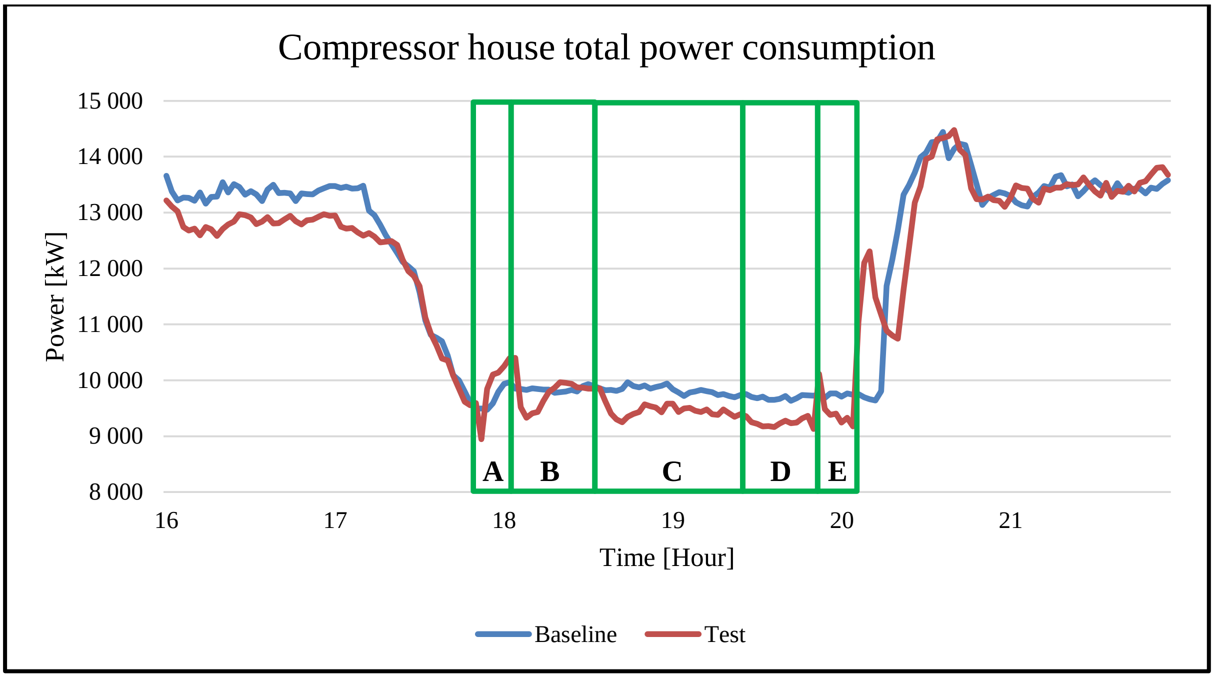


Figure 64: Compressor house total power consumption during offloading test

By reducing the delivery pressure set point, the power consumption reduced to the power consumption of the baseline of 9 850 kW. It clearly shows that during compressor offloading, the delivery pressure must also be lowered and not be kept on the normal set point when a compressor is not offloaded. The set point was further reduced with 10 kPa in Block C. This further reduced the power consumption to 9 550 kW. With a total set point reduction of 50 kPa, additional power savings of 300 kW can be achieved.

The set point was further reduced with 5 kPa in Block D. This further reduced the power consumption to 9 250 kW. With a total set point reduction of 55 kPa, additional power savings of 550 kW can be achieved. The compressor was loaded again in Block E and soon afterwards it continued with the normal set point schedule. All the compressed air system figures can be seen in Annexure D.

The power profiles of the compressors were investigated to see if there was potential to lower the power reduction even further. As seen in Figure 65 at Block E, Compressor 4 could further reduce the power consumption by 100 kW to meet the baseline; Compressor 2 had the potential to reduce by 250 kW. To achieve the additional saving, the set point had to be reduced further with an assumed additional pressure drop of 35 kPa. Thus, to achieve the maximum power reduction of this offloading test, the set point had to be reduced from 320 kPa to 230 kPa to gain an additional power saving of 900 kW and annual cost saving of R700 000. If the set point was not reduced, it would have had negative results on the power savings.

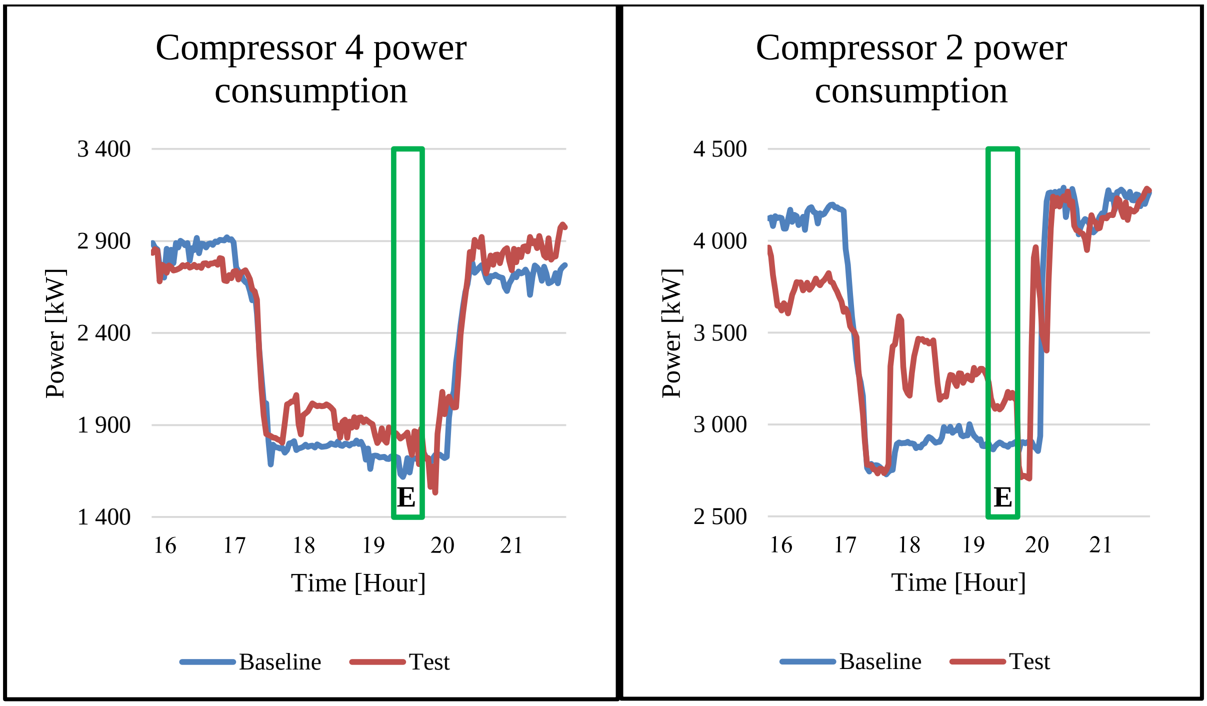


Figure 65: Evening peak period power consumption of Compressor 4 and Compressor 2

The effect that offloading Compressor 5 had on the mining levels was that the upstream pressures reduced with 70 kPa – as seen in Figure 66 at Block E with a total set point reduction of 55 kPa. This means that if the set point was reduced further with 35 kPa, it would reduce to upstream pressure on 98 L to 270 kPa, which was still an acceptable pressure. The upstream pressure on 113L would be 300 kPa. Offloading Compressor 5 and reducing the set point from 320 kPa to 230 kPa during the compressor offloaded period would have the maximum power reduction and the pressures underground would still be acceptable.

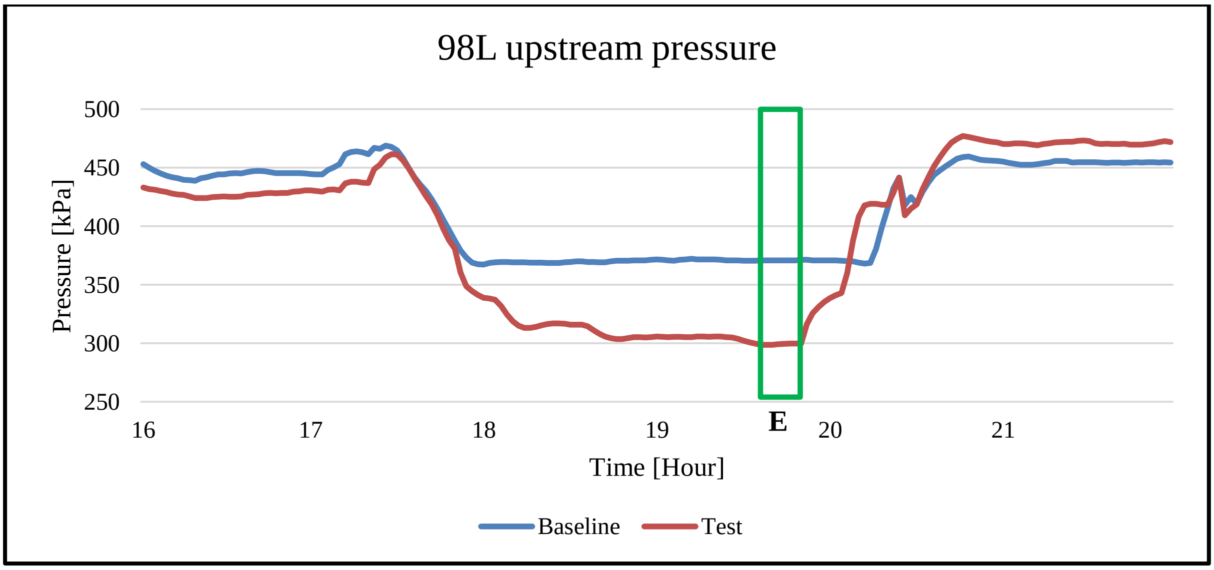


Figure 66: 98L upstream pressures during compressor offloading test

During the offloading period of Compressor 5 and the last delivery set point change in Block E (as seen in Figure 67), the baseline guide vane position of Compressor 2 was already at its minimum. During the test period, the guide vane angle was almost at minimum. This gives scope to reduce the delivery pressure set point so that the compressors can reach their minimum guide vane positions. This leads to the possibility to control the guide vane positions of each compressor and limiting them from opening during compressor offloading periods.

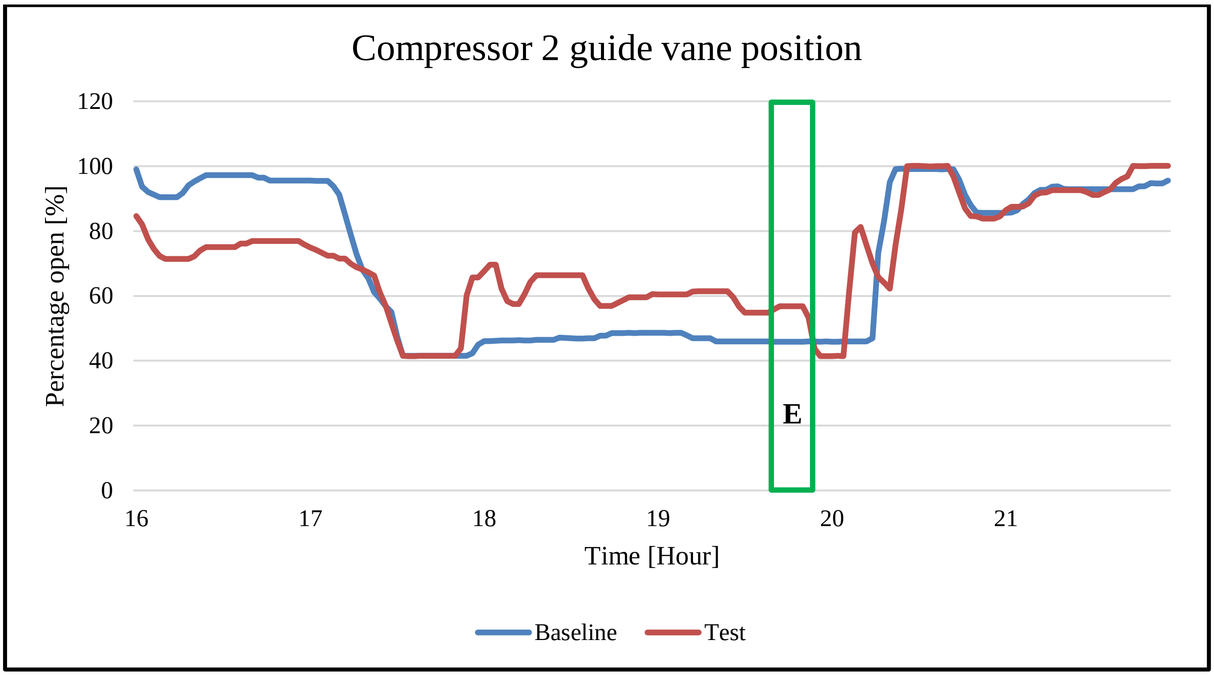


Figure 67: Guide vane angle of Compressor 2

From the results, it is evident that two control philosophies have been identified that can be implemented to increase power savings and to ensure that other compressors will not increase their power output during the compressor offloading period, thus negatively influencing the purpose of offloading a compressor. The two control philosophies are the following:

Decrease delivery pressure set point for the compressor offloading period

If there are no guide vane position controls available in the energy management system, the delivery pressure set point can be reduced to maximise the power reduction during the compressor offloading period. As mentioned during the compressor offloading test, if the set point remained unchanged, it would have a negative impact on peak clipping and a negative annual cost saving of R630 000 because the other compressors would have increased their power output to compensate for the offloaded compressor. Therefore, the delivery pressure set point was reduced. The proposed set point was 230 kPa. As seen in Table 19, the proposed control philosophy would realise an additional power reduction of 900 kW and an annual cost saving of R730 000.

Table 19: Effect of delivery pressure set point has on power savings for offloading compressor 5

Description	Delivery pressure set point [kPa]	Average total power consumption during peak clipping [kW]	Additional peak clipping impact [kW]	Additional annual cost saving
Baseline	320	9 850	0	0
Offload (Test)	320	10 400	–550	–R650 000
Offload (Proposed)	230	8 950	900	R730 000

Historical data was used to determine the power reduction when Compressor 1 was offloaded. It was found that the compressor had a minimum power consumption of 3 000 kW. During the offloading period, the power reduced to 600 kW. This is a 2 400 kW power reduction. If Compressor 1 was the chosen compressor for offloading purposes with the proposed delivery pressure set point of 230 kPa, it would have an additional peak-clipping impact of 2 400 kW and annual cost saving of R1.95 million.

A simplified control philosophy for the proposed intervention was developed and is seen in Figure 68. When a compressor is offloaded at a specific delivery pressure set point, the guide vane position of the running compressors must be monitored. The aim is to reduce the power consumption further in the evening period, therefore, the power consumed must not be higher. Thus, the guide vanes must be monitored to see if they opened when the compressor was offloaded.

If the guide vanes of the compressors opened, then the delivery set point can be reduced until the point when the guide vanes of all the running compressors are at their minimum positions. The reduced delivery set point can be used for the next offloading day to ensure maximum savings from the start.

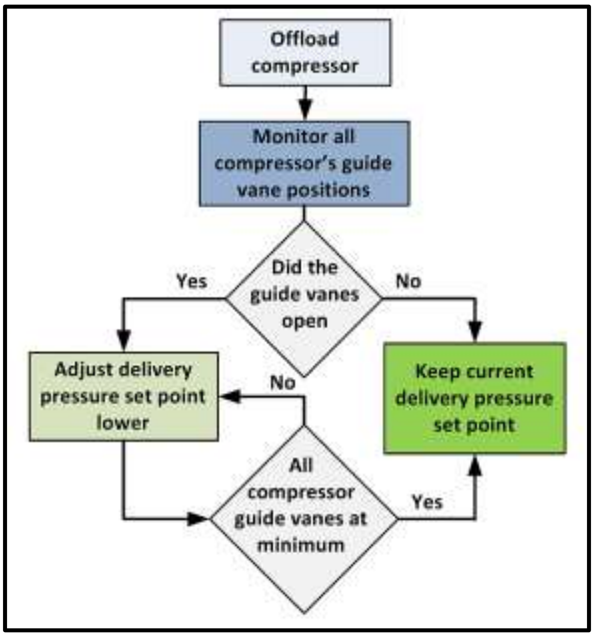


Figure 68: Delivery pressure set point adjustment control philosophy for compressor offloading

Compressor inlet guide vane position control philosophy for compressor offloading

The purpose of this control philosophy is to keep the running compressors guide vane positions on a specified minimum guide vane position during the compressor offloading period. The guide vanes are then forced to keep a certain position when a compressor is offloaded to ensure that the running compressors do not increase their power output. To implement this control philosophy, the energy management system must be able to control the guide vane positions of the compressors.

The energy management system must have a controller to control the compressor's guide vane positions according to a schedule with guide vane position set points as seen in Table 22. An operator must provide a schedule and enable the control for the specified schedule. For example, the controller will only be able to control the guide vanes of Compressor 1 from 17:30 to 20:15 at a guide vane position of 46%.

Table 20: Compressor guide vane position controller for compressor 1

Schedule	Enable control	Guide vane position [%]
00:00 to 17:30	0	
17:30 to 20:15	1	46
20:15 to 00:00	0	

Historical data was used to define the minimum guide vane angles, minimum power and offloading power consumption of each compressor, which can be seen in Table 21. The data will be useful to know what minimum guide vane position value can be used in the controller for each compressor. By using the compressor guide vane position controller, it will ensure that the compressors keep their guide vane positions during the compressor offloading period. The expected upstream pressure profiles on the mining levels of the control philosophies can be seen in Annexure D.

Table 21: Power consumption of compressors at minimum guide vane angle and offloaded state

Description		Comp 1		Comp 2		Comp 3		Comp 4		Comp 5	
Conditions	Guide vane (GV) position	GV [%]	Power [kW]	GV [%]	Power [kW]	GV [%]	Power [kW]	GV [%]	Power [kW]	GV [%]	Power [kW]
Offload	0	0	550	0	NV	0	NV	0	NV	0	1 400
Peak clipping	Min	46	2 900	46	2 900	39	1 750	37	1 750	20	2 200

4.3 Interpretation of results

This section interprets the results found in Chapter 4. Automatic control on valves requires a pneumatic or electric actuator and a positioner that controls the valve’s position. The positioner uses compressed air and a water trap preventing moisture passing through to the positioner. Water must be drained from the water traps regularly to prolong the service life of the positioners. When a positioner is faulty, significant operating costs savings are lost. It is therefore important to choose a rugged positioner and constantly drain water from the water traps.

Compressor house delivery pressure set point control is probably one of the best initiatives for improving the energy efficiency compressed air systems. It is important that the schedule of the delivery pressure set point control always meets the pressure demand on surface and underground. Another great advantage of this case study’s compressed air network is that the gold plant has its own compressors, therefore, the mine does not have to supply compressed air to the gold plant. It gives scope for using the delivery pressure set point controller to conduct evening peak clipping.

This is done by reducing the delivery pressure set point to force the guide vane positions of the compressors to operate at minimum position and minimum power consumption. This is a very sustainable way of conducting evening peak clipping, because the power will constantly reduce to the minimum. By peak clipping with bypass valves, there are pressure build-ups in the pipe network and the control may be disabled, which influences the impact of the savings negatively.

Probably the greatest factors influencing compressed air energy efficiency and service pressure on the mining levels are recovering pressure losses and fixing large leaks in the compressed air network. These factors have a direct impact on the delivery pressure of the compressors. Recovering pressure losses and fixing large leaks caused the pressures on the mining levels to increase with an average of 32 kPa and a large reduction in power consumption was evident. By recovering the pressure losses, the compressor house delivery pressure set point was lowered to the surface minimum demand pressure, further increasing the energy efficiency of the compressed air network.

