

Target profiles for critical parameters in compressed air systems to reduce missed energy savings opportunities

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ABSTRACT

Title: Target profiles for critical parameters in compressed air systems to reduce missed energy savings opportunities

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The reducing profit margins of South African mines pose a financial and economic risk for South Africa. The decrease in gold production and the increase in operational costs are contributing factors to the reduction of profit margins in the gold mining industry. With electricity being one of the biggest expenses of deep-level gold mines, it is one of the focus points in reducing operational costs and increasing the profit margins of gold mines.

An estimated 17% of the total electricity demand of deep-level mines is compressed air. Compressor energy savings initiatives can reduce compressor energy usage by as much as 30%. For this reason, compressor energy savings initiatives are typically implemented on deep-level mines.

Sustaining the implemented compressor energy savings initiatives is a challenge in the mining sector. Compressor energy savings initiatives may achieve fewer savings than the maximum achievable savings due to various factors, causing missed energy savings opportunities. Compressor energy savings initiatives may experience missed energy savings opportunities due to:

- Interference with automatic control,
- high demand or unfavourable conditions,
- infrastructure constraints or breakdowns, or
- control system problems.

Unless the abovementioned causes are identified and rectified, the missed energy savings opportunities will lead to decreased energy savings and unforeseen costs. The reduced energy savings leads to reduced profit margins, despite the efforts to implement such energy savings

initiatives. The literature contains methods to identify missed energy savings opportunities in compressed air systems and rectify the cause of missed energy savings opportunities once it has been identified. The literature lacks a detailed method to identify missed energy savings opportunities and the cause thereof.

By applying the case study methodology, a method was developed that can be implemented with existing or previously implemented compressor energy savings initiatives. The method aims to reduce missed energy savings opportunities in compressed air systems by successfully identifying the cause thereof. The method incorporates target profiles for critical parameters in a compressed air system to identify areas where the technical requirements have not been met which results in missed energy savings opportunities.

The method was implemented with four previously implemented compressor energy savings initiatives on three gold mining shafts of Mine A. The identification of missed energy savings opportunities and the cause thereof led to solutions implemented that reduced the missed energy savings opportunities calculated at 6.70 MWh per year, which relates to a cost avoidance of R 12 million per year.

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NOMENCLATURE

Symbol	Description	Units
P_{abs}	Absolute air pressure	kPa
P_{leak}	Absolute air pressure at leak	kPa
T	Air temperature	K
T_{leak}	Air temperature at leak	K
v	Airflow velocity	m/s
P_{in}	Atmospheric pressure	kPa
η_{comp}	Compressor efficiency	—
A_{leak}	Cross-sectional area of the leak	m^2
ρ	Density of air	kg/m^3
h	Depth from surface	m
C_d	Discharge coefficient of a leak	—
P_{out}	Discharge pressure	kPa
η_{motor}	Efficiency of the compressor motor	—
P_{comp}	Electrical power of the compressor	kW
P_{motor}	Electrical power of the motor	kW
z_0	Final altitude	m/s^2
p_0	Final pressure	kPa
f	Friction factor	—
R	Gas constant (0.278)	$kJ/kg \cdot K$
g	Gravitational acceleration (9.81)	m/s^2
z_i	Initial altitude	m
p_i	Initial pressure	kPa
T_{in}	Inlet air temperature	K

L	Length of vertical pipeline	m
$\dot{m}_{air}$	Mass flow rate of air	kg/s
$\dot{m}_{leak}$	Mass flow through the leak	kg/s
W_{comp}	Mechanical energy of the compressor	kJ/kg
d	Pipe inner diameter	m
n	Polytropic constant for isentropic compression (1.4)	—
$P_{required}$	Power required to supply the leak	kW
ΔP	Pressure increase due to auto compression	kPa
ΔP_{Total}	Pressure impact due to auto compression with the effect of pressure losses	kPa
C_p	Specific heat capacity of compressed air	$kJ/kg \cdot K$
k	Specific heat ratio of compressed air (1.4)	$kJ/kg \cdot K$
T_1	Temperature of compressed air	K

LIST OF ABBREVIATIONS

DSM	Demand-side management
EMS	Energy management system
ESCo	Energy savings company
PID	Proportional-integral-derivative
PLC	Programmable logic controller
SCADA	Supervisory control and data acquisition

Chapter 1 INTRODUCTION

1.1 Gold mining in South Africa

1.1.1 Value of gold

Gold mining is a valued part of the world's mining sector. In the past, the value of a country's currency was directly influenced by the value of gold, which is known as the "gold standard". While today the value of gold no longer directly influences a country's currency per se, gold is still highly valued and therefore plays a major role in the economy [1], [2].

Gold is seen to be valuable because it does not diminish to the extent that other currency systems do and can therefore be seen as a hedge against inflation [3], [4]. During economically challenging times, the value of gold increases and can therefore be used to secure funds for national and private investment portfolios [1], [2].

1.1.2 Start of gold mining in South Africa

Gold was first discovered in South Africa in 1884 in the Witwatersrand. This set off an influx of miners from across the world. Later, from 1886 to 1900, the first large gold company was established, which led to the development of the city of Johannesburg. During this time, South Africa became the world's largest gold producer, producing 118 tonnes in 1898 [5].

As the gold reserves on the surface were depleted, mine level depth increased to extract the gold ore. This development marked the beginning of deep-level mining in South Africa. New technology made it possible to reach deeper into the earth to reach more gold reserves. During 1970, for the first time in 86 years after the discovery of gold in South Africa, production soared to over 1 000 tonnes in a year. The increase in gold production restored the status of South Africa as the leading gold producer in the world [5]. Evidently, deep-level mining has helped the South African economy recover and sustain the life of the mining industry.

The South African mining industry is an important role player in the country's economy. In 2019, it contributed 7% of the country's gross domestic product (GDP) [6], [7]. Unfortunately, the mining industry's GDP contribution decreased by 1.7% from 2017 to 2018 and 1.9% from 2018 to 2019 [6], [7], which is unfavourable for South Africa's economy.

1.1.3 Reduction of profit margins for gold mines

The profit margins of gold mines in South Africa are decreasing. In 2018, 75% of the gold mines operating in South Africa were unprofitable [8]. Besides the decrease in production, the increase in the price of electricity and labour costs negatively affect the profitability of gold mines in South Africa. The reasons for a decline in profit margins are discussed in more detail below.

1.1.3.1 Production rate

As of 2018, South Africa contributed 3.3% to global gold production. South Africa now has the third-largest gold reserve in the world, after Australia, then Russia, with the largest reserve [9].

Gold mines in South Africa have seen a 54% drop in production from 2007 up to 2018, as shown in Figure 1 below:

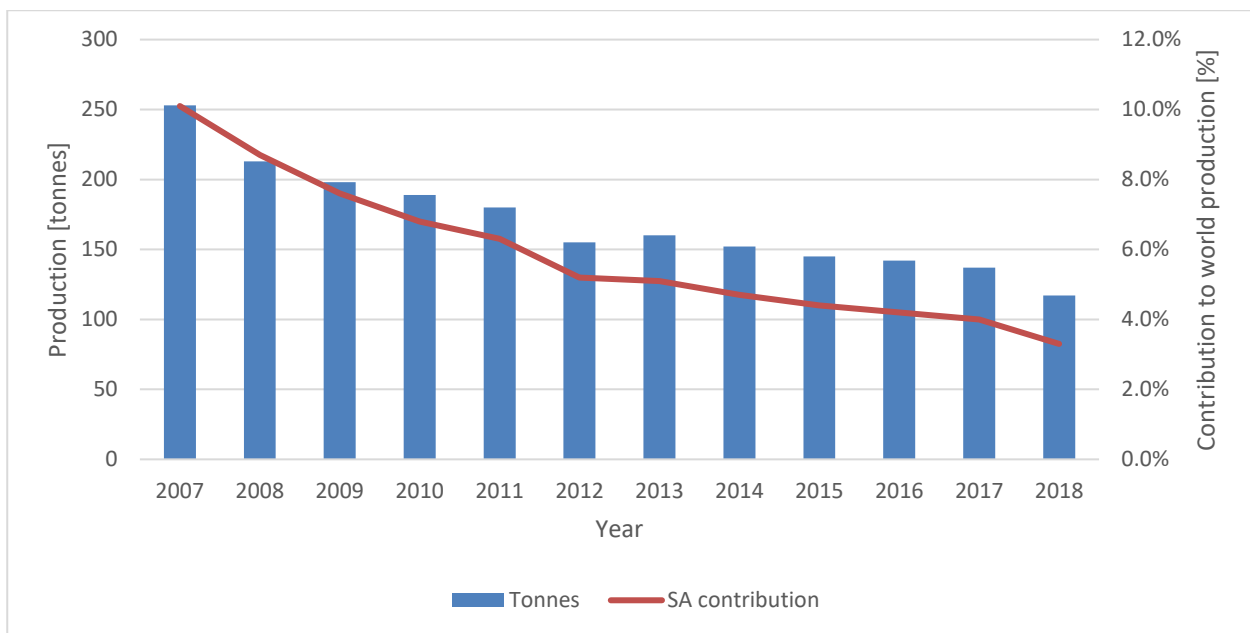


Figure 1: Production of gold mines in South Africa [9]

This steady decline in gold production results from operational challenges such as increasing mining depths and distances from the shaft infrastructure to working areas and the associated rising costs [8].

1.1.3.2 Labour costs

The labour costs for gold mines in South Africa have increased significantly in the last decade. Even though the number of people employed in the gold mining industry of South Africa reduced, labour costs have increased from R4.59 billion in 2008 to R9.75 billion in 2018 for Harmony Gold [10]. This shows an average increase of R0.52 billion each year in labour costs. The labour cost increase from 2008 to 2018 is compared to the total inflation rate increase from 2008 and 2018 in Table 1 below [10], [11].

Table 1: Labour cost increase vs inflation from 2008 until 2018 for Harmony Gold

Description	Increase from 2008 until 2018
Mining labour costs	112%
Inflation	70%

Table 1 shows that labour costs have increased 42% more than inflation from 2008 until 2018.

1.1.3.3 Operational and electricity costs

The mining industry is a large consumer of electricity in South Africa. The total mining industry consumes a total of 14% of the electricity supplied by Eskom, of which 6.7% accounts for the gold mining sector [8]. The cost of electricity in South Africa has increased by 81% from 2007 to 2019 [12]. This cost increase significantly impacts the cash flow margins of mines as their utilities can make up as much as 20% of the mining sector's operational cost [13].

A major concern for South African mines is the high operating costs that can lead to reduced life of mine [14]. Electricity costs account for as much as 20% of a deep-level mine's total operating costs [13]. The utility bill for the South African mining sector was R 27.72 billion in 2018, and R 33.2 billion in 2019 [15]. This is a 20% increase in a mine's utility costs in just one year. The impact of the high electricity costs is a great concern for mining groups, especially mines with narrow profit margins [16].

High electricity costs are one of the reasons that the South African mining industry is declining and losing its competitiveness [17]. Since the mining industry is highly dependent on the supply of electricity to keep operations going, high electricity costs can cripple the industry.

The electricity costs of mines are due to the high electrical energy demand to extract gold from underground working areas. Over 6 400 tonnes of rock can be extracted per day from up to four kilometres underground [18]. Various systems and equipment must function to extract rock from these depths, which require a high amount of electrical energy. The largest single commodity energy demander in the gold mining industry is compressed air [19]. Compressed air can account for up to 19% of a deep-level mine's electricity consumption, although it has been seen to consume a total of 50% [17].

With compressed air being a large energy consumer in the mining industry, it is also seen as a very inefficient system. Only 19% of the energy provided by compressed air is usable [20]. Due to the inefficiency of compressed air systems, it has been a major focus of energy efficiency projects to reduce the energy demand of the commodity in mines [21].

1.2 Deep-level mining compressed air systems

1.2.1 Overview

The process of extracting gold from underground depends highly on compressed air thanks to the reliability and ease of use of pneumatic equipment [22], [21], [23]. Compressed air systems can consist of a compressed air supply section and a compressed air demand section [24]. Compressed air supply refers to the generation of compressed air through compressors, and compressed air demand refers to the usage of compressed air [25], [24].

Compressed air is generated by compressors, typically located on the surface [24]. The compressed air is then distributed across a mine's underground working areas through a piping network [22]. A compressed air system's complex network of pipes can at times extend over several kilometres underground [25]. The following section provides more detail regarding the supply and demand of compressed air.

1.2.2 Compressed air networks

A compressed air system can be connected to more than one compressor. One or more compressors connected to a singular pipe distributing the compressed air is referred to as a

compressor house. Compressed air systems may contain one or more compressor houses, each consisting of one or more compressors.

A compressed air system may be supplied with compressed air by one or more compressor houses. There are mainly two ways to utilise compressor houses located on the surface to supply compressed air to mining shafts, namely a stand-alone system and a ring-feed system [26].

If a compressed air system is supplied from a single compressor house, the system is referred to as a stand-alone system [26]. A visual illustration of a stand-alone system is shown in Figure 2 below.

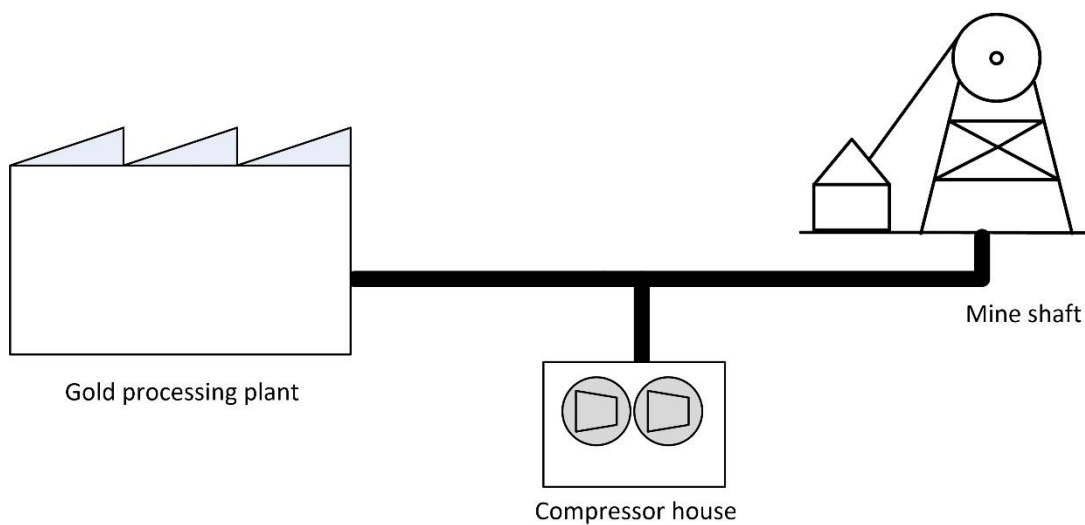


Figure 2: Stand-alone compressed air system

If the system is supplied by more than one compressor house, the system is referred to as a ring-feed system [22], [26]. A visual illustration of a ring-feed system is shown in Figure 3 below.

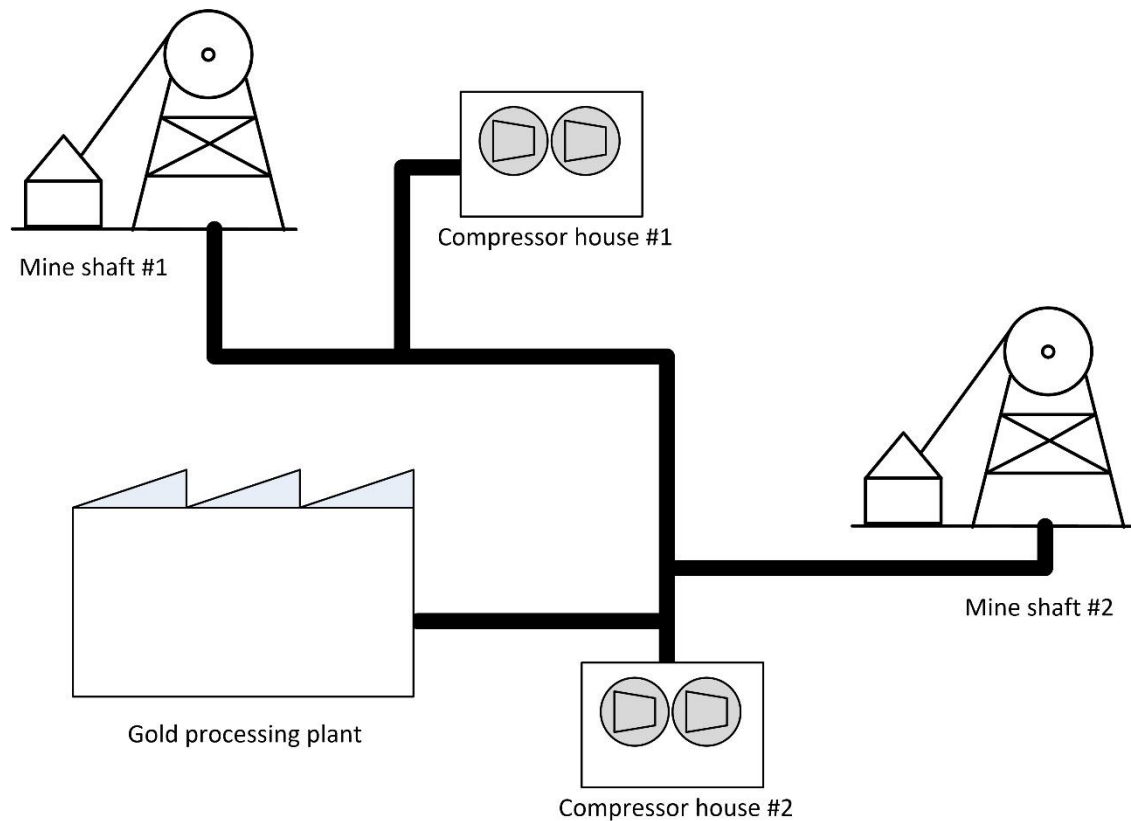


Figure 3: Ring-feed compressed air system

Both stand-alone systems and ring-feed systems have their respective advantages and disadvantages. Ring-feed systems are more common in the mining industry [26]. Some advantages and disadvantages of a ring-feed system are listed below [26].

Advantages of a ring feed system:

- Various control options can be implemented,
- the compressed air supply can be decentralised, and
- the logistics surrounding ring maintenance is simplified.

Disadvantages of a ring-feed system:

- The maintenance cost is high due to the large infrastructure, and
- the system pressure at various points will differ due to various compressed air consumers.

1.2.3 Compressed air supply

Various types of compressors are available to be used in the mining sector. Each type has its advantages and disadvantages when it comes to specific compressed air needs. A diagram depicting some of the types of compressors is shown in Figure 4 below.

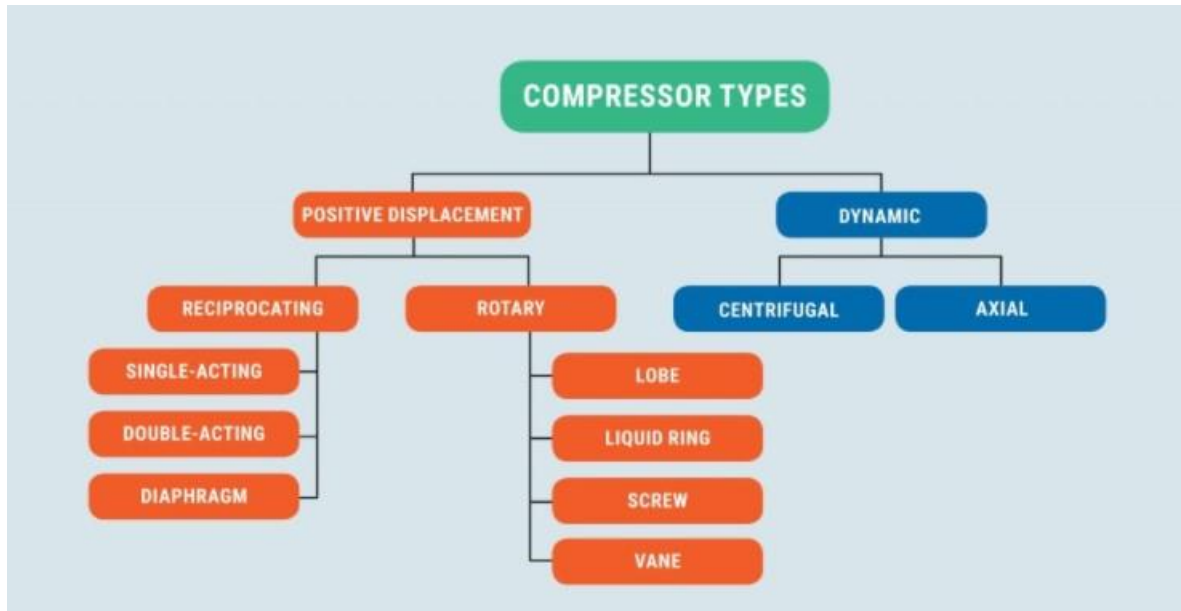


Figure 4: Types of compressors [27]

Centrifugal compressors are a common type of compressor in the mining industry [26]. Some of the advantages of centrifugal compressors are listed below [28]:

1. Suitable for continuous compressed air supply,
2. higher-flow rate than the positive displacement compressor,
3. relatively energy-efficient,
4. reliable and low maintenance, and
5. generates a higher pressure ratio per stage than axial flow compressors.

It is common for mines to use more than one compressor in parallel to meet the required flow demand [25]. The compressed air generated is combined into a common supply manifold [25].

Centrifugal compressors can effectively meet the compressed air demand through various control mechanisms [25]. An example of such a control mechanism is guide-vane control, which enables the compressor to vary its supplied flow depending on the demand [25]. Guide-vane control can reduce the supplied flow of a compressor to a set limit, after which the additional compressed air

is released into the atmosphere through a blow-off valve to prevent the compressor from surging [25].

The compressed air is supplied to a pipe reticulation network that feeds various end-users. The end-users utilise the supplied compressed air to perform various tasks to, ultimately, remove gold from underground. The compressed air demand in these processes is discussed in the following section.

1.2.4 Compressed air demand

Various pneumatic equipment is used in a mine to perform specific tasks. A selection of pneumatic equipment used in the mining industry is described briefly in the sections below.

1.2.4.1 Pneumatic drills

The process of drilling into the rock to make holes for the explosives is achieved mainly by using pneumatic drills [21], [23], [20]. The drills are used at developing ends, and the production areas are also referred to as stopes [22]. More than one pneumatic drill will typically be used in a mine. An example of a pneumatic drill is shown in Figure 5 below.

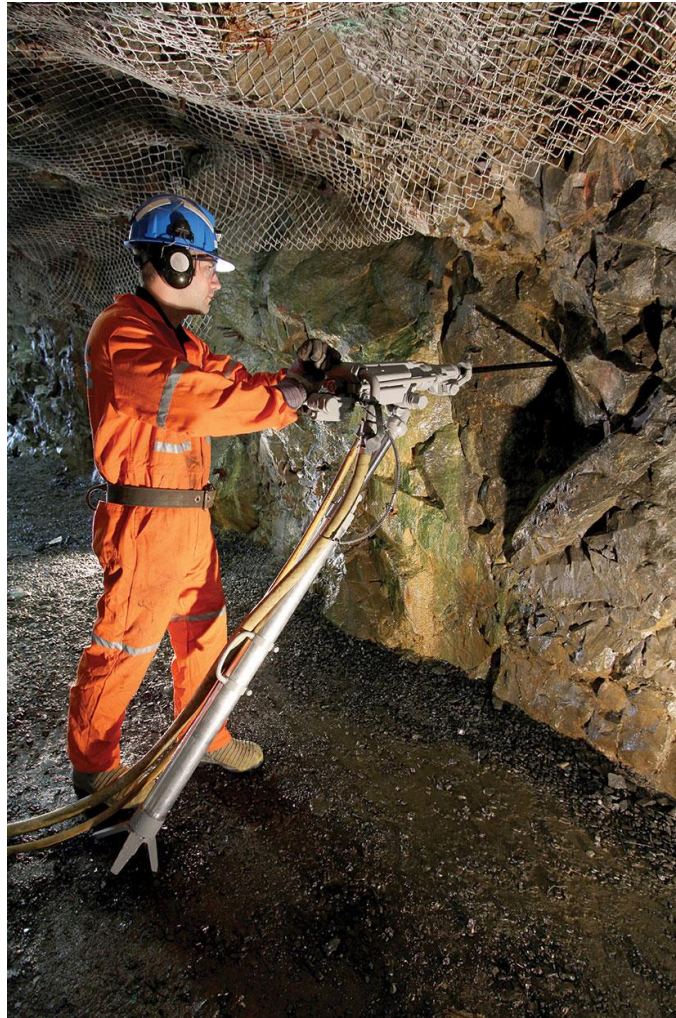


Figure 5: Boart Longyear's S250 pneumatic rock drill [29]

1.2.4.2 Pneumatic loaders

Pneumatic loaders are used to move/throw loose rocks into hoppers for transportation and tipping. These loaders are rail-bound and are only available in areas where rails are available. An example of a pneumatic loader is shown in Figure 6 below.



Figure 6: Ortas Mining mine loader PPN [30]

1.2.4.3 *Pneumatic cylinders*

Pneumatic cylinders are typically used to operate loading boxes. These loading boxes are used to load ore into skips or belts [26]. An example of a pneumatic cylinder on a loading box is shown in Figure 7 below.



Figure 7: Pneumatic cylinder operating a loading box ¹

¹ Photo by the author

1.2.4.4 Cooling applications

Open-end compressed air pipes/hoses are used to alleviate the harsh conditions of underground working places such as heat and humidity [26]. An example of an open-end compressed air hose alleviating harsh temperatures is shown in Figure 8 below.



Figure 8: Open-end compressed air hose ²

1.2.4.5 Ventilation applications

Refuge bays are secure chambers that provide fresh air and water to workers inside. These bays require positive atmospheric pressure inside (relative to the atmospheric pressure outside the bay) to prevent harmful gases from entering [24], [26]. The fresh air and positive air pressure are achieved by using compressed air. Compressed air pipes are located in the refuge bay, allowing compressed air to blow into the bay. An example of the inside of a refuge bay is shown in Figure 9 below.

² Photo by the author



Figure 9: Underground refuge bay ³

1.2.4.6 Processing plants

Processing plants extract ore from the rock. These plants use compressed air for various applications, including instrumentation and agitation [22]. These processing plants are a vital part of the gold production process, and the mine cannot afford to stop operations due to a lack of compressed airflow or pressure. Gold processing plants typically require high compressed air pressure to function but not a high flow [31]. An example of a typical gold processing plant is shown in Figure 10 below.

³ Photo by the author



Figure 10: Avgold Target gold mine processing plant [32]

1.2.4.7 Pneumatic winches

Pneumatic winches are used to lift and pull heavy objects. This can be used in various areas of a mine. An example of a scraper winch is shown in Figure 11 below.



Figure 11: Ortas Scraper winch VSS-206 [33]

All pneumatic equipment requires different compressed air pressures and flow rates to function. The different equipment is used in different shifts. This creates a compressed air pressure and flow demand curve that varies during the day. The typical required compressed airflow rate and pressure for different compressed air applications are shown in Table 2 below [26], [33], [34].

Table 2: Typical compressed air requirements for different compressed air users

Compressed air user	Required pressure [kPa]	Required flow [m³/s]
Pneumatic drills	400-600	0.08-0.7
Pneumatic loaders	400-550	0.12-0.28
Pneumatic cylinders	350-600	0.006-0.14
Cooling application	350-620	0.019-0.091
Ventilation application	200-300	0.0014
Agitation	400	0.47
Pneumatic winches	500	0.1

1.2.5 Typical operation of a deep-level mine

The compressed air demand of a mine is not constant in a 24-hour workday. Different tasks are completed in succession to extract gold from underground working areas. These tasks are performed during specific shift times. The 24-hour workday of a mine consists of three main shifts, which are discussed below [25].

- Drilling shift: Holes are drilled into the rock for explosives to be placed inside.
- Blasting shift: Explosives are placed inside the holes created in the drilling shift and then detonated.

- Sweeping and cleaning shift: The blasted rock is removed from the area and transported to dedicated loading areas.

The three main shifts, with the respective typical starting and ending times, are shown in Table 3 below [25].

Table 3: Typical operating schedule of a mine

Shift	Start time	End time
Drilling shift	07:00	14:00
Blasting shift	16:00	21:00
Sweeping and cleaning shift	21:00	04:00

The different tasks executed during the different shifts of a mine require different equipment to execute tasks successfully. The different pneumatic equipment that may be used in the different shifts is shown in Table 4 below [34]. The green block indicates that the equipment is used during the specified shift.

Table 4: Pneumatic equipment used during the different shifts of a mine

Compressed air user	Drilling shift	Blasting shift	Cleaning and sweeping shift
Pneumatic drills			
Pneumatic loaders			
Pneumatic cylinders			
Cooling application			
Ventilation application			
Agitation			
Pneumatic winches			

As shown in Table 4 above, the most equipment is typically used during the drilling shift, whereas the least amount of equipment is used during the blasting shift.

1.2.6 Conclusion

Compressed air systems were evaluated in this section. The supply of compressed air to the compressed air networks was discussed, together with the typical compressed air users found in deep-level mines. With a better understanding of compressed air systems, the next step is to determine how the energy consumption of these systems is reduced.

1.3 Existing energy management strategies for compressed air systems

1.3.1 Introduction

Compressed air systems are regarded as one of the most inefficient and power-intensive systems in deep-level mines [20]. The inefficiency of a deep-level mine's compressed air system has created a large opportunity for improvement and optimisation [21]. While there are substantial opportunities to increase the efficiency of a compressed air system, these improvements should be implemented without affecting production activity, as it is the main priority of a gold mine [35].

The following sections will evaluate existing methods to reduce the energy consumption of compressed air systems in deep-level mines.

1.3.2 Electrical power consumption of compressors

The electrical power consumption of a centrifugal compressor motor can be calculated when the compressed air requirements and conditions are known [36]. To calculate the power requirements of a compressor motor, Equation 1 can be used [37], [38].

Equation 1: Power of a compressor motor [37], [38]

$$P_{motor} = \frac{P_{comp}}{\eta_{motor}} \quad (1)$$

where:

P_{motor} = Electrical power of the motor kW

P_{comp} = Electrical power of the compressor kW

η_{motor} = Efficiency of the compressor motor —

The efficiency of the compressor motor can typically be found in the compressor specifications [36]. An assumption of 0.9 can be used for the compressor motor efficiency if it cannot be obtained from the specifications [22], [21]. Equation 2 below can be used to calculate the electrical power of a compressor [21], [37].

Equation 2: Electrical power of a compressor [21], [37]

$$P_{comp} = \dot{m}_{air} W_{comp} \quad (2)$$

where:

P_{comp} = Electrical power of the compressor kW

$\dot{m}_{air}$ = Mass flow rate of air kg/s

W_{comp} = Mechanical energy of the compressor kJ/kg

The mass flow rate of the compressed air can be calculated by dividing the volume flow rate measured at the outlet of the compressor by the air density [36]. The density of the air can be calculated using the ideal gas law as shown by Equation 3 [37].

Equation 3: Ideal gas law equation to calculate the density of air [37]

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

where:

ρ = Air density kg/m^3

P_{abs} = Absolute air pressure kPa

R = Gas constant (0.278) $kJ/kg \cdot K$

T = Air temperature K

From Equation 3, it is noted that the density of air is directly proportional to the air pressure and inversely proportional to the air temperature. The air densities at different temperatures at atmospheric pressure of 1.10325 bar are shown in Table 35 in Appendix A.

To calculate the electrical power consumption of a compressor as formulated in Equation 2, its mechanical energy consumption is required. The mechanical energy consumption of a compressor can be calculated using Equation 4 [21], [39].

Equation 4: Mechanical energy consumption of a compressor [21], [39]

$$W_{comp} = \frac{nRT_{in} \left(\left(\frac{P_{out}}{P_{in}} \right)^{\frac{n-1}{n}} - 1 \right)}{\eta_{comp}(n-1)} \quad (4)$$

where:

W_{comp}	= Mechanical energy of the compressor	kJ/kg
n	= Polytropic constant for isentropic compression (1.4)	—
R	= Gas constant (0.278)	$kJ/kg \cdot K$
T_{in}	= Inlet air temperature	K
P_{out}	= Discharge pressure	kPa
P_{in}	= Atmospheric pressure	kPa
η_{comp}	= Compressor efficiency	—

The compressor efficiency can be obtained from the compressor specification sheet [36]. An assumption of 0.8 can be used for the compressor efficiency if the compressor specification sheet is unavailable [22], [21]. The electrical power consumption of a compressor motor can be calculated using Equation 1 by obtaining all relevant information from Equation 2, Equation 3, and Equation 4 above.