As leaks are large contributors to decreasing compressed air energy efficiency, a time effective strategy was developed and tested. It is important to firstly identify the compressed air distribution network and determine the locations that require leak auditing. In the case of Mine X, the problem locations were at the non-production side and closed levels. The closed levels were never fully blanked off. Therefore, it is important to identify high air-consuming locations, note all the leaks and report the high priority leaks that must be fixed as soon as possible, because leaks cause unwanted pressure losses and decrease compressed air energy efficiency.

Bypass valves on the mining levels are useful for improving the energy efficiency of a compressed air system. It can be used for evening and morning peak clipping during the changeover period of miners, because only enough pressure is required for the refuge bays. It was discovered that the bypass valve and mainline valve require a positioner so that the energy management system can have full control over these valves for optimum daily pressure control. The bypassed pipe diameter must be designed to deliver pressure that is near the required pressure. Then the bypass valve can be used to reduce the pressure to desired pressure set point.

A positioner is also required on the mainline valve to reduce the pressure of the overpressurised level to the demand pressure. This will also contribute to increasing the energy efficiency of the compressed air system. By having full control of the bypass valve, it can be useful to help the mine when a compressor trips during the drilling period. The valves can be used to shut certain levels off to force the airflow to the desired mining levels. The energy management system does not have full control over the bypass valves and the shut-off valve. The initiative was put into practice when a compressor tripped at the mine.

The pressure dramatically increased and the desired mining levels could continue with drilling. Three different control philosophies were developed for maximum-, medium- and low-pressure drop control situations. To put all three control philosophies into practice, it is therefore important to have full control of the mine’s bypass valve, mainline valve and shut-off valve. It is therefore important for a deep level mine to have bypass valves installed on their mining levels and to have full control over these valves. The valves will aid in improving their compressed air energy efficiency as well as preventing production losses on some of the mining levels, where previously all the levels would have been affected when a compressor tripped during the drilling period.

Compressor offloading is another initiative that can contribute to power reduction during the evening peak clipping period. Literature states that the power consumption of other compressors will increase when a compressor is offloaded. This is true; it had a negative impact on peak clipping when the delivery pressure set point was not reduced during the compressor offloading test. Therefore, if a compressor should be offloaded, the delivery pressure set point must either be reduced or there should be a guide vane position controller in the energy management system that will keep the guide vane positions of the other compressors at minimum.

Thus, two control philosophies were developed to maximise the energy savings during compressor offloading. The delivery pressure set point must be reduced or the guide vane positions of the other compressors must keep their minimum guide vane position. This will have the maximum impact. It should be noted that when offloading a compressor and implementing either one of two control philosophies, the pressure of the compressed air system will be up to 90 kPa lower. Thus, these philosophies should only be implemented if the compressed air system does not require high surface pressures during the evening peak period.

4.4 Verifying additional savings

To verify the results of the improved compressed air system of Mine X, three-month average optimised profiles were developed after all the initiatives had been implemented. By fixing leaks and recovering pressure losses in the compressed air network, the compressor house delivery pressure set point could be adjusted (as seen in the Figure 69). The delivery pressure set point was lowered and adjusted more evenly throughout the day – by starting to reduce the pressure at 16:00 for evening peak clipping and increasing the pressure to meet the demand from 21:00.

The actual delivery pressure profile follows the same profile as the set point. It can be seen that during the drilling period there is a smaller pressure drop than for the baseline profile. With this current set point schedule, no complaints occurred. This validates the profile as successful.

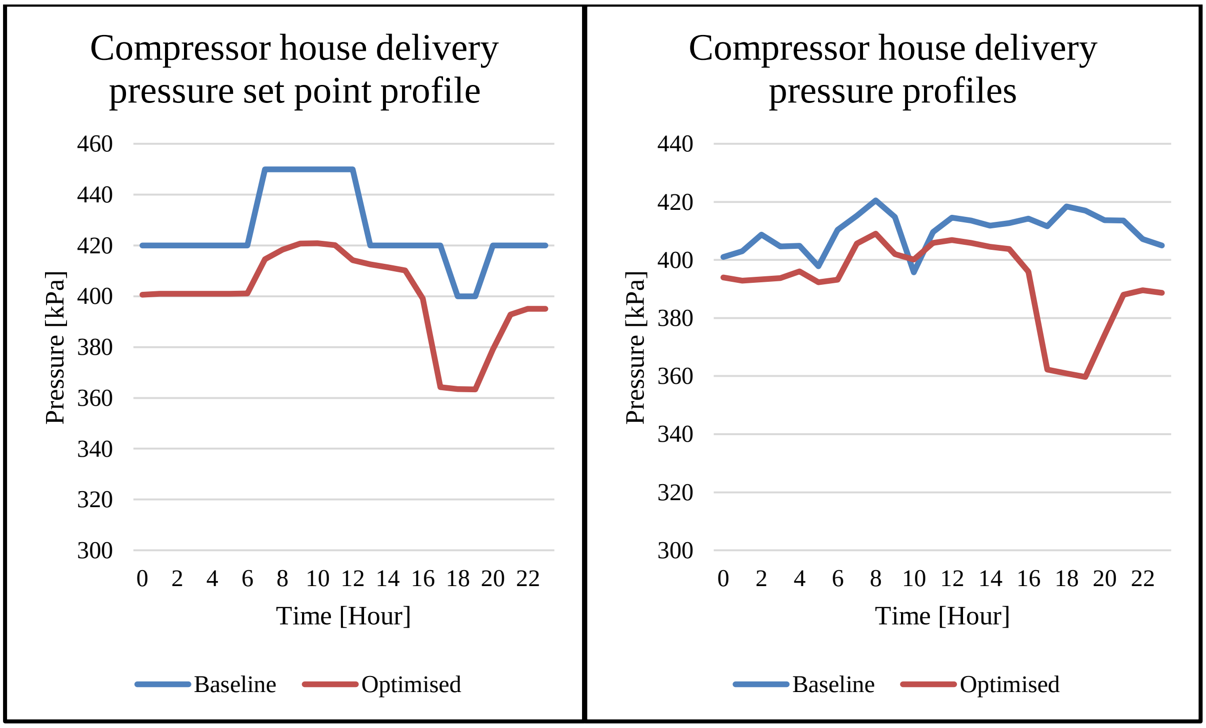


Figure 69: Compressor house delivery pressure set point and actual delivery pressure profiles

By enabling the bypass valves during the morning changeover period from 04:00 to 06:15, it reduced the airflow as seen in Figure 70. This caused additional power savings of 1.3 MWh that contributed R400 000 annual cost savings to the total energy efficiency of the compressed air system.

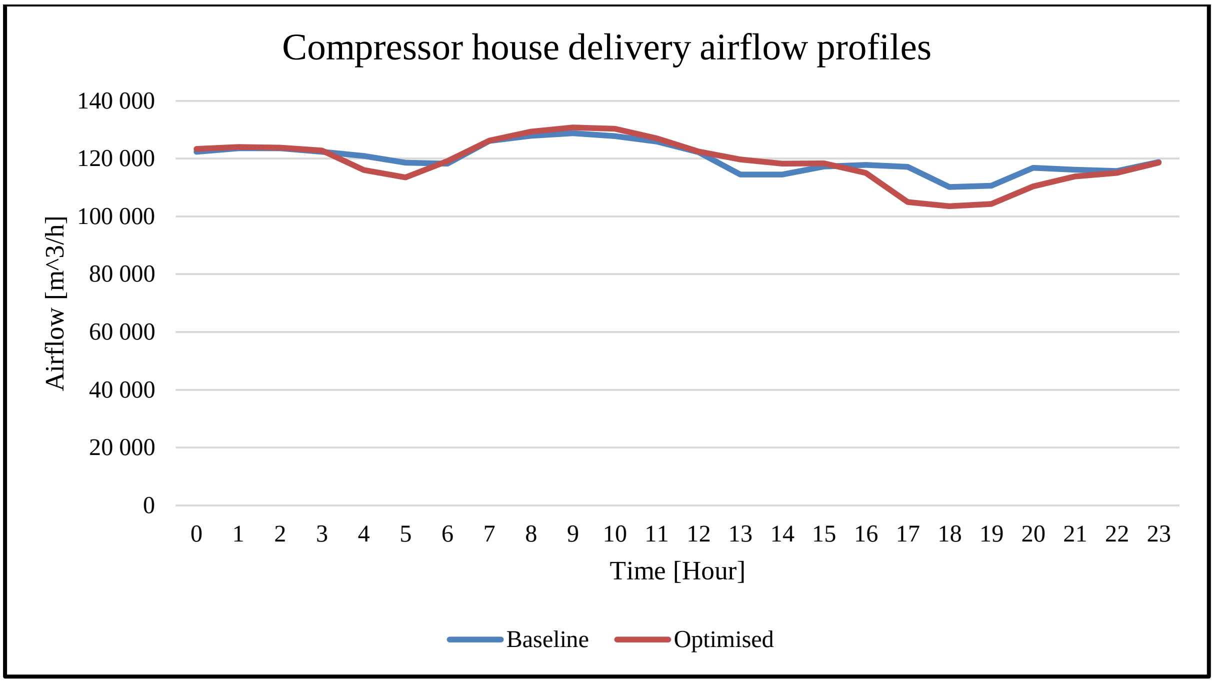


Figure 70: Compressor house delivery airflow profiles

As discussed, all the implemented initiatives – such as fixing leaks, recovering pressure losses in the compressed air network, lowering the overall compressor house delivery pressure set point, doing evening peak clipping and morning changeover peak clipping – resulted in an overall average energy efficiency of 1 350 kWh and annual cost saving of R8 million.

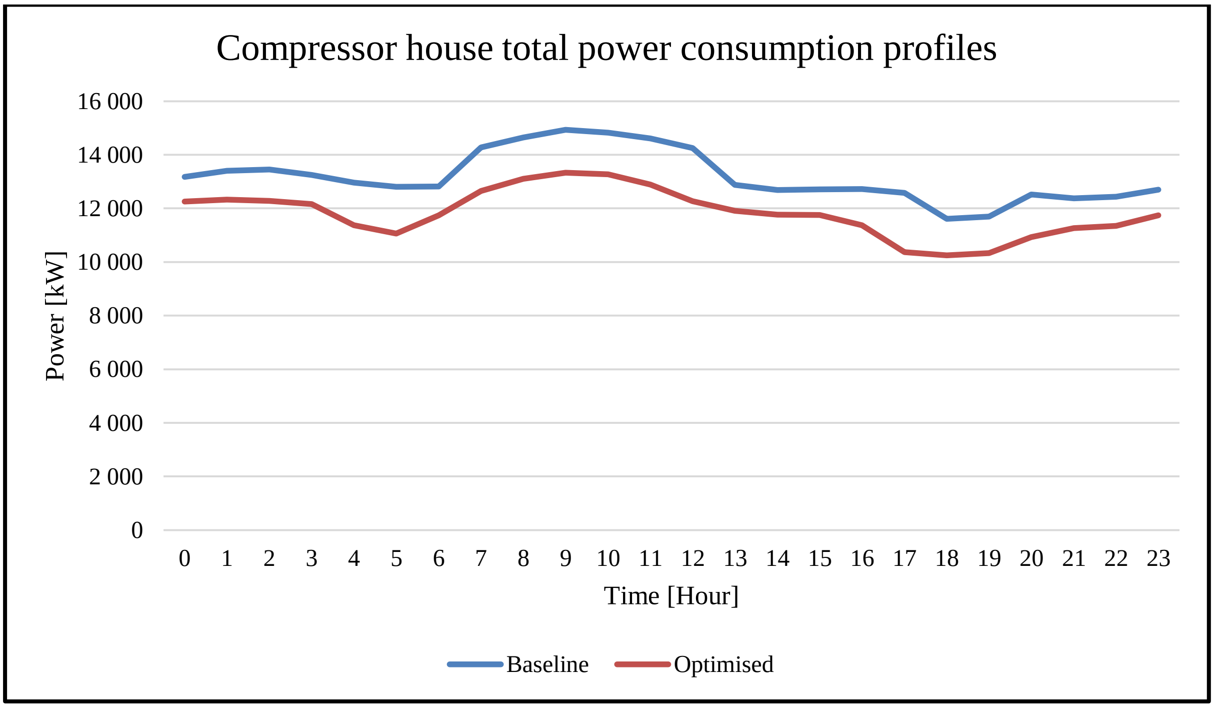


Figure 71: Compressor house total power consumption profiles

The optimised compressed air system reduced the power consumption of the compressed air system, while still having the same pressure during the drilling period until the blasting period at 16:00 when the delivery pressure set point was adjusted. It is therefore important to constantly improve the compressed air network to retain the same underground pressures and sustain the improved power profile. (The individual downstream profiles of the mining levels are seen in Annexure E.)

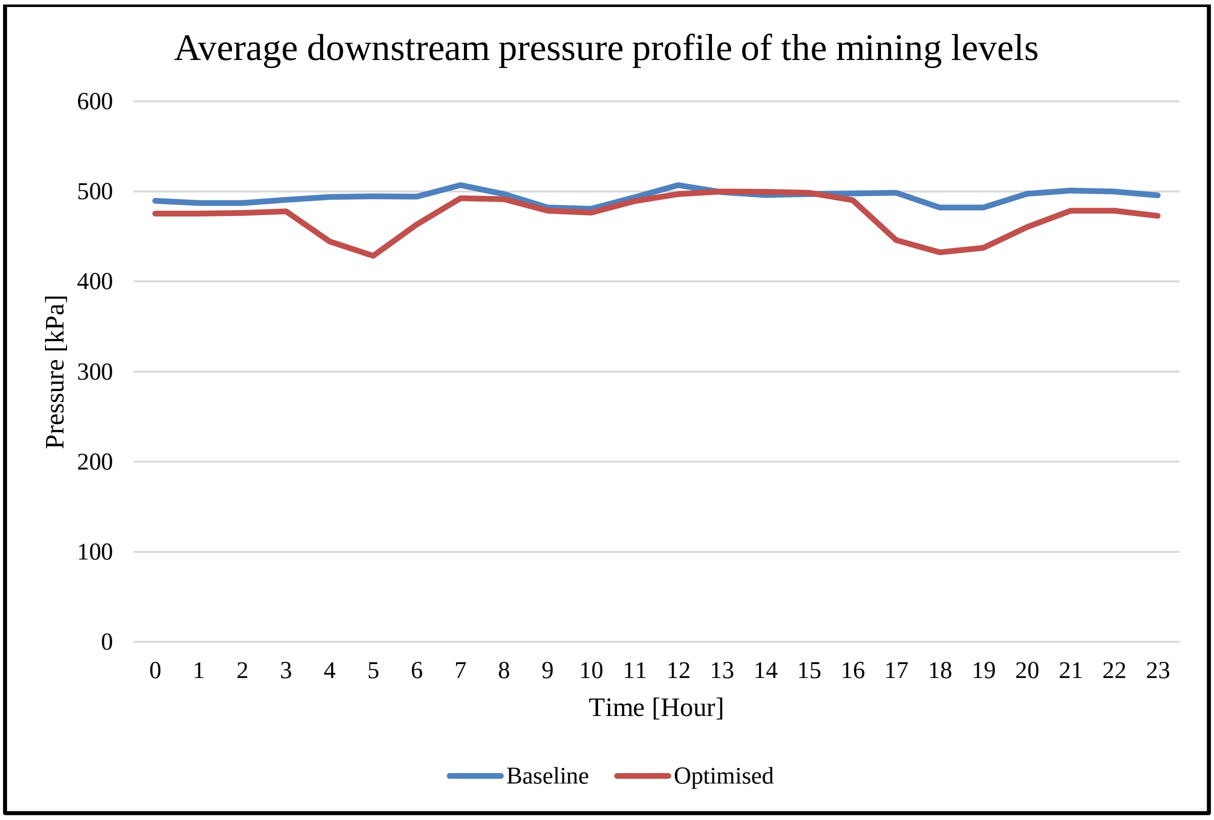


Figure 72: Average downstream pressure profile of the mining levels

4.5 Conclusion

Background on centrifugal compressors on deep level gold mines and strategies of improving energy efficiency on the compressor power consumption were discussed in Chapter 2. An inefficient mine was selected and opportunities were identified in Chapter 3 that could be implemented to improve the efficiency of the compressed air system. The initiatives were implemented and discussed in Chapter 4. The improved compressed air system resulted in a significant annual cost saving profile of R8 million while not haltering production. The compressed air system remained on the same downstream pressure profiles on the mining levels during the drilling period compared with the downstream pressure baselines of the mining levels.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Eskom is a state-owned electricity supplier in South Africa that generates and transmits 95% of South Africa's electrical energy. ESCOs implement DSM initiatives to help prevent the electricity demand shortfall in South Africa. The initiatives are also beneficial to clients, which will reduce their operating costs. The mining industry has various electricity consumers, of which compressed air consumes 17% of the mining industry's total electricity. It gave ESCOs the opportunity to investigate compressed air systems on mines to implement DSM initiatives to reduce their operating costs.

With the increasing electricity tariffs of Eskom, deep level mines have the need to reduce the operating costs of their compressed air systems, because they consume a large amount of their total electricity consumption. There was a need to identify existing DSM initiatives that could be implemented to improve the efficiency of the compressed air system of a deep level mine and reduce their operating costs.

Background on deep level mine compressed air systems was mainly provided on standalone compressed air systems comprising multistage centrifugal compressors with inlet guide vane control. The typical standalone compressed air network consists of surface users and a gold processing plant, which in some cases has its own compressors, making it independent from the mine. The air is then distributed underground to mining levels for drilling, pressurising of refuge bays and other pneumatic purposes.

An ESCO typically installs its energy management system on a mine and connects it to the mine's SCADA system. The energy management system uses tags to control different compressed air systems or to log data. The compressed air system of the mine can be controlled against various set points and critical parameters can be logged. Existing DSM initiatives were evaluated to investigate options to reduce the electricity costs on a compressed air system.

The importance of inlet guide vanes on compressors and how they follow the airflow profile of the mine's compressed air demand was discussed. The daily airflow demand profile of a typical mine compressed air system was discussed, which indicated that during the morning changeover and evening peak period there was a possibility of reducing the mine's compressed air power consumption. It is at this stage that ESCOs use their energy management systems to control delivery pressure via a pressure set point according to the mine's daily airflow demand.

The delivery pressure set point can be optimised in a customised daily schedule to improve the delivery pressure profile of the mine's compressed air system. Fixing leaks and recovering pressure losses in the compressed air network will increase the underground pressures so that the delivery pressure may be adjusted to improve the energy efficiency of the compressed air system further. Pressure losses and leaks decrease the pressure gain through auto compression. The pressure gain is made possible through the long vertical distance air must travel, and the compression by its own weight.

The effect of leaks on the compressed air system was discussed. Reducing compressed air leaks is an effective initiative for improving the efficiency of a compressed air system. Leak detection methods and the typical leak management process were discussed. Wasted airflow because of leaks is recovered by fixing the leaks. Using control valves on the mining levels can also reduce the airflow and increase the energy efficiency of the compressed air system.

Background on control valves for surface and underground pressure control was provided. These control valves require actuators, positioners and control from the energy management system to effectively control pressures on the mining levels. Different valve types, actuator types and the bypass valve configuration were discussed for pressure demand control.

There are also other initiatives available to increase the compressed air energy efficiency of a compressed air system. A compressor can be offloaded. By selecting the most efficient compressors to run, the mine will ensure that the most efficient compressor setup is used. Old compressors can be replaced with new or different compressors. Inlet air filters can be replaced with new technology air filters to improve the efficiency of the compressed air system.