The air mass flow, discharge pressure, and inlet temperature are directly proportional to the power usage of the compressor, as seen in Equation 2 and Equation 4 above. The values of these parameters are determined by the compressed air demand of a compressed air network. Initiatives have, according to the literature, been implemented that led to the reduction in compressor power consumption, as discussed in the next section.

1.3.3 Reducing the energy consumption of compressed air systems

The energy consumption of a compressed air system can be reduced by improving various sections of a compressed air network [26]. Initiatives to reduce the energy consumption of compressed air systems can be subdivided into supply- and demand-side initiatives. Compressed

air supply refers to the generation of compressed air utilising compressors, while compressed air demand refers to compressed air usage. Listed below are some notable methods for reducing energy consumption and optimising the supply of a compressed air system [26], [40].

Examples of optimising the supply side:

- Decrease the system pressure,
- optimise the compressor delivery control, and
- implement compressor control.

Examples of optimising the demand side:

- Compressed air pressure and mass-flow control, and
- reduce air leaks.

The methods for reducing the energy demand of a compressed air system above are discussed in the subsections below.

1.3.3.1 Energy savings through supply-side optimisation of compressed air networks

The energy of compressed air systems can be reduced by controlling the compressed air amount and pressure delivered to the system [26], [41]. This method is called supply-side control. The electrical demand of a compressor will reduce when reducing the delivery pressure of the compressor [42], [43], [44]. The compressor power decrease caused by reducing the delivery pressure can be calculated using Equation 4 above.

The power consumption of a compressor can be reduced **by installing inlet guide vanes** at the suction part of the first stage of a compressor [23], [44]. The inlet guide vanes control the compressed air supplied to and by a compressor [44]. Inlet guide vane control can, given its ability to effectively reduce compressed air supply, also reduce power consumption [45]. In fact, implementing inlet guide vane control on a compressor is more efficient at reducing power consumption than reducing the airflow with valve throttling [46].

Inlet guide vane control has a more significant impact on the system performance when it is adjusted correctly [47]. The inlet guide vanes provide no benefit to the system when the compressor is operating at full-load conditions; they are most beneficial by providing flow control during fluctuations in system resistance and backpressure [45]. The guide vanes can be programmed to sustain delivery pressure and assist in avoiding compressor blow-off [46].

The inlet guide vane angles are dependent on the compressor delivery pressure setpoint and the system's compressed air demand [45]. A reduction in compressed air demand leads to a pressure build-up in the pipe manifold, causing back pressure [45]. The inlet guide vane angles reduce when the backpressure exceeds the pressure setpoint to maintain the desired pressure setpoint [23]. The backpressure decreases when the compressed air demand increases [45].

The backpressure can reduce to a point lower than the pressure setpoint where the guide vane angles will increase, leading to increased compressor power consumption [45]. The inlet guide vanes are controlled to match the compressor delivery pressure setpoint by reacting to changes in the compressed air demand [23]. The guide vane angles directly affect the power consumption of compressors as a result of the controlling mechanism described above [26]. The effect of the guide vane angle on the compressor power consumption is shown in Figure 12 below.

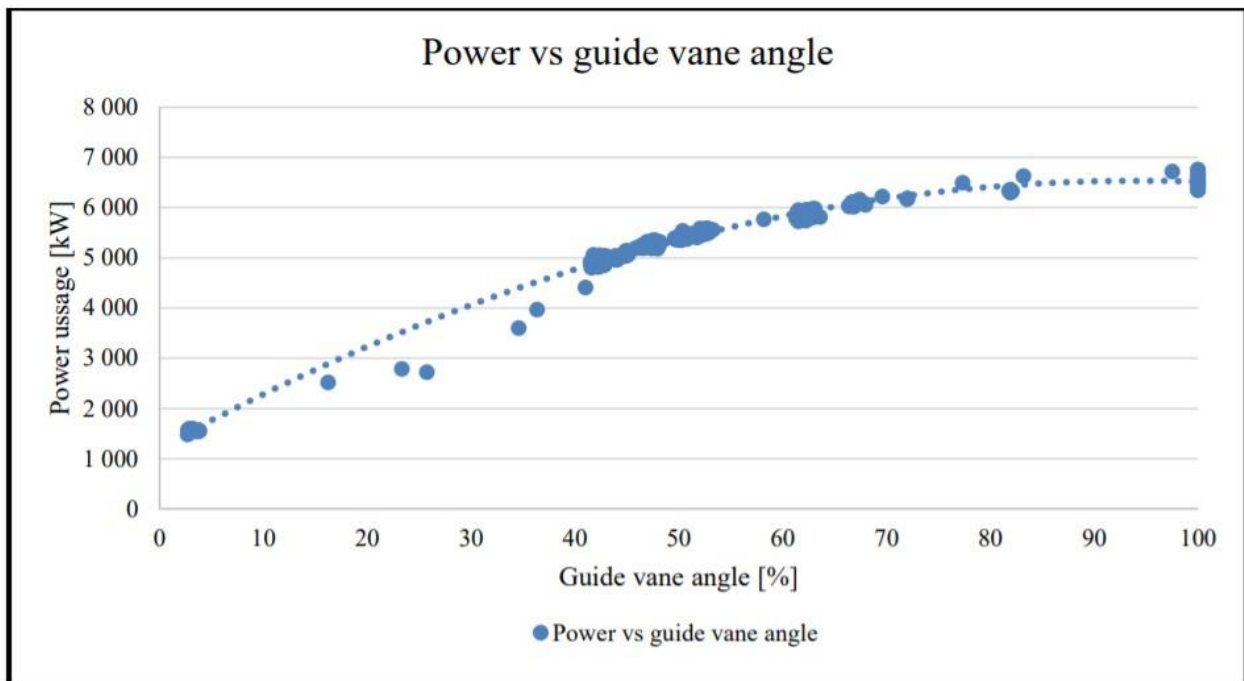


Figure 12: Guide vane angle vs compressor power [45]

The following sections contain **methods to reduce the power consumption of compressors using inlet guide vane control**.

Compressors can deliver compressed air to a compressed air network with or without inlet guide vanes. Compressors with inlet guide vanes installed must have the correct delivery pressure setpoints to supply the correct compressed airflow and pressure to the consumers. Furthermore, it is necessary to **adjust compressed air delivery pressure setpoints** according to the maximum compressed air requirement at specific times. If the setpoints are not monitored and

adjusted according to the compressed air requirements, the compressed air system may become overpressurised [26], [45], [48].

Overpressurised compressed air systems' efficiency can be increased by decreasing the supply to meet the required demand [45]. The efficiency can also be increased by adjusting the discharge pressure setpoints to match the highest demand required in the compressed air network.

The compressor power consumption to supply the required pressure can be reduced when **reducing leaks in the compressed air system** [45]. The guide vane angles reduce when the repaired leaks reduce the airflow demand of the system, resulting in a reduction in compressor power consumption [45].

It is important to include the entire compressed air system's requirements, as certain surface consumers may have a high-pressure requirement. A gold plant typically requires high compressed air pressure to function [45].

Auto compression can be defined as the increase in air pressure due to the weight of the air on itself [21], [25], [39]. Auto compression can have a substantial effect on the compressed air networks of gold mines due to their extreme depths [21]. The effect of auto compression can be calculated using Equation 5 below.

Equation 5: Effect of auto compression at a specific depth [45]

$$\Delta P = \rho gh \quad (5)$$

where:

ΔP = Pressure increase due to auto compression kPa

ρ = Density of air kg/m^3

g = Gravitational acceleration (9.81) m/s^2

h = Depth from surface m

The effect of auto compression at constant adiabatic flows can be calculated using Equation 6 below.

Equation 6: Effect of auto compression at constant adiabatic flows [36]

$$p_0 = p_i \left[1 - \frac{g(z_i - z_0)}{T_1 C_p} \right]^{\frac{1}{k}} \quad (6)$$

where:

p_0	= Final pressure	kPa
p_i	= Initial pressure	kPa
g	= Gravitational acceleration (9.81)	m/s^2
z_i	= Initial altitude	m
z_0	= Final altitude	m
T_1	= Temperature of compressed air	K
C_p	= Specific heat capacity of compressed air	$kJ/kg \cdot K$
k	= Specific heat ratio of compressed air (1.4)	$kJ/kg \cdot K$

From Equation 5 and Equation 6, it is noted that a deeper mine shaft will experience a greater effect of auto compression. Auto compression is beneficial when setting the compressor delivery pressure setpoint lower than the highest underground pressure requirement [45]. Figure 13 below shows the effect of auto compression with different surface delivery pressures at different depths below the surface using Equation 5 above.

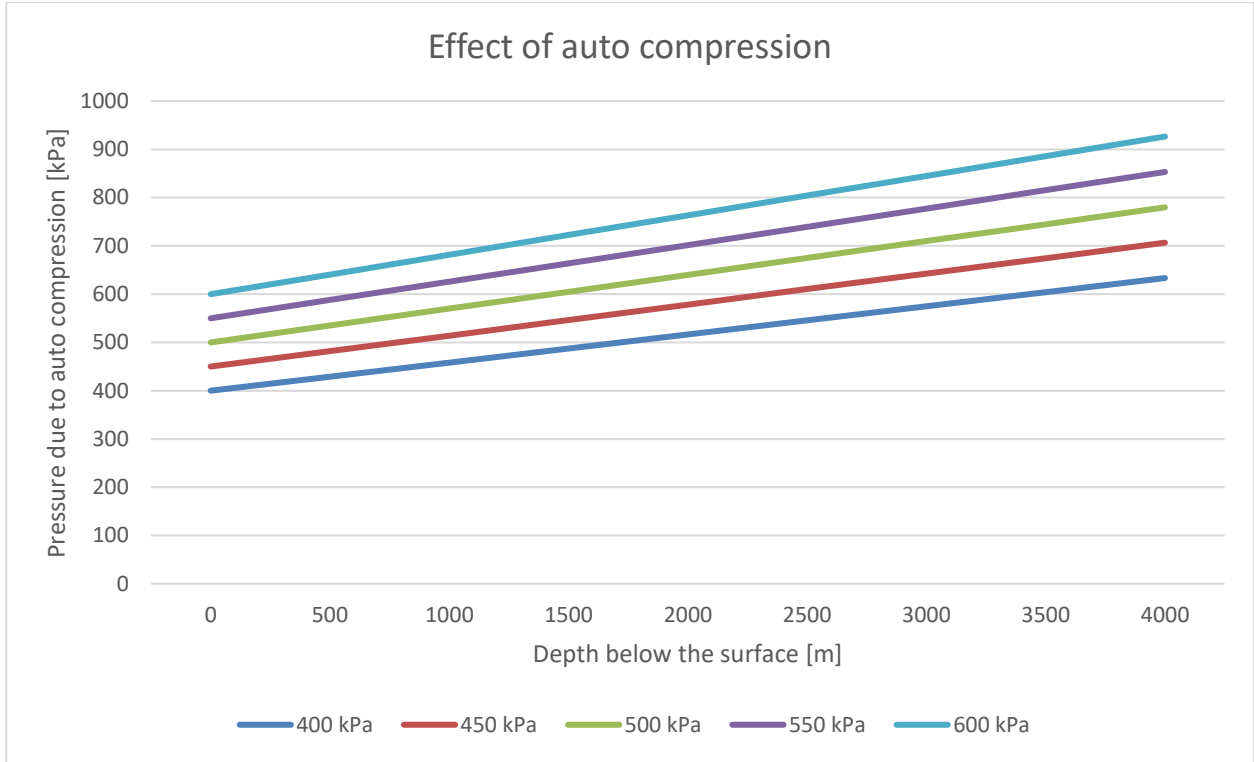


Figure 13: Effect of auto compression on underground air pressures [36]

Friction and airflow losses in the pipe network have a negative effect on the auto compression and thus the required compressor discharge pressure setpoint. The losses reduce the auto compression effect on the compressed air, which in turn reduces the pressure supplied to underground consumers. The reduced supplied pressures to the consumers require a higher compressor delivery setpoint to match the required pressure at underground working levels. The increased compressor delivery setpoint causes the compressor power consumption to increase, reducing electricity savings [48].

Equation 7 below can be used to calculate the effect of auto compression by considering the effect of pressure losses in the compressed air pipe network.

Equation 7: Effect of auto compression considering the effect of pressure losses [48]

$$\Delta P_{Total} = \rho g \left(h - f \frac{Lv^2}{d2g} \right) \quad (7)$$

where:

ΔP_{Total} = Pressure increase due to auto compression kPa

f	= Friction factor	—
L	= Length of vertical pipeline	m
v	= Airflow velocity	m/s
d	= Pipe inner diameter	m
g	= Gravitational acceleration (9.81)	m/s^2

The size and efficiency of compressors on the same network can vary. The power consumption of the compressors can be reduced when the most efficient combinations of compressors share the load created by the demand for compressed air [26]. A larger compressor will deliver more compressed airflow at a lower power consumption [49].

A **control strategy** can be created to favour specific compressors under specific conditions based on the compressor efficiency. The control strategy can be automated by employing a supervisory control and data acquisition (SCADA) system or manual. The SCADA system is generally installed at a central control node where the instrumentation and equipment connected to the communication network can be viewed and controlled [26].

1.3.3.2 Energy savings through demand-side optimisation of compressed air networks

Compressed air demand can be controlled with **control valves** installed on the surface pipes or underground on mining levels [45], [50]. The goal of the control valves is to reduce the pressure of overpressurised pipelines by reducing the compressed air supplied to consumers based on the requirements [39], [45], [51]. The pressure can be reduced by restricting the compressed airflow through the control valve so that the downstream pressure can be maintained at a predetermined value. Alternatively, the main valve with a smaller bypass can be installed where the main is closed and flow is restricted by a smaller pipe [31].

The desired downstream pressure is sustained by **controlling the valve position** and is typically obtained by using proportional-integral-derivative (PID) control [45], [48]. The actual downstream pressure is measured by a pressure transmitter installed in the pipeline [45], [48]. The measured downstream pressure is used as a process variable, and the desired downstream pressure serves as a setpoint [48]. The valve position is determined by the difference between the process variable and the setpoint, also referred to as the system error [48].

The PID controller calculates the system error to calculate a new valve position to minimise the system error [48]. The valve position is obtained by a positioner installed on the actuated valve that provides feedback on the actual valve position [48]. The actuator changes the valve position according to the newly calculated valve position [48].

Control valves can be installed for each consumer, where each is assigned a specific pressure setpoint corresponding to their specific requirement [31]. Reducing the downstream pressure will cause a pressure build-up in the upstream pipeline [45]. As discussed in 1.3.3 above, a pressure build-up in the compressor outlet manifold will cause the inlet guide vanes to close, leading to a reduction in compressor power consumption [26], [45].

Two types of **control valve configurations** can be used to obtain a desired downstream pressure, namely inline and bypassed configurations [45]. Inline valve control generally consists of installing an actuated butterfly valve in the pipeline. The valve is fully open during the drilling shift when the demand for compressed air is highest. The valve can throttle during low-demand periods to obtain the desired downstream pressure [45].

A bypass valve configuration is commonly used to control low downstream pressures. During the drilling shift, all valves are fully open and no control is implemented. During the low-demand periods, the control valves reduce the downstream pressure by fully closing the main line valve and controlling the bypass valve [45], [52]. The pressure is typically reduced to match the pressure requirements of the underground refuge bays [45].

Compressed air networks typically consist of several interconnected shafts and processing plants [21]. The compressed air requirements of consumers vary during a production day, as discussed in Section 1.2.5 above. A processing plant requires a constant high pressure to function, while the compressed air requirements of mine shafts vary depending on the operational schedule [22], [31].

The pressure of the compressed air network is determined by the highest pressure requirement of all the consumers [22], [36]. Ineffective compressed air distribution occurs when the network pressure is kept high for the processing plant during a low-demand period of the mine shaft [36]. Compressed air networks are therefore typically divided into high- and low-pressure sub-networks with surface control valves [22], [26], [31]. A simplified compressed air network with a control valve on the surface is illustrated in Figure 14 below.

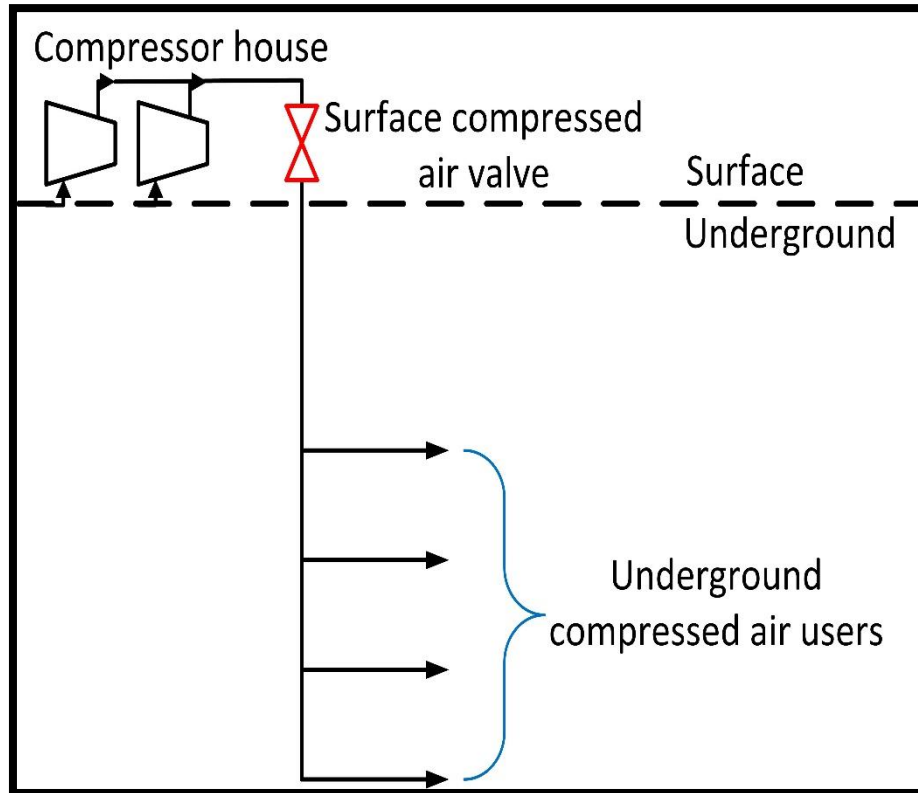


Figure 14: Compressed air control valve on the surface

Control valves on the surface are typically installed in the main compressed air pipe supplying the different sections with compressed air [26], [48]. These control valves control the downstream pressure of each consumer based on their compressed air requirements [36], [45]. Identifying the compressed air requirements for all consumers is critical to implementing effective valve control [26], [51]. The compressed air valves located on the surface can be operated manually or automatically by making use of actuators [26], [36], [51]. Manually operated valves will typically be an open and closed schedule where a mine employee is tasked with opening and closing the valve according to the work schedule [26]. Automatic valve control consists of installing actuators on the valves that control the flow through them to maintain a

specific downstream pressure [26]. Figure 15 below shows a typical manual valve located on the surface.



Figure 15: Manual compressed air valves on the surface⁴

The valves located on the surface are used to reduce the pressure supplied to the different consumers, thus maintaining the high-pressure requirement of the processing plant [36].

The energy consumption of compressors can be reduced by reducing the compressed air supplied to underground mining levels [26], [48], [53]. Installing control valves on mining levels can reduce pressed air supplied to the level in low-demand periods where the required pressure is less [45], [53]. The underground control valves are generally installed close to the main shaft. Figure 16 below shows a simplified mine compressed air network with underground control valves installed.

⁴ Photo was taken by the author.

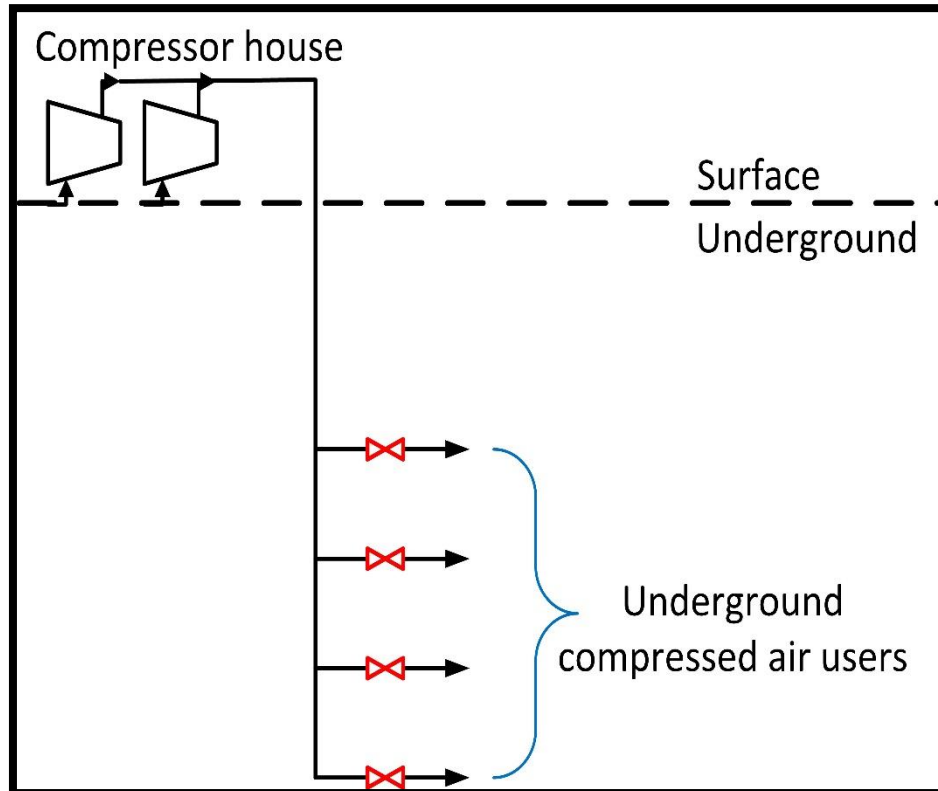


Figure 16: Underground valve control

The ***underground control valves*** are generally controlled according to the downstream pressure of the valve. When the compressed air flow rate suddenly increases on a mining level, the valve will open to sustain the desired downstream pressure [48].

Each control method has specific advantages and disadvantages, which are essential to understand to apply the correct method to a specific system. Below are some notable disadvantages of valve control on the surface and underground.

- Disadvantages of valve control on the surface:
 - Loading boxes require 400 kPa to function [38],
 - high demand on higher levels can reduce pressure on lower levels [54], [55], and
 - compressed air agitation setups require high air flow rates to function [34].
- Disadvantages of underground valve control:
 - Valves can be opened manually, resulting in lost savings [56],

- increased shaft pressure will lead to increased shaft leak flow [22], and
- difficult to maintain.

Compressed air leaks and areas of wastage are common in the compressed air networks of deep-level mines [36]. Leaks and wastage are factors that affect the efficiency of compressed air networks the most [57]. One study indicated that as much as 52% of a mine's generated compressed air was wasted on leaks [25]. Supplying leaks with compressed air will naturally waste compressor power consumption [36]. Therefore mines need to monitor and maintain their compressed air networks to minimise the negative effect of leaks on compressor power consumption [36]. The compressor power wastage on leaks can be calculated by using Equation 8.

Equation 8: Power wasted to supply leaks with compressed air leaks [21], [25]

$$P_{required} = \dot{m}_{leak} W_{Comp} \quad (8)$$

where:

$P_{required}$	= Power required to supply the leak	kW
$\dot{m}_{leak}$	= Mass flow through the leak	kg/s
W_{Comp}	= Mechanical energy of the compressor	kJ/kg

The mechanical energy of the compressor consumed to supply the leak with compressed air can be calculated by using Equation 4, while the mass flow rate of compressed air through a leak can be calculated by using Equation 9:

Equation 9: Compressed air mass flow rate through a leak [21]

$$\dot{m}_{leak} = C_d \left[\frac{2}{k+1} \right]^{\frac{1}{k-1}} \left[\frac{P_{leak}}{RT_{leak}} \right] A_{leak} \sqrt{kR \left[\frac{2}{k+1} \right] T_{leak}} \quad (9)$$

where:

$\dot{m}_{leak}$	= Mass flow through the leak	kg/s
------------------	------------------------------	--------

C_d	= Discharge coefficient of a leak	—
k	= Specific heat ratio of compressed air (1.4)	$kJ/kg \cdot K$
P_{leak}	= Absolute air pressure at leak	kPa
R	= Gas constant (0.278)	$kJ/kg \cdot K$
T_{leak}	= Air temperature at leak	K
A_{leak}	= Cross-sectional area of the leak	m^2

Using Equation 4, Equation 8, and Equation 9 above, the compressor power wasted on supplying leaks with compressed air can be calculated.

1.3.4 Implemented energy reduction initiatives

The energy savings obtained from implementing different energy reduction initiatives will be discussed in this section. Different case studies were taken to see what previous studies have identified as the energy savings obtained.

1.3.4.1 Quantifying energy savings

Energy savings achieved by implementing energy reduction initiatives can be quantified using various methods. It is typically done by comparing the energy usage after the project has been implemented [58]. The energy savings achieved can be calculated by using the equation below:

Equation 10: Energy savings [59]

$$Energy\ Savings = (Baseline - Actual) \pm Adjustments \quad (10)$$

Where:

Baseline: The baseline is a set of data gathered for a pre-agreed duration (usually a minimum of a month) which is compared to the data after the project implementation.

Actual: Actual is the energy data gathered during the assessment period of the project. This represents the project performance after the implementation is done.

Adjustments: If any adjustments occur to the baseline conditions during the project duration, M&V will make suitable amendments to the energy savings calculation.

Energy savings: Energy savings are the results which represent the reduction in energy consumption. If the actual is less than the baseline it results in energy savings.

1.3.4.2 Effect of various energy reduction initiatives on compressor power

The first set of results is from J. Vermeulen [60]. Energy savings initiatives were implemented on a compressed air system of a mine. In this case study, four energy savings initiatives were implemented. The energy savings initiatives are:

1. Load clipping strategy test: Stop a compressor that oversupplies compressed air during Eskom's evening peak period.
2. Leak repair: Repair major leaks on a mismanaged compressed air network to improve load clipping results.
3. Energy-saving strategies implemented after leak repair: Select optimal compressor combinations for improved savings.
4. Cost-effective throttle control: Implement a cost-effective control to reduce the oversupply of compressed air.

The result of the implementation was shown to be a 2.93 MW reduction during Eskom's evening peak period. The compressor power actual and baseline are shown in Figure 17 below.

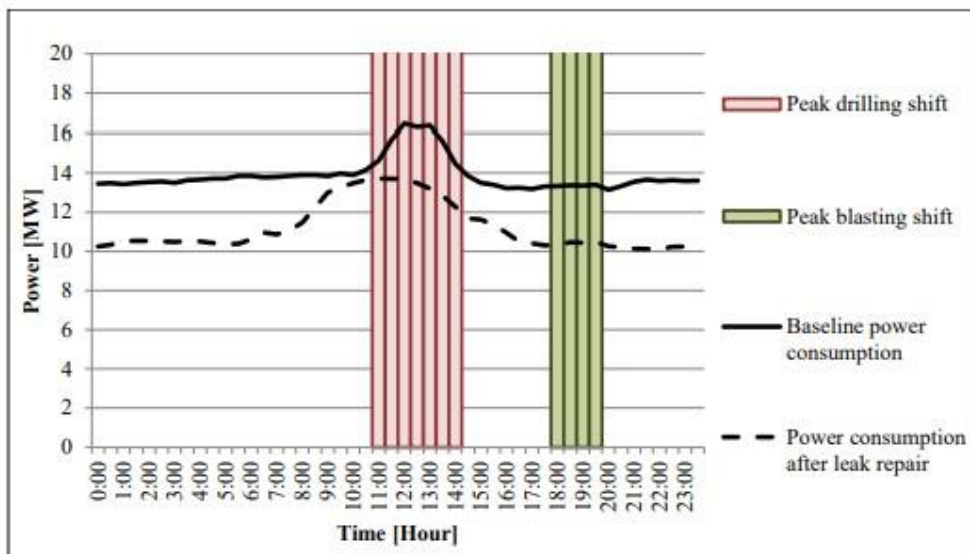


Figure 17: Effect of various energy savings initiatives on compressor power [60]

The second result obtained from Vermeulen was a load-clipping initiative implemented during the peak blasting period. The load clipping initiative was achieved by reducing the pressure setpoints during the peak blasting period.

The result of implementing the level pressure control initiative was a 3.25 MW reduction in compressor power during the peak blasting period. The compressor power actual, baseline and simulated power are shown in Figure 18 below.

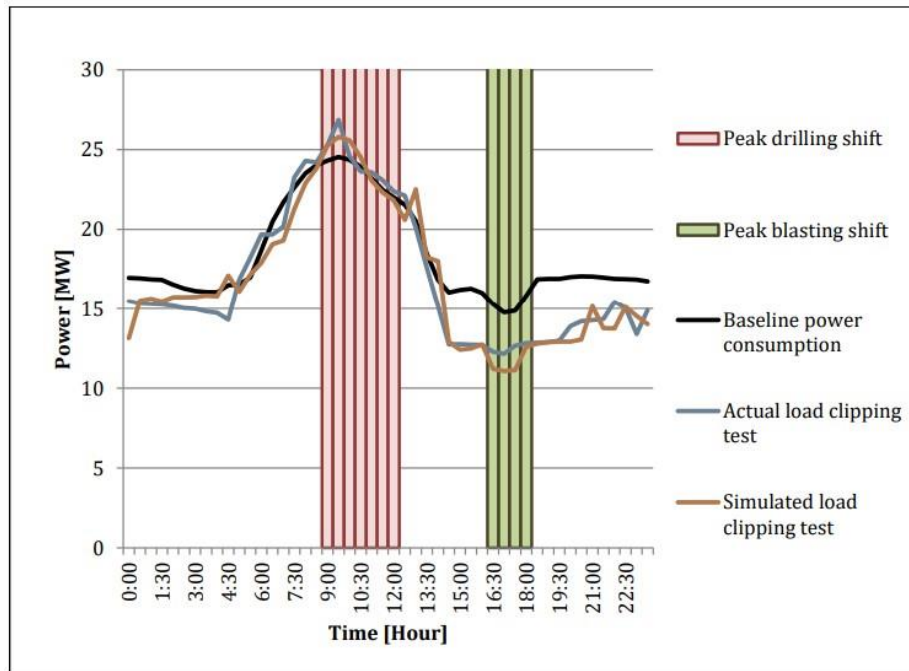


Figure 18: Effect of level compressed air pressure control on compressor power [60]

The next results are obtained from Fouché [45]. The study included the results of an energy savings initiative implemented on a compressed air system of a mine. The compressor house setpoint was reduced from 16:00 until 18:00 on a weekday. The results from implementing this energy-saving initiative was an average power reduction of 780 kW from 16:00 until 18:00. The compressor's actual power, baseline and the simulated result are shown in Figure 19 below.

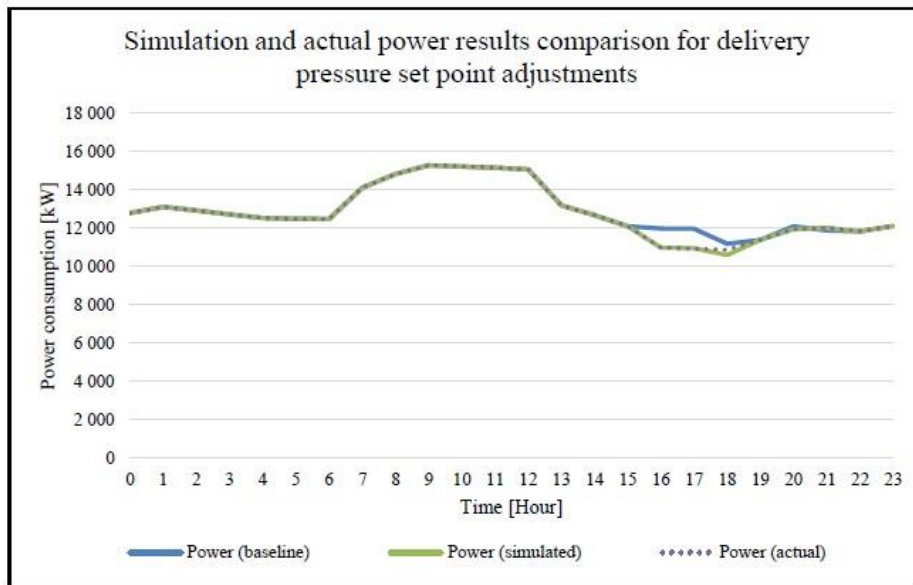


Figure 19: Effect of reducing the compressor house setpoint on compressor power [45]

The last set of results is from van Staden [61]. Underground level pressure control together with compressor discharge pressure reduction was implemented as energy savings initiatives on a mine's compressed air system. The effect of implementing these energy savings initiatives was an average power reduction of 1.35 MW over a day. The compressor's actual power and baseline are shown in Figure 20 below.