Previous studies state that fixing leaks and recovering pressure losses can improve the energy efficiency of a compressed air system, although no results were found of how these initiatives improved compressed air systems. Reducing air leaks is important for improving the energy efficiency of a compressed air system and leak management. There is not a general approach for leak auditing available to improve the time efficiency in the search and identification of leaks.

Bypass control valves are mainly used to reduce the airflow on mining levels during the evening peak period. The bypass valve configuration with a small bypass pipe causes a large pressure drop when it controls and limits overall pressure control. These valves can also shift airflow to the other mining levels when a compressor trips, causing a large pressure drop in the compressed air system. Pressure control through valves can be maximised to improve overall compressed air energy efficiency as well as aid as a backup mechanism when large sudden pressure drops occur during the drilling period.

Compressors can be offloaded to improve the peak clipping saving during the evening peak period. Literature states that the power output of other compressors will increase when a compressor is offloaded to compensate for the reduction in airflow. There was not a control philosophy in place that could be implemented to prevent the other compressors from increasing their power output and maximising the evening peak-clipping savings.

Thus, there was a need to indicate the effect that fixing large leaks and recovering pressure losses have on the compressed air system. Thus, to provide a leak auditing approach that can maximise the efficiency of leak detection. Different control philosophies for improving pressure control with valves and control philosophies for maximising compressor offloading savings were developed.

Therefore, an existing DSM project on an inefficient deep level mine was identified to improve its compressed air energy efficiency and to reduce its operating cost. Background on the mine was provided – the mine had a standalone compressed air system with five compressors with inlet guide vane control. The bypass valve configuration and the ESCO’s energy management system for compressor management were discussed.

Interventions were identified for improving the energy efficiency on the compressed air system of the inefficient mine. Most of the positioners on the bypass valves have deteriorated because of internal breakages and lack of maintenance on the water traps, which should prevent moisture from entering the positioners. More rugged positioners are required. The intervention for bypass valve control was identified for control during the morning changeover period. It was simulated and the proposed annual saving of each level’s bypass valve was provided.

The mine had an inefficient delivery pressure set point daily profile compared with typical pressure requirements of a deep level gold mine. The intervention was identified to reduce the set point during the evening peak period, because the gold plant was separate from the mine with its own compressors. It gave scope to reduce the set point below 400 kPa. It was simulated, and annual cost saving of R650 000 calculated.

An efficient leak auditing approach for identifying high air consumers was developed. The approach was to compile a layout indicating the compressed air distribution network and the amount of airflow that was distributed to those areas. Two approach strategies were developed that could be used before and during the leak auditing period to ensure efficient time management during the leak management process.

Bypass valves are normally used to reduce pressure during the evening peak period but they can also be used to shift airflow and pressure to other mining levels when the required pressure drops below the minimum pressure required for drilling when a compressor trips. An incident was described when a compressor tripped that led to the need to maximise pressure control on the valves underground.

Control valve control philosophies were developed for three maximum-, medium- and low-pressure drop-control scenarios. The maximum pressure drop-control philosophy will mainly be used to shut off a level to shift the airflow to required mining levels when the pressure dropped during a compressor trip period. A control philosophy was developed for bypass valve control for medium pressure-drop scenarios to reduce the pressure during the morning changeover and evening peak period. The low-pressure drop-control philosophy was for small pressure drops using the mainline valve when certain levels were overpressurised. All the valve actuators required positioners to gain maximum pressure control.

The interventions were implemented and rugged positioners were implemented on the deteriorated positioners. The faulty water traps were replaced and control over the bypass valves was regained. A one-day peak-clipping test of the bypass valves during the morning changeover period was implemented. This test realised an annual cost saving of R540 000 by controlling four of the five bypass valves. The accuracy of the simulated and actual results was 89%.

A one-day test on reducing the delivery pressure set point during the evening peak period was implemented. The actual and simulation results were compared and had an accuracy of 83%. The test resulted in an R540 000 annual cost saving, therefore improving the energy efficiency of the compressed air system.

Research was used to determine the potential underground pressures at the depths of the mining levels. It was found that the mine’s underground pressures were not near the potential underground pressures. A very large leak was fixed, causing the underground pressures to increase by an average of 32 kPa, which dramatically increased the energy efficiency of the compressed air system. The results of the findings were discussed and the delivery pressure set point could be adjusted for further energy efficiency improvements.

The leak detection approach was implemented and it indicated that 40% of the mine’s airflow was distributed to levels that were inactive, which was almost the design flow rate of a 4.8 MW compressor. Those areas were then audited using the proposed guidelines, easing the development of the leak report. The leak report and proposals were provided to mine personnel. Fixing these identified leaks can greatly contribute to improving the energy efficiency of the mine’s compressed air system.

The maximum pressure-drop control philosophy was proposed to mine personnel for scenarios where pressure loss occurred during the drilling shift. A compressor did trip early one morning, causing a large pressure drop in the compressed air system. The mainline shut-off valve was closed on certain levels forcing the airflow and pressure to open mining levels where the pressure increased so that mining could continue. This control philosophy was proven successful. It is therefore important to have maximum pressure control over the valves.

A one-day compressor offloading test was conducted during the evening peak period and the results were explained. The other compressors' power output did increase and by reducing the delivery pressure set point during the test, savings started to realise. Control philosophies were developed to maximise the cost savings of compressor offloading. The delivery pressure set point must be reduced by at least 90 kPa or there should be guide vane controllers that force the compressors to keep their positioners during the compressor offloading period.

The results of the study were interpreted and it was found that positioners on the valve actuators must be rugged and water traps must be drained frequently. Compressor house delivery pressure set point control is a very effective initiative to improve the power profile of compressed air system. Fixing compressed air leaks largely contribute to increasing the pressure on the mining levels as well as improving the compressed air energy efficiency. There are different valve control philosophies to maximise pressure control and two control philosophies to maximise the compressor offload savings during the evening peak period.

The three-month average profiles of the optimised compressed air system were developed and discussed. By implementing all the initiatives mentioned, the compressed air system achieved an average daily energy efficiency of 1 350 kWh. The optimised power profile compared with the baseline power profile realised and annual cost saving of R8 million according to 2016/2017 tariff. With the adjusted delivery pressure set point profile and improved energy efficiency power profile, the pressures on the mining levels remained the same during the drilling period.

5.2 Recommendations for future work

A leak auditing procedure was developed during this study. This strategy can be implemented by other mines as a helpful guide in identifying problem areas in a compressed air network as it saves time during the leak searching process. Although leaks can be identified, it is very crucial to have a strategy in place to fix the leaks as soon as possible. The mine may not have boilermakers available, thus the ESCO should ensure to have their own team available with mine access and the required certification to repair the identified leaks.

During the study it was found that changing the compressor house delivery pressure set point to low can cause the surface pneumatic cylinders which requires a certain amount of pressure and not necessary a high airflow to not function. A solution should be provided for pneumatic cylinders to meet their pressure requirements on a separate system at the moment when they need it and not to constantly overpressure the compressed air network with high pressure set points to keep the pressures within requirements for the time pneumatic cylinders when they are bound to be used. Lower delivery pressure set points can then be used to increase the overall pressure set point schedule and energy efficiency.

A daily report of the compressed air system can be developed that will summarise the previous day’s compressed air system profiles. Baselines must be developed prior to the generic report for comparison with the actual compressed air system profiles. This can be helpful to quickly identify problem areas in the compressed air system as well as identify an increase in leaks. The airflow during the evening peak period should be measured only for the increase in airflow, because it is the most stable airflow period.

All critical systems within the compressed air system must have alarms. This will allow the operator to notice instantly when something has happened on-site while not being there. The operator can then make time to investigate the problem. It would also be useful if the operator could work on the energy management system using a mobile Android™ device, because breakdowns can occur at any time requiring instant changes from the operator to fix the problem that has occurred.

Full control is recommended over the bypass and mainline valves on the mining levels. The control philosophies provided can be implemented on any deep level mine to maximise pressure control on the mining levels. This also ensures that a production recovery strategy is in place, because the amount of production loss is more than the annual cost savings of energy efficiency of the compressed air system. While having full control over the valves, the mine can implement the three control philosophies to its compressed air system.

There is a need for a strategy to sustain the operational life of the pneumatic positioners and the water trap drainage. There is also a need to investigate all the downstream pipelines for water in the pipelines causing pressure loss. Water traps on the pipelines should be maintained regularly to keep water from downstream pipes. It will prolong the lifetime of pipes, because pipe walls get thinner and leaks occur because of internal rust. Water in the pipeline may also cause the actual pipe diameter to be smaller causing pressure loss. Thus, downstream pipelines should be investigated as well as water traps to ensure maximum airflow reaching the end users.

The control philosophies for compressor offloading for maximum power and cost savings can be implemented. The energy management system therefore needs a guide vane position controller. The power consumption at Mine X was reduced during the evening period by reducing the compressor house delivery pressure set point. The same control philosophy of the guide vane controller can be used to force the guide vanes of the compressors to minimum during the evening peak period. This will ensure a sustainable and maximum power reduction during peak clipping.

As one of the large compressors was in for its five-year maintenance, a feasibility study can be done to determine of it would be better to replace the old inefficient compressor with a new or different compressor. It may increase the airflow and pressure of the compressed air system as well as improve its energy efficiency. As all the compressors use inlet air filters, new technology air filters can be installed and tested to determine the impact they will have on the energy efficiency of the compressors and compressed air system.

During the study the potential underground pressures were determined by using Figure 16. (Section 2.5.3.2) from an article “Energy savings through auto compression and the air distribution control of a deep level gold mine” [52] to give an quick estimation of what the underground pressures can be for Mine X at various depths. Due to the large compressed air pipe network of an underground mine, the calculation of friction losses were neglected which was a limitation of this study. The pressure loss caused by pipe sections, pipe diameters, pipe distances, friction, etc. can be determined to indicate what the pressure losses to the specific end-user are. Increasing the pressure at the end-user may increase production and energy efficiency.

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ANNEXURE A: LEAK COST CALCULATION FORMULAS

Compressed air leakages have a financial impact on the compressed air system due to energy wastage. It is useful to express compressed air energy losses in monetary terms [50]. This shows mine personnel how much money they are currently losing through leaks. The costs can be calculated using Equation 7 to Equation 11 [29], [50].

$$W_{comp_{in}} = \frac{W_{reversible\ comp_{in}}}{\eta_{comp}} = \frac{nRT_1}{\eta_{comp}(n-1)}\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right] \tag{7}$$

- $W_{comp_{in}}$ = wasted mechanical energy [kJ/kg]
- $W_{reversible\ comp_{in}}$ = compressor energy input to generate compressed air [kJ/kg]
- η_{comp} = compressor efficiency
- n = polytrophic constant taken as 1.4 (isentropic compression)
- R = molar gas constant (0.287 [kJ/kg.K])
- T_1 = compressor inlet air temperature [K]
- P_1 = atmospheric pressure [kPa]
- P_2 = discharge pressure (gauge pressure + atmospheric pressure) [kPa]

$$\dot{m}_{air} = C_{discharge}\left(\frac{2}{k+1}\right)^{\frac{1}{k-1}} \frac{P_{line}}{RT_{line}}\ A\sqrt{kR\left(\frac{2}{k+1}\right)T_{line}} \tag{8}$$

- $\dot{m}_{air}$ = mass flow rate of air through leak [kg/s]
- $C_{discharge}$ = discharge coefficient of leak (between 0.60 and 0.97)
- T_{line} = temperature inline at position of leak [K]
- P_{line} = line pressure at leak (gauge pressure + atmospheric pressure)[kPa]
- A = area of leak [m^2]
- k = specific heat ratio (1.4 for air)

$$P_{wasted} = \dot{m}_{air} W_{comp_{in}} \tag{9}$$

$$Energy_{saved} = \frac{(P_{wasted})(operating\ hours)}{\eta_{motor}} \tag{10}$$

$$Cost\ savings = (Energy_{saved})(unit\ cost\ of\ energy) \tag{11}$$

Determine atmospheric pressure

The pressure and density of the deepest mine of South Africa were investigated by a research team from the USA [72]. They compiled a chart indicating the variation of air pressure at certain depths for three different temperature gradient models ($\propto$ = 10, $\propto$ = 30 and $\propto$ = 50 K/km), as seen in Figure 73. They found that the lower temperature gradient ($\propto$ = 10) had the highest magnitudes of pressure at a depth up to 3.5 km.

At a depth deeper than 2 km, temperature become the main cause for the state of air in deep level mines, but the effect of the temperature gradient is not the same for air density [72]. Figure 74 indicates the variation of air density at certain depths for three different temperature gradient models ($\propto$ = 10, $\propto$ = 30 and $\propto$ = 50 K/km). It was also found that the lower temperature gradient ($\propto$ = 10) had the highest magnitude of air density. It reached a factor of 1.3 times the value of the surface density at 3.5 km. The temperature gradient ($\propto$ = 30) remained almost constant while air density decreased with a temperature gradient of ($\propto$ = 50).

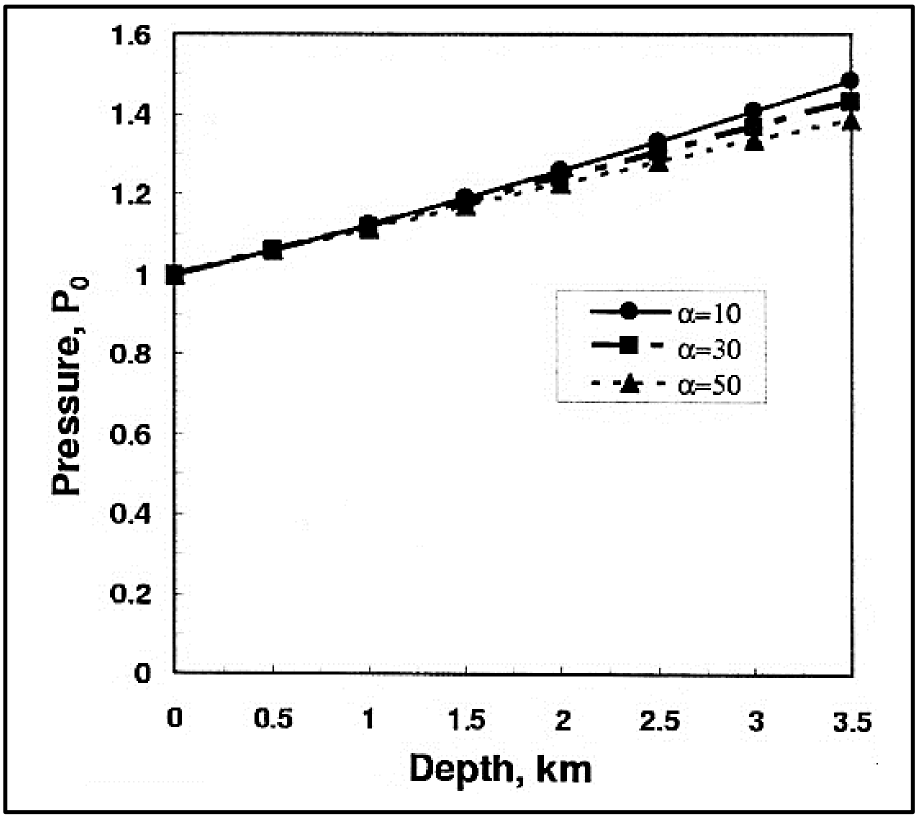


Figure 73: Air pressure variation at certain depths inside mines for temperature gradients [72]

The authors of the article emphasised that because of the high virgin rock temperatures caused by temperature gradients, a mine's major safety concern is to have lower temperatures underground. Refrigerated air and water are used to cool down the ambient temperatures of the surroundings to 28°C. This results in a lower temperature gradient that causes the ambient pressure factor to increase 1.35 times the pressure on surface. Therefore, they suggest using upper lines ($\propto$ = 10) for underground air pressure and density comparisons [72].

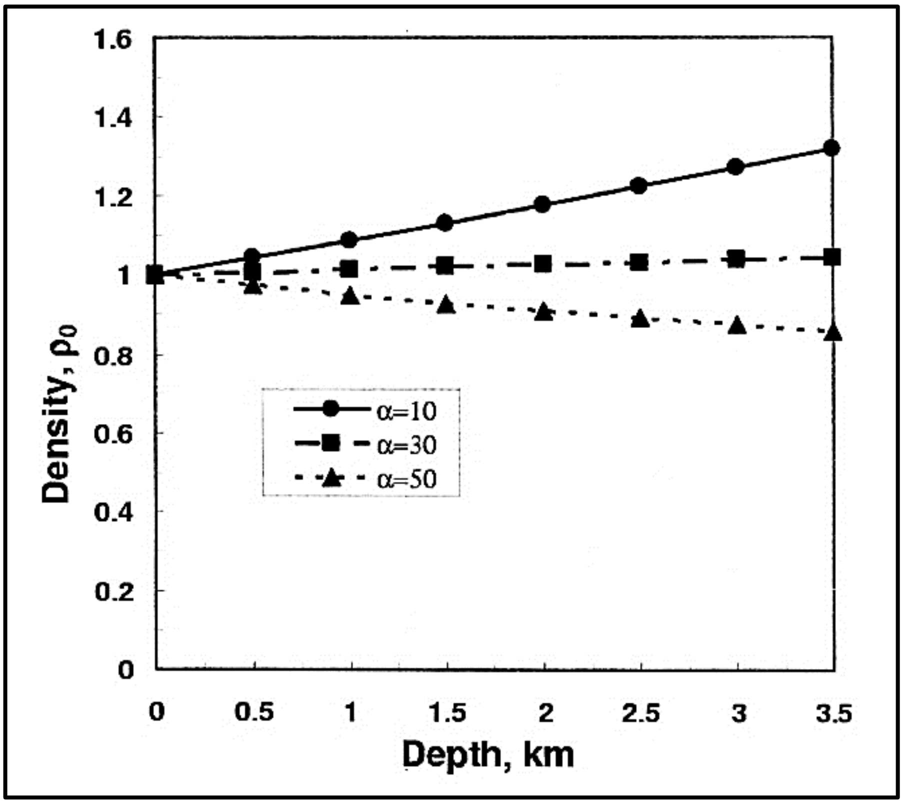


Figure 74: Air density variation at certain depths inside mines for temperature gradients [72]

ANNEXURE B: INDIVIDUAL MINING LEVEL PRESSURE PROFILES

The figures that follow show the upstream pressures on the mining levels for the period when a large leak was fixed in Section 4.2.4. The "Baseline" profiles in the figures reflect when the leak has not been fixed yet. The "Fix" profile is the profile after the leak was fixed. The "After" profile is when the compressor configuration was changed. The "Adjusted" profile is when the delivery pressure set point was adjusted for the compressor configuration change profile.