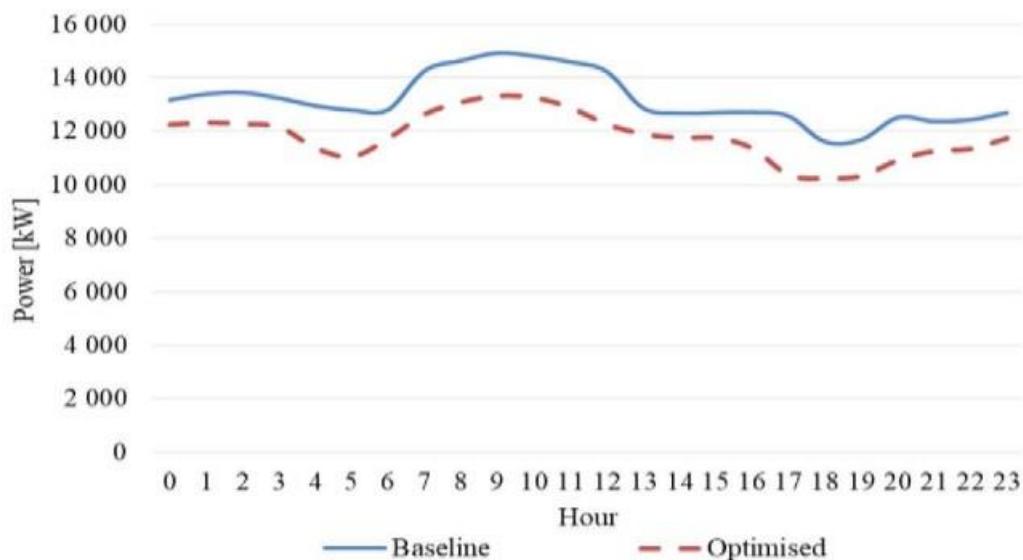


Figure 20: Effect of implementing underground level and compressor pressure control on compressor power [61]

From the results gathered from studies, it is clear that the effect of implementing energy reduction initiatives can be quantified by comparing a baseline to the compressor power actual data.

It was noted in the study of van Staden [61] that previously implemented energy savings projects deteriorated and did not provide the same energy savings as when the projects were implemented. In the study of van Staden, the level downstream pressure setpoint was compared to the downstream pressure value. This is shown in Figure 21 below.

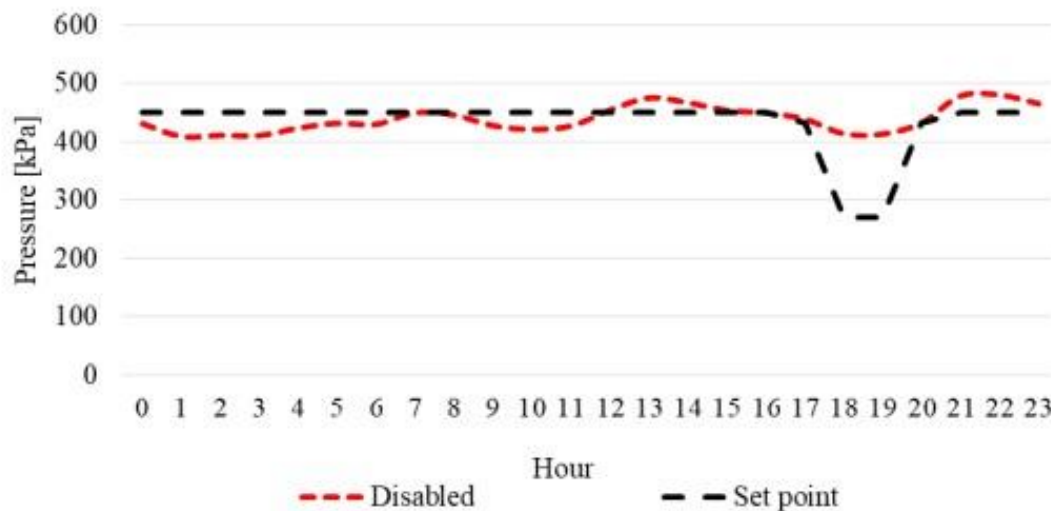


Figure 21: Pressure setpoint vs actual downstream pressure of a disabled control valve [61]

From Figure 21 above it is noted that the downstream pressure is far greater than the setpoint value from 17:00 until 20:00. According to van Staden, this indicated that the pressure control project was not achieving the desired compressor energy savings.

The control valves were re-instated in the study of van Staden. The comparison was made between the setpoint value and the pressure profile before and after the project was re-instated in Figure 22 below.

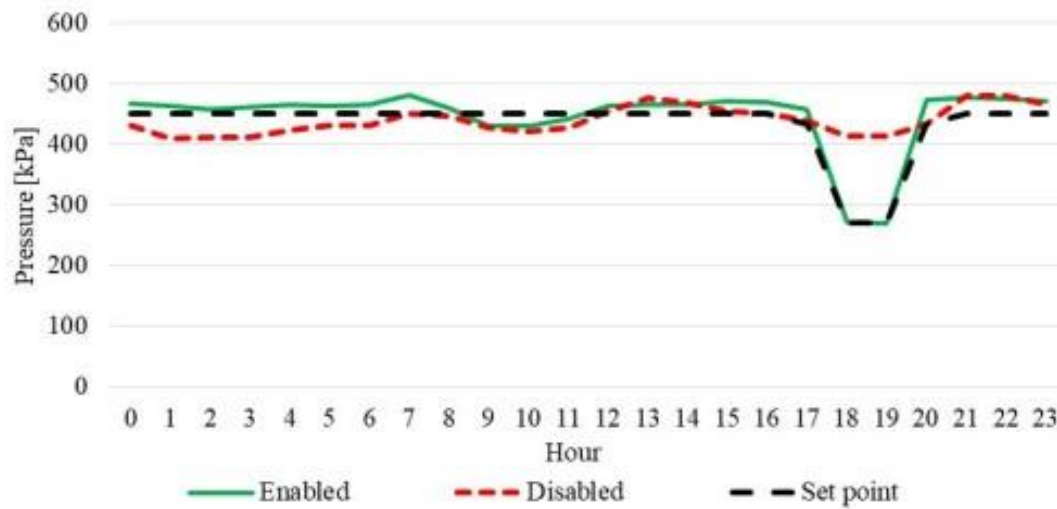


Figure 22: Pressure setpoint vs downstream pressure before and after enabling control [61]

From Figure 22 it is noted that the pressure profile correlates more with the setpoint value after the control was enabled.

1.3.5 Conclusion

Several energy management strategies exist to reduce the energy consumption of compressed air systems. While several management projects are implemented on mine compressed air systems that incorporate these strategies, some of these projects lack sustainability [61]. A lack of sustainability interferes with the mine's cash flow, as the mine's budget is according to the projected savings from their implemented projects [61]. Challenges to the sustainability of energy management projects are discussed in the next section.

1.4 Challenges regarding the sustainability of energy management projects

1.4.1 Introduction

Declining mine profit margins force mines to explore initiatives to reduce operational costs. One method to reduce operational costs is to implement energy reduction initiatives to reduce the electricity costs of a mine [14], [62]. New opportunities are often investigated to reduce the electricity costs of mines [53]. Investigating new opportunities is beneficial to mines, but the benefits of maintaining existing initiatives are often overlooked [53]. While it is worthwhile to consider initiatives that underperform to reduce electricity costs – as the majority of these projects require a relatively low capital input when compared to the cost of implementing new initiatives – sustaining project performance remains a challenge [53].

Implementing a maintenance strategy on new projects is beneficial to ensure continued performance, re-implementation and maintenance on underperforming electrical cost reduction projects [63].

Projects are often incorporated into mine operations without a dedicated person accepting responsibility for maintaining the project [61], [63], [64]. Therefore, changes and events affecting the project are not communicated to the relevant personnel [64] and, consequently, the project engineer only becomes aware of an issue when a drop in performance is observed.

Project maintenance is experienced as an increase in the workload for mine personnel that leads to a lack of project responsibility when there is no dedicated maintenance team [63]. Reducing the electrical cost is not prioritised as highly as, for example, production volumes [63].

The sustainability of energy reduction initiative performance is crucial in ensuring that projects produce constant revenue [64]. If an initiative lacks sustainability, it may interfere with the mine's cash flow, as mines create budgets based on current performances and then rely on the project to sustain impact [61].

Sustainability can be described as the process of maintaining a certain state for a predetermined period [58]. A project's sustainability can be divided into two components, namely the life span and performance of the project [64]. The lifespan can be defined as the time between the start and closure of a project or the time to failure [64].

Project failure can be said to follow constant project underperformance. Project over- or underperformance is relative to the project type and the baseline. A project's baseline is measured as a reference point before the project is implemented, to which the implemented project is compared to determine the performance [64], [58].

Research regarding demand-side management (DSM) initiatives that were implemented in South Africa shows that projects underperform when an energy management company (ESCO) is no longer in charge of maintaining the project performance [53], [64]. This indicates that the performance of energy reduction initiatives is less effective when there is not a dedicated team assigned to manage the project performance [53], [64]. Energy management in energy-intensive mines is often neglected because production is the number one priority [25], [58].

Terblanche [64] analysed the performance of 20 energy reduction projects implemented in the industrial sector in South Africa. The projects were implemented on different systems in the industrial sector. The type of system that was implemented in a project, as well as the number of projects analysed for that system, is shown below [64].

- Compressed air network (6)
- Air cooling system (2)
- Pumping system (7)
- Production line (1)
- Water cooling system (3)
- Rock hoisting system (1)

The cumulative impact and the project targets over a year were used to determine where the projects started to underperform. It is clear from Terblanche's analysis that the project's performance reduces significantly when the assigned team is no longer responsible for its performance.

1.4.2 Cause of project underperformance

Project performance cannot be sustained unless project requirements are met [64]. The technical requirements of a project are seen as limitations that can affect the project's potential [64]. It is therefore important to evaluate the technical requirements of a project to identify which requirements are not met that may affect project performance. It is important to note that no two projects are alike. While this means that the specific causes of a project's underperformance cannot be compared to other projects, they can help identify higher-level causes [64].

1.4.2.1 Interference with automatic control

Interference with the control philosophy of an energy management project may affect the project's ability to achieve the desired electrical cost savings [53]. Control room operators that interfere with the control philosophy by incorrectly changing the control system from an automatic mode to a manual mode can affect the project impact negatively [64]. Inadequate project awareness of relevant personnel may lead to actions that are not aligned with the ongoing project [64]. Another issue is a lack of awareness among mine personnel of the cost-benefits to the mine and the initiative's performance [61]. Moreover, overriding the automatic control, ineffective setpoint monitoring, and following the incorrect control philosophy in the case of manual control can also reduce project performance [64].

The project system equipment can be damaged by individuals, resulting in the control philosophy not being followed [64]. This interferes with the automatic control on which an initiative depends to achieve the design impact [53]. A lack of understanding regarding the control of the project system for electrical cost savings causes the project to perform below its potential. Personnel may revert to the previous control due to forgetting the new control philosophy [64]. A lack of experience and training can interfere with automatic control, reducing the impact of the implemented project [53], [58] in the case that the actuator controls the valve position and the valve is set to manual, thus interfering with the control philosophy [56].

Tampering with the automatic control can result in an ineffective control philosophy and underperformance as a result of unwanted conditions created by the automatic control [64], [65]. Failure to consider mining schedules and requirements with the utilisation of equipment when creating a control philosophy can lead to an ineffective control philosophy which, in turn, will lead to project underperformance [61].

1.4.2.2 High demand or unfavourable conditions

High demand scenarios are those where load reduction strategies are reduced. A high-demand scenario is created where an increase is required in the project system to maintain the system setpoints [53], [64]. Compressed air leaks and wastage in a compressed air network will lead to unnecessary compressor power usage due to an unnecessarily high compressed air demand [66], [67]. A leak on a mining level can cause an increase in the flow demand which lowers the system pressure [44], [67]. The system's pressure will remain low until additional compressors are started [68].

1.4.2.3 Infrastructure constraints or breakdowns

Project performance is often not sustained due to a lack of maintenance on broken or faulty infrastructure [53], [61], [63], [69]. Poor maintenance of broken or faulty infrastructure reduces project performance [61]. A lack of skills to ensure that specialised equipment (i.e. control systems, variable speed drives, etc.) on which the project relies is maintained can also reduce performance, as the control system is not operating at the most efficient point [63].

Furthermore, dirty valve positioners can impair automatic control [61]. This is likely to happen underground, as the conditions are harsh [61]. A control valve can also become stuck, preventing the correct control from taking place [56]. Another issue is that water can enter the valve positioner, leading to the valve being positioned in the default fail-safe position, which is fully open, which causes unnecessary compressed air usage [68].

Changes to the specification, layout and/or operation of a system are generally managed incorrectly through a catch-up method. This method entails implementing a change without proper change management, which leads to project underperformance, at which point a solution is developed instead of planning and predicting adjustments within a control philosophy [64]. A control philosophy that is not updated regularly to compensate for operational changes that occur after implementation will reduce the project's impact [63], [58].

Another cause of project underperformance is essential equipment or upgrades that were not implemented at the start of the project due to a lack of capital [64]. In the same vein, limited resources can thus also lead to project underperformance [58]. Operator control or personnel control can be used when automatic control is not available; however, the control philosophy may not be followed precisely when operators control the system manually, which can also affect the project's impact [53], [64], [58], [66].

1.4.2.4 Control system problems

The following control system issues can also affect performance: Network communication failure removes the energy management system (EMS) control capabilities; the project cannot be monitored off-site [64]; control system server breakdowns [53]; a control valve with a lower limit set too high for safety reasons, which can cause ineffective pressure control when the valve needs to control below the safe lower limit [68]; and the lack of operation of the EMS that can cause control to cease [70].

1.5 Identification of missed energy-saving opportunities

The monitoring of energy is the cornerstone of the decision-making process on energy efficiency measures [71]. If underperformance is observed in a project, a solution must be found as soon as possible, as it may become more difficult to find a solution after extended periods [64]. Monitoring project performance and operation is essential to sustain savings from a project [63]. As such, a lack of effective monitoring can cause a project to underperform [53], [63], [64], [58], [68], [72]. Project performance and operations that are not monitored, even daily, can diminish a project's impact [63], [58]. Site-specific energy KPIs can be created and monitored to provide feedback on the energy efficiency of a system [73], [74]. The added benefit of continuous monitoring is that project hardware such as valves can be monitored for ineffective control [63].

A monitoring and targeting system can be implemented to track and manage energy consumption [75]. Comparing measured values to a predetermined value, where the normal operation was followed, and identifying deviations are used in machine fault detection [69], [76]. Comparing the optimal value to the actual measured value is an effective way of identifying areas for possible improvement to increase the achieved electrical cost savings [66], [77]. Using a fault-tolerant margin for system parameters, a fault that negatively impacts the control can be identified [78], [79], [80]. A deviation of the measured value from a predetermined target value can indicate inefficiency in the system [77].

1.5.1 Project impact

The standard way of determining the success of an implemented project is to determine the impact of the project on electricity consumption [53]. The method of using a compressor power baseline and the actual as shown in Equation 10 above, can be used to identify a reduction in energy savings achieved.

Figure 23 shows the underperformance of a compressor power reduction project taken from the study of Terblanche.



Figure 23: Compressor project underperformance [64]

1.5.2 Using parameters

The impact of the implemented project on electricity consumption is, however, not the only way to judge the performance of a project [53], [75]. Another way to judge the performance of a project is by ensuring that the project requirements are met. Parameters in a system, like flow rate, have been shown to have a large effect on energy consumption [75].

Parameters that are identified as large energy drivers of a system should be monitored [75]. Compressed air flow is a single independent parameter to be monitored and will be advantageous [56]. From Equation 2 it is determined that compressed air flow is directly correlated to the energy consumption of a compressor. Compressed air flow is thus monitored to indicate any increase that increases the energy usage of a compressor. The compressed air flow of a shaft and the mining levels are critical parameters.

The valve position can be used to determine whether or not a valve is stuck, and alarms can be used to alert engineers when an alteration has been made to the control so that they can identify the issues that resulted in the adjustments [56]. If interference from the control room is an ongoing problem, interference statistics that illuminate how and when the control room operators removed the system from automatic control should be implemented and monitored [64].

The control system and communication equipment can also be monitored for any faults to identify improvements in a control philosophy [63]. Data from sensors and measuring devices can be compared to a threshold of predefined parameters [81].

The pressure setpoint can be used as the optimal value in the case of automatic pressure control. Using the pressure setpoint and comparing it to the actual measured downstream pressure can indicate whether the automatic control is effective [36], [61], [68].

A compressor supply optimisation project can be monitored with specific parameters [42], [44], [70]. The flow and pressure measurements of compressors can be compared to predetermined values to illuminate a problem with the system. The supply pressure of the compressors can be compared to the pressure setpoint to ensure that the automatic control is effective, and alarms can be used to notify relevant personnel if a parameter is out of bounds.

Project infrastructure (such as valves and compressors) can be controlled via serial communication by one or more programmable logic controllers (PLCs) [53]. The PLCs are connected to a SCADA through ethernet. The SCADA communicates and sends control commands to the PLCs. All valves are monitored, opened, and closed via a communication network from the central control room [26], [75].

Performing an on-site investigation to determine whether the project infrastructure is still controlled to obtain maximum electricity cost savings can aid in determining whether the project is achieving its full electrical cost savings [53]. This can be fairly easy if the control system is in working condition and the component statuses are logged on the control system or available on the site's SCADA [75]. Historical data can be downloaded from the control system or the SCADA and analysed to determine whether the various components are controlled to achieve electricity cost savings [53]. If it is found that all project infrastructure is controlled to achieve maximum electricity cost savings, no intervention is required.

1.6 Identifying the cause of missed energy-saving opportunities

A compressed air flow mass balance is effective for identifying areas in a shaft where leaks or wastage are present [66]. Areas of wastage can be identified using compressed air flow data to create a mass balance with various measuring points in a shaft, together with the compressed air flow on mining levels [66].

Monitoring the compressed air flow, downstream pressure and the pressure setpoint can help to identify a leak on a mining level [68]. Comparing the measurements to the measurements from

the previous month can indicate whether an increase in flow is due to the control valve malfunctioning or whether the downstream pressure correlates with the pressure setpoint [68].

Using the setpoint method to obtain the valve percentage in periods where control is deemed ineffective can determine whether a valve's safety lower limit is set too high and cause the control to be ineffective [68]. Analysing the valve percentage can also illuminate the solution for a valve that does not control according to the prescribed setpoint after the setpoint method is used to identify ineffective control [68]. Resetting the valve actuator solved a dirty valve positioner problem. Cleaning the positioner will effectively solve the control problems caused by a dirty positioner [68].

In some cases, general EMS problems causing limited control can be avoided by upgrading the EMS [65], [82]. It may be that the EMS software does not allow for full control to take place, and by upgrading the EMS more control is possible that can lead to increased energy savings [82]. By upgrading the EMS software, full control can be implemented. In the case where the EMS server experience a breakdown, replacing the EMS server will re-implement automatic control and make the control philosophy efficient [53]. Monitoring the operationality of the EMS can indicate problems with the EMS that cause a project to lose savings [70].

When personnel tamper with automatically controlled equipment in such a way that the automatic control is overridden, the control philosophy must be re-evaluated [65]. Since the tampering is a result of unwanted conditions created by the automatic control, in which case the automatic control is disabled [65]. By re-evaluating the control philosophy, all unwanted conditions during control can be removed [65]. Automatic control can therefore be re-implemented, and tampering can be prevented if all unwanted conditions are removed.

In the case of an operator-controlled system, the optimal value can be communicated to the operator to adjust the actual value to match the optimal value [66], [75]. A schedule that notifies operators of the time when the control needs to be effected is a method of implementing the optimal solution in a system that is manually controlled [58].

1.7 State of the art

It is now clear from the literature that intervention is required on projects that do not achieve their full electricity cost-saving potential [53]. The standard way of determining the success of an implemented project is to determine the impact of the project on electricity consumption [53]. The impact of the implemented project on electricity consumption is, however, not the only way to

judge the performance of a project [53], [75]. Another way to judge the performance of a project is by ensuring that the project requirements are met. Parameters in a system, like flow rate, have been shown to have a large effect on energy consumption [75].

Project infrastructure (such as valves and compressors) can be controlled via serial communication by one or more programmable logic controllers (PLCs) [53]. The PLCs are connected to a SCADA through ethernet. The SCADA communicates and sends control commands to the PLCs. All valves are monitored, opened, and closed via a communication network from the central control room [26], [75].

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As mentioned in Section 1.4.2 above, incorrect interference from control room operators may cause a control system to operate in a manual mode instead of an automatic mode [64]. The negative effect of this adjustment on the project's impact can be countered by switching the system to automatic mode again.

Another related challenge is control room operators that do not follow the correct control philosophy, which can be overcome by training operators to implement the prescribed control philosophy [53], [64], [58]. However, training the control room operators will not always be as effective as automated control and regular training sessions may be necessary [53], [64].

Other factors or systems may affect a control philosophy's ability to achieve the desired electrical cost savings [53]. These factors or systems must be monitored to ensure that there is no interference with the control philosophy [53]. Table 5 below contains a summary of the literature that focussed on reducing missed energy savings opportunities and whether the identification method was included.

Table 5: State of the art

Study	Interference with automatic control	High demand or unfavourable conditions	Infrastructure constraints or breakdowns	Control system problems	Identification method	Compressed air system	Comments
[64], [58]							
[61]							Used setpoint vs downstream pressure to determine that control was ineffective, did not include the method used to identify why control was ineffective.
[66]							Mass balance of compressed air flow to identify areas of wastage/leaks.
[56]							Alarms for interference with valve control and mentions using valve percentage to be used if the valve is stuck.
[70]							Used limits for limited parameters (total flow and comp pressure setpoint). Did not lead to the cause of the

							problem. Used EMS operational data to determine control system problems.
[68]							Used level air flow, downstream pressure and setpoint to identify leaks on the mining level. Used pressure setpoint and valve percentage to determine ineffective control, then determined that the valve's lower limit is too high and changed it to determine position feedback was broken.
[66]							Optimised vs actual air mixture ratio of a steel plant.
[78], [79]							Used a fault-tolerant margin to identify performance deteriorating faults in the control system.
[77]							Identified possible inefficiencies by comparing the measured data to a target value for district heating stations.

[82]							Proposed an upgraded EMS to reduce the energy consumption of a reverse osmosis plant.
[53]							Monitored the status of an external system that can affect current project performance.
[65]							

Table 6 below is a summary of the studies that focussed on reducing missed energy savings opportunities in compressed air systems by effectively identifying the cause.

Table 6: Summary of compressed air studies that focus on reducing missed energy savings opportunities

Conditions	Study 1 [61]	Study 2 [66]	Study 3 [56]	Study 4 [70]	Study 5 [68]
Utilised compressed air critical parameters to successfully identify missed energy savings opportunities.					
Utilised compressed air critical parameters to successfully identify the cause of missed energy savings opportunities.					
Utilised target profiles for compressed air critical parameters to successfully identify the cause of lost savings.					

Comments	Did not use critical parameter data to identify the cause of missed savings opportunities.	Used flow mass balance equation and not a target profile.	Only states a critical parameter to identify the cause of the problem, not how.	Utilised critical parameter limit to identify the high-level feedback that missed savings opportunities are present.	Used critical parameter data to compare against historic data and not a target profile.
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1.8 Need for the study

Profit margins on deep-level gold mines are on a dangerous decline. The increase in labour and electricity costs paired with reduced production contributes to the need to implement cost-reduction initiatives. Compressed air systems are the third-largest contributor to a mine's total operational cost. For this reason, numerous compressor electrical cost reduction projects have been implemented in the mining sector. From the literature, it has been identified that energy reduction initiatives can lose the energy savings achieved. This is seen as a missed energy savings opportunity.

From the literature, it was identified that implementing effective project monitoring can avoid lost savings. The general method of identifying a project that is not achieving the desired energy savings is to compare a compressor energy baseline to the actual compressor energy. This is, however, a high-level method of monitoring, and the cause of the problem can rarely be identified by using only this method.

Compressor energy savings projects have technical requirements that must be met to achieve the desired energy savings. Not meeting the technical requirements will reduce current and potential energy savings. From the literature, projects may miss energy savings opportunities due to:

- interference with automatic control,
- high demand or unfavourable conditions,
- infrastructure constraints or breakdowns, and
- control system problems.

The existing literature identifies critical parameters in a compressed air system that can be used to identify whether any energy savings opportunities are missed and to identify the cause thereof separately. The literature contains methods that use critical parameters to identify whether ineffective control is affecting energy savings opportunities by comparing the current parameter data to a target profile.

A common method to identify ineffective automatic pressure control is to compare the downstream pressure to the predefined pressure setpoint. The pressure setpoint is the target profile to which the actual downstream pressure is compared to identify any deviations. If there is a deviation between the target profile and the actual value, ineffective control is present. This can lead to missed energy savings opportunities when the cause is not identified and rectified.

However, this method fails to identify the cause of the missed savings opportunities. Further investigation is therefore required to determine the cause of the ineffective control to rectify it.

The literature also details methods that use critical parameters to identify the cause of missed energy savings opportunities by comparing the current parameter data to historical trends to identify abnormalities. Abnormalities are illuminated when comparing the current data to historical data at a time when the control was deemed effective. The cause is therefore illuminated only when the current data is compared to historical data and not by analysing only the current parameter data.

From the above findings from the literature, a need has been identified to develop a method that utilises target profiles for critical parameters to identify missed energy savings opportunities and the causes thereof.

1.9 Study objectives

A method will be developed and tested to reduce missed energy savings opportunities in compressed air systems. The following objectives were included in the study:

- Develop a method to identify missed energy savings opportunities by utilising critical parameters of a compressed air system; and
- develop a method to identify the cause of missed energy savings opportunities by utilising critical parameters of a compressed air system.

The developed method will be implemented in case studies where incidents caused missed energy savings opportunities; thereafter, actions were taken to reduce the missed energy savings. The case studies included at least one incident where energy savings were lost due to the following causes of missed energy savings opportunities:

- Interference with automatic control,
- high demand or unfavourable conditions,
- infrastructure constraints or breakdowns, and
- control system problems.

Chapter 2 Methodology

2.1 Research methodology

The environment to which this study will be applied is the compressed air systems in deep-level mines as discussed in Chapter 1. The compressed air network of deep-level mines is seen as a dynamic system and behavioural events cannot be controlled. For these reasons, a case study research methodology will be applied to this study [83], [84]. The flow diagram of a case study research methodology is shown in Figure 24.

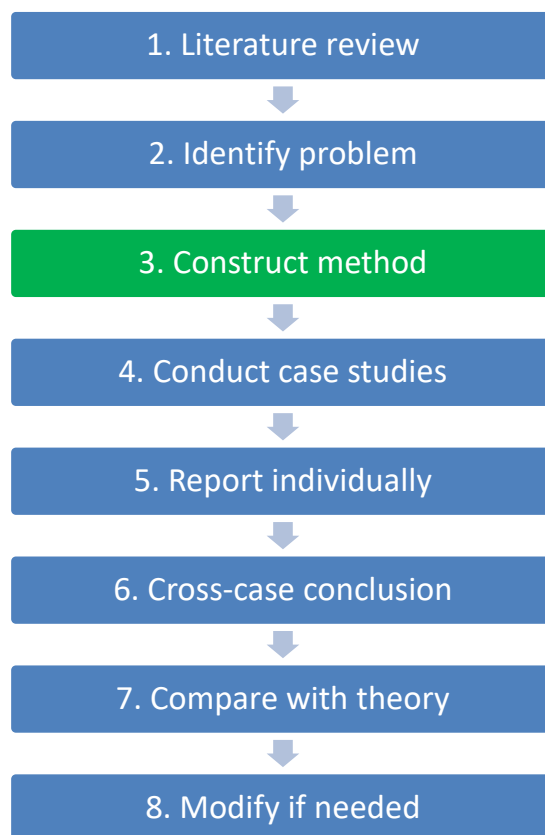


Figure 24: Flow diagram of a Case Study Research Methodology

In Chapter 1 the literature review and problem identification was completed, which correlates to Step 1 and 2 of the Case Study Research Methodology shown in Figure 24. This chapter will focus on Step 3 of the Case Study Research Methodology, namely constructing a method.

2.2 Introduction

Compressed air networks in deep-level mines are large systems with intricate pipe reticulations and components which makes them difficult to investigate. Identifying the cause of missed energy savings can be challenging if the problem is not identified correctly. This chapter aims to develop a method that can be used to effectively identify missed energy savings opportunities and the cause thereof. By identifying the cause of missed energy savings opportunities, rectifying action can be taken to satisfy the objective of this study which is to reduce missed energy savings opportunities. The method developed is discussed below.

2.3 Step 1: Define project scope

The first step of the developed method is to determine the energy savings project scope. The scope of the project determines the method used to achieve the desired energy savings. The project scope also illuminates the project's technical requirements, which must be satisfied to achieve the desired energy savings [64]. The technical requirements of specific energy-saving projects will be investigated in the following step.

Determining the project scope can aid in identifying areas where energy savings opportunities are missed. From the project scope, the period where specific outcomes are expected can be used to place focus on the actual and target profile data. Periods, where parameters are affected due to the project implementation, will assist in identifying ineffective or incorrect implementation of the project.

The project scope will assist in determining the requirements of the critical parameters. It must be determined from the project scope that energy savings opportunities are missed if the critical parameter is less or greater than the target profile. If it is determined that inefficiencies will occur when the measured value is greater than the target profile, a positive deviation is said to cause inefficiencies. If it is determined that inefficiencies will occur when the measured value is less than the target profile, a negative deviation is said to cause inefficiencies.

The project scope will have to include the energy savings project type as discussed in Section 1.3. The different energy savings projects identified in Section 1.3 are listed below.

- Compressor guide vane control
- Compressor setpoint reduction
- Compressor load sharing

- Level pressure control
- Surface pressure control
- Reduce wastage on a mining level
- Reduce wastage in the shaft

The project scope must also contain any detail concerning the energy savings that are set out to be achieved. If the energy savings is achieved during specific periods of the mining schedule, the schedule must be noted. By determining the scope of the project, the way the savings are achieved is known. The project scope will assist in identifying if missed energy savings opportunities are present. By knowing what savings the project is designed to achieve and how it can be used to identify why missed energy savings opportunities are present.

2.4 Step 2: Identification of critical parameters

Project performance cannot be sustained if project requirements are not met [64]. The technical requirements of a project are seen as limitations that can affect the project's potential [64]. It is therefore important to identify the technical requirements of a project to identify which unmet requirements negatively affect project performance.

The intended outcome of an implemented project on certain parameters in a compressed air system will determine a project's technical requirements for achieving energy savings. Parameters in a compressed air network are measurable parameters for which historic data can be obtained. The effect of implementing energy-saving projects on specific parameters in a compressed air network will be investigated below.

2.4.1 Compressor guide vane control

In the case of this study, compressor guide vane control will lead to a decrease in the total compressed air flow to the shaft. The compressors will cut back using the guide vanes to fulfil the surface pressure setpoint. The surface pressure setpoint is set based on the relationship between the surface pressure and the pressure underground [39], [45], [51], [85]. If the underground pressure deviates from the relationship with the surface pressure, the project will not be feasible, as the specific surface pressure setpoint is no longer valid.

2.4.2 Compressor setpoint reduction

If an oversupply of compressed air is noted, the compressor pressure setpoints can be reduced in such a way as to provide only the necessary compressed air to the mining levels. The valve

percentage of the control valve on a mining level can be used to determine when there is an oversupply. The compressor setpoints can be reduced so that the valve is fully open when following a setpoint. This indicates that there is no oversupply, and the valve does not have to cut back to supply the required pressure to the mining level [31], [36], [39], [45], [61]. The pressure setpoint can also be reduced to supply the necessary pressure to a measuring point in the shaft [45]. There will be a reduction in the total compressed air supplied to the shaft when reducing the compressor pressure setpoints. The compressor setpoints should be lowered in such a way that the mining level pressure is sufficient for the equipment used.

2.4.3 Compressor load sharing

Load sharing of compressors can also be implemented when an oversupply of compressed air is noted [31], [36], [39], [45], [61]. The same method of identification for the valve percentage can be used to implement load sharing. A reduction in the total compressed air flow to the shaft will be noted and, therefore, the pressure in the shaft and mining levels will be less. The load sharing should hence be done in such a way that the pressure on the mining levels is sufficient.