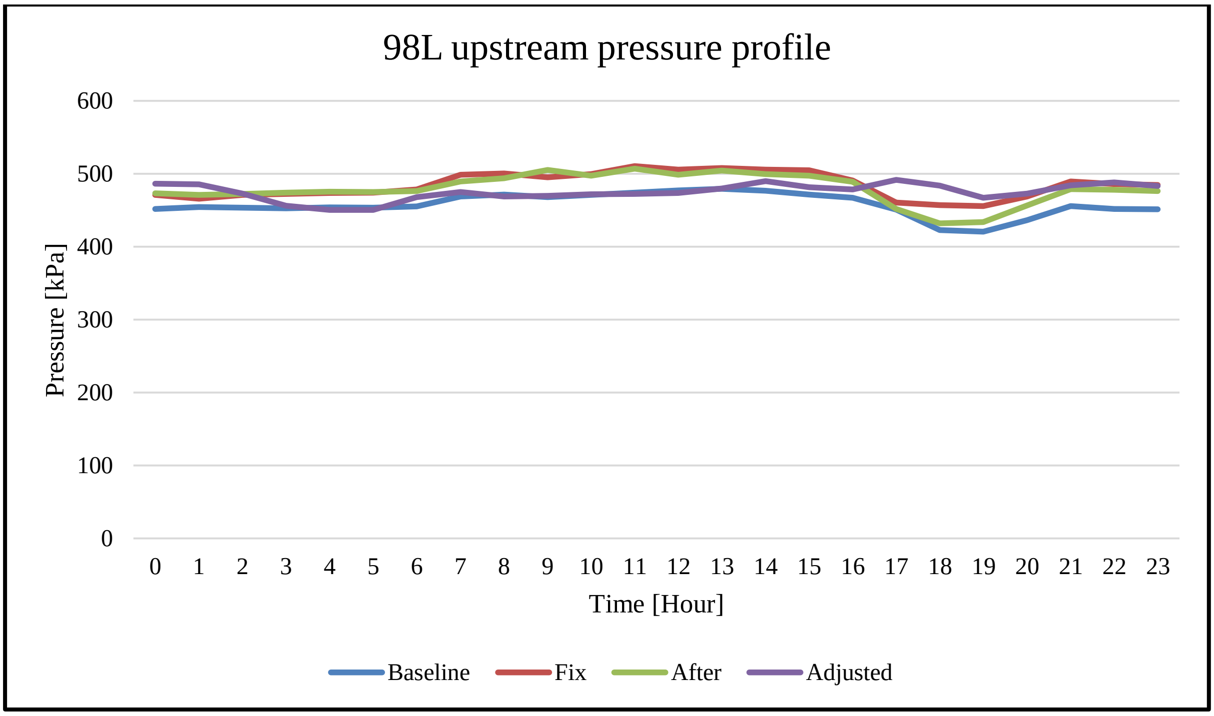


Figure 75: Effect fixing large leak has on 98L upstream pressure profile

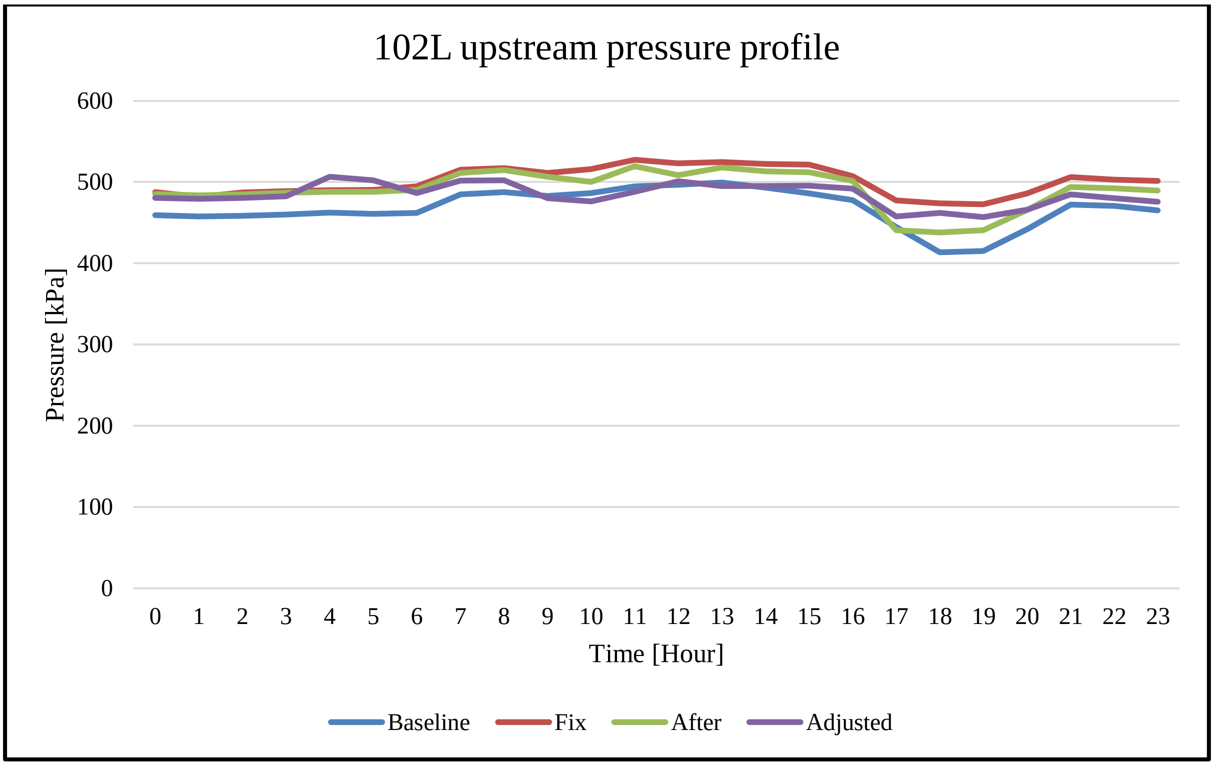


Figure 76: Effect fixing large leak has on 102L upstream pressure profile

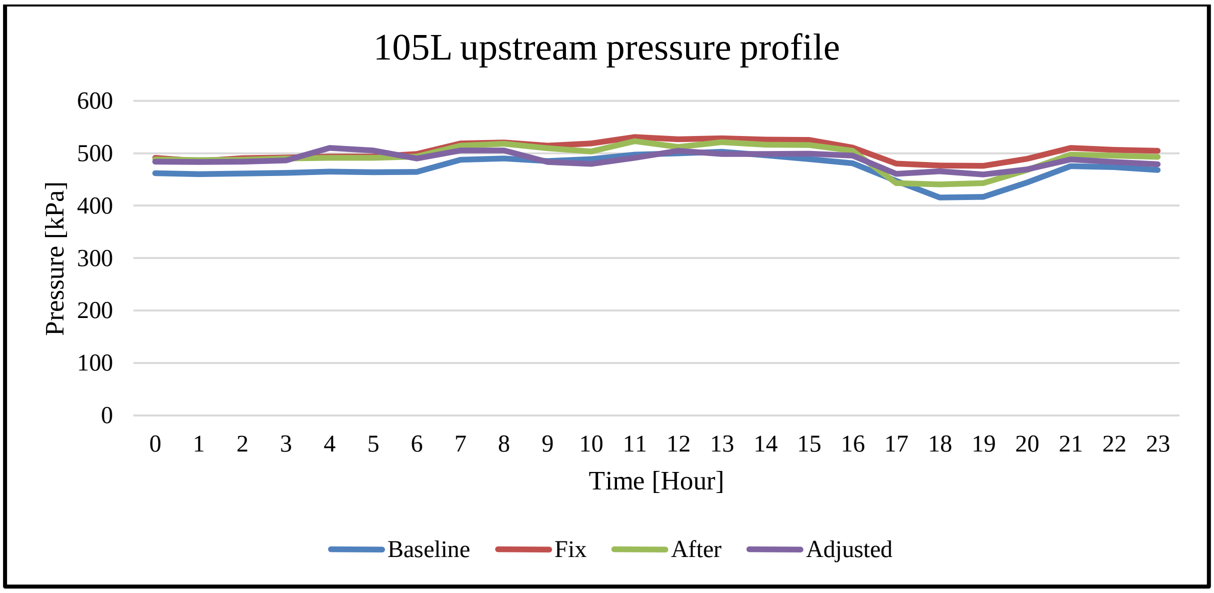


Figure 77: Effect fixing large leak has on 105L upstream pressure profile

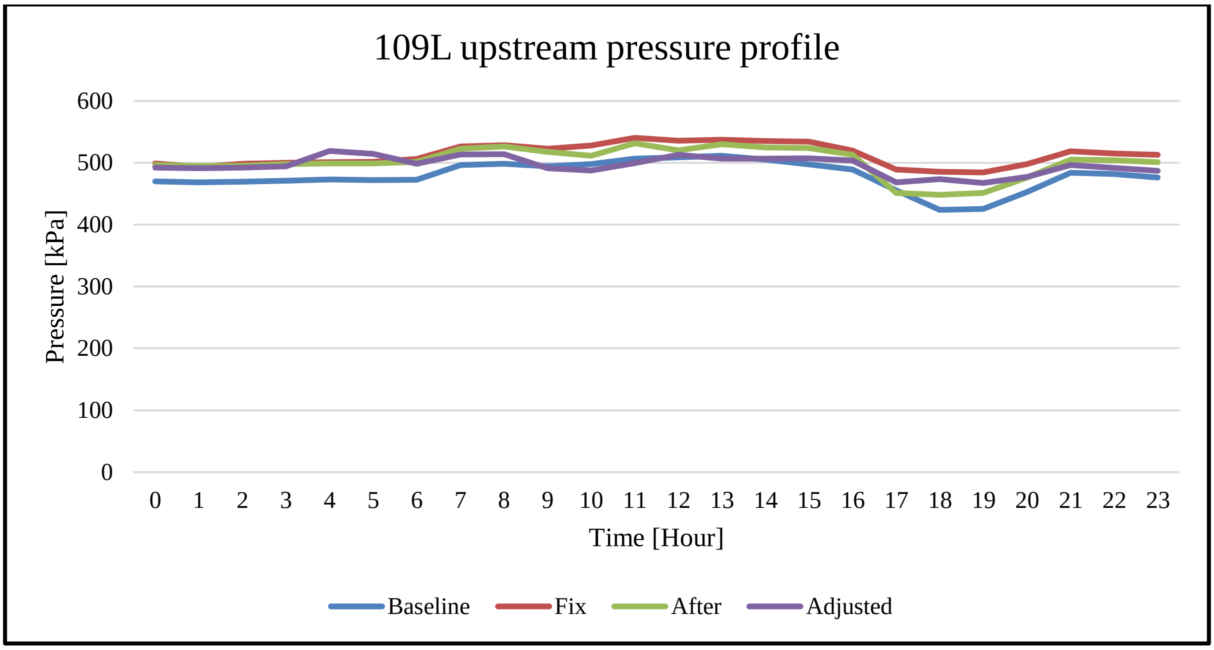


Figure 78: Effect fixing large leak has on 109L upstream pressure profile

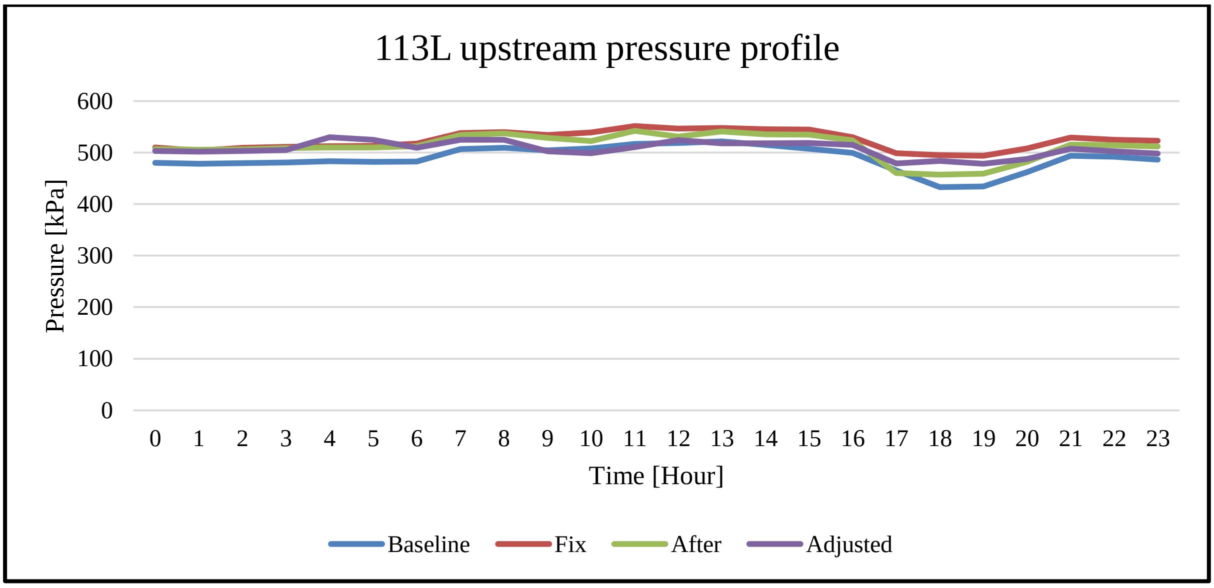


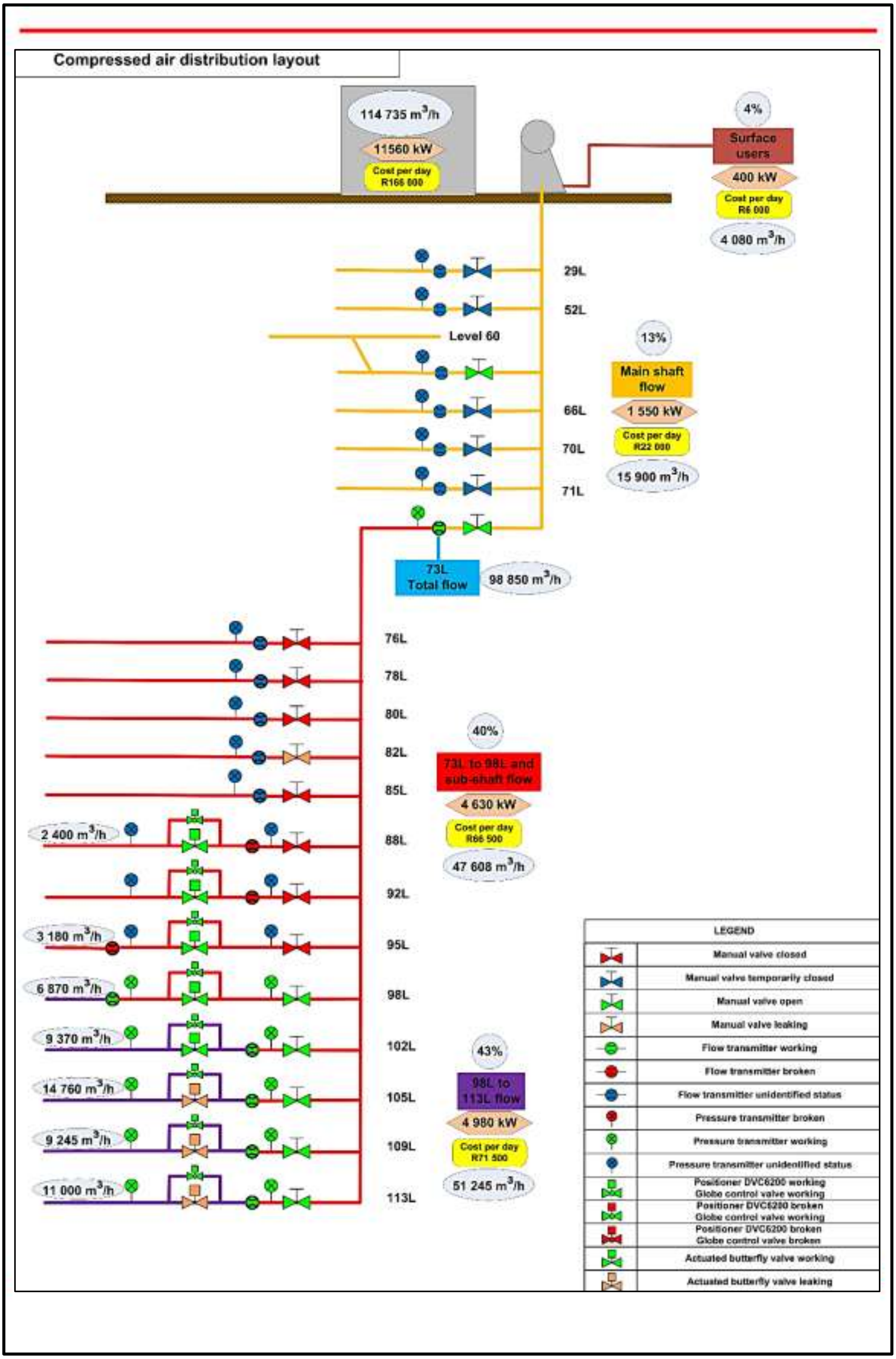
Figure 79: Effect fixing large leak has on 113L upstream pressure profile

ANNEXURE C: LEAK REPORT

This leak report was sent to mine personnel. The leak auditing process was discussed in Section 4.2.5.

Mine X

Underground compressed air leak audit report


Compressed air distribution layout
114 735 m³/h
11560 kW
Cost per day R166 000
4%
Surface users
400 kW
Cost per day R6 000
4 080 m³/h
29L
52L
Level 60
66L
70L
71L
13%
Main shaft flow
1 550 kW
Cost per day R22 000
15 900 m³/h
73L Total flow
98 850 m³/h
76L
78L
80L
82L
85L
88L
92L
95L
98L
102L
105L
109L
113L
40%
73L to 98L and sub-shaft flow
4 630 kW
Cost per day R66 500
47 608 m³/h
2 400 m³/h
3 180 m³/h
6 870 m³/h
9 370 m³/h
14 760 m³/h
9 245 m³/h
11 000 m³/h
43%
98L to 113L flow
4 980 kW
Cost per day R71 500
51 245 m³/h
LEGEND
Manual valve closed
Manual valve temporarily closed
Manual valve open
Manual valve leaking
Flow transmitter working
Flow transmitter broken
Flow transmitter unidentified status
Pressure transmitter broken
Pressure transmitter working
Pressure transmitter unidentified status
Positioner DVC6200 working Globe control valve working
Positioner DVC6200 broken Globe control valve working
Positioner DVC6200 broken Globe control valve broken
Actuated butterfly valve working
Actuated butterfly valve leaking

Sub-Shaft: shaft air leaks

Identified date: 2016-09-12							
No.	Position	Description	Pipe info	Est. repair	Leak size [mm]	Repair date	Cost p/m
1	98L - 95L (Near 98L Station)	Flange leak (Loud)	700mm	Replace Gasket	15		R 8 000
2	98L - 95L (Between the two levels)	Flange leak (Loud)	700mm	Replace Gasket	15		R 8 000
3	98L - 95L (Near 95L station)	Flange leak (Loud)	700mm	Replace Gasket	15		R 8 000
4	At 100L station	Flange leak (Large)	700mm	Replace Gasket	30		R 15 000
5	105L - 102L (Near 105L station)	Flange leak (Loud)	700mm	Replace Gasket	15		R 8 000
			Total hole size [mm]		90	Total	R 47 000

Notes	Leaks No.1 to 5 are loud air leaks found on the sub-shaft while traveling in the cage to the various levels.

Level 73

Identified date: 2016-09-12							
No.	Position	Description	Pipe info	Est. repair	Leak size [mm]	Repair date	Cost p/m
73L No.1	T-junction to sub-shaft station	Clamp Leak	8	Replace Gasket	2.5		R 343

Notes	

Level 76 - Non-active level

Identified date: 2016-09-12							
No.	Position	Description	Pipe info	Est. repair	Leak size [mm]	Repair date	Cost p/m
76L No.1	Near station	Punched hole type leak	20	Replace Gasket	2.5		R 343
76L No.2	Hallway	Clamp leak	3	Replace Gasket	2.5		R 343
76L No.3	Hallway	Valve open to mining	16	Close valve	30		R 15 000
			Total hole size [mm]		35	Total	R 15 686

Notes	This is a non-active level; therefore air flows in the 16" pipe down the hallway to other sections. From the 16" a 3" pipe taps off air which feeds a refuge bay near the station. Repair option 1: There are already 2" pipes laying on the ground that can be used to reduce the 16" pipe at the station to 2", supplying only air to the refuge bay (76 R). Repair option 2: The same refuge bay (76 R) already has a 2" pipeline, which is not connected at the station. The 16" pipe therefor must be blanked off and the short route of the existing 2" pipeline to the refuge bay must be connected. See Attached layout of 76L explaining the repair proposal.

Level 78 - Training centre

Identified date: 2016-09-12							
No.	Position	Description	Pipe info	Est. repair	Leak size [mm]	Repair date	Cost p/m
78L No.1	Near station	Punched hole type leak	20	Repair Hole	2.5		R 343
78L No.2	At station hallway	Flange leak	2	Replace Gasket	2.5		R 343
78L No.3	FP 1	Shut-off valve leak	4	Blank-off pipe	2.5		R 343
78L No.4	FP 92	Punched hole type leak	20	Replace Gasket	5		R 2 000
78L No.5	FP 101	Punched hole type leak	20	Replace Gasket	2.5		R 343
78L No.6	Classroom at x/c 18	Punched hole type leak	2	Replace Gasket	10 (20 off)		R 20 000
78L No.7	Classroom at x/c 16 stopes	Valve leak/ broken valve	1	Replace Valve	15		R 8 000
			Total hole size [mm]		80	Total	R 31 372

Notes	

Level 80 - Non-active level (mechanical backfill agitation)

Identified date: 2016-09-12							
No.	Position	Description	Pipe info	Est. Repair	Leak size [mm]	Repair date	Cost p/m
80L No.1	Station refuge bay	Clamp leak	3	Replace clamp	10		R 8 000
80L No.2	Hallway near station	Punch Hole Leak	16	Replace Pipe	8 (2 off)		R 8 000
80L No.3	Hallway near station	Clamp leak	8	Replace clamp	10		R 8 000
80L No.4	Hallway near station	Clamp leaks	8	Replace clamp	10		R 8 000
80L No.5	Hallway near station	Clamp Leak	4	Replace clamp	5		R 2 000
80L No.6	Hallway near station	Valve Leak	1	Replace valve	20		R 20 000
80L No.7	Hallway near station	Clamp leak	4	Replace clamp	5		R 2 000
			Total hole size [mm]		76	Total	R 56 000

Notes	This is a non-active level. Air flows in the 16" pipe down the hallway to other sections. From the 16" at the station a 2" pipeline is required for use of the refuge bay and backup purposes for the mechanical agitation process. All sections where air is unnecessary supplied must be blanked off.

Level 82 - Non-active level

Identified date: 2016-09-12							
No.	Position	Description	Pipe info	Est. Repair	Leak size [mm]	Repair date	Cost p/m
82L No.1	Station bypass valve leak	Valve leak	20	Replace valve	30		R 30 000

Notes	The level 's air is blanked off, but there is a large leak at the station's bypass valve on the mainline pipe. All water and air sections must be blanked off and the stations doors closed permanently.

Level 85 - Non-active level

Notes	This level is a non-active level. The compressed air pipeline could not be audited due to the station door that is permanently closed. Through the other station door that is open the grove valve at the station measures 12 l/s on the flow meter and the valve was open supplying chilled water to the mining levels. The chilled water and the air must be blanked off at the station.

Level 88 - Non-active level

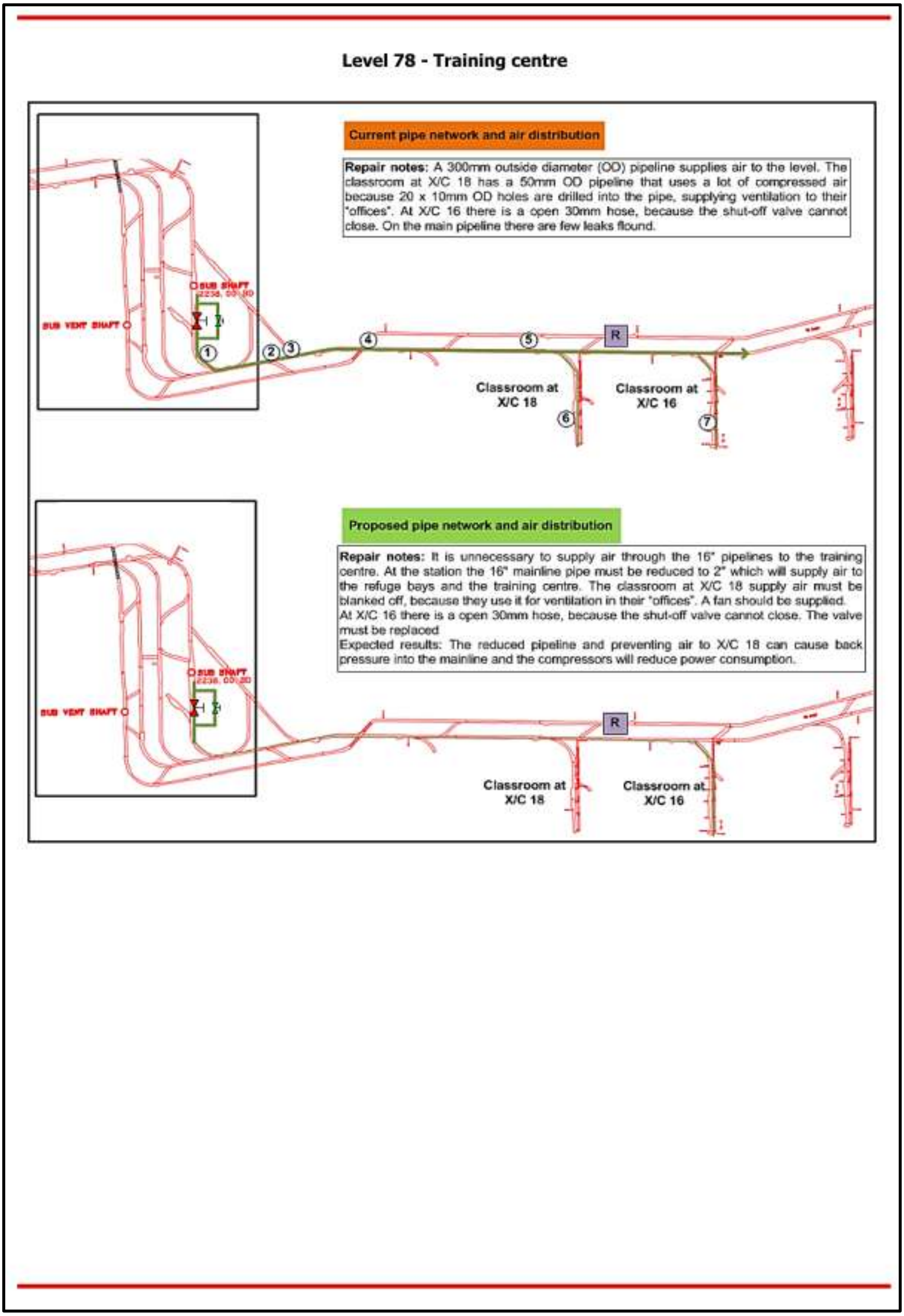
Notes	This level is a non-active level. The compressed air pipeline is blanked off before the bypass valve. This level must be ensured that the chilled water and air are blanked off at the station. The control valves, actuators and instrumentation can be removed for maintenance that can be installed on other areas. A lot of chilled water from 85L was running from the mining areas on the foot walls to the station area.

Level 92 - Turbine level

Notes	Only a large chilled water leak ws found on the 20" pipe near the turbine. The compressed air mainline pipe can be reduced to a 2" pipeline which can supply air to the refuge bay.

Level 95 - Non-active level

Notes	This is a non-active level. This level is mainly used to open or close the 95L valve which supplies chilled water to the active mining levels. At the station the bypass valves on the compressed air mainline can be audited, because it is unreachable high. The mainline pipe can be reduced close to the station to a 2" pipeline which can supply air to the refuge bay. The flow meter is broken and can be repaired. The mainline pipe must also be replaced if mining on 95L will start again in the future, because the mainline pipe wall thickness is very thin and won't last long. The valves and instrumentation may be removed for maintence and to store it in a less harsh environment.


Level 78 - Training centre
Current pipe network and air distribution
Repair notes: A 300mm outside diameter (OD) pipeline supplies air to the level. The classroom at X/C 18 has a 50mm OD pipeline that uses a lot of compressed air because 20 x 10mm OD holes are drilled into the pipe, supplying ventilation to their "offices". At X/C 16 there is a open 30mm hose, because the shut-off valve cannot close. On the main pipeline there are few leaks flound.
SUB SHAFT
SUB VENT SHAFT
R
Classroom at X/C 18
Classroom at X/C 16
Proposed pipe network and air distribution
Repair notes: It is unnecessary to supply air through the 16" pipelines to the training centre. At the station the 16" mainline pipe must be reduced to 2" which will supply air to the refuge bays and the training centre. The classroom at X/C 18 supply air must be blanked off, because they use it for ventilation in their "offices". A fan should be supplied.
At X/C 16 there is a open 30mm hose, because the shut-off valve cannot close. The valve must be replaced
Expected results: The reduced pipeline and preventing air to X/C 18 can cause back pressure into the mainline and the compressors will reduce power consumption.
SUB SHAFT
SUB VENT SHAFT
R
Classroom at X/C 18
Classroom at X/C 16

Figures

73L No.1

76L No.1

73L No.2

76L No.3

78L No1

78L No.2

78L No.3

76L No4

73L No.5

76L No.6

Figures

78L No.7

80L No.1

80L No.2

80L No.3

80L No.4

78L No.5

80L No.6

80L No.7

82L No.1

Fix	No.	Location	Description	Est. pipe OD	Est. leak size	Est. R/m	Repair notes	Fig ref.
Est. R/m: Estimate leak cost per month based on Kusasalethu orifice chart								
Legend								
Fixed								
High priority								
Medium priority								
Low priority								
Shaft								
	1	Near 102L station	Possible flange leak	700	15	R 35 000		
	2	Near 82L station	Possible bypass valve leak at station	200	30	R 77 000		82L-1
						R 112 000		
73L								
	3	T-junction to sub-shaft station	Clamp leak (Noisy)	200	5	**R 2 500**		73L-1
76L - Non active level								
	4	Near station	Punched hole leak	500	5	R 2 500		76L-1
	5	Hallway	clamp leak	75	5	R 2 500		76L-2
	6	Hallway	Valve open	400	350	R 215 000	Investigate and close valve	76L-3
						R 220 000		
	The open valve valve (76L-3) goes into the mine. The valve can be closed or the whole level can be blanked off at the station.							
78L - Training centre								
	7	Near station	Punched hole leak	500	3	R 1 200		78L-1
	8	Near station in hallway	Flange leak	50	3	R 1 200		78L-2
	9	FP1	Shut-off valve leak	100	3	R 1 200		78L-3
	10	FP92	Punched hole leak	500	5	R 5 000		78L-4
	11	FP101	Punched hole leak	500	5	R 5 000		78L-5
	12	Classroom at XC18	Punched hole leak	50	10 (15 off)	R 77 000	Solution will be proposed	78L-6
	13	Classroom at XC16 near stopes	Valve leak	1" or 1 &1/2"	10	R 9 000	Replace valve	78L-7
						R 99 600		
80L - Backfill agitation level - Non active								
	14	Refuge bay near station	Clamp leak	100	10	R 9 000		80L-1
	15	Hallway near station	Punched hole leak	400	15	R 16 000		80L-2
	16	Hallway near station	Clamp leak	200	10	R 9 000		80L-3
	17	Hallway near station	Clamp leaks	200	10	R 9 000		80L-4
	18	Hallway near station	Clamp leak	100	5	R 5 000		80L-5
	19	Hallway near station	Valve leak	1" or 1 &1/2"	15	R 16 000	Replace valve	80L-6
	20	Hallway near station	Clamp leak	100	5	R 5 000		80L-7
						R 69 000		
82L - Non-active level								
	21	At station	Mailine bypass valve leak	200	40	**R 110 000**	Replace valve	82L-1
	The level 's air is blanked off, but ther is a large leak at the station's bypass valve on the mainline pipe. All water and air sections must be blanked off. Stations doors can be closed permanently.							
85L - Non-active level								
	22	This level is a non-active level. The compressed air pipeline could not be audit due to the station door that is permanently closed. This level can be re-audit and the air pipelines can be blanked off at the station to ensure there is no flow into this level.						

Fix	No.	Location	Description	Est. pipe OD	Est. leak size	Est. leak cost	Repair notes	Fig ref.
88L - Non-active level								
	23	This level is a non-active level. The compressed air pipeline is blanked off before the bypass valves. Remove the bypass valves, actuators, positioner and transmitters to surface for possible use at other locations.						88L-1
92L - Turbine level								
	24	This is the turbine level. No airflow in the pipeline could be noticed to the mining levels. The pipeline can be blanked off by the bypass valves. Remove the bypass valves, actuators, positioner and transmitters to surface for posible use at other locations.						
95L - Non-active level								
	25	This is a non-active level. This level is mainly used to open or close the 95L valve, which supplies chilled water to the active mining levels. At the station the bypass valves on the compressed air mainline can be audit, because it is unreachable high. The mainline pipe can be reduced close to the station to a 2" pipeline which can supply air to the refuge bay or an orifice can be used to reduce the flow. The airflow meter is broken and can be repaired. The mainline pipe must also be replaced if mining on 95L should start in the future, because the mainline pipe wall thickness is very thin due to rust. Remove the bypass valves, actuators, positioner and transmitters to surface for posible use at other locations.						
105L - Hallway								
	26	FP22	Clamp leak	100	5	R 5 000	Replace clamp	105L-1
	27	Refuge bay FP95	Valve leak	50	15	R 16 000	Replace 50mm OD valve	105L-2
	28	FP149	Valve leak	400	3	R 1 200	Replace 1" valve	105L-3
	29	FP156	Valve leak	400	8	R 4 500	Replace 1" valve	105L-4
	30	FP173	Valve leak	400	8	R 4 500	Replace 1" valve	105L-5
	31	Refuge bay FP194	Possible open-end (Pipe goes through wall)	50	40	R 85 000	Blank-off pipe / Investigate	105L-6
	32	FP208	Valve leak	400	3	R 1 200	Replace 1" valve	
	33	FP223	Valve leak	400	3	R 1 200	Replace 1" valve	
	34	FP220	Flange leak	400	3	R 1 200	Replace gasket	
						R 119 800		
105L - East								
	35	Refuge bay E-FP24	T- Pipe connection leaks	50	10	R 9 000	Replace clamps & valve	105LE1
	36	Water trap E27 before XC31	Valve leak	1&1/2"	10	R 9 000	Replace valve	105LE2
XC31 - Not active								
	37		Punched hole leak	100	10	R 9 000		105LE3
	38		Clamp leak	100	25	R 60 000		105LE4
		Small other leaks in the stoping areas. This XC was not active and very warm						
XC30 - Active (started drilling 09:00)								
		Pipes in stopes can be audit. Shut-off valves can be installed on each pipe feeding a drill machine.						
XC29 - Not active								
	38		Valve leak 0.1 kPa	100	5	R 5 000	Blank off pipe	105LE5
XC28 - Not active								
		XC28 can be investigated and closed of not active.						
XC27 - Not active								
	39	15 kW booster fan was running. Fan can be stopped if this XC is not active.		14kWh		R 6 500	Booster fan can be switched off	
	40		Possible open-end	100	50	R 120 000	Investigate pipeline/ blank off	
XC26 - Not active								
	41	Closed						

Fix	No.	Location	Description	Est. pipe OD [mm]	Est. leak size	Est. leak cost	Repair notes	Fig ref.
105L - East								
XC24 - Active								
	42		Pipe leak	40	7	R 6 500	Replace small pipe	105LE6
	43		Large punched hole leak	100	10	R 9 000		
		Pipes in stopes can be audit. Shut-off valves can be installed on each pipe feeding a drill machine.						
XC23 - Active ?								
	44	Corner into stopes	Clamp leak	100	5	R 5 000		
	45	Pipes in stopes can be audit. Shut-off valves can be installed on each pipe feeding a drill machine.						
XC22 - Active ?								
	46	Pipes in stopes can be audit. Shut-off valves can be installed on each pipe feeding a drill machine.						
XC21 - Active ?								
	47	Pipes in stopes can be audit. Shut-off valves can be installed on each pipe feeding a drill machine.						
XC20 - Active (Drilling starts 07:30)								
	48	Pipes in stopes can be audit. Shut-off valves can be installed on each pipe feeding a drill machine.						
XC19 - Active								
	49	Pipes in stopes can be audit. Shut-off valves can be installed on each pipe feeding a drill machine.						

Description	Description
82L-1	73L-1
	
76L-1	76L-2
	
76L-3	78L-1
	
78L-2	78L-3
	
78L-4	78L-5
	
78L-6	78L-7
	 

Description	Description
80L-1	80L-2
	
80L-3	80L-4
	
80L-5	80L-6
	
80L-7	82L-1
	
88L-1	105L-1
	
105SL-2	105SL-3
	

Description	Description
105L-4	105L-5
	
105L-6	105LE1
	
105LE2	105LE3
	
105LE4	105LE5
	
105LE6	
	

ANNEXURE D: PROFILES DURING OFFLOADING OF COMPRESSOR 5

This section indicates the compressed air system profiles during the evening peak period for the effect that offloading Compressor 5 had on the compressed air system. The "Baseline" profile is the profile before the compressor was offloaded; the "Test" profile is the profile when the compressor was offloaded. The offloading test was discussed in Section 4.2.8.