2.4.4 Level pressure control

Pressure control can be implemented on the mining levels to attain a reduction in the level pressure and thus the compressed air flow supplied to the level [36], [45], [56], [61]. Where control is present, the valve percentage will change, and where the control is effective, the pressure of the mining level will follow the pressure setpoint [61].

2.4.5 Surface pressure control

Controlling the compressed air supplied to mining shafts with surface valves will decrease the total compressed air flow to the shaft and the shaft pressure. The pressure of the mining levels will hence be the determining factor in how the surface valve is controlled [31], [39], [51], [85]. The minimum pressure requirement of underground working areas must be satisfied when using control valves on the surface.

2.4.6 Reduce wastage on a mining level

Reducing leaks and wastage on a mining level will also reduce the total compressed air flow supply to the mine shaft and the specific mining level and increase the shaft pressure due to the lowered demand [24], [57].

2.4.7 Reducing wastage in the shaft

Consequently, reducing leaks and wastage in the shaft can increase the pressure in the shaft and the mining level [45]. Furthermore, adjusting the compressed air supply to match the previous shaft and mining level pressure can also decrease the total flow and mining level flow [45], [66].

Following the above discussion, the parameters that are affected when implementing various compressor energy savings projects are summarised in Table 7 below.

Table 7: Summary of parameters affected by various compressed air energy savings projects

Project description	Total flow	Level flow	Shaft pressure	Downstream pressure	Control valve position	Setpoint schedule	Reference
Compressor guide vane control	✓		✓	✓		✓	[39], [45], [51], [85]
Compressor setpoint reduction	✓		✓	✓	✓	✓	[31], [36], [39], [45], [61]
Compressor load sharing	✓		✓	✓	✓		[31], [36], [39], [45]
Level pressure control		✓		✓	✓	✓	[36], [45], [56], [61]
Surface pressure control	✓		✓	✓		✓	[31], [39], [51], [85]
Reduce wastage on a mining level	✓	✓	✓				[24], [57]

Reduce wastage in the shaft	✓	✓	✓	✓			[45], [66]
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Specific parameters are affected when implementing specific energy savings projects as seen in Table 7. The parameters that were identified in this step will be referred to as critical parameters. The critical parameters are the specific parameters affected when implementing specific energy savings projects as identified in this step of the method.

As previously stated in Section 1.4, the energy savings achieved by implemented energy savings initiatives can reduce.

2.5 Step 3: Developing target profiles for critical parameters

2.5.1 Introduction

The third step is to develop target profiles for the critical parameters identified in the previous step. Target profiles are created to be used to identify missed energy savings opportunities and their cause. Research has shown that by comparing the actual measured value to values that were obtained during normal operation, early fault detection can be made [76].

The literature review in Chapter 1 established that comparing the actual measured value of certain parameters to the optimal value indicates whether or not the optimised control philosophy is followed [66]. A deviation between the measured value and the optimised value is an indicator of ineffective control and missed energy savings opportunities. Using a margin for parameter values can identify areas in a control system that may negatively impact performance [78], [79]. The margin for the parameters is the target profiles developed in this section.

Based on the principle of comparing the actual value to a target value to ensure effective control, target profiles will be developed for the critical parameters identified in the section above. Target profiles for the critical parameters are referred to as the profiles to which the measured critical parameter value must adhere to ensure that no energy savings opportunities are missed.

2.5.2 Creating the target profiles

The consumption profiles of each production step can accurately be determined by using raw data [86]. The target profiles can thus be created from data where the project achieved the desired savings. This will ensure that the target profiles reflect accurate data correlating to a project achieving the desired savings.

As discussed in the section above, the identified critical parameters are affected in specific ways when specific compressor energy savings projects are implemented. The parameters, therefore,

illuminate the technical requirements for a compressor energy savings project to achieve the desired energy savings. The project can only achieve the desired savings if the critical parameters meet the requirements. It is thus important to ensure that the critical parameters remain within a range where no energy savings opportunities are lost.

Studies have used the pressure setpoint and the downstream pressure to determine whether or not valve control is effective [36], [61], [68]. A deviation between the actual downstream pressure and the pressure setpoint indicates that the automatic pressure control is not effective. The pressure setpoint is, therefore, the target value for the downstream pressure to ensure that the desired energy savings are achieved.

Moreover, target profiles must be adjusted to suit the specific project's requirements. The data for the target profile and the actual measured value must be treated the same to ensure consistency and accuracy. Given that there are different production steps in a workday at a mine, the power profile and parameter profiles vary during a 24-hour workday. The target profiles are also different for specific days in the week. For example, the production steps that are implemented on Sundays are different to weekdays due to the mine's work schedule. The correct target profile must therefore be created and compared in correlation with the day that is monitored.

Creating a graph for visual inspection between the target profile and the actual critical parameter value is a simple method to determine whether the project's technical requirements are satisfied. The graph must contain the target profile and the actual measured value on the same axis to easily identify any deviations between the two profiles.

Figure 25 shows the notable effect on the downstream pressure of a mining level after a valve control project was implemented.

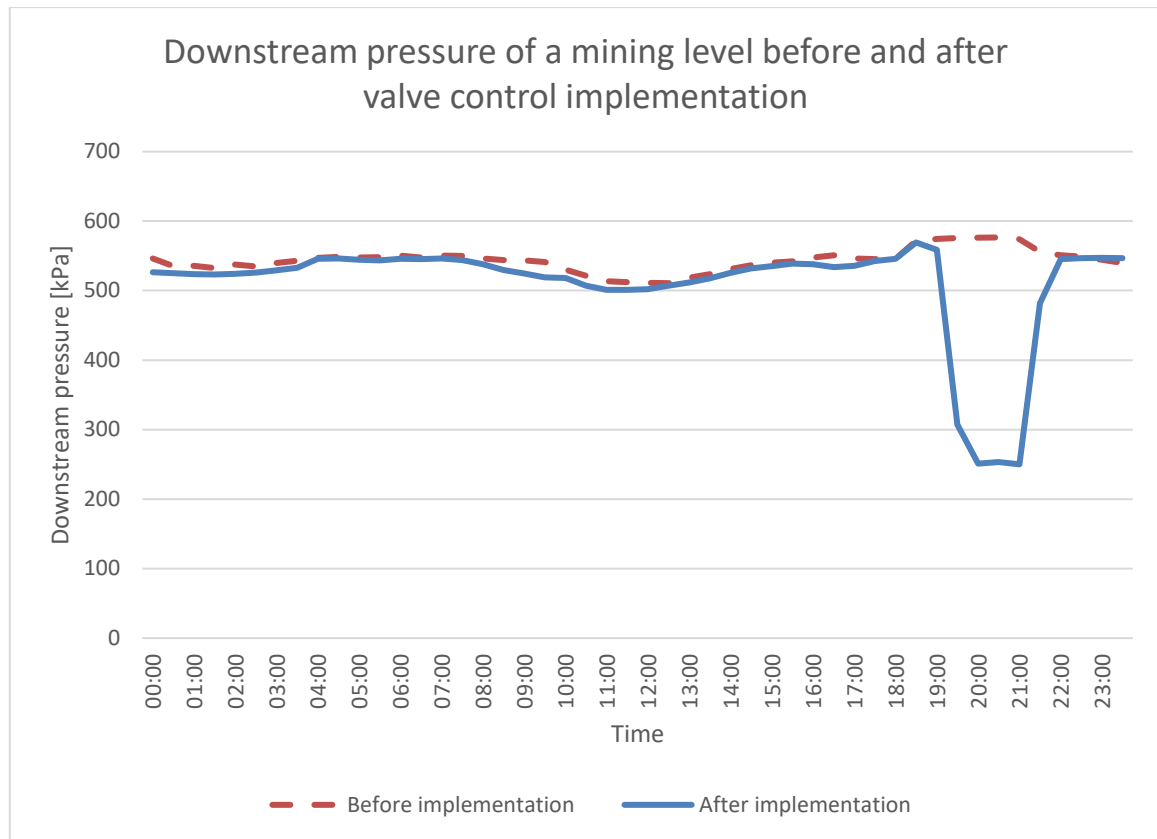


Figure 25: Downstream pressure of a mining level before and after valve control implementation

The goal of the target profiles is to ensure that the project's technical requirements are met, to achieve the desired energy savings. From Figure 25 above it is clear that the downstream pressure reduces between 19:00 and 22:00. This is due to a control valve project being implemented. The compressor energy savings that are achieved from this project is due to the reduction in demand during 19:00 and 22:00. The pressure profile after project implementation is the desired pressure profile to achieve energy savings.

In the example shown in Figure 25, the pressure profile after the energy savings project was implemented becomes the target profile for the downstream pressure of that mining level. Figure 26 shows an example of the target profile for the valve control project.

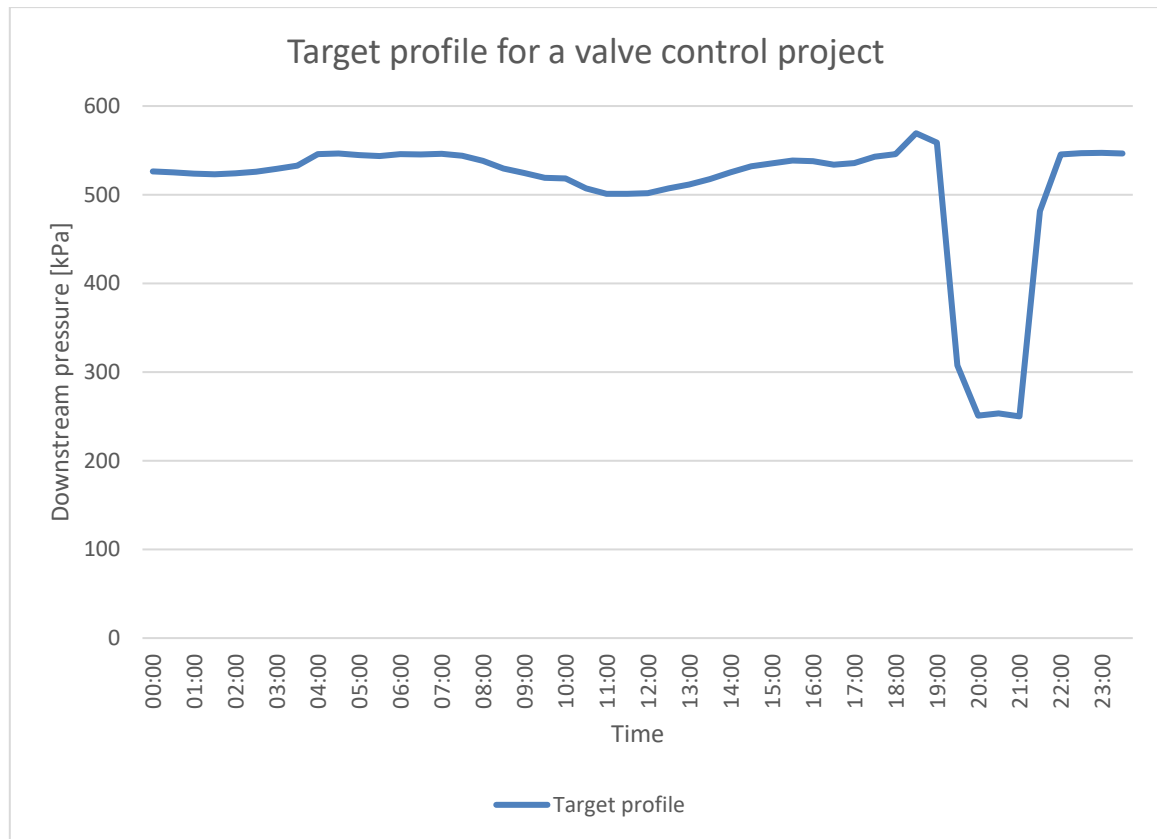


Figure 26: Target profile for a valve control project

Various compressor energy savings projects affect the compressor power and critical parameters differently. The nature of the project will determine the period where the effect is present. The critical parameter and target profile data should be presented to effectively identify parameters that do not follow the target profiles and avoid missed energy savings opportunities.

In Figure 26 it is noted that the specific valve control project only affects the downstream pressure from 19:00 until 22:00. This means that the project will only achieve energy savings between 19:00 and 22:00. For the example used the critical time of energy savings is determined as 19:00 until 22:00. If the downstream pressure deviates from the target profile during the critical period, missed energy savings opportunities are present.

The target profiles should be developed for every parameter in Table 7 correlating to the specific project. After the target profiles are developed there must be a critical analysis of the parameters and target profiles.

2.5.3 Analysis of parameters

An analysis of the critical parameters should be conducted to understand what the data means. When comparing the target profiles to the actual data, it must be clear what certain deviations mean. To ensure that the target profiles are used effectively, specific information must be gathered for the critical parameters. An analysis of the following point should be done:

1. What will lead to missed energy savings opportunities when the parameter is above or below the target profile?
2. What is the period when savings are achieved?
3. What is the maximum percentage deviation between the parameter value and the target profile before the energy savings reduce?

Table 8 shows a simple analysis of critical parameters.

Table 8: Critical parameter analysis

Parameter	Above/below	Savings period	Margin of deviation
Parameter 1	Above	19:00 – 22:00	10%
Parameter 2	Below	All	20%

Table 8 shows a simplified method of having information on the critical parameters. In a study conducted by Fouché [45], the compressor power profile was recorded after a project had been implemented. This profile was obtained from a test day, and it changed during a year when a compressor had been serviced. This, in turn, changed the compressor power profile but not the flow profile. While the pressure setpoints were adjusted when the compressor was serviced to maintain the same pressure, the power output did increase. This is important to note, as changes to the network may require an adjustment to the target profiles to accurately represent the project performance.

2.5.4 Monitoring

The monitoring of energy is the cornerstone of energy efficiency measures as identified in the literature [71]. Monitoring the critical parameters and target profiles is thus important to implement in this developed method. The method used to display the target profile and actual data visually can provide respective benefits, depending on the compressor energy savings project that is implemented. Two methods of representing the data are using a 24-hour profile or a daily average value. The two methods are discussed in the subsections below.

2.5.4.1 Daily profiles

A study conducted by De Villiers [24] illuminates the fact that a daily profile can provide accurate monitoring capabilities for a pressure control project. An energy efficiency project was implemented to reduce the refuge bay compressed air consumption continuously and the compressor baseload power throughout a 24-hour profile [24]. For this reason, it was believed that the power reduction would be constant throughout the day while the usage profile would remain reduced.

The actual compressor power's daily profile was compared to the baseline to illustrate the project's impact. It was noted that the usage profile did not remain the same because, during the project implementation, an additional compressed air reduction project was implemented. The additional project focused on optimising the pressure delivered to each level. The effect of the additional project can be seen at 17:30, 20:30 and 07:30, where the consumption sharply declines or inclines to meet the demand in that period.

The average decrease in the compressors' power demand during a 24-hour day after the refuge bay project was implemented was taken as 1 215 kW. The impact was found to be a result of the additional projects that were implemented rather than the refuge bay crack valve project. Therefore, the average reduction in power consumption during the times when the additional project had no impact was taken to accurately measure the impact of the refuge bay crack valve project. The refuge bay crack valve project's impact was calculated as 962 kW by using the average power reduction in specific periods of a 24-hour day profile and not the daily average power reduction.

Displaying the target profile and the actual critical parameter data on a 24-hour profile will be beneficial for projects where specific periods need to be monitored. The period where the control is present can be isolated and analysed.

2.5.4.2 Daily average and sum

If a parameter deviated from the target profile, it will be beneficial to identify the exact time at which the violation occurred, as this can assist in identifying the cause of the parameter deviating from the target profile.

In certain instances, it may be beneficial to identify the exact day on which the parameter started to deviate from the target profile as a result of possible actions taken on the system, such as valve maintenance or repairs. Knowing what happened on the day may reduce the time to identify the component that is causing the project to underperform.

For ease of use, a daily average or sum of a parameter and target profile can be used to identify the day on which a critical parameter deviated from the target profile for a long period where it is impractical to work through the daily profiles. With this method, the specific day when the parameter started to deviate from the target profile can be identified to aid in the diagnostics process. However, using a daily average or daily sum to compare to a target profile does not give the precise time of day when a critical parameter deviated from the target profile but rather an overview of the critical parameter performance.

It must be noted, therefore, that using the daily average or sum may mask the fact that the peak periods may increase due to production, and as such, it cannot help determine whether the control philosophy was followed correctly.

2.5.5 Effective grouping of critical parameters

Compressed air flow is a single independent parameter to be monitored and as such will be advantageous [56]. Pressure transmitters and air flow meters need to be installed in the air pipes to continually monitor the compressed air pressure and flow [26]. This monitoring instrumentation gives continuous feedback on the system parameters through the same communication network that controls the valves.

The critical parameters identified in this method are grouped into two sections, namely:

1. Critical parameters for identifying missed energy savings opportunities; and
2. critical parameters for identifying the cause of the missed energy savings opportunities.

2.5.6 Conclusion

The important steps to conduct in this step of the method are shown below:

Determine the date when the project was achieving the desired energy savings. The data used to create the target profiles will be obtained from this day. After the target profiles are created from raw data, each parameter should be analysed. By conducting critical analysis, information is gathered that describes the critical parameters and target profile data in an informative way. The method of how the parameter monitoring will be conducted needs to be determined. This is simply deciding whether to use 24-hour profiles or daily averages.

2.6 Step 4: Identifying missed energy savings opportunities

The objective of the developed method is to reduce missed energy savings opportunities. To reduce missed energy savings opportunities, they must first be identified. Missed energy savings opportunities are present when the technical requirements of a project are no longer met. The effect the compressor energy savings project has on certain parameters has been identified above. These effects lead to energy savings.

Missed energy savings opportunities are identified by comparing the data from the critical parameters with the corresponding target profiles. By comparing these values, deviations can be identified. The information gathered in the previous steps should be used to identify deviations that reduce the energy savings achieved from a project. Figure 27 illustrates the difference between a target profile and the actual downstream pressure.

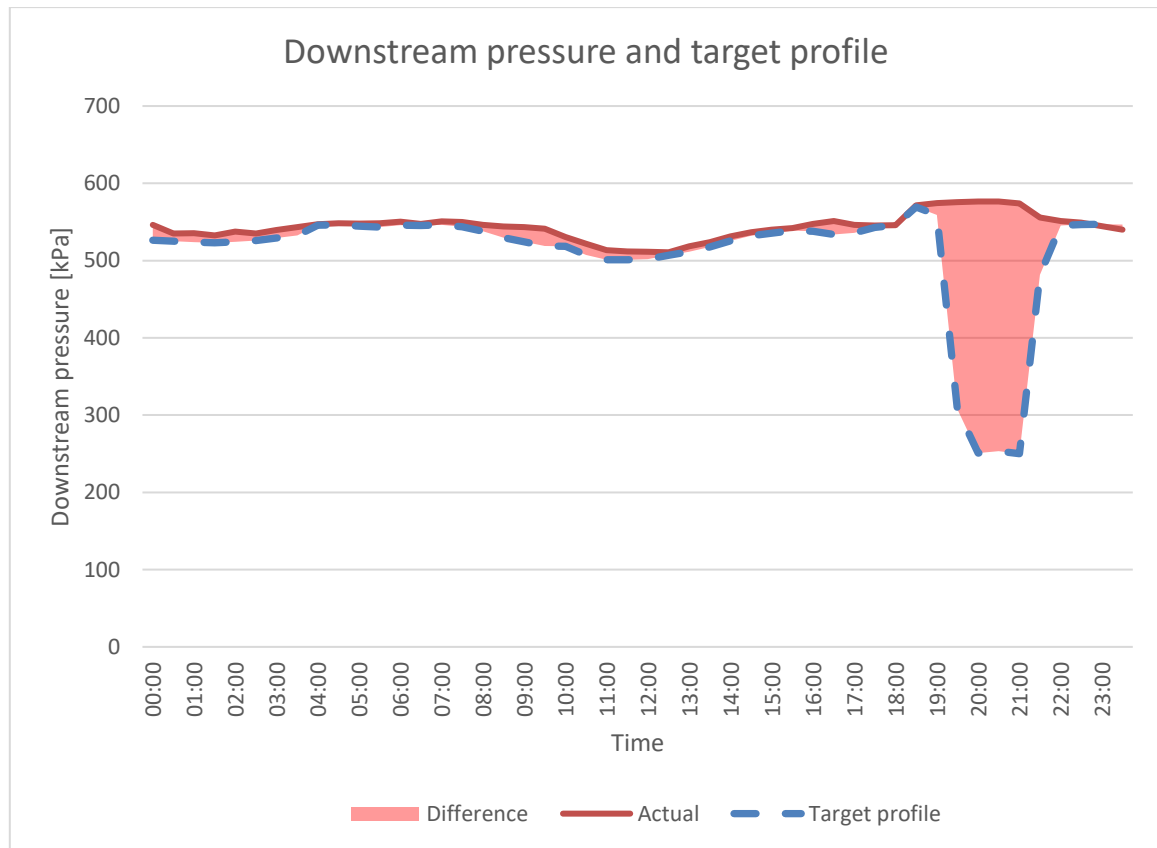


Figure 27: Downstream pressure and target profile deviation

Figure 27 illustrates the difference between the actual parameter value and the target profile with a red area. The red area is seen to be substantial in the area where control is expected. This deviation between the target profile and the parameter value indicates a missed energy savings opportunity.

If a deviation between the critical parameter value and the target profile is noted in the state where energy savings opportunities are missed, it must be established whether it is significant or not. False alarms of inefficiencies can be avoided by determining the magnitude of the deviation between the target profile and the measured data which leads to missed energy savings opportunities [77]. A deviation of 10% is used in this study as an indication of missed energy savings opportunities. The decision to assume a 10% deviation in the method is due to the lack of literature on a dynamic and unique system as the flow, pressure, valve percentage and setpoints as described in the document.

2.7 Step 5: Identifying the cause of missed energy savings opportunities

Following the missed energy savings opportunities identified in the previous step, the cause has to be identified. The cause of the missed energy savings opportunities will enable a further investigation to ultimately rectify the cause. By rectifying the cause of the missed energy savings opportunities, the planned savings will be achieved.

The same method will be used as in the previous step to determine the cause of the missed energy savings opportunities, but with different parameters. The cause of missed energy savings opportunities is identified using the following critical parameters:

- Valve percentage,
- pressure setpoint,
- level flow,
- current setpoint vs current downstream pressure, and
- auto-compression relationships.

An identified parameter that does not adhere to the target profile does so for a specific reason that may be difficult to identify if there is no in-depth knowledge of the compressed air system or control philosophy. This chapter includes a flow diagram to identify the cause of a project's missed savings by utilising target profiles for critical parameters.

The control philosophy of the project will assist in identifying what causes a parameter to exceed the target profile. The control philosophy will state what is required for the project to achieve the maximum electrical cost savings. If a control philosophy depends on a control valve that reduces the demand for compressed air, it should be kept in mind that components such as the valve and actuator can fail.

Control valves have multiple control modes that may inhibit the control, leading to reduced electricity cost savings [56]. Common problems faced with underground valve control are discussed below.

1. A valve can be set in manual mode, which would not control the valve according to schedule.
2. The physical valve can be set in manual mode and not remote control, which has the same effect.
3. Valves can get stuck in the fully open position and cannot be controlled.

If the information on the specific state of the valve, actuator and valve position is not available, it will be difficult to identify the problem immediately. The loss of control should therefore be investigated while considering the points above.

One of the largest risks to the success of an energy efficiency project is the change in client operations, whether the change is planned or unplanned [64]. These risks must be identified, and response planning and condition monitoring should be implemented [64] (working schedule change causes valves to trip). The risks should be monitored, and actions should be implemented to manage such risks throughout the project life cycle [64].

After missed energy savings opportunities are identified, the cause can be identified using specific steps developed in this method. The steps developed to identify the cause of missed energy savings opportunities when the level's pressure deviated from the target profile are shown in Figure 28.

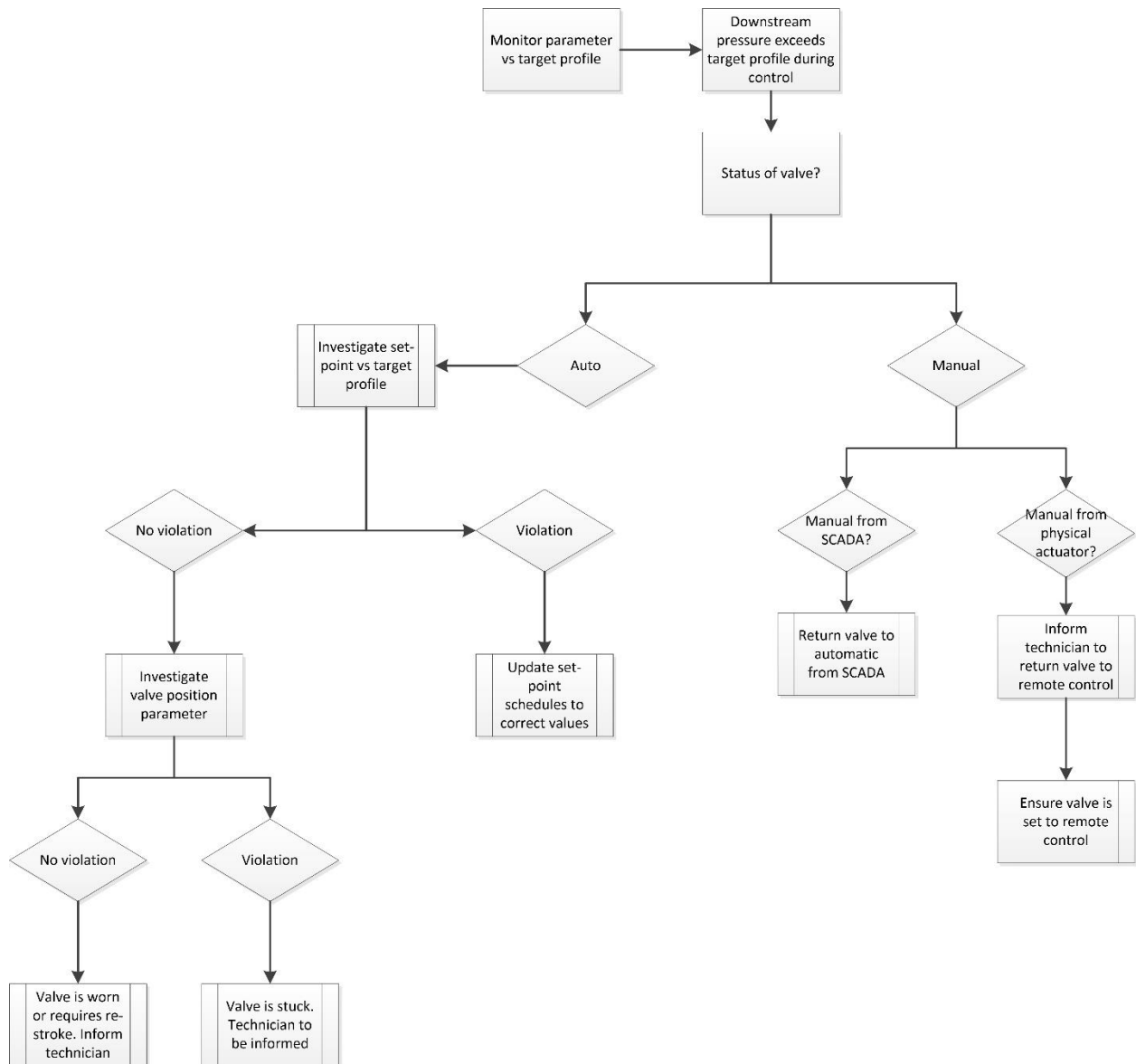


Figure 28: Downstream pressure violation flow chart

The steps developed to identify the cause of missed energy savings opportunities when the total flow deviates from the target profile are shown in Figure 29.

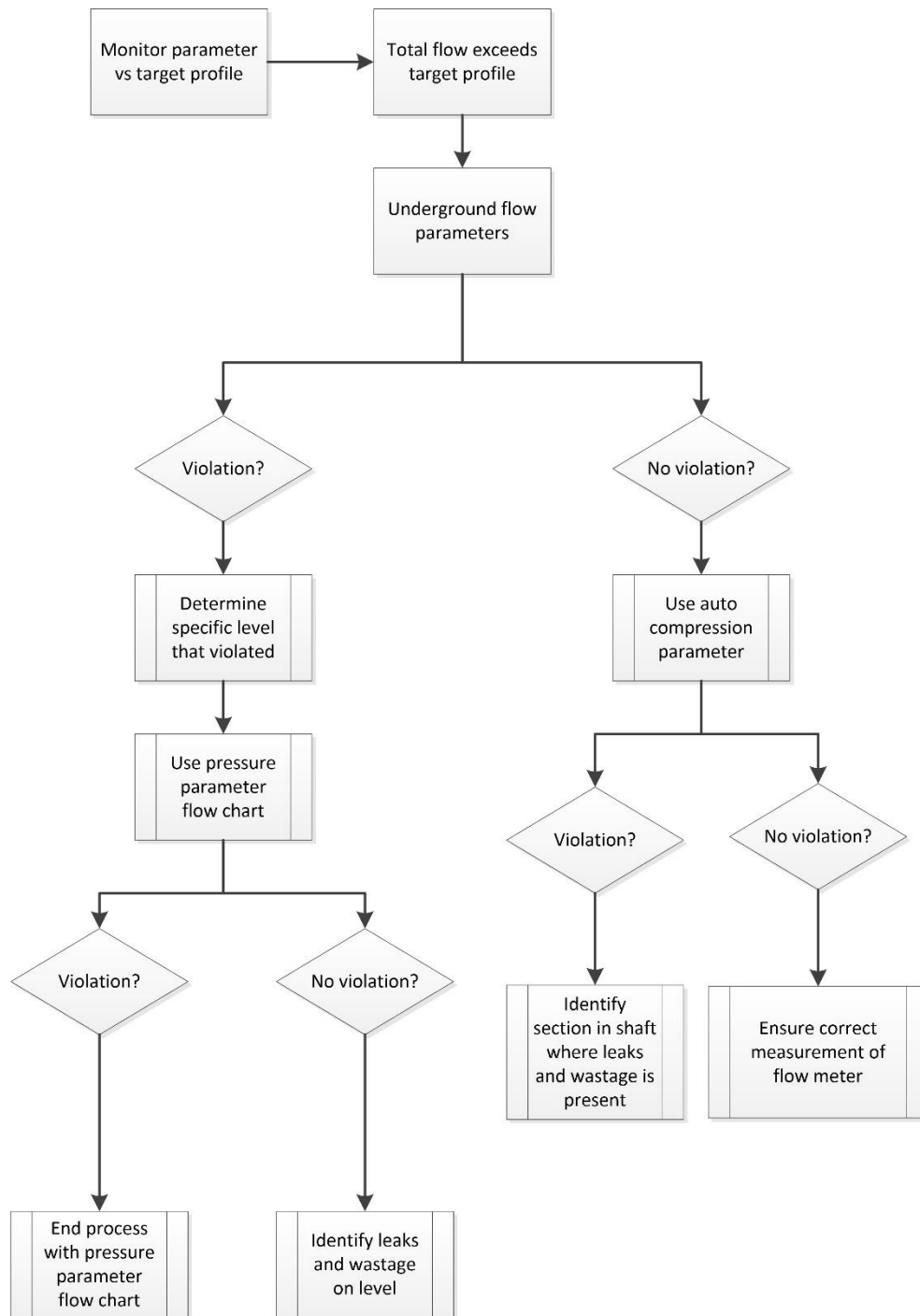


Figure 29: Total flow violation flow chart

Using the flow charts illustrated in Figure 28 and Figure 29 the cause of the missed energy savings will be identified. Actions should be taken to correctly rectify the identified cause. The cause of the missed energy savings should be reported to the responsible person, whereafter rectifying action can be taken.

2.8 Step 6: Ensuring that missed energy savings opportunities are reduced

The fault identified and reported should now be fixed to reduce the missed energy savings opportunities. This is done using the target profiles. After the intervention, the measured actual data should again be compared to the target profiles to ensure that the missed energy savings opportunity is reduced [78].

First, the critical parameter that identified the cause of the missed energy savings opportunity must be compared to the target profile to ensure that the actions taken to repair the fault were implemented correctly. If no deviation is noted for the cause-identifying critical parameter, the critical parameters that deviated from the target profiles during the cause-identification step must be used. These critical parameters must be compared to the target profiles to ensure the cause was successfully identified and rectified.

The final step is to compare the compressed air flow critical parameter that identified the missed energy savings opportunity. If there is no deviation between the abovementioned critical parameters and target profiles, the project requirements will have been satisfied and the missed energy savings opportunities successfully reduced. The method is validated by comparing the compressor power or energy when the project was achieving the desired savings to the power or energy after the method was applied.