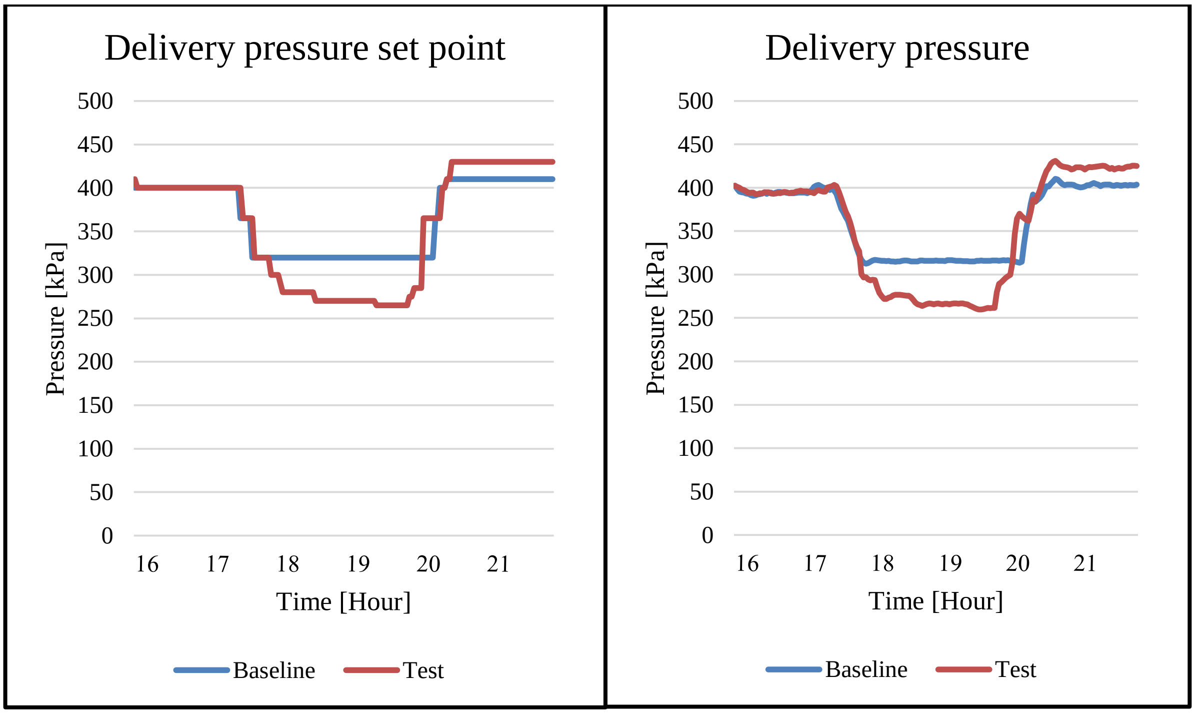


Figure 80: Offloading test delivery pressure set point and delivery pressure profiles

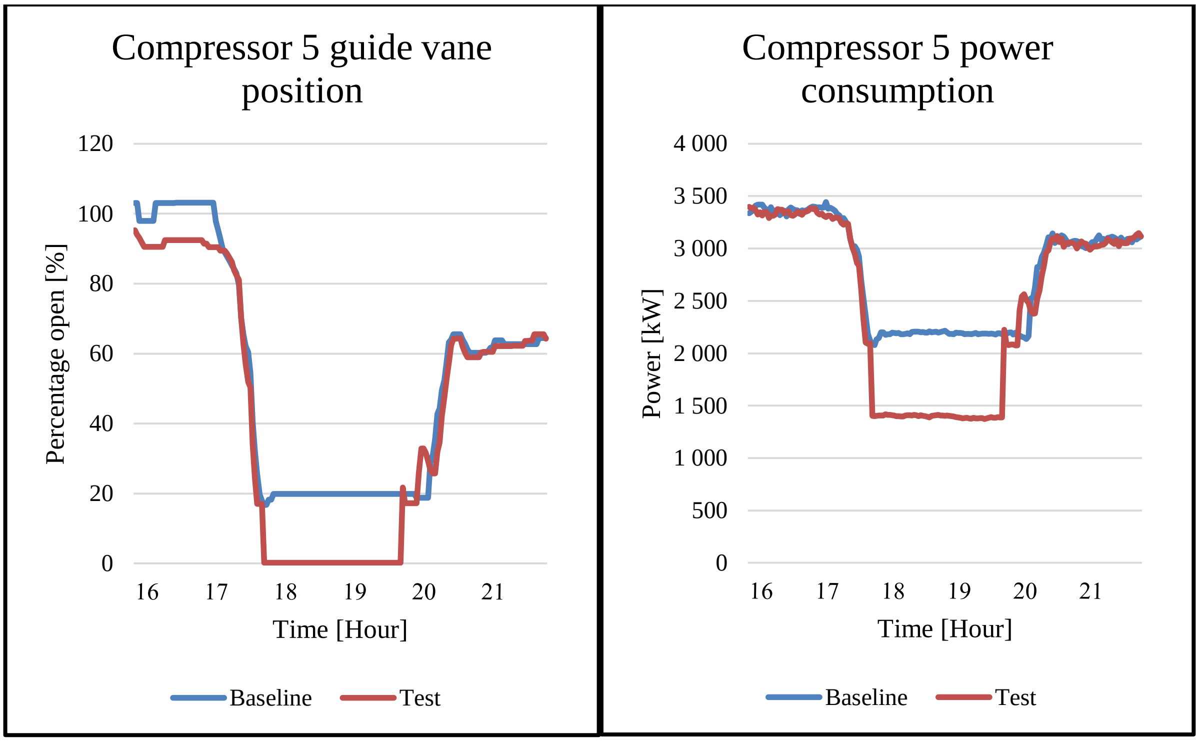


Figure 81: Offloading test guide vane position and power consumption profiles for Compressor 5

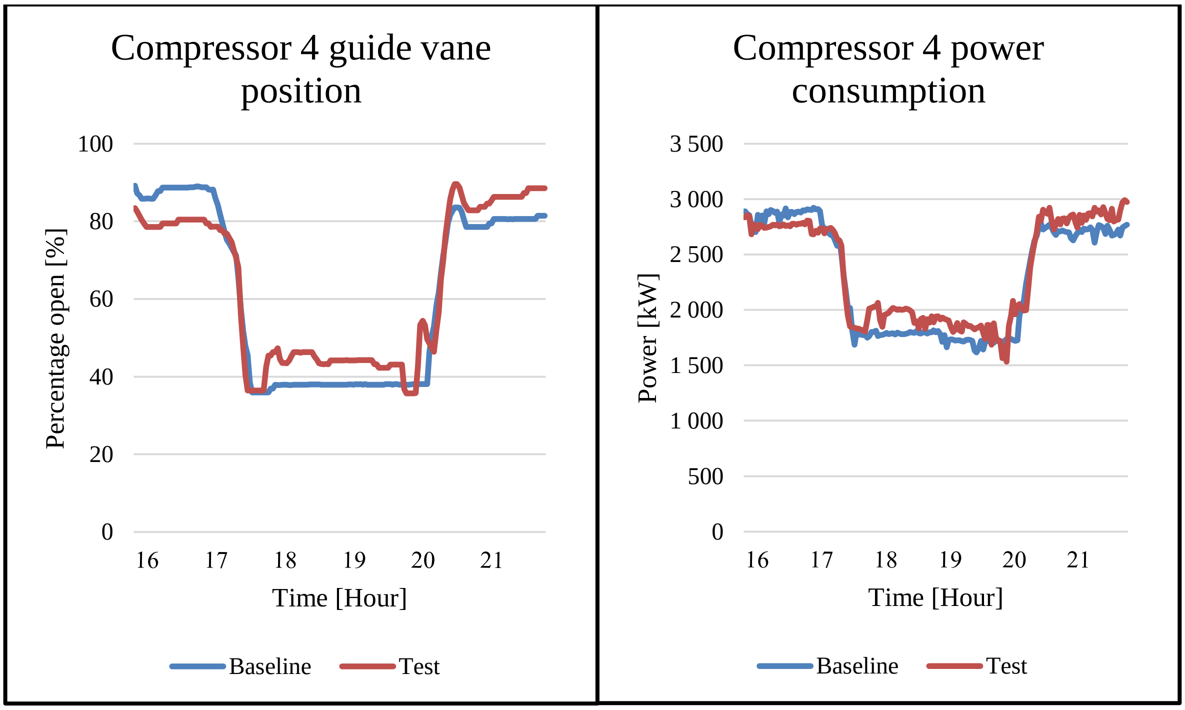


Figure 82: Offloading test guide vane position and power consumption profiles for Compressor 4

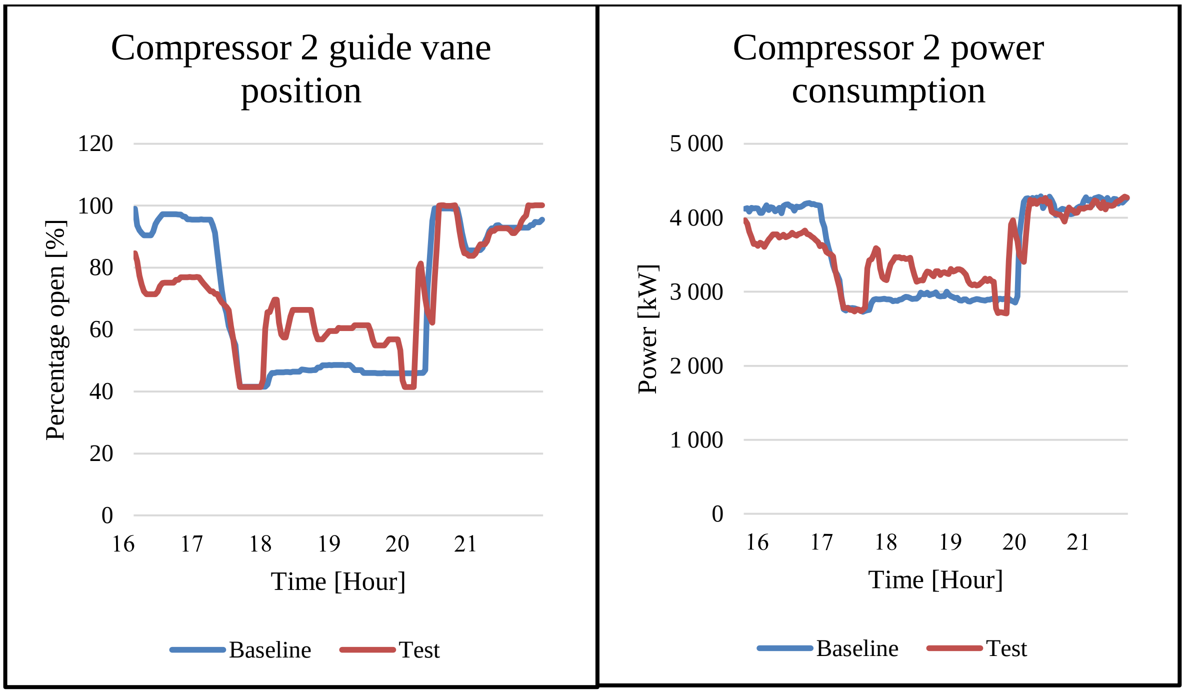


Figure 83: Offloading test guide vane position and power consumption profiles for Compressor 2

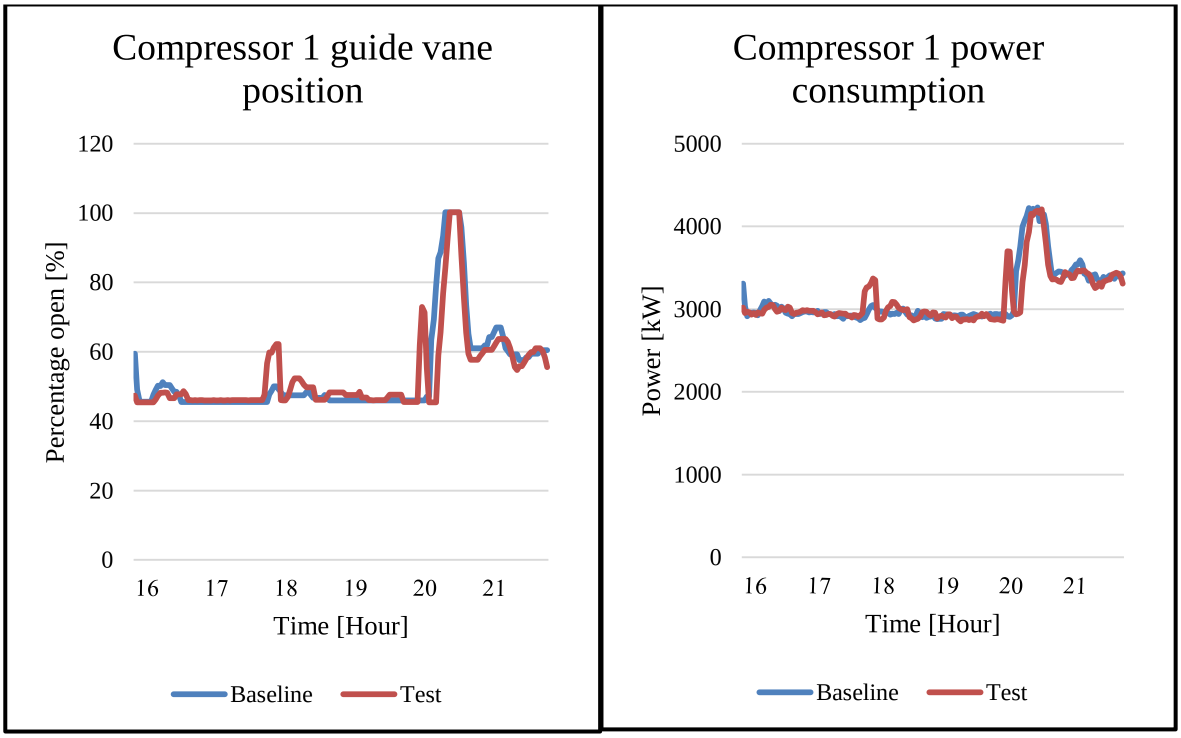


Figure 84: Offloading test guide vane position and power consumption profiles for Compressor 1

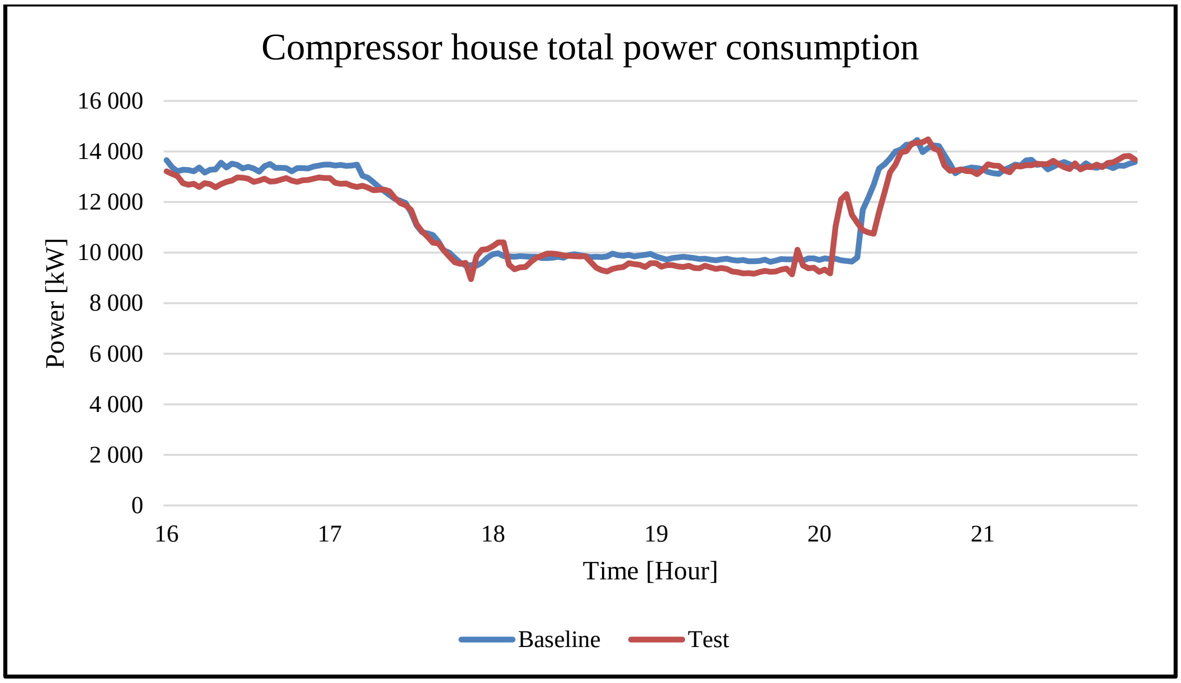


Figure 85: Offloading test total power consumption profile for compressor house

The figures below indicate the baseline upstream pressure profiles of the mining levels and the pressure profile (Test) when the compressor was offloaded, and when the delivery pressure set point was adjusted during the test. The proposed pressure profiles of the control philosophies are also displayed for each mining level.