2.9 Conclusion

In this chapter, a method was developed from the literature to identify missed energy savings opportunities and the cause thereof. First, the project scope is obtained for the specific energy savings project in question. The project scope included vital information that is used to characterise the project. Secondly, the parameters in a compressed air system that are affected when implementing a compressor energy savings project were identified. These critical parameters were grouped to correlate with the various compressor energy savings projects so that they can be applied to existing projects.

Next, the development of target profiles for the respective critical parameters was explained. Raw data for a critical parameter when a project is achieving the desired energy savings are used to create the target profiles. The project scope is used to determine the period that should be used as target profiles.

Then, the method to identify missed energy savings opportunities was developed. Using compressed air flow as a critical parameter was determined to be an effective way to identify missed energy savings opportunities because the flow is directly proportional to compressor energy consumption. The goal of the target profile is to identify deviations between the actual data and the profile. By using the project scope, the correct method of identifying missed energy savings opportunities is applied. The project scope is used to determine if energy savings opportunities are missed when the critical parameter is less or greater than the target profile. Deviations between the critical parameter data and the target profile that indicates missed energy savings opportunities are identified.

The critical parameters that apply to the project scope are used with the target profiles to determine the cause of the identified missed energy savings opportunities. The same method applies when identifying missed energy savings opportunities. The deviation between the critical parameter and the target profile is evaluated to determine the cause of the identified missed energy savings opportunities.

After the cause of the missed energy savings opportunities has been identified using the method, a solution is determined by using the literature or knowledge from site personnel. After the identified solution is implemented, the method is verified. The method is verified by ensuring that the deviation between the critical parameter data and the target profile is reduced after the identified solution is implemented. The critical parameters that identified the cause of the missed energy savings opportunities are first used to verify the effectiveness of the implemented solution. If the deviation between the critical parameters and target profiles is found to be smaller, the critical parameters that identified missed energy savings opportunities are compared to the target profiles. If the deviation between all the identified critical parameters and respective target profiles has been reduced, it will mean that the identified solution has successfully reduced the missed energy savings opportunities.

The compressor power is used to validate the method. The compressor power before missed energy savings opportunities that were identified is compared to the compressor power of the day on which missed energy savings opportunities were identified using the method. If the compressor power is greater on the day when missed energy savings opportunities are identified using the method, the method can successfully identify missed energy savings opportunities. After the identified solution is implemented, the compressor power is used to validate the method's effectiveness in identifying the cause of the missed energy savings opportunities. The deviation between the initial compressor power profile and the power profile after the identified solution is used to determine the reduction of missed energy savings opportunities.

The flow diagram of the developed method is shown in Figure 30 below.

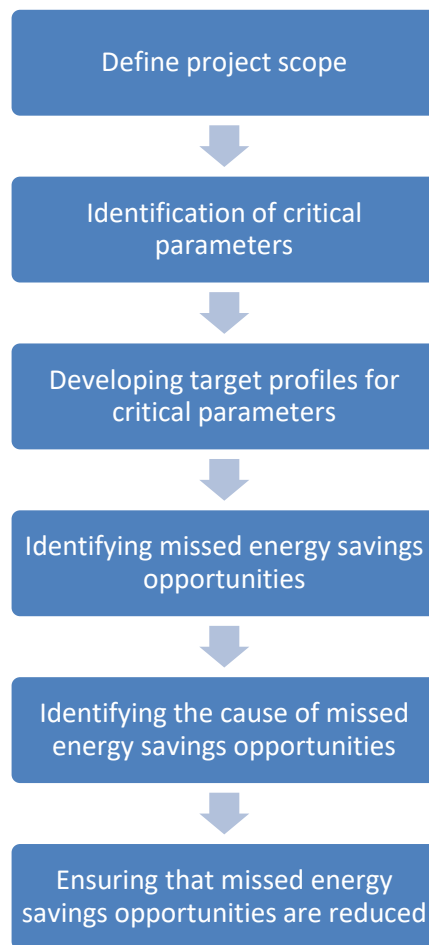


Figure 30: Developed method flow diagram

Chapter 3 Results and discussion

3.1 Introduction

This chapter focuses on implementing the developed method in practical case studies and reporting individually, as specified in the third and fourth steps of the case study methodology. The case studies aim to prove that missed energy savings opportunities can be reduced by identifying the cause with the developed method.

The developed method was implemented at a deep-level gold mine located in the southern part of Gauteng, South Africa. The mine will be referred to as Mine A throughout this document due to confidentiality. The developed method was implemented on the compressed air systems of three mining shafts of Mine A, which are referred to as Shaft A, Shaft B and Shaft C.

The results obtained through the implementation of the developed method are analysed and discussed throughout this chapter.

3.2 Case study 1: Interference with automatic control

3.2.1 Background

Case study 1 is an application of the developed method on the compressed air system of Shaft 1. Shaft 1 has two mining levels, namely level 39 and level 40. The levels consume compressed air to complete actions to produce gold. There are four compressors located in the surface compressor house of Shaft 1 that supplies the compressed air network with compressed air. Levels 39 and 40 have automatic compressed air pressure control valves installed. The developed method was applied to this case study and is discussed below.

3.2.2 Step 1: Define project scope

The project is a level pressure control project. It relies on automatic pressure control valves to reduce the pressure during blasting periods when the compressed air demand is low on levels 39 and 40. The downstream pressure of the levels is controlled with a setpoint schedule from the SCADA system. The setpoint schedule is the same for both levels, which is shown in Table 9 below:

Table 9: Case study 1 setpoint schedule

Time	Shift	Pressure setpoint [kPa]
05:00 – 18:00	Drilling shift	500
18:00 – 22:00	Blasting shift	150
22:00 – 05:00	Cleaning shift	500

The control system is created so that the valve will fully open if a value of 500 kPa is set for the setpoint. The only control that is present is between 18:00 and 21:00, where the setpoint is set to 150 kPa.

3.2.3 Step 2: Identification of critical parameters

An extract from Table 7 was taken that applies to a level pressure control initiative and is shown in Table 10. This was used to identify the critical parameters for Case study 1.

Table 10: Case study 1 critical parameters

Project description	Total flow	Level flow	Shaft pressure	Downstream pressure	Control valve position	Setpoint schedule
Level pressure control		✓		✓	✓	✓

From Table 10 the following critical parameters are identified:

1. Total compressed air flow to Shaft A,
2. compressed air flow to level 39, and
3. compressed air flow to level 40,

4. downstream pressure to level 39,
5. downstream pressure to level 40,
6. pressure setpoint of level 39, and
7. pressure setpoint of level 40.

3.2.4 Step 3: Developing target profiles for critical parameters

3.2.4.1 Creating target profiles

The target profiles for the critical parameters were developed from the data of a single day where the project engineer agreed that the project was achieving the desired savings. The automatic control on levels 39 and 40 was satisfactory, and the project requirements were that the pressure on these levels is reduced to 150 kPa from 17:00 until 20:00.

The target profiles that were created are shown in the figures below.

The target profile for critical parameter 1, total compressed air flow to shaft A, is shown in Figure 31 below.

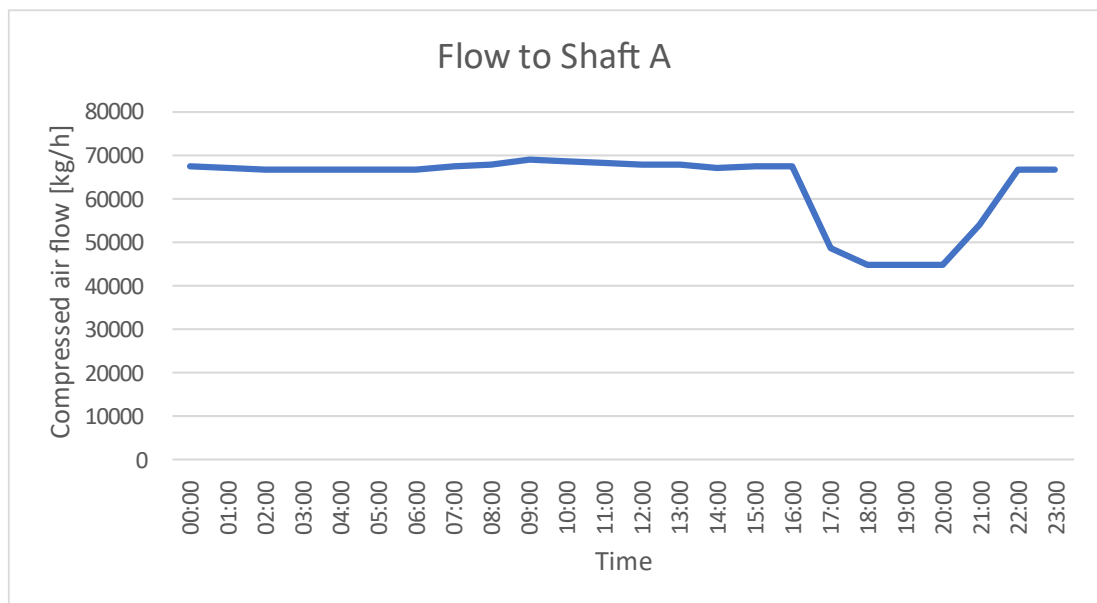


Figure 31: Target profile for Case study 1, critical parameter 1

The target profile for critical parameter 2, compressed air flow to level 39, is shown in Figure 32 below.

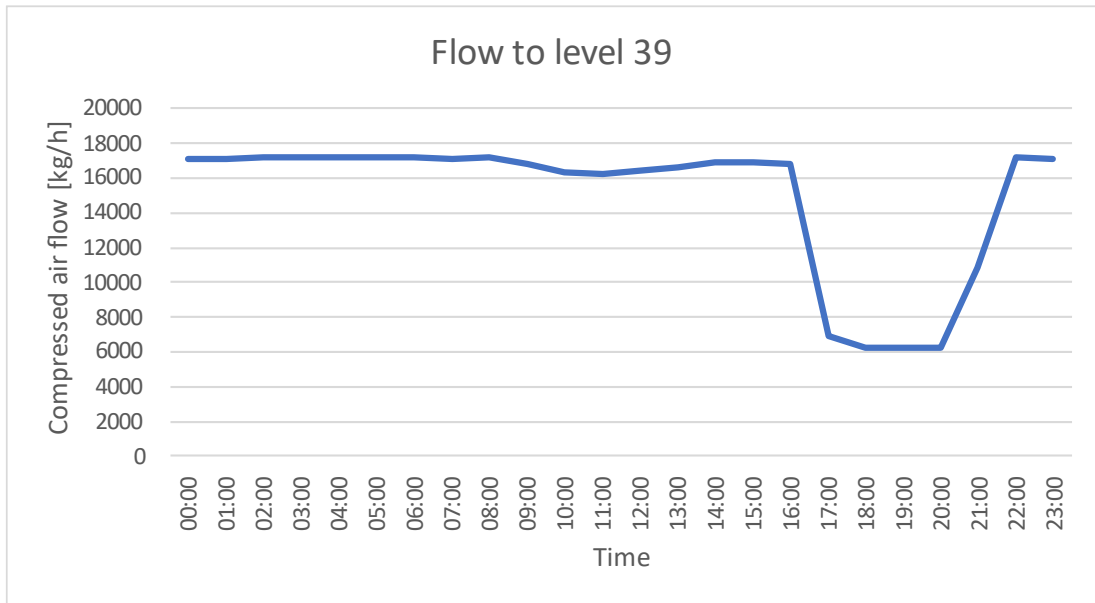


Figure 32: Target profile for Case study 1, critical parameter 2

The target profile for critical parameter 3, compressed air flow to level 40, is shown in Figure 33 below.

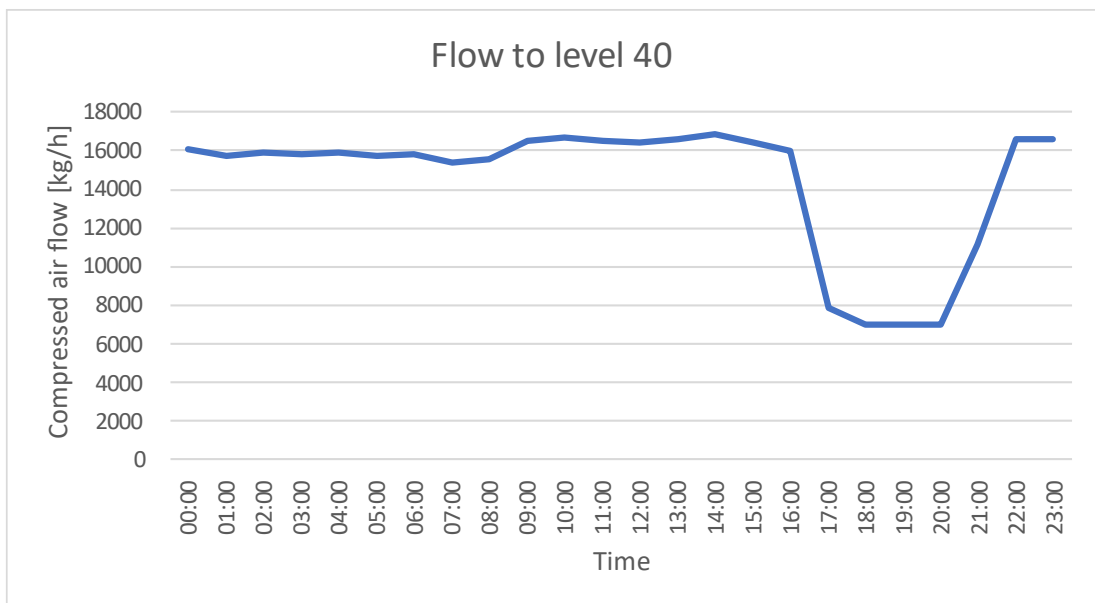


Figure 33: Target profile for Case study 1, critical parameter 3

The target profile for critical parameter 4, downstream pressure to level 39, is shown in Figure 34 below.

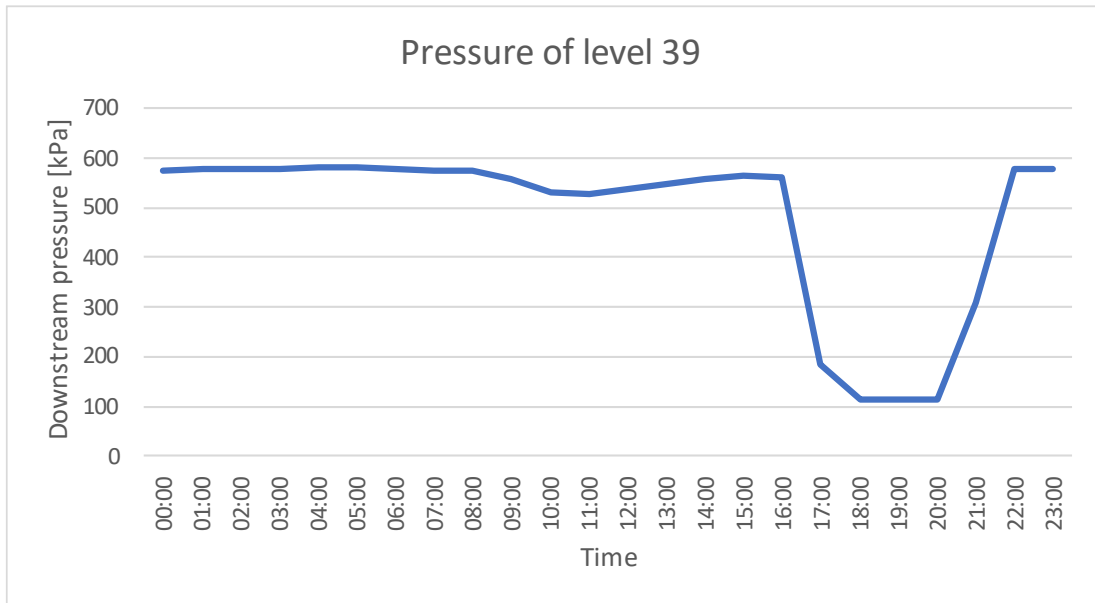


Figure 34: Target profile for Case study 1, critical parameter 4

The target profile for critical parameter 5, downstream pressure to level 40, is shown in Figure 35 below.

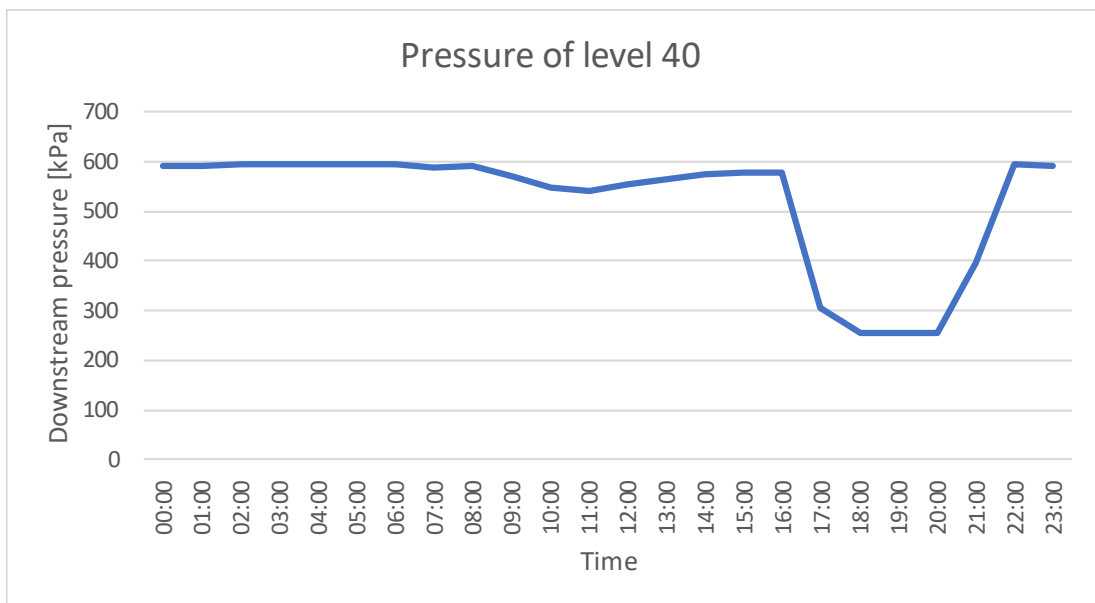


Figure 35: Target profile for Case study 1, critical parameter 5

The target profile for critical parameter 6, pressure setpoint of level 39, is shown in Figure 36 below.

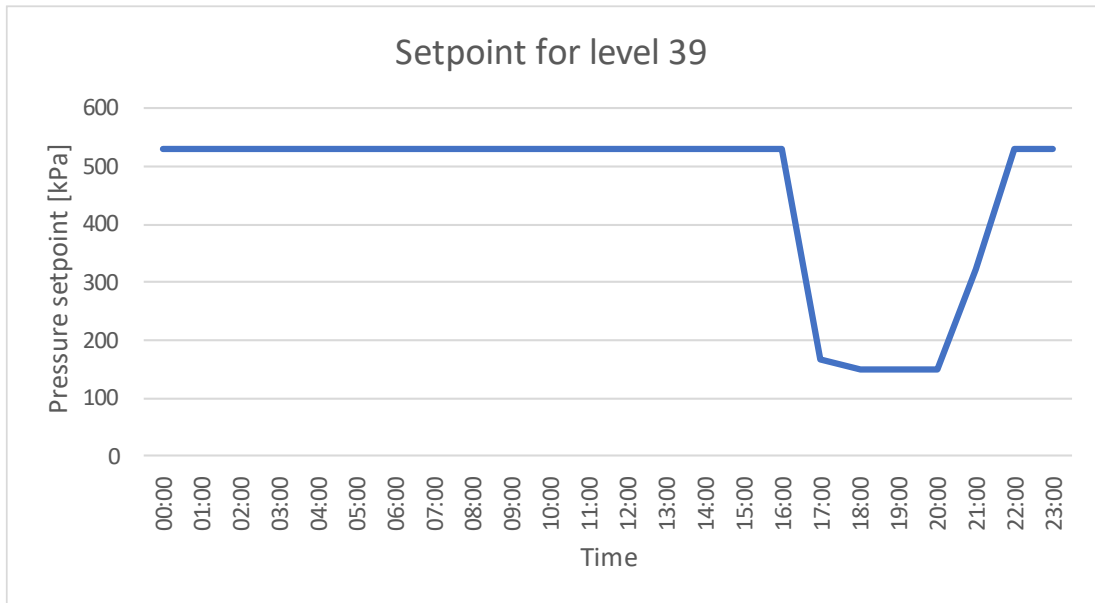


Figure 36: Target profile for Case study 1, critical parameter 6

The target profile for critical parameter 7, pressure setpoint of level 40, is shown in Figure 37 below.

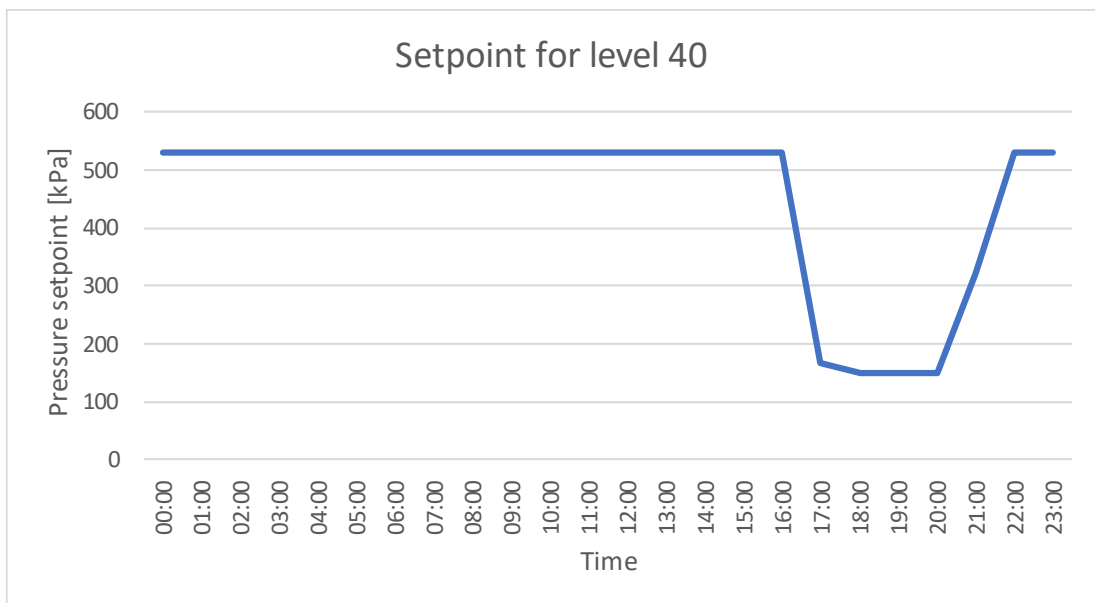


Figure 37: Target profile for Case study 1, critical parameter 7

The target profiles for the critical parameters were created from raw data.

3.2.4.2 Analysis of parameters

The analysis of the critical parameters was performed. The information was obtained through the project scope as discussed in step 1. The data is shown in Table 11.

Table 11: Critical parameter analysis for Case study 1

Parameter	Above/below	Savings period
Parameter 1	Above	17:00 – 20:00
Parameter 2	Above	17:00 – 20:00
Parameter 3	Above	17:00 – 20:00
Parameter 4	Above	17:00 – 20:00
Parameter 5	Above	17:00 – 20:00
Parameter 6	Above	17:00 – 20:00
Parameter 7	Above	17:00 – 20:00

3.2.5 Step 4: Identifying missed energy savings opportunities by utilising target profiles for critical parameters

On 8 June 2020, the total compressed air flow to the shaft deviated from the target profile. There was an average difference of 53% between the flow and the target profile between 17:00 and 20:00. This is shown in Figure 38 below, where it is seen that the flow is above the target profile during the control period.

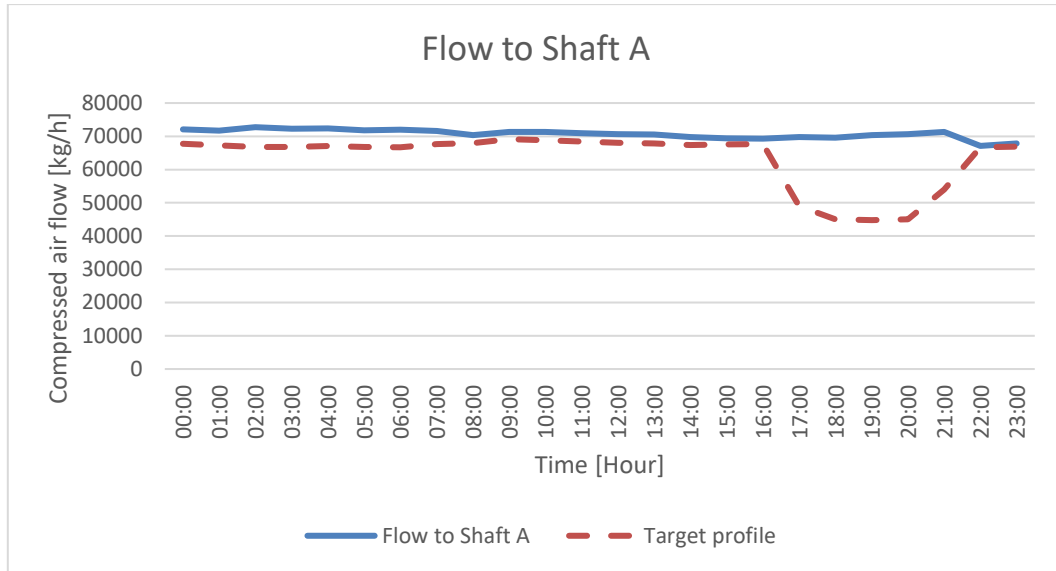


Figure 38: Flow and target profile to Shaft A (8 June 2020)

From Figure 38 it is determined that there are missed energy savings opportunities. The percentage deviation for the specific periods is shown in Table 12 below.

Table 12: Flow to Shaft A deviation percentages

Description	Period	Deviation from the target profile
Total	00:00 – 23:00	14%
During control period	17:00 – 20:00	53%
Outside control period	00:00 – 17:00, 20:00 – 23:00	6%

Figure 38 and Table 12 show that the missed energy savings opportunity is during the blasting period when the demand for compressed air is low. As indicated in Table 9 and Table 12, the deviation is during the period where pressure control on levels 39 and 40 is present. The compressed air flow to levels 39 and 40 is compared to the respective target profiles to determine whether the excessive flow is also present.

The compressed air flow to levels 39 and 40 for 8 June 2020 was compared to the respective target profiles to determine whether these critical parameters also deviated from the target profiles during the blasting period. The compressed air flow and target profile for level 39 is shown in Figure 39 below.

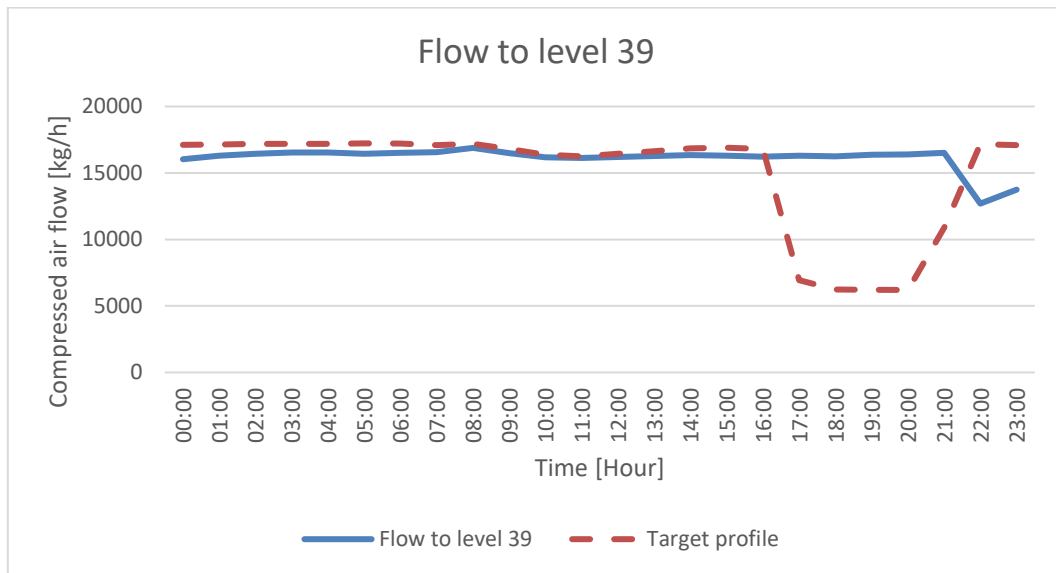


Figure 39: Flow and target profile to level 39 (8 June 2020)

The flow to level 39 deviated from the target profile during the blasting period, similarly to the flow to Shaft A shown in Figure 38 above. The average deviation between the flow to level 39 and the target profile from 17:00 until 20:00 is 156%. The compressed air flow and target profile for level 40 is shown in Figure 40 below.

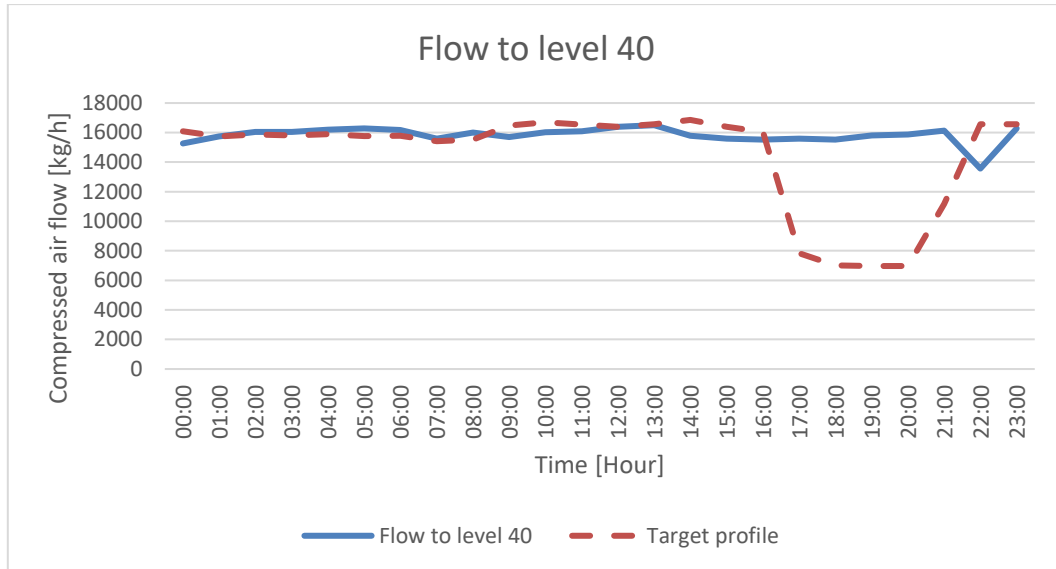


Figure 40: Flow and target profile to level 40 (8 June 2020)

From Figure 39 and Figure 40 above it is seen that the compressed air flow for levels 39 and 40 deviated from the target profile during the blasting period on 8 June 2020. The flow for level 39 deviated with an average of 156% and for level 40 with an average of 119% during the blasting period, whereas the flow to the shaft deviated with an average of 53% during blasting.

The level flow is seen to have a larger deviation from the target profile than the shaft flow deviation. This difference in percentage deviation is due to the total flow consisting of many areas that demand flow in the mine and not only levels 39 and 40. From this, it is seen that the deviation can be identified in smaller resolutions from the level flows than with the shaft flow profile.

It is concluded that there are missed energy savings opportunities from 17:00 until 20:00.

3.2.6 Step 5: Identifying the cause of missed energy savings opportunities by utilising target profiles for critical parameters

The cause of the missed energy savings opportunities must be determined for them to be minimised. In the section above it was concluded that the missed energy savings opportunities are present from 17:00 until 20:00 on levels 39 and 40. The period where the missed energy savings opportunities are present is the period where pressure control is expected. To ensure that the control was effective for levels 39 and 40, the pressure setpoint and the downstream pressure for levels 39 and 40 were compared on 8 June 2020. The pressure setpoint and downstream pressure of 8 June 2020 for levels 39 and 40 are shown in Figure 41 and Figure 42 respectively below:

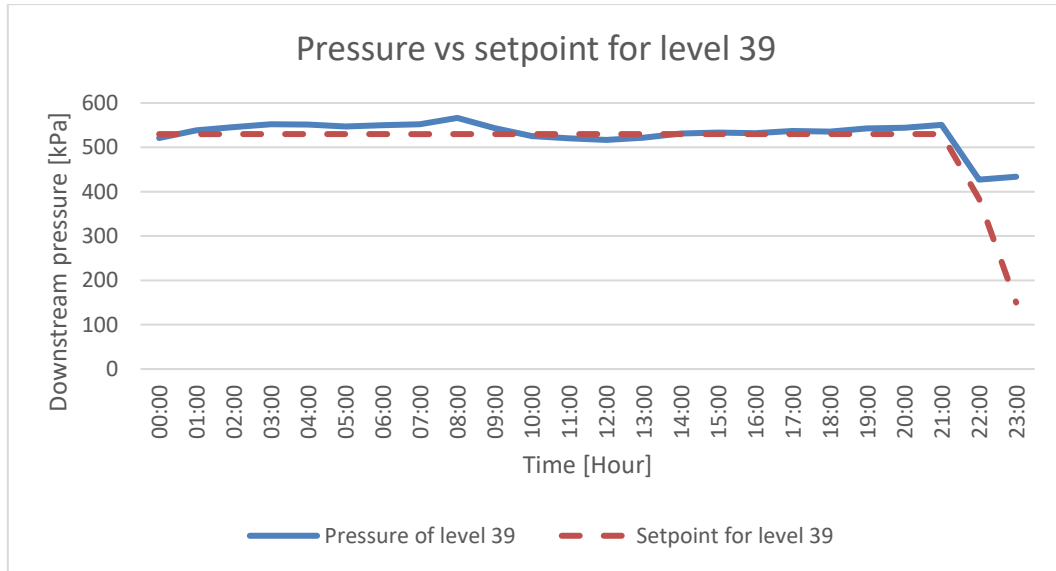


Figure 41: Pressure and setpoint for level 39 (8 June 2020)

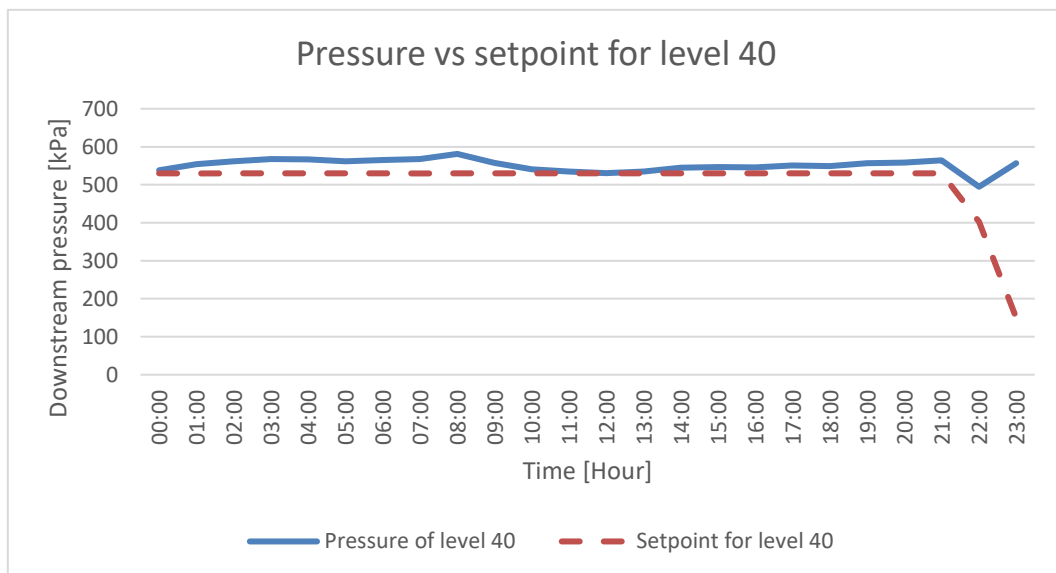


Figure 42: Pressure and setpoint for level 40 (8 June 2020)

In Figure 41 and Figure 42 can be seen that the control was effective as the downstream pressure did not deviate from the setpoint during the blasting period. The average deviation between the pressure and the setpoint during the blasting period is 2% and 4% for levels 39 and 40, respectively. Figure 38, Figure 39 and Figure 40 above indicate that there are missed energy savings opportunities because the compressed air flow for the shaft, levels 39 and 40 deviated from the target profiles. It is, however, clear from Figure 41 and Figure 42 that the cause is not ineffective pressure control on levels 39 and 40.

The setpoint of 8 June 2020 was compared to the target profile for levels 39 and 40 respectively to determine whether the setpoint was according to the project requirements as specified in Table 9 above. The setpoints and target profiles for levels 39 and 40 are shown in Figure 43 and Figure 44 respectively below:

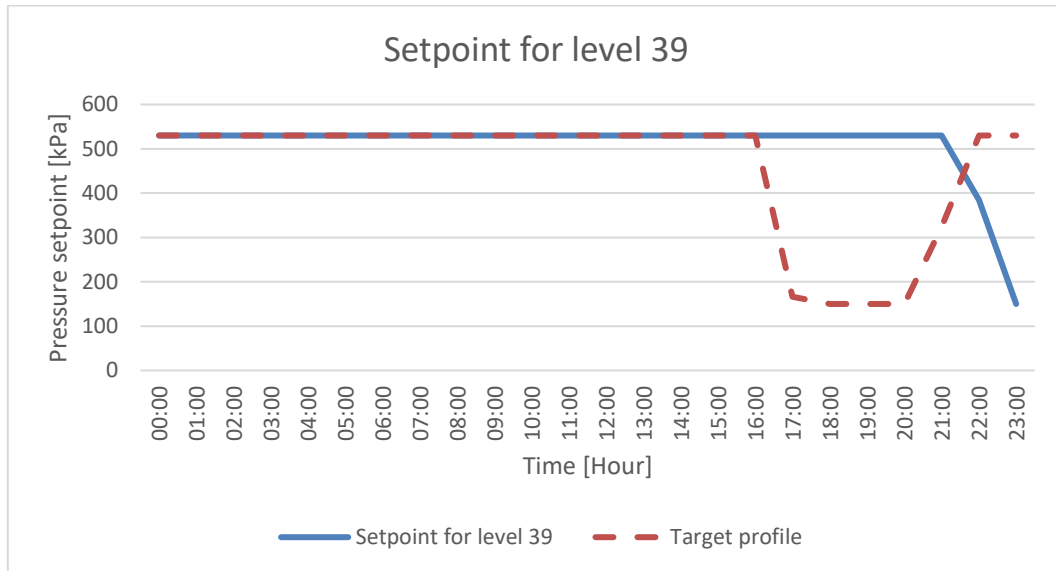


Figure 43: Setpoint and target profile for level 39 (8 June 2020)

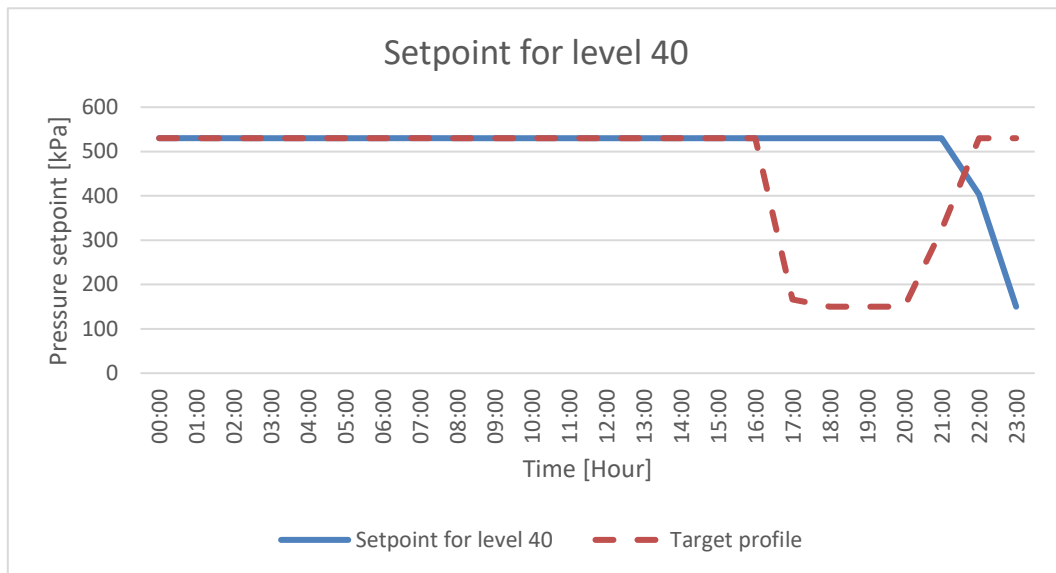


Figure 44: Setpoint and target profile for level 40 (8 June 2020)

From Figure 43 and Figure 44 it is determined that the setpoints for levels 39 and 40 are not according to the project requirements. The average deviation between the setpoint and target profile is 245% for levels 39 and 40. This indicates that the cause of the missed energy savings opportunities is that the setpoint is not in accordance with the project requirements. The SCADA

was used to compare the current setpoint schedule input with the project requirements. It was found that the control room operator had incorrectly changed the setpoint schedule for levels 39 and 40 by adjusting the setpoint value to 500 kPa during the blasting period due to a misunderstanding. The setpoint was incorrectly changed to 150 kPa from 21:00 by the control room operators which can be seen in Figure 41, Figure 42, Figure 43 and Figure 44.

3.2.7 Step 6: Ensuring that missed energy savings opportunities are reduced

The control room was contacted, and the setpoints for levels 39 and 40 were changed back according to the project requirements on 9 June 2020. The critical parameters were compared to the respective target profiles to ensure that the method used did manage to reduce missed energy savings opportunities. The critical parameters that identified the cause of the missed energy savings opportunities are compared to the respective target profiles in Figure 45 and Figure 46 respectively for 9 June 2020:

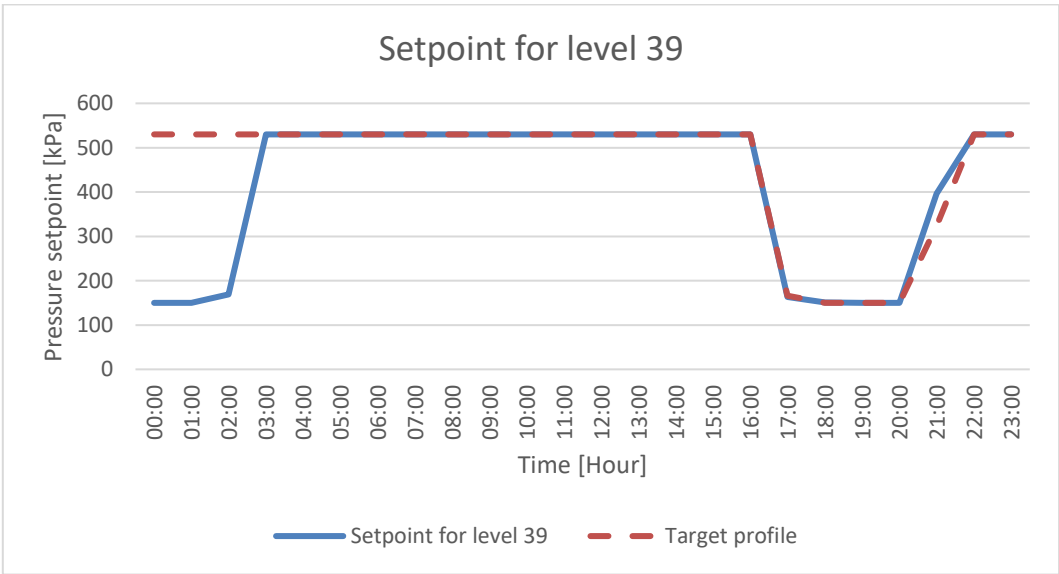


Figure 45: Setpoint and target profile for level 39 (9 June 2020)

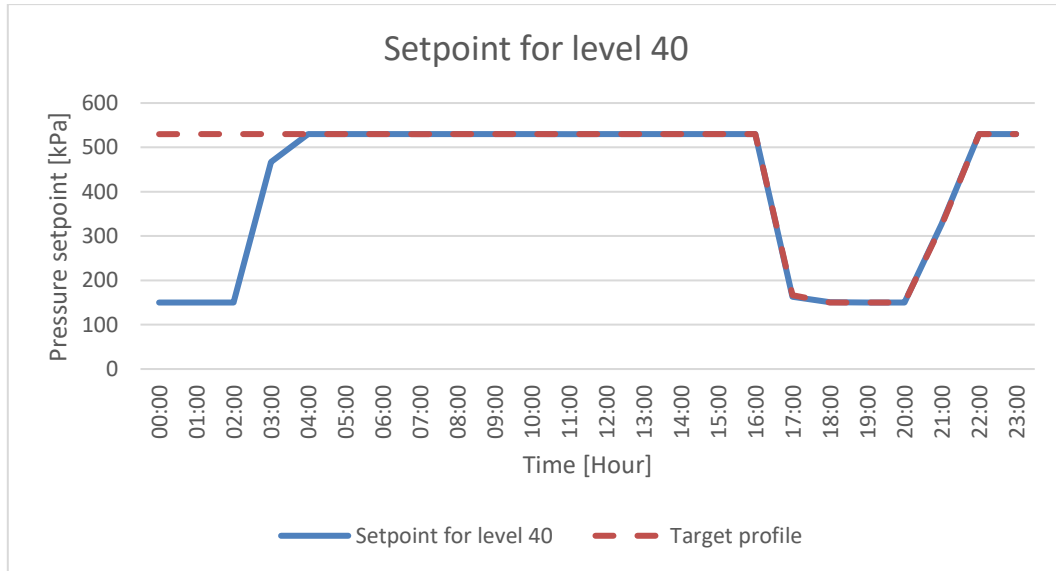


Figure 46: Setpoint and target profile for level 40 (9 June 2020)

Figure 45 and Figure 46 indicate that the identified cause of the missed energy savings opportunities has been rectified. The setpoints for levels 39 and 40 were updated during the day of 9 June 2020. The target profiles ensured that the setpoint was set according to the project requirements during the blasting period. The average deviation between the setpoint and the target profile during the blasting period was subsequently reduced to 0% for levels 39 and 40.

To ensure that the missed energy savings opportunities are reduced, the critical parameters that identified the missed energy savings opportunities are compared to the respective target profiles in Figure 47, Figure 48 and Figure 49 respectively below:

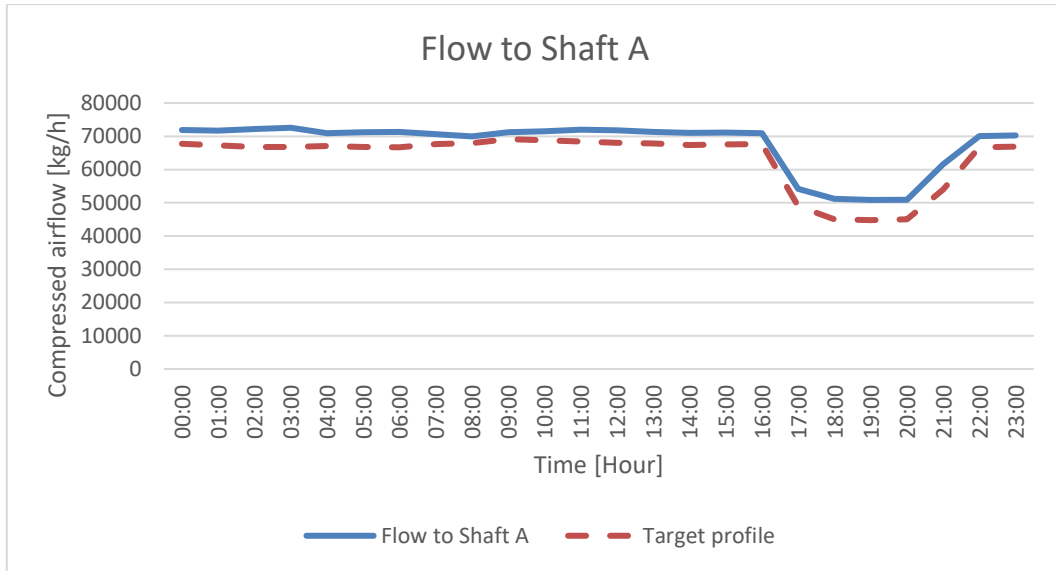


Figure 47: Flow and target profile to Shaft A (9 June 2020)

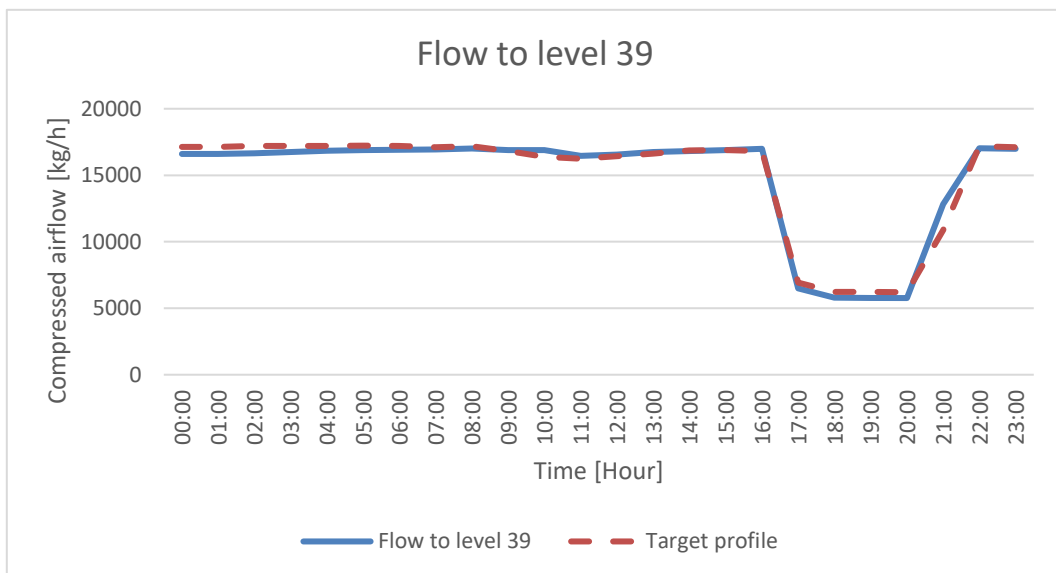


Figure 48: Flow and target profile to level 39 (9 June 2020)

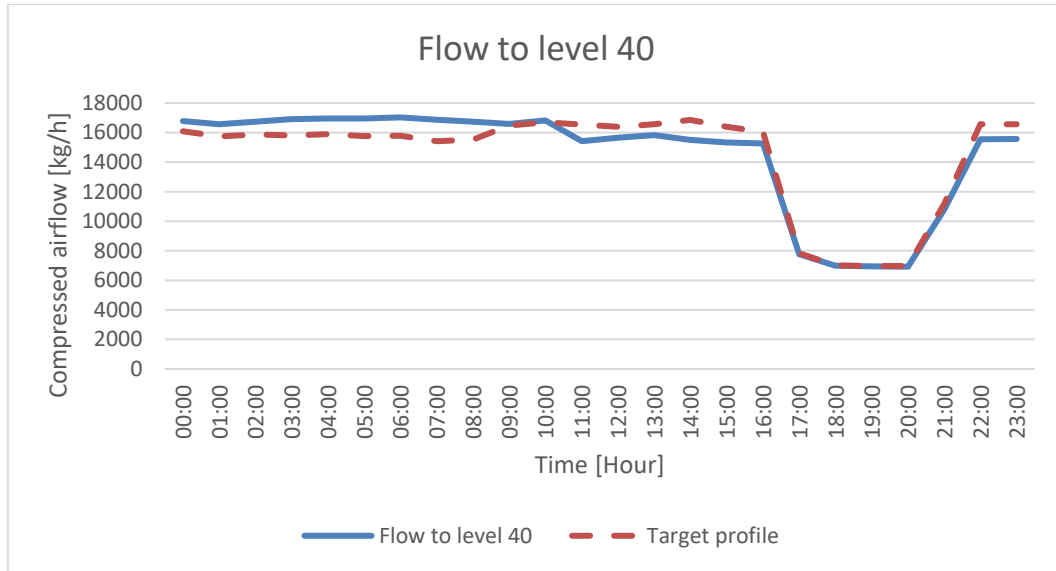


Figure 49: Flow and target profile to level 40 (9 June 2020)

Figure 47, Figure 48 and Figure 49 show that a flow reduction during the blasting period on levels 39 and 40 is according to the project requirements. The method managed to reduce the deviation between the flow to Shaft A and the target profile during the blasting period from 53% to 13%. This reduction ensured that the identified cause of the missed energy savings was rectified and the missed energy savings opportunities reduced.

The compressor power was obtained for Shaft A for the day on which the target profiles were created, the incident, and after the solution had been implemented, as shown in Figure 50 below.

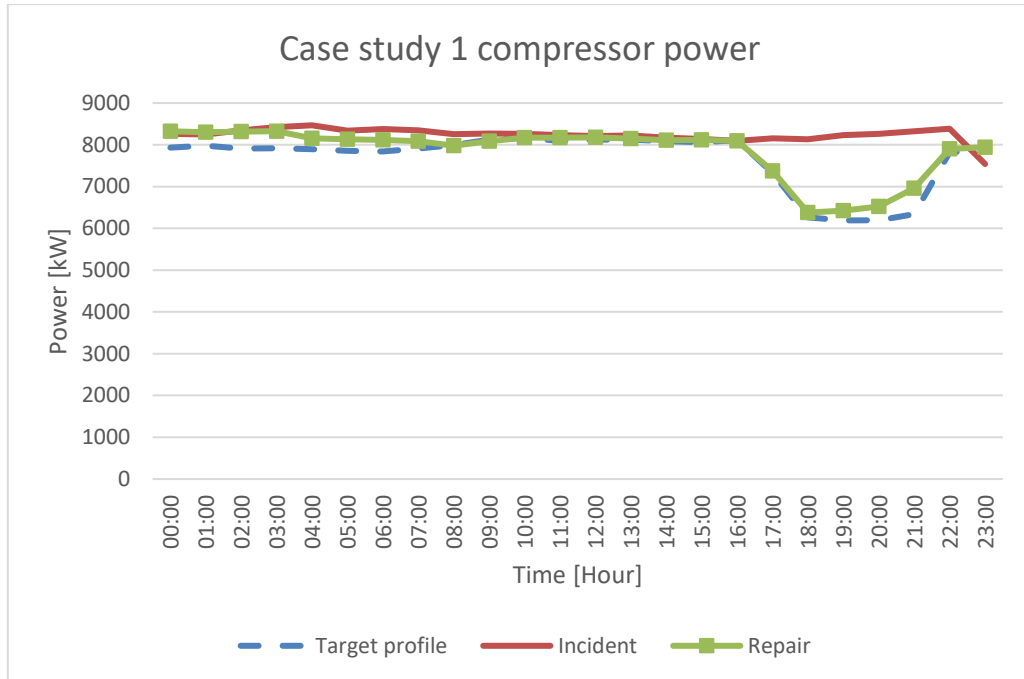


Figure 50: Case study 1 compressor power

From Figure 50 above, it is clear that the compressor power deviated significantly from the target profile from 17:00 until 20:00. The method managed to identify a missed energy savings opportunity in the form of a 53% deviation from the target profile during that period. The deviation caused the compressor power demand to be an average of 1 700 kW higher from 17:00 until 20:00 than the target profile. The missed energy savings opportunity was identified through the method as a setpoint schedule that was incorrectly changed by the control room, which reduced savings achieved during the blasting period.

After the cause was identified, the solution was determined, namely that the setpoint should be changed back to the prescribed schedule. After the solution was implemented, the average compressor power was 179 kW higher from 17:00 until 20:00 than the target profile. This indicates that an average power demand reduction of 1 521 kW was attained from 17:00 until 20:00 by using the method. The compressor power deviation from the target profile for the day of the incident and the day the solution was implemented is shown in Table 13 below.

Table 13: Case study 1 compressor power deviation comparison

Description	Deviation on incident (8 June 2020)	Deviation on repair (9 June 2020)
Total	7%	2%
During control period	21%	3%
Outside control period	4%	2%

A deviation in the compressor power target profile was reduced from 21% to 3% from 17:00 until 20:00, as shown in Table 13 above. The missed savings opportunity from 17:00 until 20:00 was an average power demand of 1 521 kW. The developed method assisted in identifying the missed energy savings opportunity and its cause, which led to a solution that could be implemented. The solution was deemed satisfactory and was validated, as it managed to increase the energy savings opportunity by 4 563 kWh per day by reducing the average compressor power demand by 1 521 kW for three hours. The missed energy savings cost was reduced by approximately R 3 million per year.

The results from the case study are used to determine if the study objectives were obtained. The objectives and a comment stating whether the objective was achieved and how are shown in Table 14.

Table 14: Case study 1 objectives

Objective	Comment
Develop a method to identify missed energy savings opportunities	Achieved satisfactory. The method identified missed energy savings opportunities by using the critical parameter of total flow to the shaft
Develop a method to identify the cause of missed energy savings opportunities	Achieved satisfactory. The method identified the cause of missed energy savings opportunities by using the critical parameter of level pressure setpoints

The identified causes of missed energy savings opportunities as identified in the literature review are shown in Table 15, together with the applicable one for this case study.

Table 15: Case study 1 validation

Case study	Interference with automatic control	High demand or unfavourable conditions	Infrastructure constraints or breakdowns	Control system problems
Case study 1	✓			

3.3 Case study 2: High demand or unfavourable conditions

3.3.1 Background

The developed method was implemented at another shaft at Mine A. The shaft will be referred to as Shaft B. Shaft B has three major underground mining levels, namely levels 41, 42 and 43. Level 42 is supplied with compressed air from level 43 at the station.

3.3.2 Step 1: Define project scope

The project is a level pressure control project. Levels 41 and 43 have automatic pressure control valves installed at the station. As stated in the background of this case study, level 42 is supplied with compressed air from level 43. The pipe supplying level 42 is after the control valve is installed on level 43. This means that the automatic pressure control valve controls the compressed air supplied to levels 42 and 43 as a whole with the control valve installed on level 43. The downstream pressure of the levels is controlled with a setpoint schedule from the SCADA system, similarly to case study 1. The pressure control aims to reduce the compressed air demand during the blasting period from 15:00 until 21:00. The only control that is present is in the blasting period, where the setpoint is set to 150 kPa. The setpoint schedules for levels 41 and 43 are shown in Table 16 and Table 17.

Table 16: Case study 2 level 41 setpoint schedule

Time	Shift	Pressure setpoint [kPa]
05:00 – 16:00	Drilling shift	500
16:00 – 21:00	Blasting shift	150
21:00 – 05:00	Cleaning shift	500

Table 17: Case study 2 level 43 setpoint schedule

Time	Shift	Pressure setpoint [kPa]
05:00 – 19:00	Drilling shift	500
19:00 – 22:00	Blasting shift	150
22:00 – 05:00	Cleaning shift	500

The control system is similar to the one in case study 1, where a setpoint value of 500 kPa will fully open the valve. The only control that is present is when the setpoint is set to 150 kPa.

3.3.3 Step 2: Identification of critical parameters

The critical parameters identified for case study 2 were done in the same manner as that of Case study 1. From the developed method, in Table 7, the following parameters were obtained for the level pressure control project.

An extract from Table 7 was taken that applies to a level pressure control initiative and is shown in Table 18. This was used to identify the critical parameters for Case study 1.

Table 18: Case study 1 critical parameters

Project description	Total flow	Level flow	Shaft pressure	Downstream pressure	Control valve position	Setpoint schedule
Level pressure control		✓		✓	✓	✓

From Table 18 the following critical parameters are identified:

1. Total compressed air flow to Shaft B,
2. compressed air flow to level 41,
3. compressed air flow to level 43,
4. downstream pressure of level 41
5. downstream pressure of level 43,
6. pressure setpoint of level 41, and
7. pressure setpoint of level 43.

3.3.4 Step 3: Developing target profiles for critical parameters

3.3.4.1 Creating target profiles

The target profiles for the critical parameters were developed from the data of a single day where the project engineer agreed that the project was achieving the desired savings. The automatic control on levels 41 and 43 was satisfactory, and the project requirement is that the pressure on these levels is reduced to 150 kPa during the respective periods stated in Table 16 and Table 17 above.

The target profiles for the relevant critical parameters are added to the report in Appendix B.

3.3.4.2 Analysis of parameters

The analysis of the critical parameters was performed. The information was obtained through the project scope as discussed in step 1. The data is shown in Table 19.

Table 19: Critical parameter analysis for Case study 2

Parameter	Above/below	Savings period
Parameter 1	Above	16:00 – 22:00
Parameter 2	Above	16:00 – 21:00
Parameter 3	Above	19:00 – 22:00
Parameter 4	Above	16:00 – 21:00
Parameter 5	Above	19:00 – 22:00
Parameter 6	Above	16:00 – 21:00
Parameter 7	Above	19:00 – 22:00

From Table 19 it is seen that the control period for parameter 1 was taken from 16:00 until 22:00. This was done because this period contains the control periods for both levels 41 and 43.

3.3.5 Step 4: Identifying missed energy savings opportunities by utilising target profiles for critical parameters

On 17 September 2020, the total compressed air flow to the shaft deviated from the target profile at 06:00 and 08:00 by 11%. This is shown in Figure 51 below, where the flow can be seen to increase from 06:00 by approximately 10 000 kg/h.

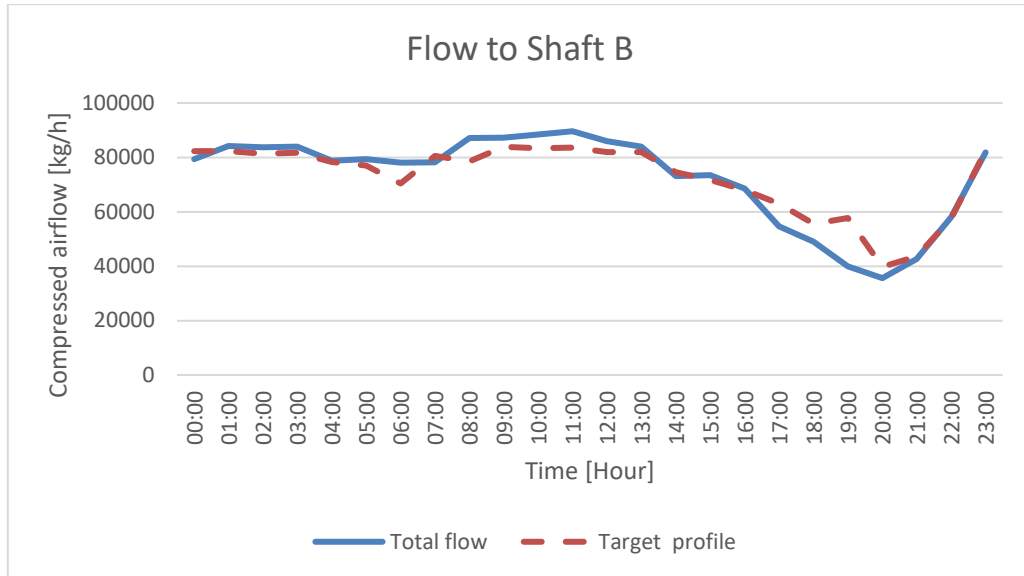


Figure 51: Flow and target profile to Shaft B (17 September 2020)

Figure 51 indicates missed energy savings opportunities as a result of the compressed air flow that exceeded the target profile by 11% at 06:00 and 08:00.

3.3.6 Step 5: Identifying the cause of missed energy savings opportunities by utilising target profiles for critical parameters

The cause of the missed energy savings opportunities must be determined to reduce them. The deviation of the airflow from the target profile was noted to be outside of the control period. This indicates that the cause of the missed energy savings opportunity is not a fault in the level valve control.

To determine the cause of the missed energy savings opportunity, the critical parameters were compared to the respective target profiles. The compressed air flow to level 41 and the target profile are shown in Figure 52 below.