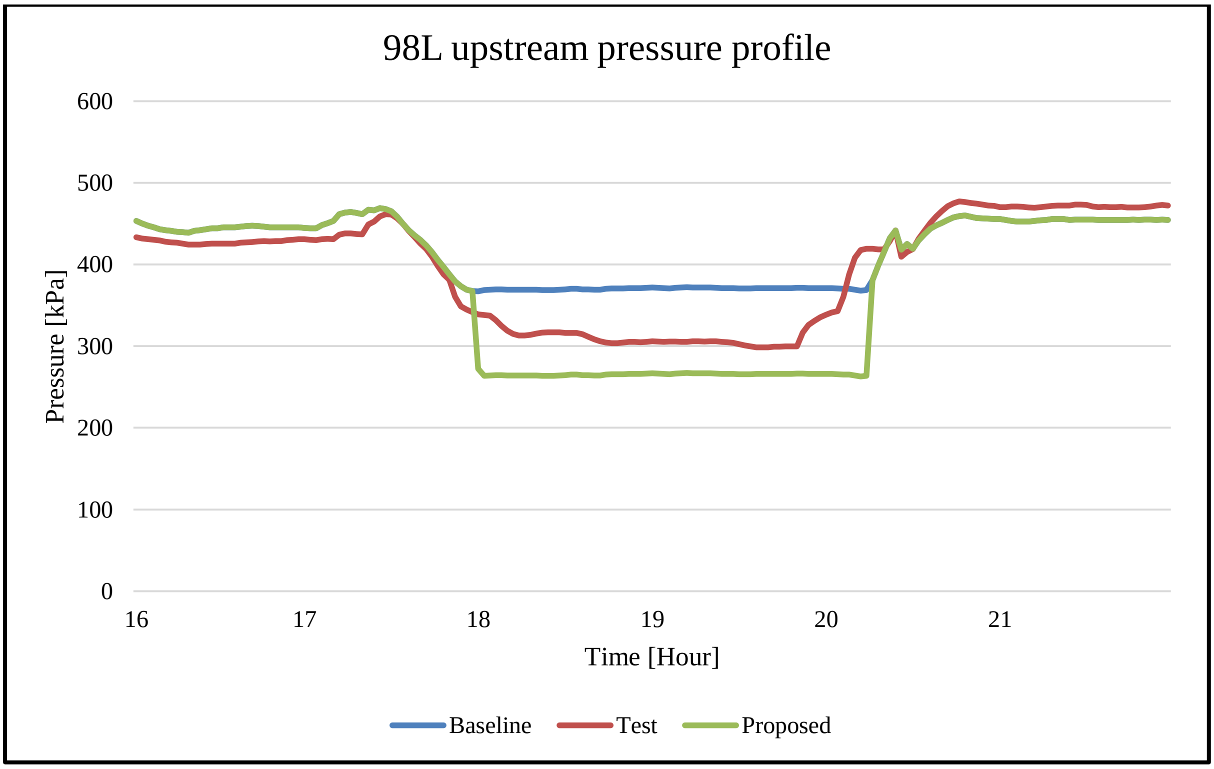


Figure 86: Offloading test upstream pressure profiles for 98L

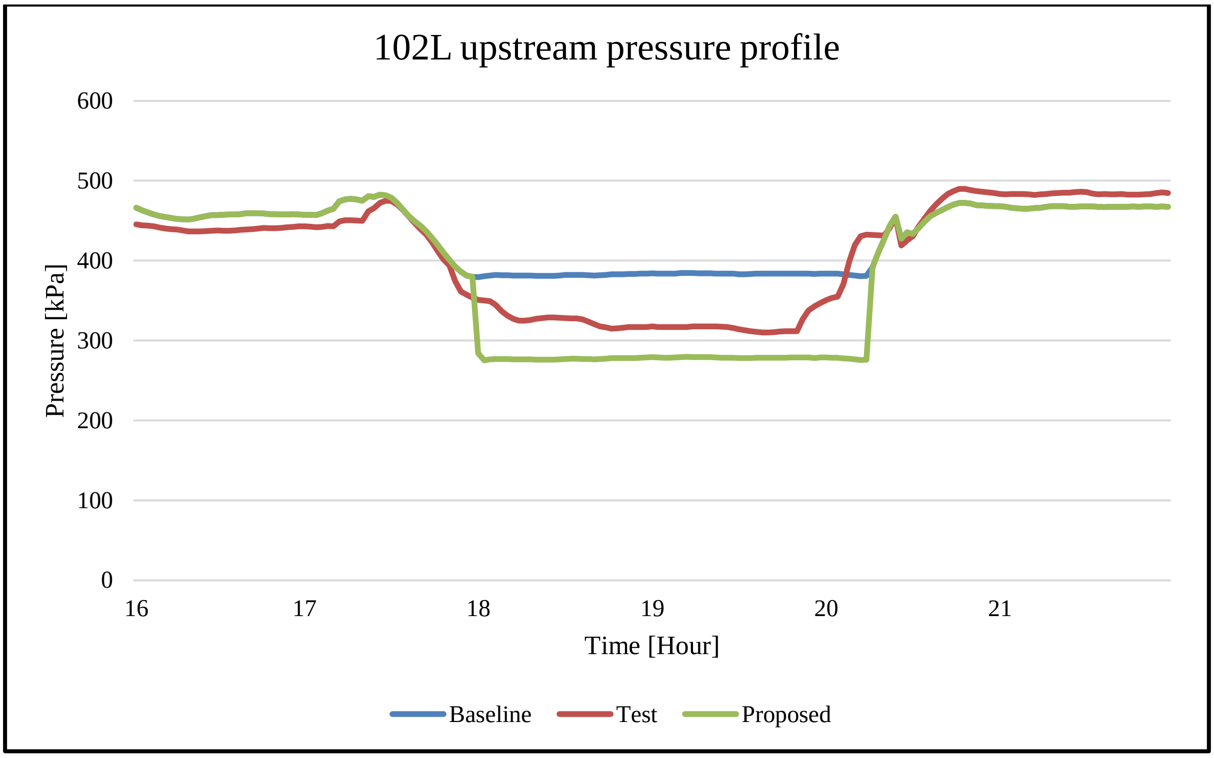


Figure 87: Offloading test upstream pressure profiles for 102L

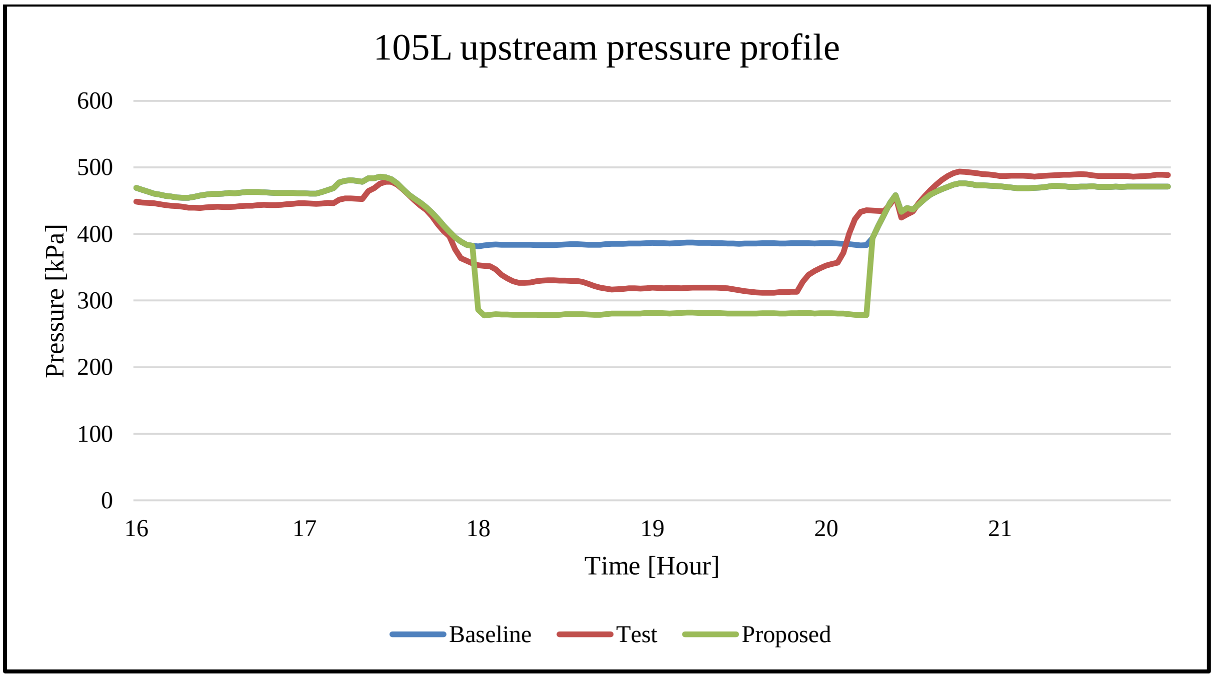


Figure 88: Offloading test upstream pressure profiles for 105L

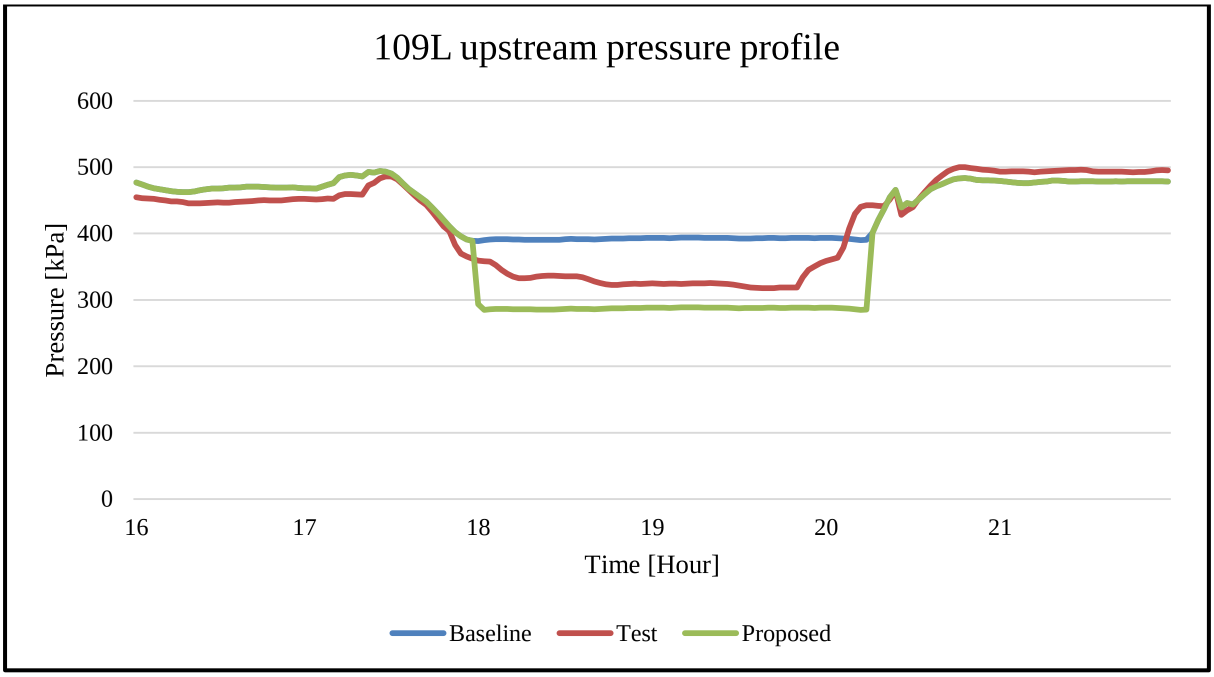


Figure 89: Offloading test upstream pressure profiles for 109L

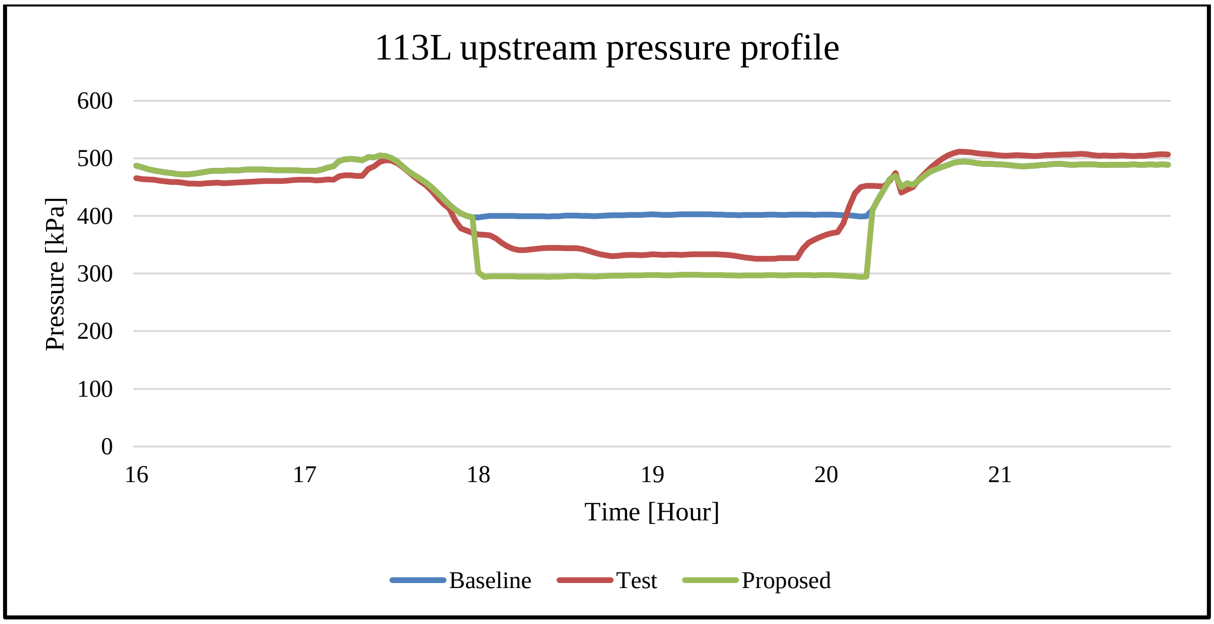


Figure 90: Offloading test upstream pressure profiles for 113L

ANNEXURE E: OPTIMISED SYSTEM PROFILES

The figures below compare the baseline profiles (when no changes to the compressed air system were done) and the optimised profiles (when all the initiatives were implemented and adjusted on the compressed air system).