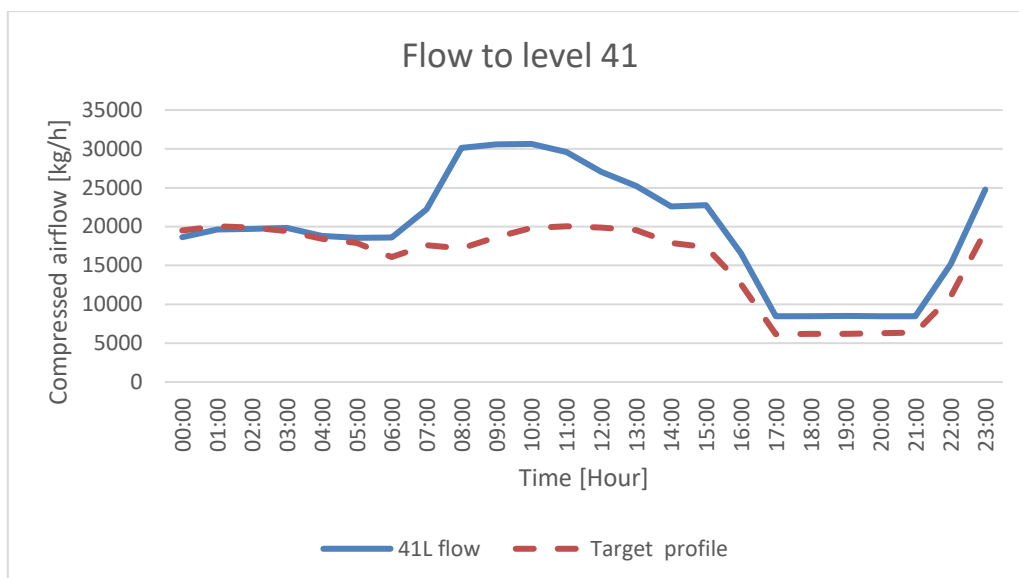


Figure 52: Flow and target profile to level 41 (17 September 2020)

The flow to level 41 is seen to exceed the target profile from approximately 06:00 on 17 September 2020 in Figure 52 above. The percentage deviation is shown in Table 20 below.

Table 20: Flow to level 41 deviation percentages

Description	Period	Positive deviation from the target profile
Total	00:00 – 23:00	33%
During control period	16:00 – 21:00	35%
Outside control period	00:00 – 16:00, 21:00 – 23:00	32%

The flow exceeded the target profile by an average of 33% on 17 September 2020. It is noted from Table 20 that the deviation is present during periods where control is expected and also not expected.

To determine whether either ineffective or incorrect valve control has caused the flow to deviate from the target profile, the downstream pressure and setpoint for level 41 on 17 September 2020 are compared in Figure 53 below:

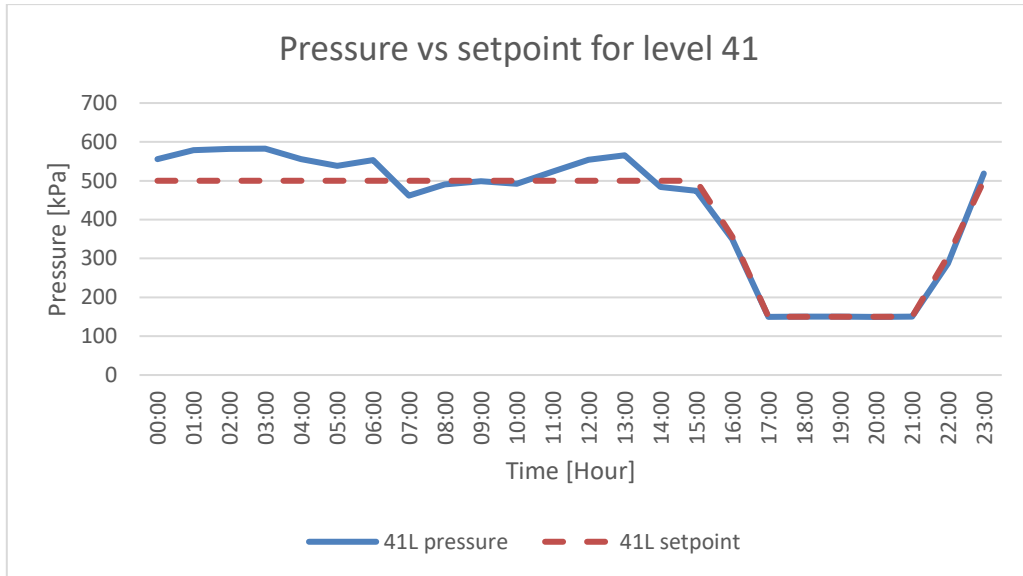


Figure 53: Pressure and setpoint for level 41 (17 September 2020)

From Figure 53 it is determined that the cause of the missed energy savings opportunity is not ineffective valve control, as the setpoint value is 500 kPa at 06:00 as it should be. This means that the control valve is 100% open. No deviation is noted from 16:00 until 21:00 when control is present, as seen in Figure 53 above. The lack of deviation between the setpoint schedule and the pressure indicates that the pressure control was effective on 17 September 2020.

To determine whether the setpoint meets the project requirements, the setpoint is compared to the target profile in Figure 54 below:

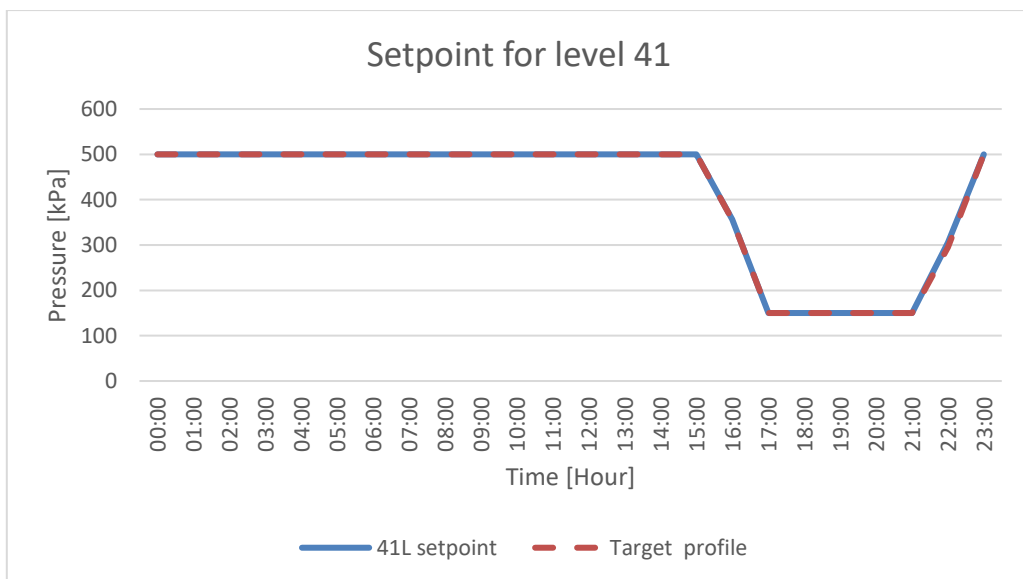


Figure 54: Setpoint and target profile for level 41 (17 September 2020)

There is no deviation between the setpoint schedule for 17 September 2020 and the target profile, as seen in Figure 54. From Figure 53 and Figure 54 is determined that the cause of the missed energy savings opportunity is not ineffective and incorrect valve control.

The cause of the missed energy savings opportunity was identified as an increased compressed air demand on level 41 by using the critical parameters and target profiles shown in Figure 52 and Table 20 above. The mine personnel were informed of the increased compressed air demand on level 41 and they conducted audits on level 41 to determine the cause of the increased demand. The audits were aimed specifically at identifying compressed air leaks and wastage on level 41 because this was the cause identified using the developed method.

During the audits, a valve was identified to be fully open where it was supposed to have been partially open. The valve controls the compressed air flow that is supplied to a section on level 41 where low compressed air pressure is required to supply the refuge bays with sufficient air. The valve was – incorrectly – fully opened, thus increasing the compressed air demand of level 41 unnecessarily. The cause of the missed energy savings opportunity was identified as an unnecessary high demand created by incorrectly opening a manual valve supplying a low-pressure section on level 41.

3.3.7 Step 6: Ensuring that missed energy savings opportunities are reduced

The mine personnel throttled the abovementioned valve to supply only the required compressed air to the low-pressure section on level 41 on Saturday, 19 September 2020. The critical parameter that identified the cause of the missed energy savings opportunity was the compressed air flow to level 41. This critical parameter was compared to the target profile for 19 September 2020 in Figure 55 below to ensure that the cause was identified correctly.

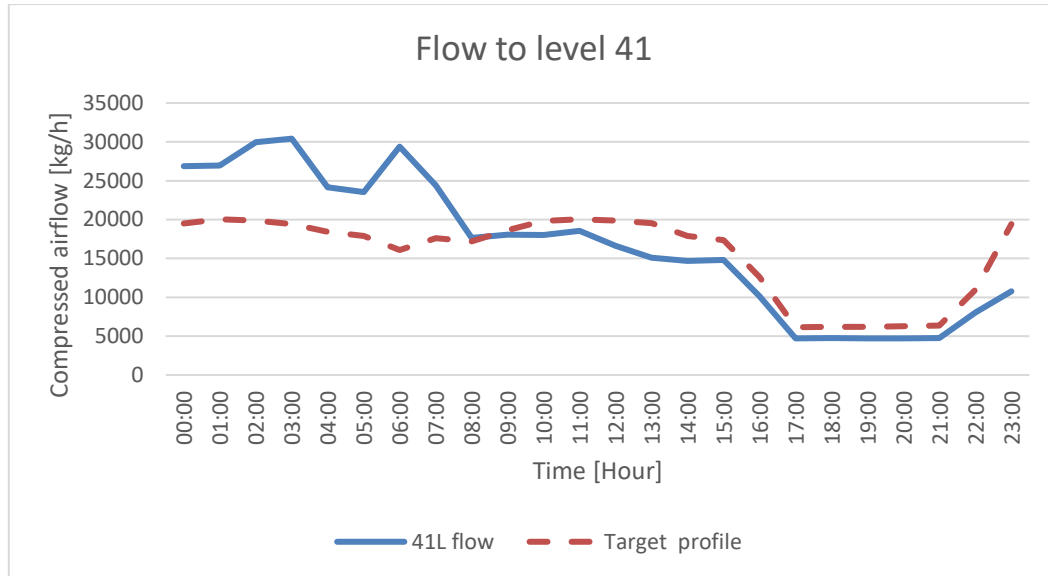


Figure 55: Flow and target profile to level 41 (19 September 2020)

The valve was throttled on Saturday, 19 September 2020, at approximately 08:00, as seen in Figure 55 above. The average positive deviation between the flow and the target profile from 00:00 until 08:00 on 19 September 2020 is 45%. From 08:00 onwards, the flow does not exceed the target profile. It is verified that reducing the valve opening on level 41 effectively reduced the positive deviation between the flow and target profile on 19 September 2020.

To verify that the cause of the missed energy savings opportunity was effectively rectified, the flow for level 41 was compared to the target profile for the first weekday, which was Monday, 21 September 2020. The flow and target profile for level 41 for Monday, 21 September 2020, is shown in Figure 56 below.

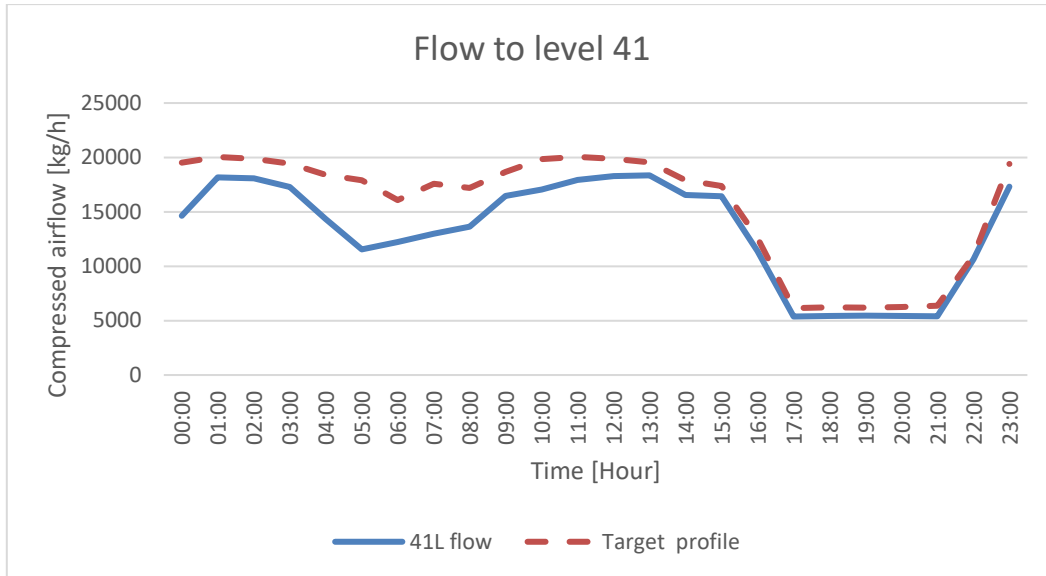


Figure 56: Flow and target profile to level 41 (21 September 2020)

From Figure 56 it is noted that the flow for level 41 no longer exceeds the target profile. To verify that the cause was correctly identified and rectified, the critical parameter that identified the missed energy savings opportunity is compared to the target profile. The compressed air flow of Shaft B is compared to the target profile for 21 September 2020 in Figure 57 below.

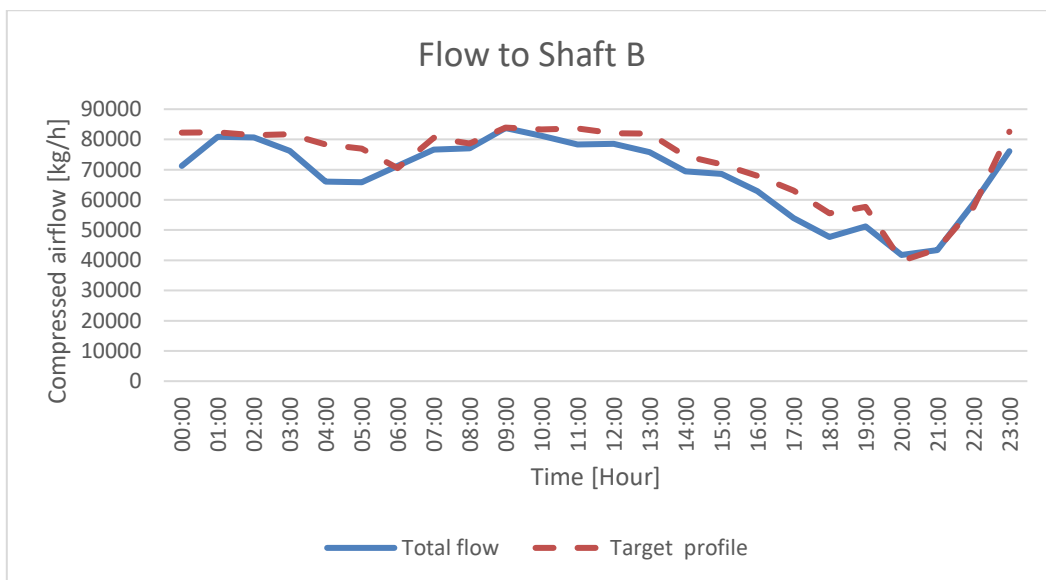


Figure 57: Flow and target profile to Shaft B (21 September 2020)

In Figure 57 is seen that the flow for Shaft B no longer exceeds the target profile. This indicates that the missed energy savings opportunity is reduced.

As mentioned in this case study, Shaft B is part of a ring-feed compressed air network. The compressor power may be affected by two other shafts on Mine A. The specific power of the compressors was obtained to calculate the compressor power for level 41 accurately. The calculated compressor power was obtained for level 41 for the day on which the target profiles were created, the incident, and after the solution had been implemented, as shown in Figure 58 below.

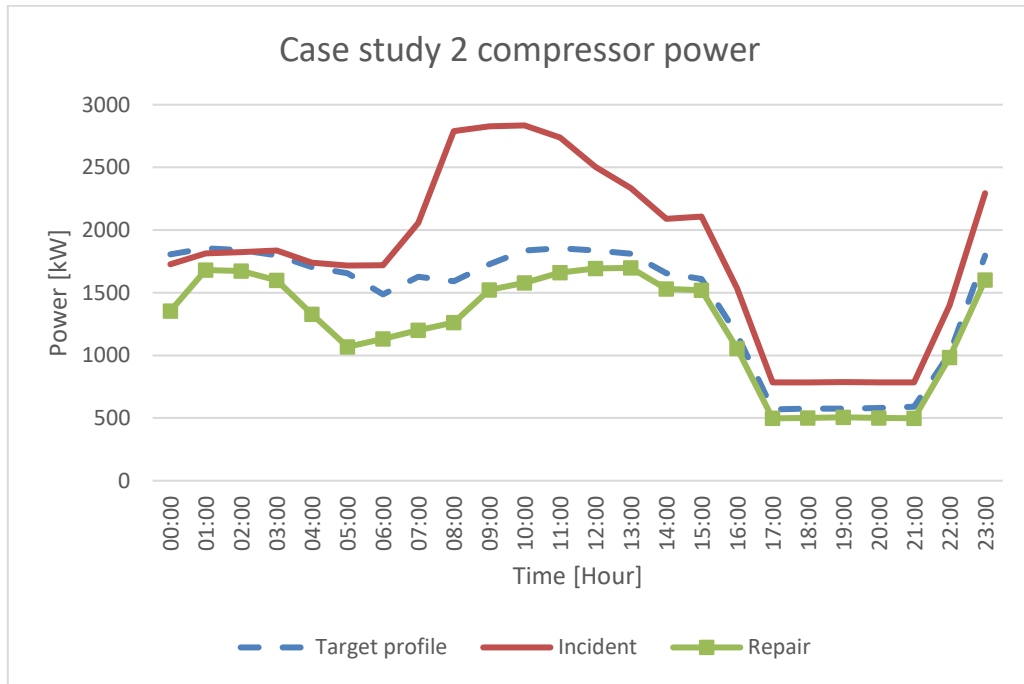


Figure 58: Case study 2 compressor power

From Figure 58 above, it is clear that the compressor power deviated significantly from the target profile on 17 September 2020, from 06:00 until 23:00. The developed method managed to identify a missed energy savings opportunity in the form of an initial 13% deviation from the target profile during that period. The deviation caused the calculated compressor power for level 41 to be an average of 514 kW higher from 06:00 until 23:00 than the target profile. The missed energy savings opportunity was identified by using the developed method. The valve opening on level 41 was increased, which reduced the energy savings achieved throughout a working day.

After the cause was identified, the solution was determined, namely that the valve opening on level 41 was reduced to supply low pressure to the designated area. After the solution was implemented, the compressor power was an average of 164 kW less from 06:00 until 23:00 than the target profile. This indicates that the flow of level 41 has reverted to the specified amount as per the target profile. The average of 514 kW of power reduction was attained from 06:00 until 23:00 by using the developed method. The calculated compressor power deviation from the target

profile for the day of the incident and the day the solution was implemented is shown in Table 21 below.

Table 21: Case study 2 compressor power deviation comparison

Description	Deviation on incident (17 September 2020)	Deviation on repair (21 September 2020)
Total	21%	-17%
06:00 – 23:00	27%	-15%
00:00 – 06:00	3%	-25%

A deviation in the calculated compressor power for level 41 target profile was reduced from 21% to 15% below the target profile from 06:00 until 23:00, as shown in Table 21 above. The missed savings opportunity from 06:00 until 23:00 was an average power demand of 514 kW. The developed method assisted in identifying the missed energy savings opportunity and the cause, which led to a solution that could be implemented. The solution was deemed satisfactory and was validated, as it managed to increase the energy savings opportunity by 9 252 kWh per day by reducing the power by an average of 514 kW for eighteen hours. The missed energy savings cost was reduced by approximately R 5.5 million per year by using the developed method.

The results from the case study are used to determine if the study objectives were obtained. The objectives and a comment stating whether the objective was achieved and how are shown in Table 22.

Table 22: Case study 2 objectives

Objective	Comment
Develop a method to identify missed energy savings opportunities	Achieved satisfactory. The method identified missed energy savings opportunities by using the critical parameter of total flow to the shaft
Develop a method to identify the cause of missed energy savings opportunities	Achieved satisfactory. The method identified the cause of missed energy savings opportunities by using the critical parameter of level flow.

The identified causes of missed energy savings opportunities as identified in the literature review are shown in Table 23, together with the applicable one for this case study.

Table 23: Case study 2 validation

Case study	Interference with automatic control	High demand or unfavourable conditions	Infrastructure constraints or breakdowns	Control system problems
Case study 1	✓			
Case study 2		✓		

3.4 Case study 3: Infrastructure constraints or breakdowns

3.4.1 Background

Case study 3 involves a compressed air demand reduction project implemented on a mine shaft that is part of a compressed air ring. The shaft is part of Mine A and will be referred to as Shaft C. There is a control valve situated on the surface in the main compressed air column that supplies the shaft with compressed air.

3.4.2 Step 1: Define project scope

The project entails a control room operator reducing the surface valve position remotely to reduce the compressed air supplied to the shaft during the blasting period. The blasting period for this shaft is generally from 19:00 until 22:00. The valve position is controlled remotely but not automatically. The project relied on manual input for the valve position, in percentage, on the SCADA system. The only control that is present is in the blasting period, where the valve position is set to 6%. The valve position schedule for Shaft C is shown in Table 24 below:

Table 24: Case study 3 surface valve position schedule

Time	Shift	Valve position [%]
05:00 – 19:00	Drilling shift	100
19:00 – 22:00	Blasting shift	6
22:00 – 05:00	Cleaning shift	100

3.4.3 Step 2: Identification of critical parameters

An extract from Table 7 was taken that applies to a surface pressure control initiative and is shown in Table 25.

Table 25: Surface pressure control critical parameters

Project description	Total flow	Level flow	Shaft pressure	Downstream pressure	Control valve position	Setpoint schedule
Surface pressure control	✓		✓	✓		✓

The developed method states that for a surface pressure control project, the pressure setpoint must be taken as a critical parameter. The valve in this case study is not controlled with a pressure setpoint so it is not available. The control is determined by a control room operator adjusting the valve percentage when he has confirmed that the workers have cleared. The position of the valve is a method to determine what schedule was followed. For this reason, the valve position was taken as a critical parameter instead of the pressure setpoint.

The following parameters were obtained for the surface pressure control project:

1. Total compressed air flow to Shaft C,
2. shaft pressure,
3. downstream pressure of the surface control valve, and
4. valve position of the surface control valve.

3.4.4 Step 3: Developing target profiles for critical parameters

3.4.4.1 Creating target profiles

It was determined that the valve schedule was not constant, as loading boxes rely on high pressure to function. If the mine employees were working later than usual, the pressure could not be reduced. The time varies when the control is implemented, so the target profiles are created to ensure that the control room operators do not forget to reduce the valve position even if the time varies.

The target profiles were created from the raw critical parameter data obtained from a single day where the downstream pressure was 200 kPa during the blasting period, which was the requirement for the project according to the project engineer that implemented the project.

The target profiles for the relevant critical parameters are added to the report in Appendix B.

3.4.4.2 Analysis of parameters

The analysis of the critical parameters was performed. The information was obtained through the project scope as discussed in step 1. The data is shown in Table 26.

Table 26: Critical parameter analysis for Case study 3

Parameter	Above/below	Savings period
Parameter 1	Above	19:00 – 22:00
Parameter 2	Above	19:00 – 22:00
Parameter 3	Above	19:00 – 22:00
Parameter 4	Above	19:00 – 22:00

It is determined from Table 26 that all the critical parameters will indicate missed energy-saving opportunities when it exceeds the target profile.

3.4.5 Step 4: Identifying missed energy savings opportunities by utilising target profiles for critical parameters

On 13 April 2021, the compressed air entering the shaft deviated from the target profile during the blasting period, as shown in Figure 59 below.

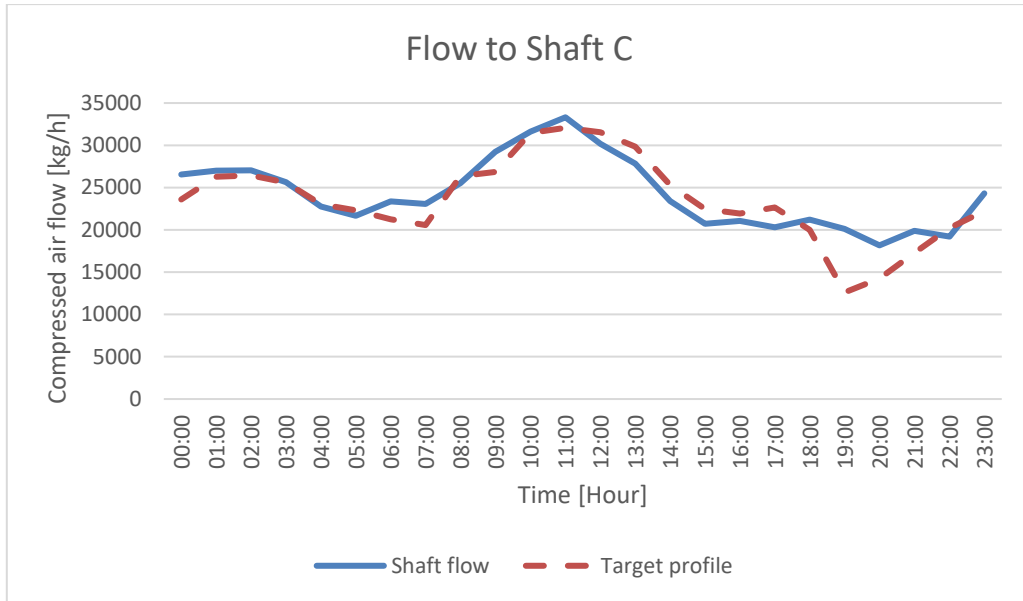


Figure 59: Flow and target profile to Shaft C (13 April 2021)

The flow exceeded the target profile by 60% at 19:00 on 13 April 2021. The flow is seen to exceed the target profile during the blasting period where control is expected, as seen in Figure 59. The flow exceeded the target period from 18:00 until 21:00 with an average of 34%.

A missed energy-saving opportunity was identified with the compressed air flow exceeding the target profile during a period where valve control is expected according to the project scope.

3.4.6 Step 5: Identifying the cause of missed energy savings opportunities by utilising target profiles for critical parameters

As the project requirement was to reduce the downstream pressure to 200 kPa during the blasting period, the downstream pressure was compared to the target profile, as illustrated in Figure 60 below.

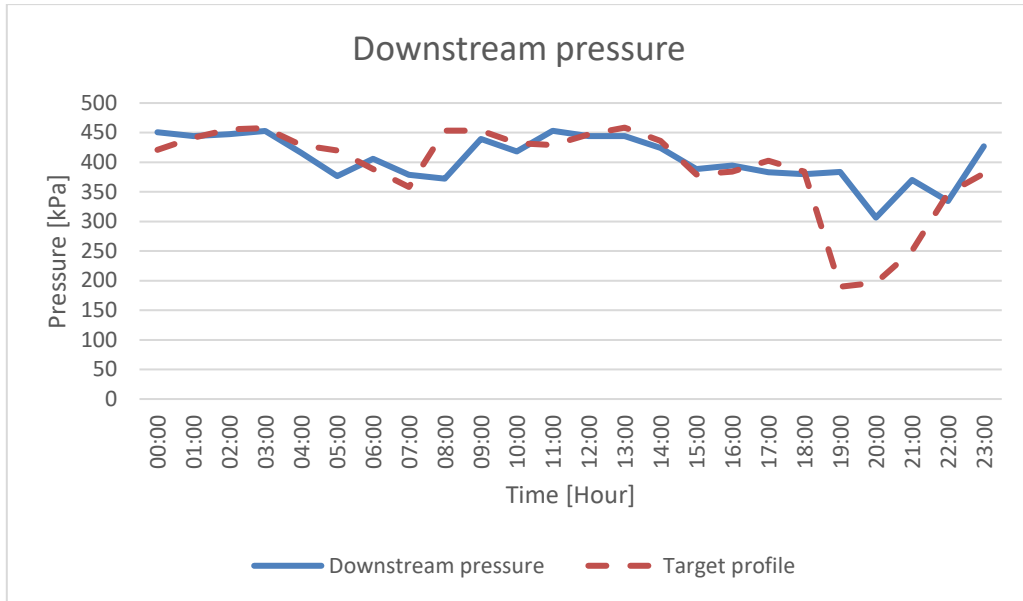


Figure 60: Downstream pressure and target profile for the surface control valve (13 April 2021)

Figure 60 shows that the downstream pressure also exceeded the target profile during the blasting period, as with the flow to the shaft discussed in step 4. The pressure exceeded the target profile from 19:00 until 21:00 by an average of 69%. As discussed above, the project relied on control room operators manually inputting a valve position value into the SCADA according to the schedule shown in Table 24 a schedule. The valve position was compared to the target profile to determine whether the prescribed schedule was followed, as seen in Figure 61 below.

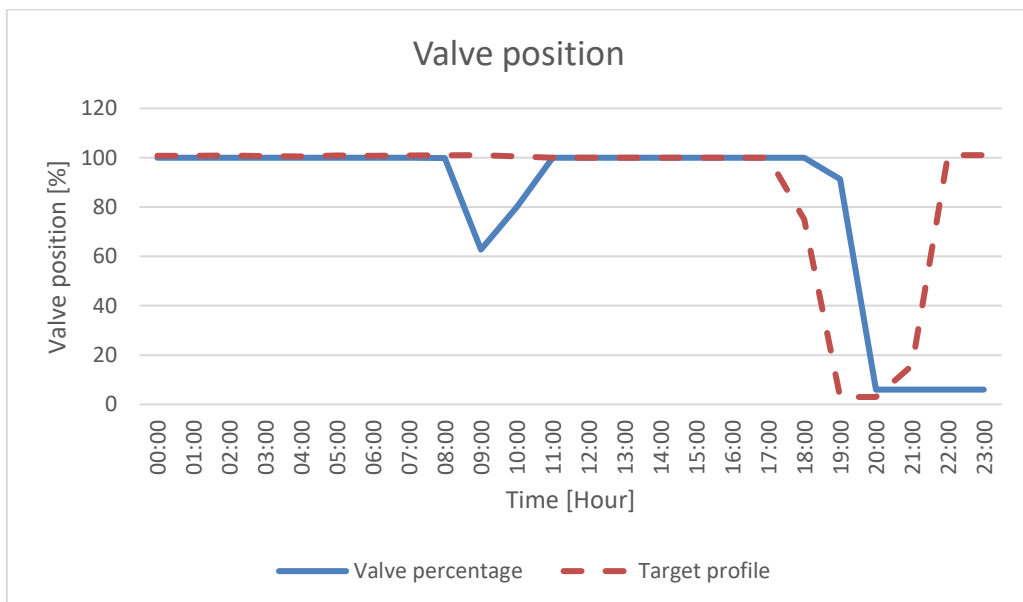


Figure 61: Valve position and target profile for the surface control valve (13 April 2021)

From Figure 61 above it is noted that the valve position reduced from 08:00 on 13 April to approximately 62%, and then returned to 100% at 11:00. The control philosophy stipulated in Table 24 shows that the valve percentage should remain 100% from 00:00 until 19:00. It was determined that the control room could not recall changing the position of the valve at 08:00. The cause of the reduction in valve position could not be identified by communicating with the control room operators.

From analysing Figure 61, it is clear that the valve position was set to 6% at 20:00. The valve position was reduced later than the prescribed schedule of 19:00, but hoisting also commenced later on 13 April 2021. These adjustments were still according to the project requirements because it was agreed beforehand that the valve position might be reduced later on certain days. From Figure 60 and Figure 61 it is concluded that the valve position was reduced correctly from 20:00; however, the downstream pressure did not reduce as expected from 20:00.

The cause of the missed energy savings opportunity was identified as the control valve not reducing the downstream pressure as expected when reducing the valve position to 6%. The target profiles for the downstream pressure and valve position indicate that the downstream pressure was 200 kPa with a valve position input of 6%, whereas on 13 April 2021, the downstream pressure is not affected by the valve position input.

The identified cause of the missed energy savings opportunity was communicated to the mine technician, who investigated the physical valve and actuator setup.

The investigation determined that the valve was physically moving by changing the valve percentage on the SCADA and monitoring the physical valve positioner. A test was conducted where the valve was set to 0% from the SCADA to confirm that the percentage that was inserted into the SCADA was correlating to the valve's actual percentage. The test concluded that with a valve percentage of 0%, there was still ample compressed air flowing past the valve.

The technician concluded that the valve needed to be stroked to ensure that the physical valve was at the position input obtained from the SCADA.

3.4.7 Step 6: Ensuring that missed energy savings opportunities are reduced

The valve was stroked on 23 April 2021 as initiated by the technician. The valve position was compared to the respective target profile in Figure 62 below as it was the critical parameter that identified the cause of the missed energy savings opportunity.