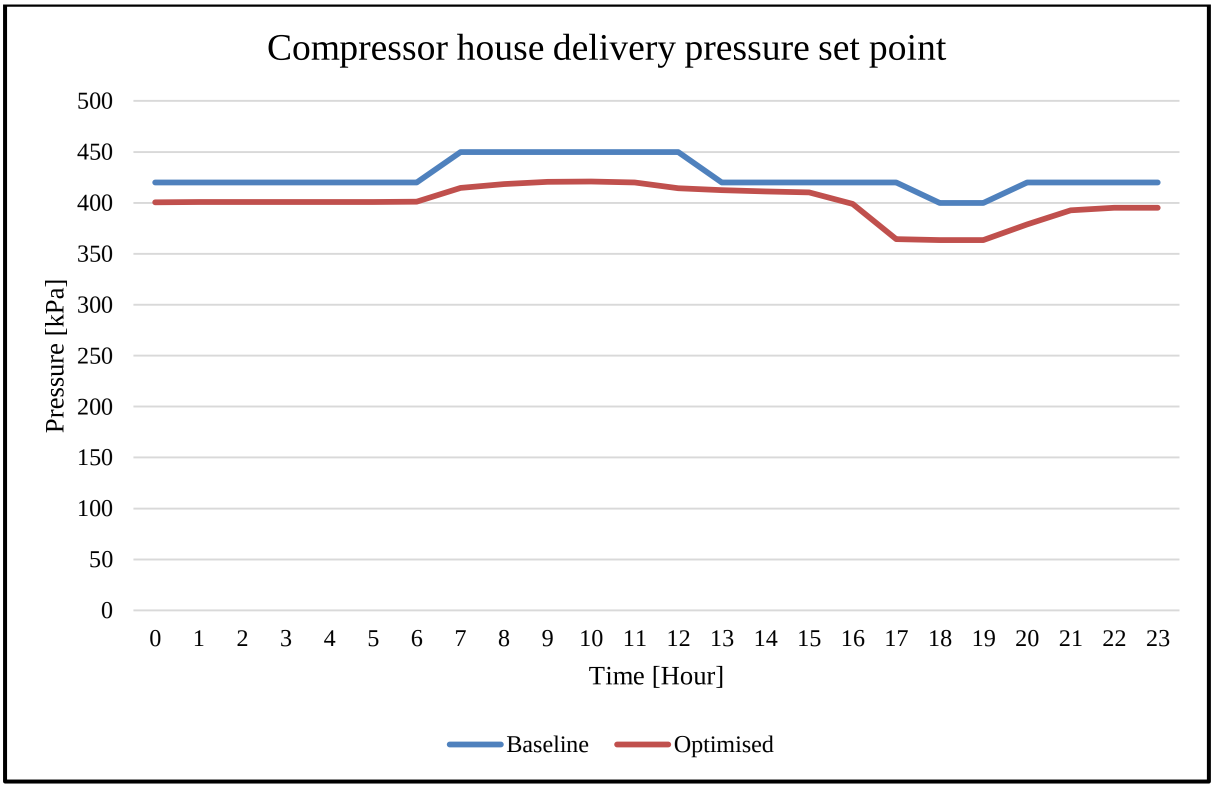


Figure 91: Optimised compressor house delivery pressure set point profile

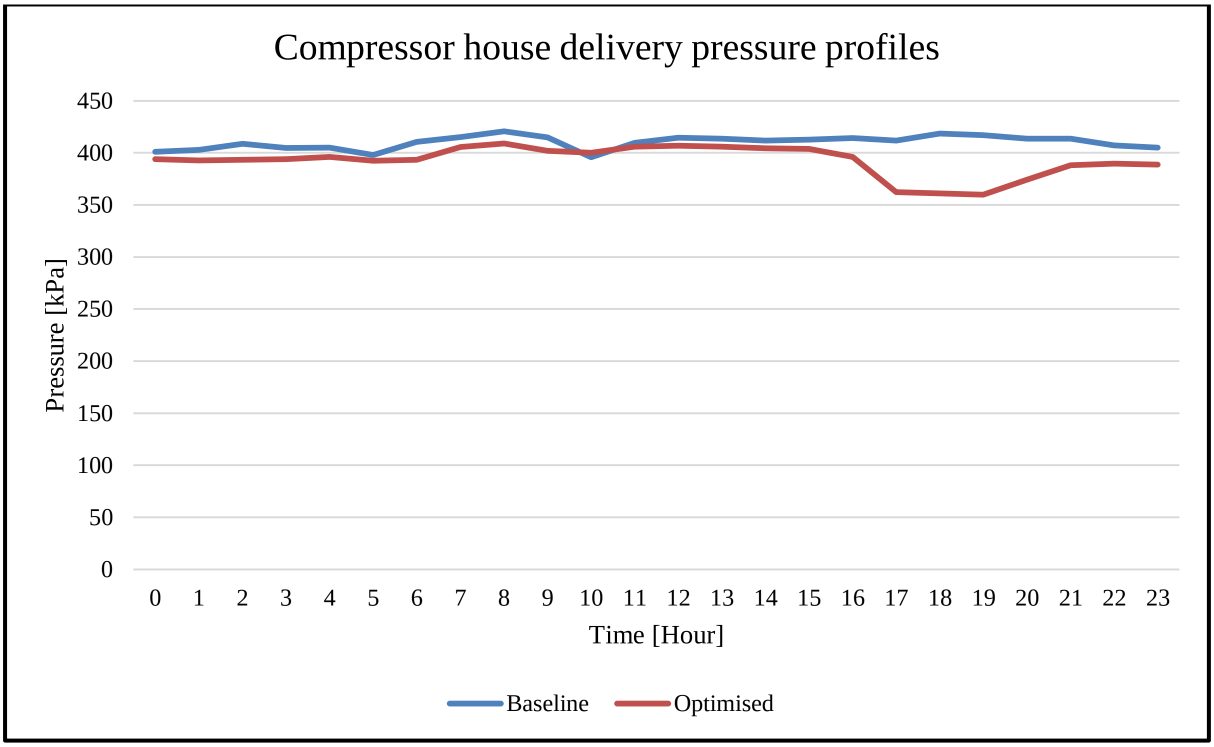


Figure 92: Optimised compressor house delivery pressure profiles

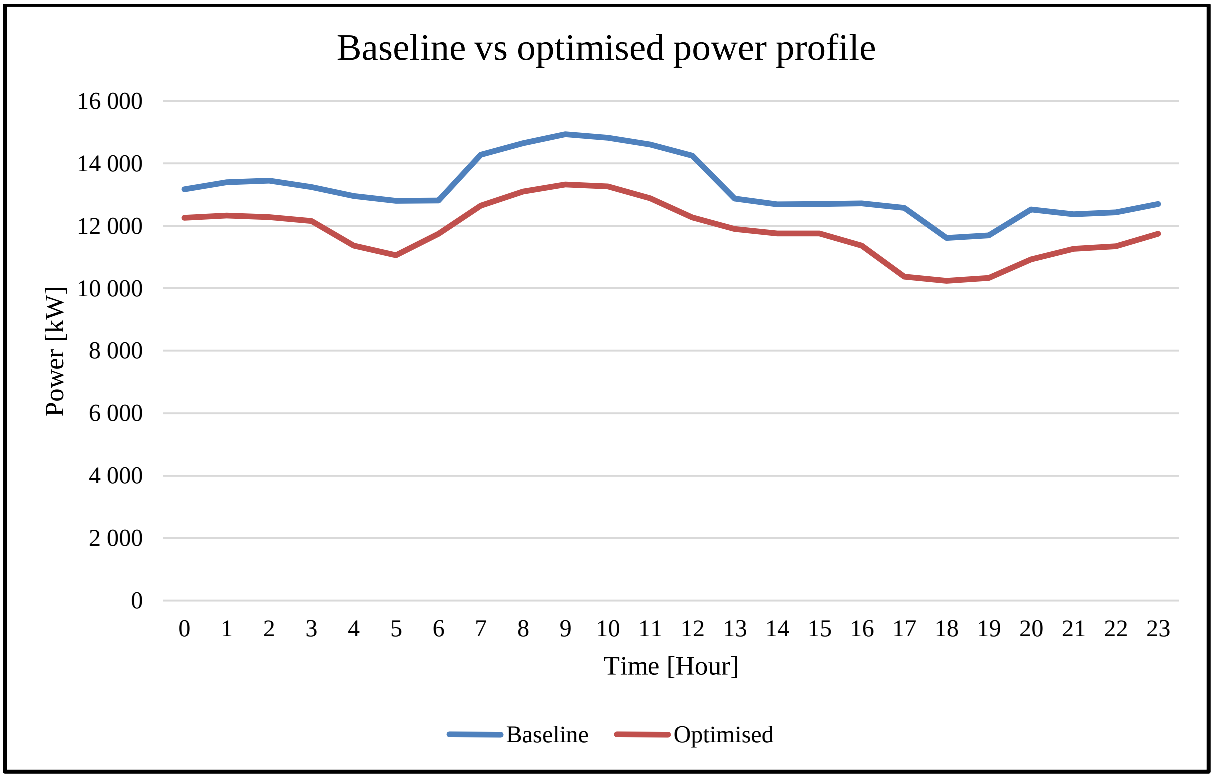


Figure 93: Optimised power profile

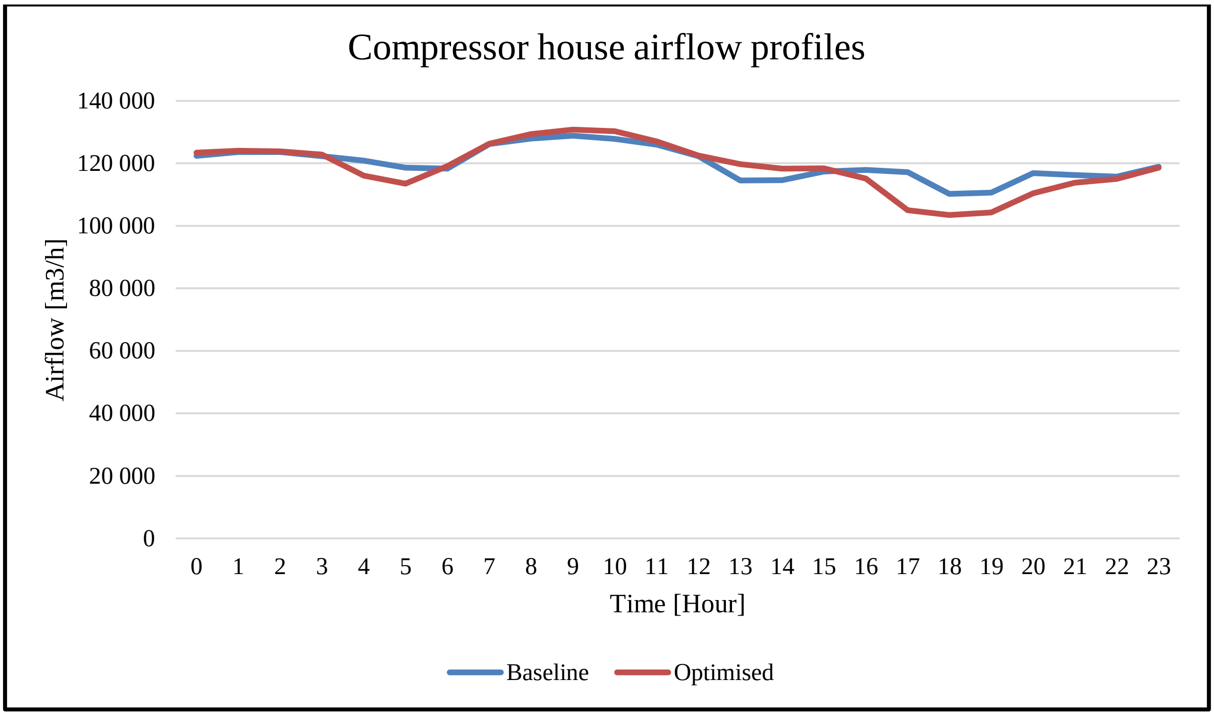


Figure 94: Optimised compressor house airflow profiles

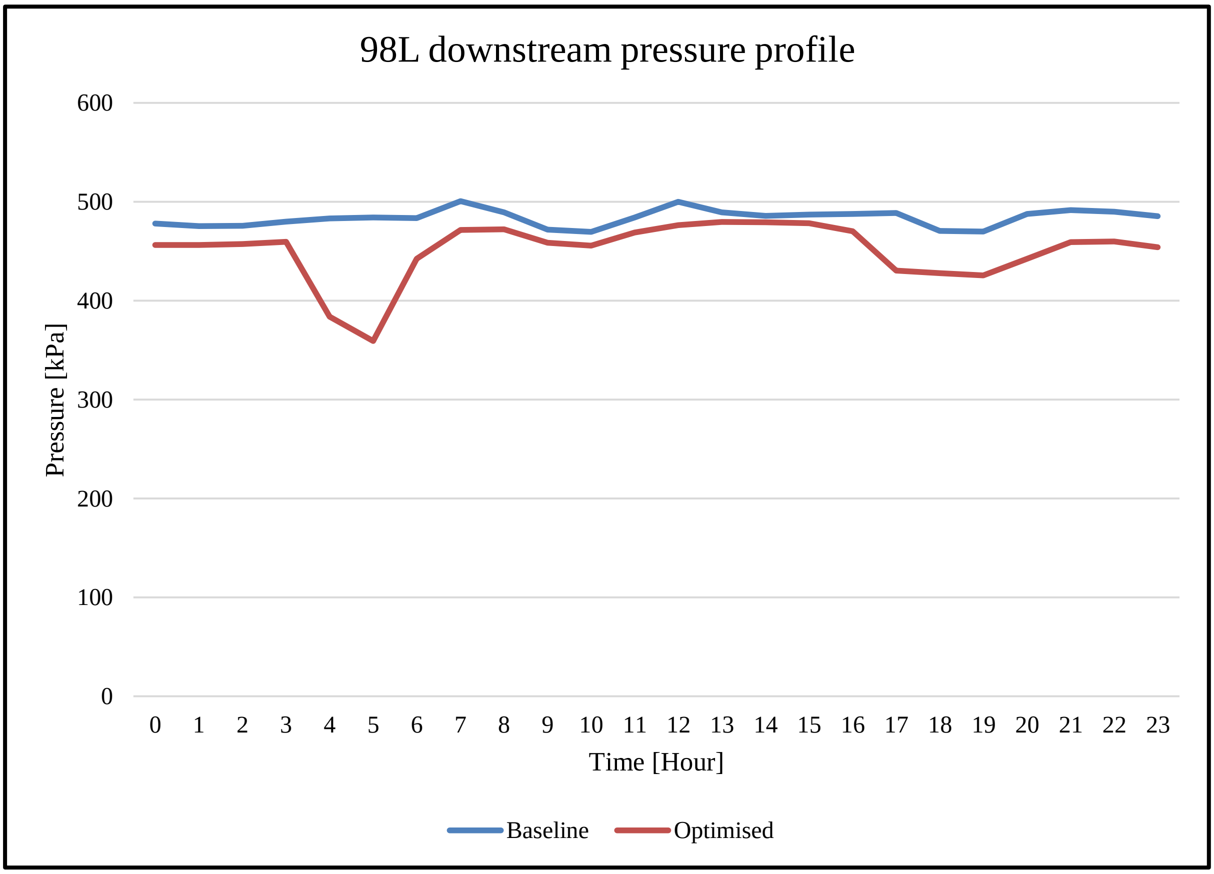


Figure 95: Optimised downstream pressure profile for 98L

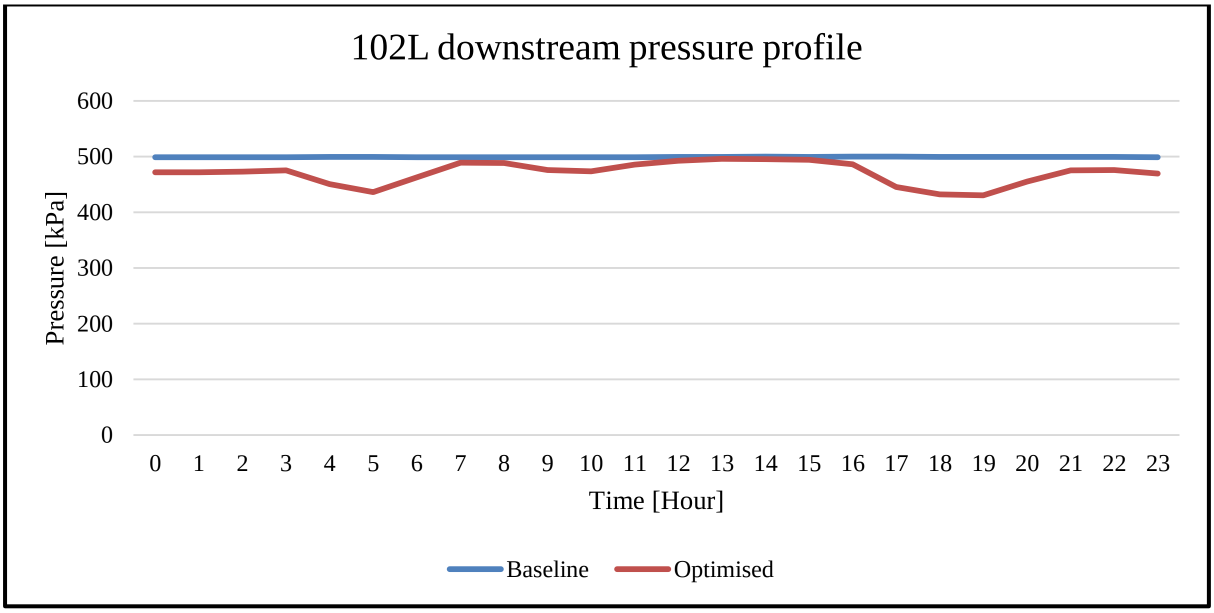


Figure 96: Optimised downstream pressure profile for 102L

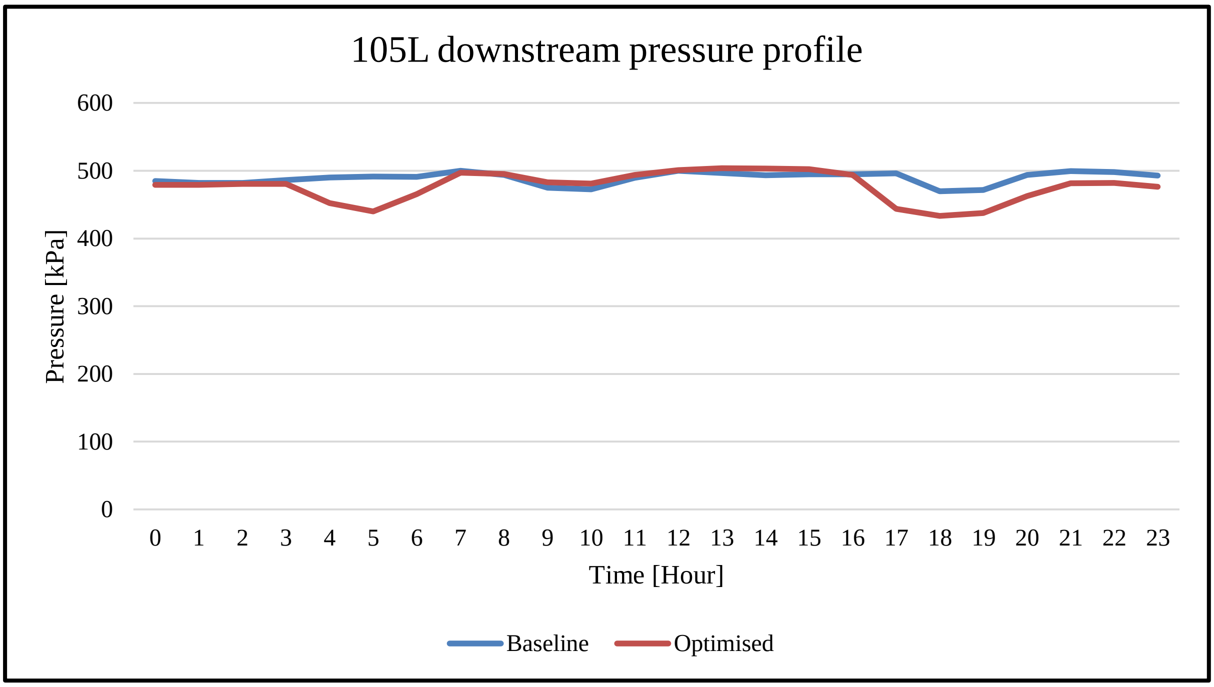


Figure 97: Optimised downstream pressure profile for 105L

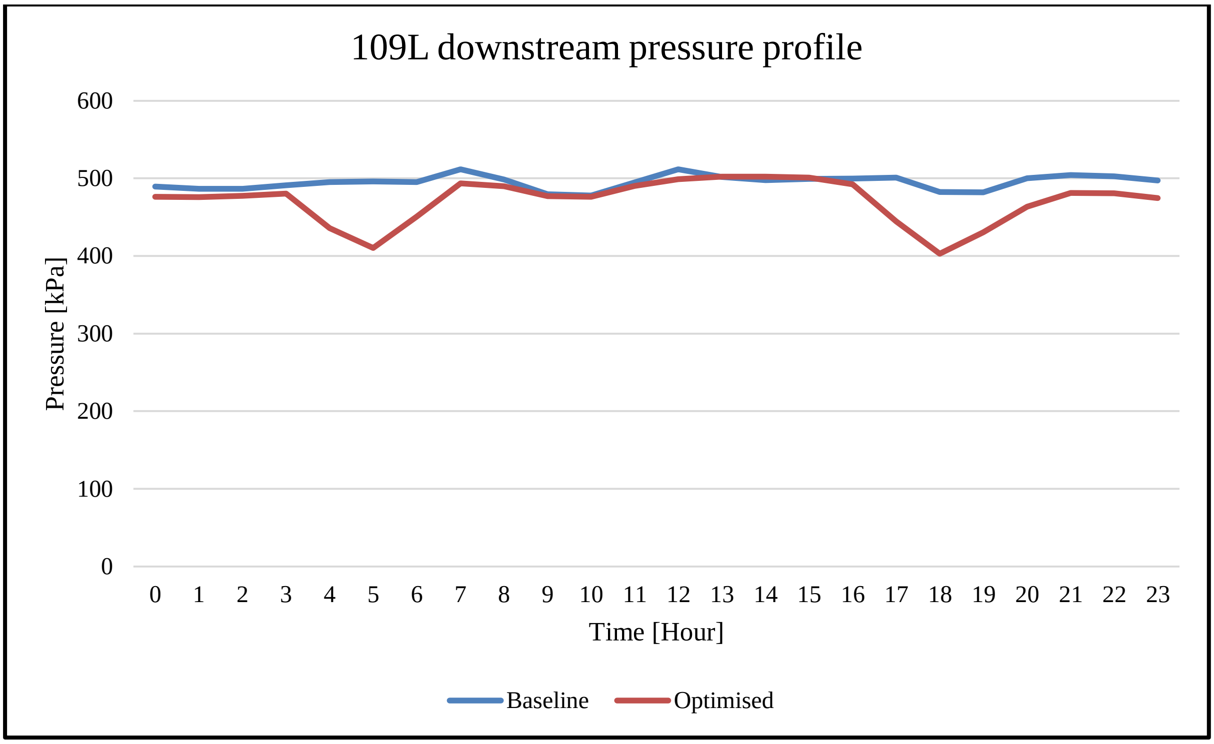


Figure 98: Optimised downstream pressure profile for 109L

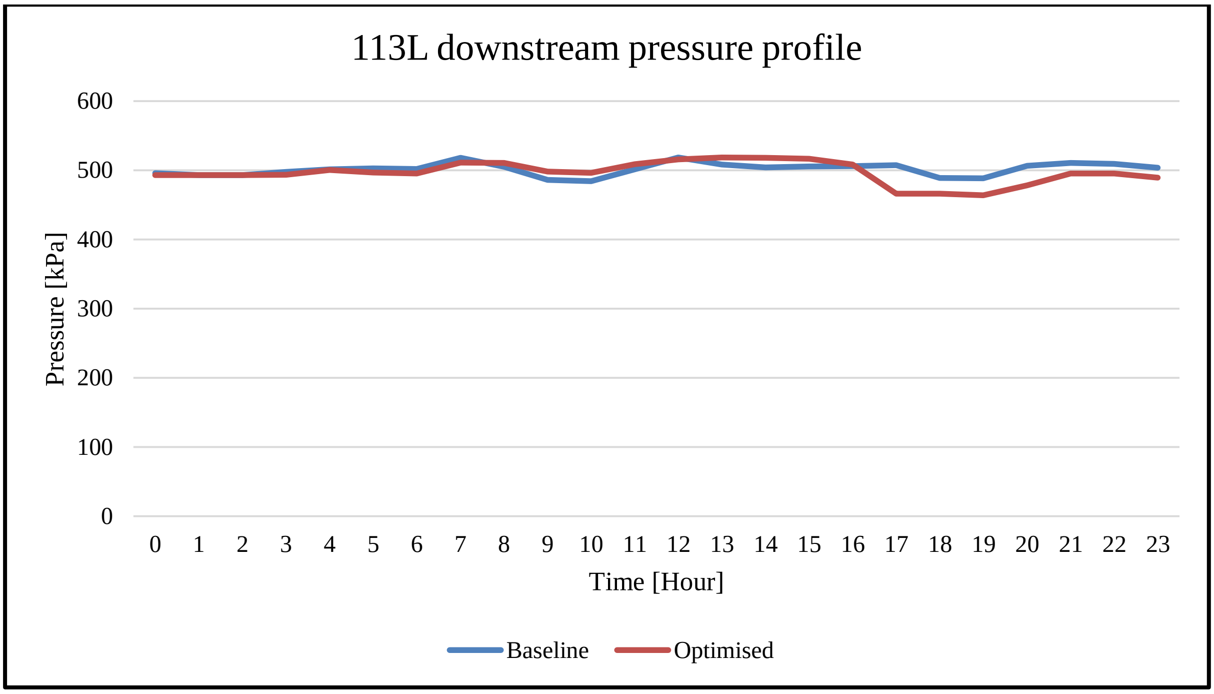


Figure 99: Optimised downstream pressure profile for 113L

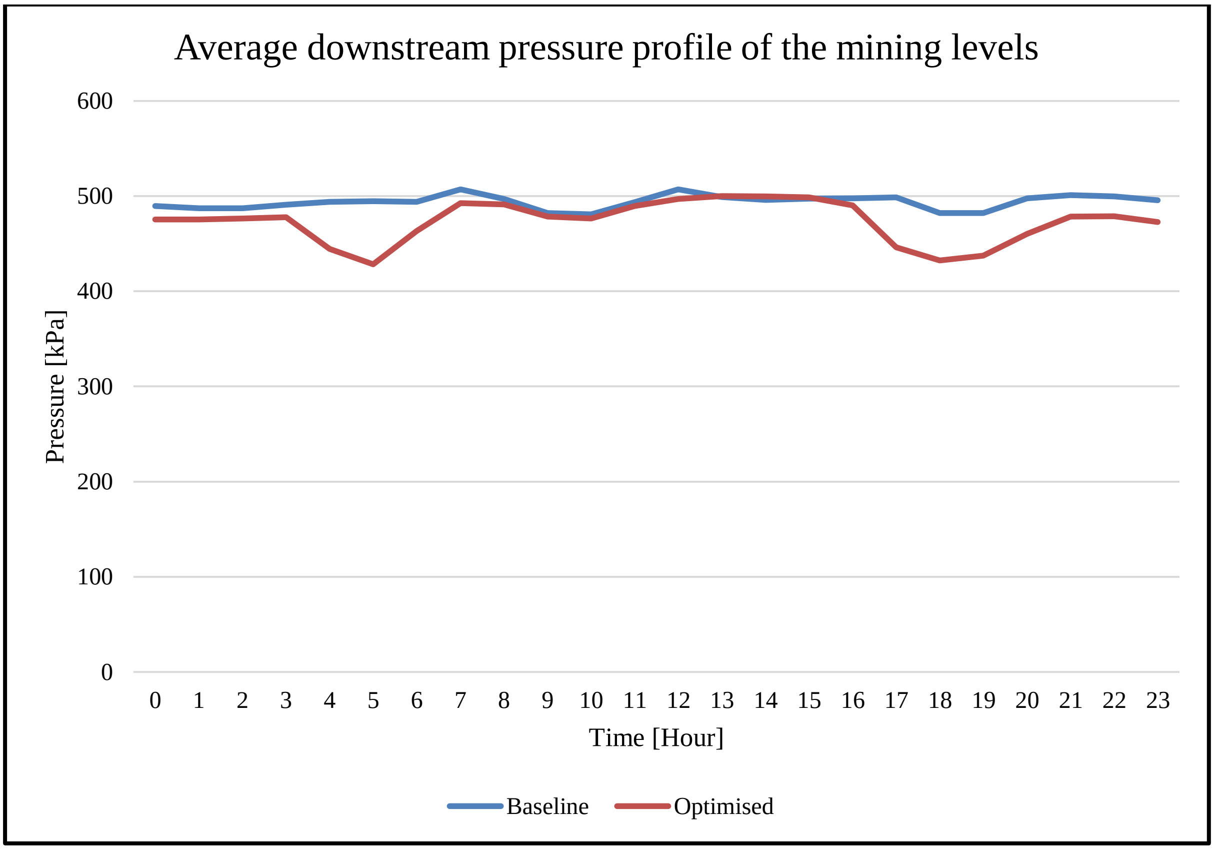


Figure 100: Average profile of the optimised downstream pressures of the mining levels