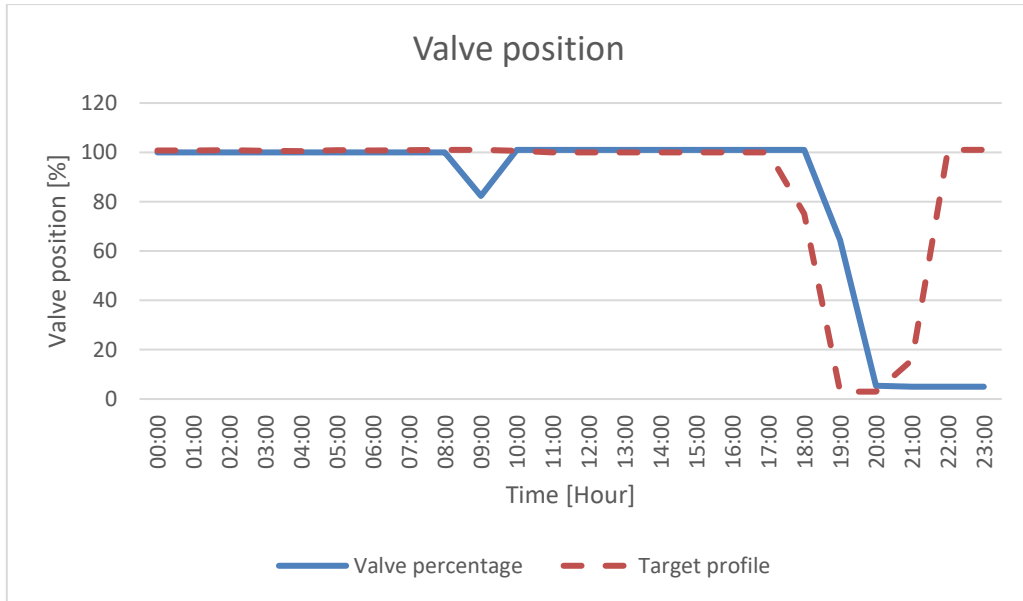


Figure 62: Valve position and target profile for the surface control valve (23 April 2021)

The valve was stroked at approximately 08:00 on 23 April 2021 by the technician. The technician conducted tests to ensure the valve input is accurately implemented by the actuator. From Figure 62 above it can be seen that the valve position was adjusted at approximately 08:00. After the tests were conducted and the technician was satisfied, the valve returned to 100% open from 10:00.

The valve position was reduced adequately during the blasting period by the control room operators on 23 April 2021, as seen in Figure 62 above. It is noted that the valve position did not return to 100% after the blasting period in Figure 62 and was determined to have been on a Friday when the night shift crew did not plan work that required high compressed air pressure. The valve was thus kept throttled for the night shift. The downstream pressure was then compared to the target profile to determine whether the valve position affected the downstream pressure as expected, as seen in Figure 63 below.

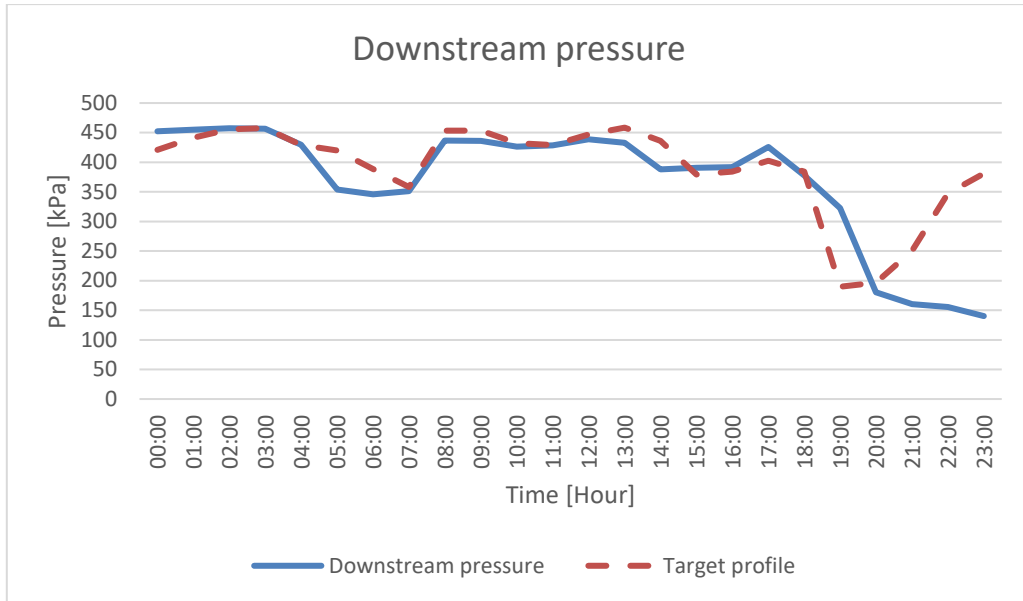


Figure 63: Downstream pressure and target profile for the surface control valve (23 April 2021)

Figure 63 illustrates that reducing the valve position did affect the downstream pressure. The valve position was reduced from 20:00, which is later than the prescribed time of 19:00. As mentioned above, this is still according to the project requirements because workers hoisted later during their shift and required high compressed air pressure.

After the valve position was reduced at 20:00, as seen in Figure 62, the downstream pressure reduced as expected, as shown in Figure 63. The downstream pressure did not exceed the target profile after 20:00 when the valve position was reduced.

To ensure that the missed energy saving opportunity was reduced, the critical parameter that identified the missed energy savings opportunity was compared to the target profile in Figure 64 below.

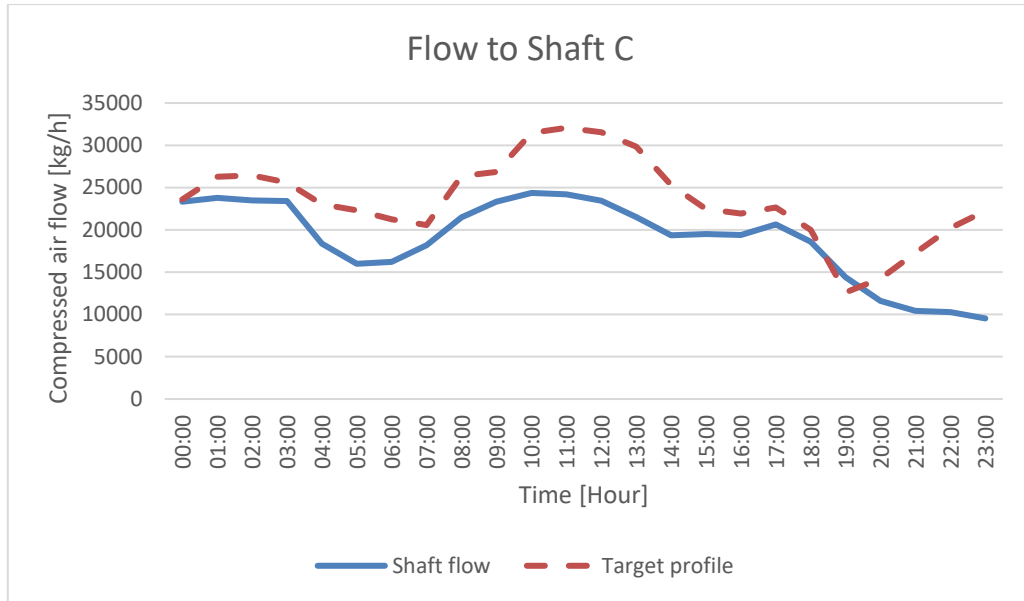


Figure 64: Flow and target profile to Shaft C (23 April 2021)

Figure 64 shows that the compressed air flow for the shaft did not exceed the target profile during the blasting period, from which it is concluded that the missed energy savings opportunity is reduced.

As mentioned in this case study, Shaft C is part of a ring-feed compressed air network. The compressor power may be affected by two other shafts on Mine A. The specific power of the compressors was obtained to calculate the compressor power for Shaft C accurately. The calculated compressor power was obtained for Shaft C for the day on which the target profiles were created, the incident, and after the solution had been implemented, as shown in Figure 65 below.

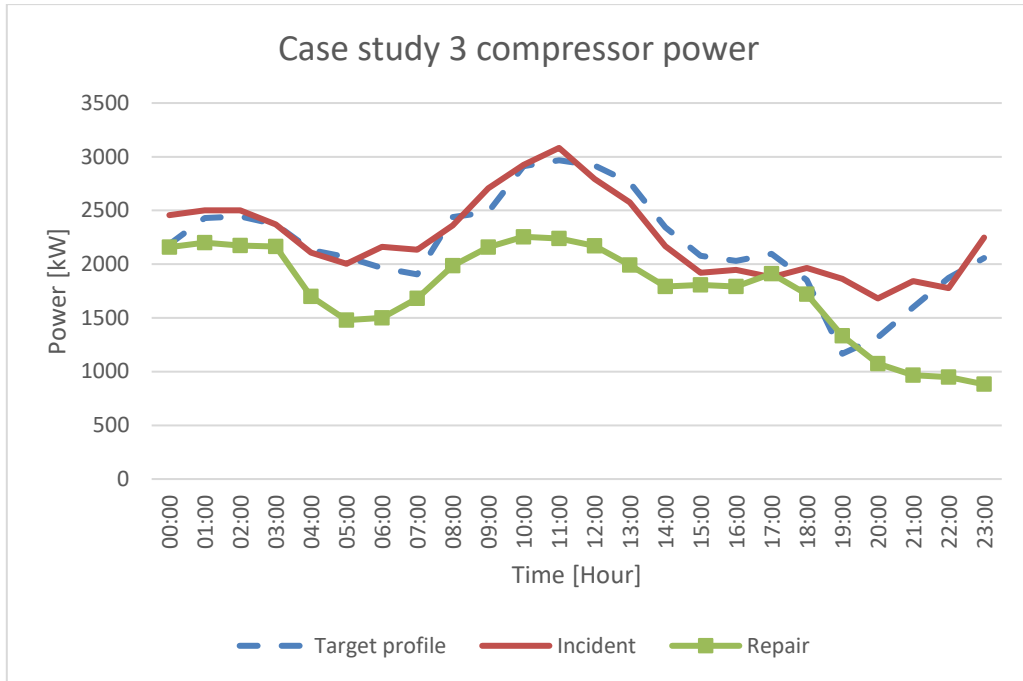


Figure 65: Case study 3 compressor power

From Figure 65 above, it is clear that the compressor power deviated significantly from the target profile from 19:00 until 22:00. The developed method managed to identify a missed energy savings opportunity in the form of a 19% deviation of the flow to shaft C from the target profile during the control period. The deviation caused the calculated compressor power for Shaft C to be an average of 302 kW higher from 19:00 until 22:00 than the target profile. The missed energy savings opportunity was identified by applying the developed method as the control valve that was not achieving the input position, which reduced the savings achieved from 19:00 until 22:00.

After the cause was identified, the solution was determined, namely that the valve had to be stroked. After the solution was implemented, the average compressor power was 408 kW less from 19:00 until 22:00 than the target profile. The average power demand reduction of 302 kW was attained from 19:00 until 22:00 by using the developed method. The calculated compressor power deviation from the target profile for the day of the incident and the day the solution was implemented is shown in Table 27 below.

Table 27: Case study 3 compressor power deviation comparison

Description	Deviation on incident (13 April 2021)	Deviation on repair (23 April 2021)
Total	8%	-30%
During control period	19%	-49%
Outside control period	6%	-26%

A deviation in the calculated compressor power for Shaft C's target profile was reduced from 19% above the target profile to 49% below the target profile from 19:00 until 22:00, as shown in Table 27 above. The missed energy savings opportunity from 19:00 until 22:00 was 906 kWh per day. The developed method assisted in identifying the missed energy savings opportunity and the cause, which led to a solution that could be implemented. The solution was deemed satisfactory and was validated, as it managed to increase the energy savings opportunity by 906 kWh per day by reducing the average compressor power by 302 kW for three hours. The missed energy savings cost was reduced by approximately R 1 million per year.

The results from the case study are used to determine if the study objectives were obtained. The objectives and a comment stating whether the objective was achieved and how are shown in Table 28.

Table 28: Case study 3 objectives

Objective	Comment
Develop a method to identify missed energy savings opportunities	Achieved satisfactory. The method identified missed energy savings opportunities by using the critical parameter of total flow to the shaft
Develop a method to identify the cause of missed energy savings opportunities	Achieved satisfactory. The method identified the cause of missed energy savings opportunities by using the critical parameters of the valve position and valve downstream pressure

The identified causes of missed energy savings opportunities as identified in the literature review are shown in Table 29, together with the applicable one for this case study.

Table 29: Case study 3 validation

Case study	Interference with automatic control	High demand or unfavourable conditions	Infrastructure constraints or breakdowns	Control system problems
Case study 1	✓			
Case study 2		✓		
Case study 3			✓	

3.5 Case study 4: Control system problems

3.5.1 Background

This Case study entails the same mine shaft as Case study 2, namely Shaft B. At the time of these results, level 41 was closed and level 42 had a dedicated pipe to supply compressed air. There was at this time no reliable data for the flow or pressure for level 42 because the measuring equipment had not yet been verified. Levels 41 and 42 are thus excluded from these results. The project applicable in this Case study is the automatic compressed air pressure control on level 43.

3.5.2 Step 1: Define project scope

The project scope is the same as that of Case study 2 for level 43. The project relies on automatic pressure control that aims to reduce the pressure supplied to level 43 during the blasting period. The pressure setpoint schedule for level 43 is shown in Table 17 above.

3.5.3 Step 2: Identification of critical parameters

An extract from Table 7 was taken that applies to a level pressure control initiative and is shown in Table 30. This was used to identify the critical parameters for Case study 4.

Table 30: Case study 4 critical parameters

Project description	Total flow	Level flow	Shaft pressure	Downstream pressure	Control valve position	Setpoint schedule
Level pressure control		✓		✓	✓	✓

From Table 30 the following critical parameters are identified:

1. Total compressed air flow to Shaft B,
2. Compressed air flow to level 43,

3. Downstream pressure of level 43,
4. Pressure setpoint of level 43.

3.5.4 Step 3: Developing target profiles for critical parameters

3.5.4.1 Creating target profiles

The target profiles for the critical parameters were developed from the data of a single day where the project engineer agreed that the project was achieving the desired savings. The automatic control on level 43 was satisfactory, and the project requirements were that the pressure on these levels is reduced to 150 kPa from 19:00 until 21:00.

The target profiles for the relevant critical parameters are added to the report in Appendix B.

3.5.5 Step 4: Identifying missed energy savings opportunities by utilising target profiles for critical parameters

On 22 September 2021, the total compressed air flow to Shaft B deviated from the target profile from 18:00 until 22:00, as shown in Figure 66 below.

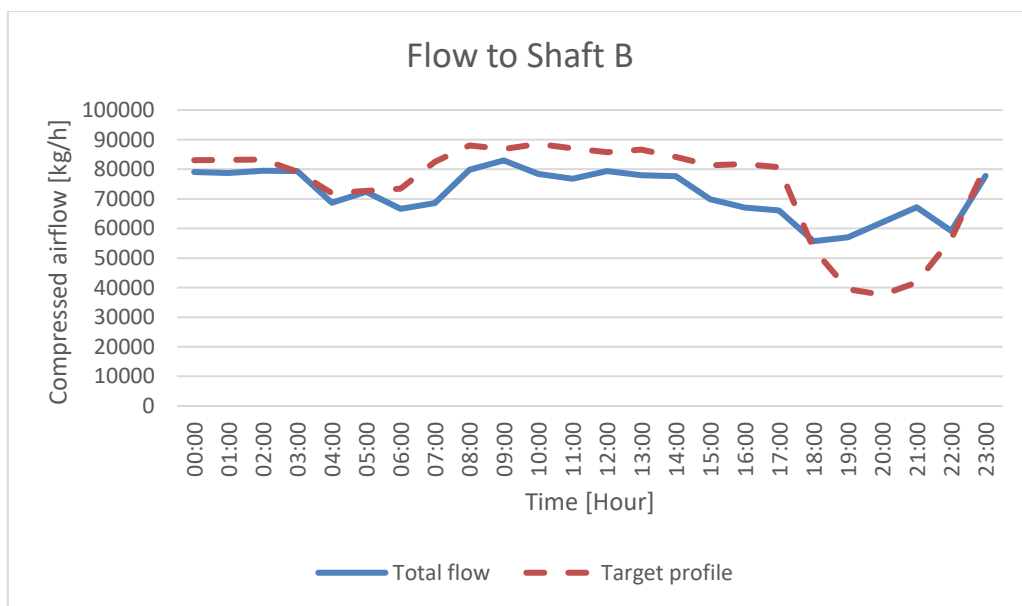


Figure 66: Flow and target profile to Shaft B (22 September 2021)

The compressed air flow for Shaft B exceeded the target profile from 18:00 until 22:00 by an average of 36%, as shown in Figure 66 above. From Figure 66 it is determined that there are missed energy savings opportunities because the compressed air flow has exceeded the target profile during the period where underground valve control is expected.

3.5.6 Step 5: Identifying the cause of missed energy savings opportunities by utilising target profiles for critical parameters

The cause of the missed energy savings opportunities must be determined if they are to be reduced. The compressed air flow of level 43 was compared to the target profile in Figure 67 below.

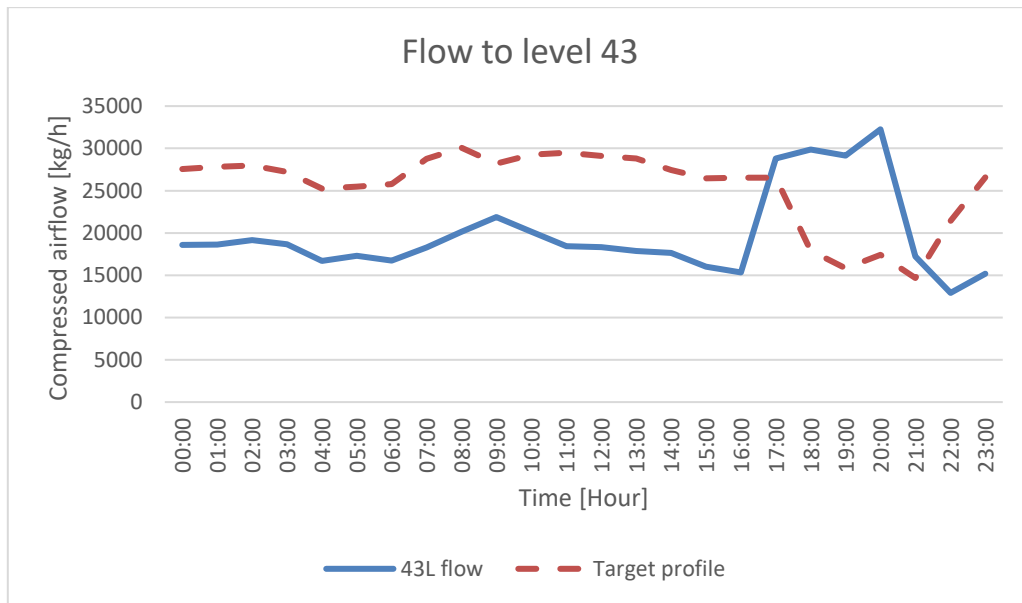


Figure 67: Flow and target profile to level 43 (22 September 2021)

From Figure 67 a constant deviation is noted between the flow for level 43 and the target profile. It is important to note that the flow for level 43 only exceeds the target profile between 18:00 and 21:00 where pressure control is expected to reduce the flow. The flow for level 43 exceeds the target profile from 18:00 until 21:00 by an average of 43%.

To determine whether the cause of the flow deviating from the target profile is either ineffective or incorrect valve control, the downstream pressure and setpoint for level 43 on 22 September 2021 are compared in Figure 68 below:

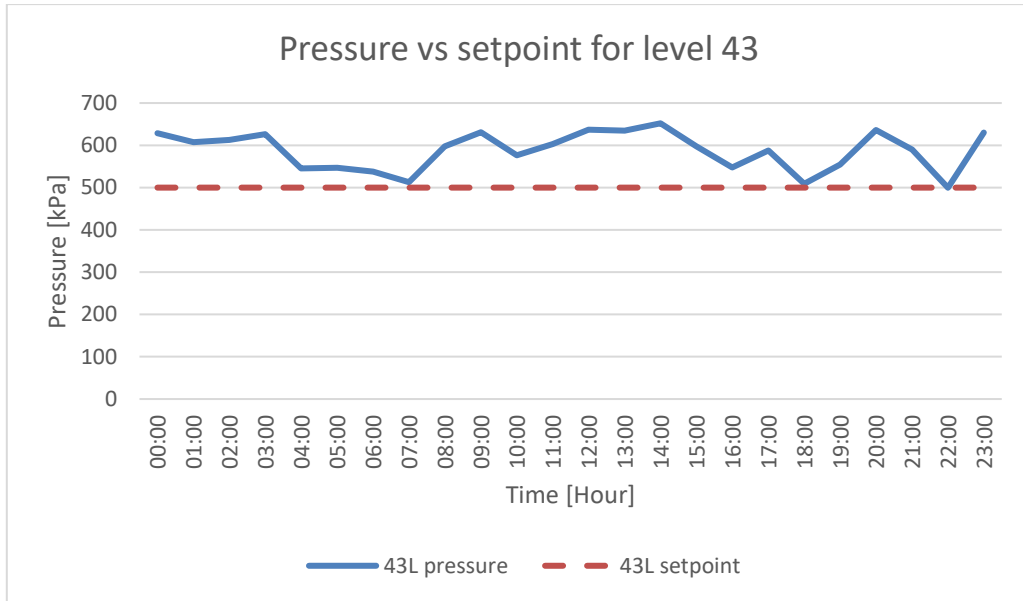


Figure 68: Pressure and setpoint for level 43 (22 September 2021)

As evident in Figure 68, no ineffective control was present, because the maximum setpoint was implemented throughout 22 September 2021. No pressure control was present, so ineffective control could not be the cause of the missed energy savings. To determine whether the setpoint is according to the project requirements, the setpoint is compared to the target profile in Figure 69 below:

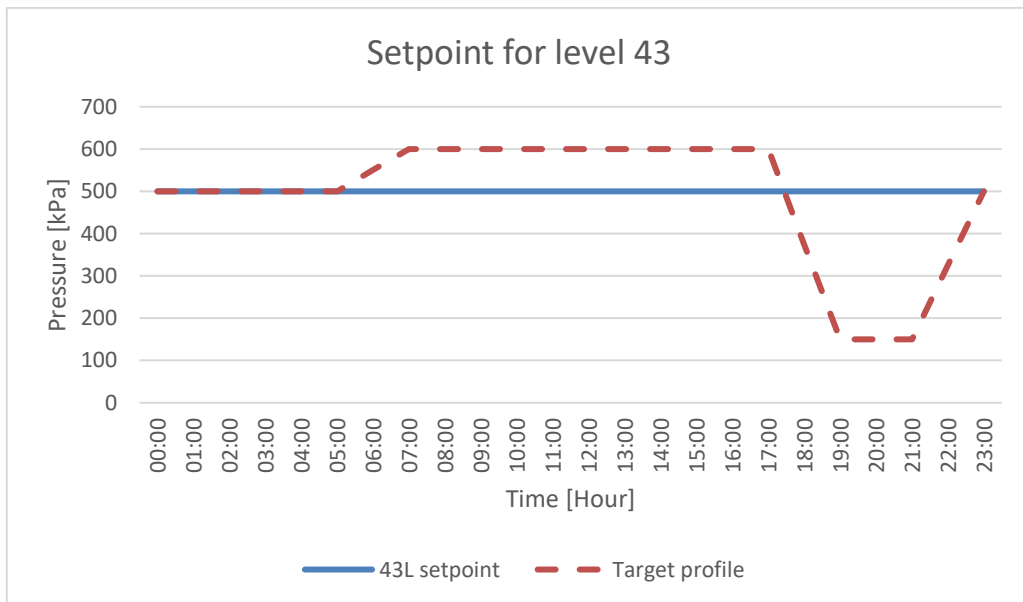


Figure 69: Setpoint and target profile for level 43 (22 September 2021)

The pressure setpoint for level 43 on 22 September 2021 deviates from the target profile, as shown in Figure 69. The deviation between the setpoint and target profile indicates that the

setpoint was not according to the project requirements. The setpoint exceeds the target profile from 18:00 until 22:00 by an average of 157%.

The SCADA was used to determine the setpoint schedule input. The setpoint schedule was satisfactory when compared to the project requirements given in Table 17 above. Using the setpoint value obtained for 22 September 2021 from Figure 69 and the input values on the SCADA, the input value for the setpoint was found to have been implemented incorrectly to the setpoint value that determined the valve control.

The cause of the missed energy savings opportunity was identified as a malfunction in the control system, which caused the input setpoint value to be implemented incorrectly. The SCADA technician was contacted and informed of the identified cause of the missed energy savings opportunity. The technician was informed that the input values for the setpoint did not correlate with the setpoint value received on the valve controller determined in Figure 69.

The SCADA technician performed diagnostics on the SCADA and determined that the scheduler was not receiving live input data. The scheduler was using a constant value of 500 kPa as a setpoint input value and not the actual setpoint input values from the SCADA. As a solution to the problem, the SCADA technician restarted the scheduler on 27 September 2021 at approximately 08:30.

3.5.7 Step 6: Ensuring that missed energy savings opportunities are reduced

To ensure the cause of the missed energy savings opportunity was correctly identified and rectified, the critical parameter that identified the cause of the missed energy savings opportunity was compared to the target profile in Figure 70 below for 27 September 2021.

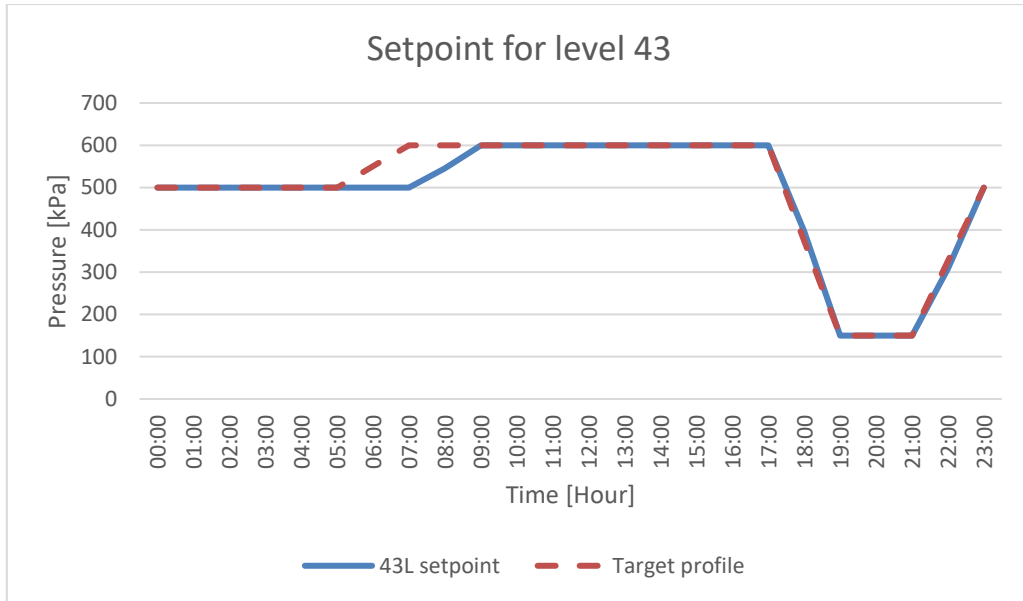


Figure 70: Setpoint and target profile for level 43 (27 September 2021)

The implemented setpoint for level 43 was restored to follow the target profile from 08:30, as seen in Figure 70. The deviation between the setpoint and the target profile from 05:00 until 09:00 is due to the scheduler being reset at approximately 08:30. After the reset was complete, the setpoint returned to the input value of 600 kPa. There was no deviation between the setpoint and the target profile from 08:30 when the scheduler was reset. The flow of level 43 was compared to the target profile shown in Figure 71 below to ensure no deviation is present.

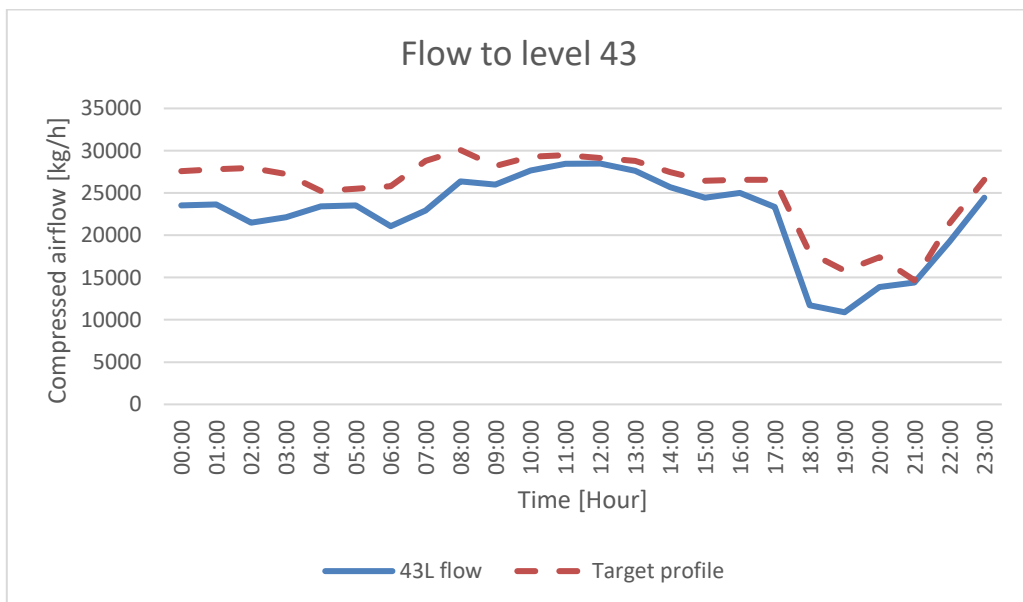


Figure 71: Flow and target profile to level 43 (27 September 2021)

The flow for level 43 did not exceed the target profile on 27 September 2021 compared to before the cause was identified and rectified, as seen in Figure 67. To ensure the missed energy savings opportunity was reduced, the critical parameter that identified the missed energy saving opportunity is compared to the target profile in Figure 72 below.

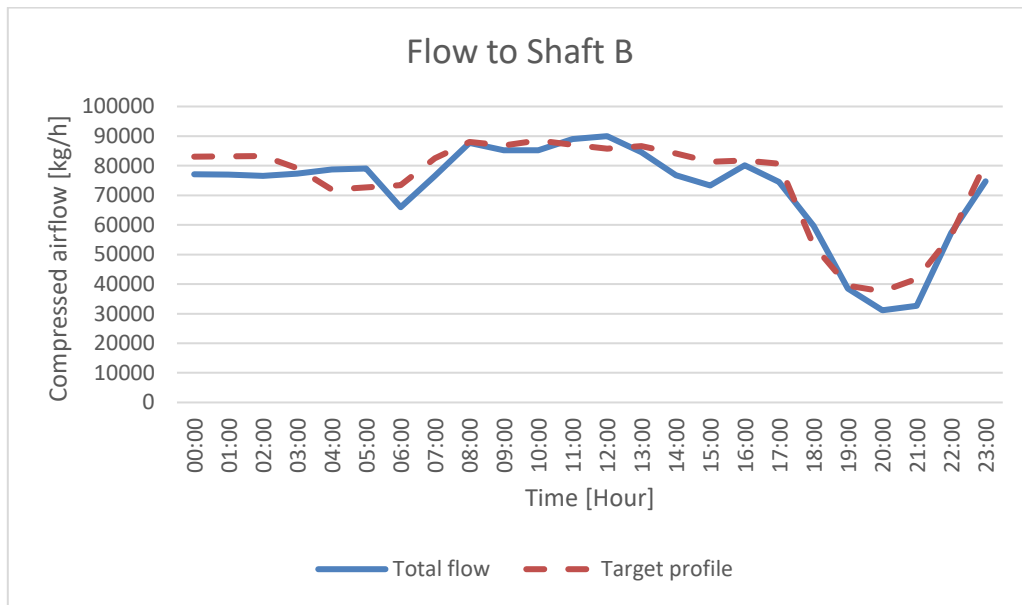


Figure 72: Flow and target profile to Shaft B (27 September 2021)

Figure 72 illustrates that the flow for the shaft no longer exceeds the target profile from 08:30 when the scheduler was restarted. After the scheduler was restarted, the flow for Shaft B did not exceed the target profile from 18:00 until 22:00 where automatic pressure control is expected on level 43. This verifies that the method was successful in reducing missed energy savings opportunities.

As mentioned in this case study, Shaft B is part of a ring-feed compressed air network. The compressor power may be affected by two other shafts on Mine A. The specific power of the compressors was obtained to calculate the compressor power for level 43 accurately. The calculated compressor power was obtained for level 43 for the day on which the target profiles were created, the incident, and after the solution had been implemented, as shown in Figure 73 below.

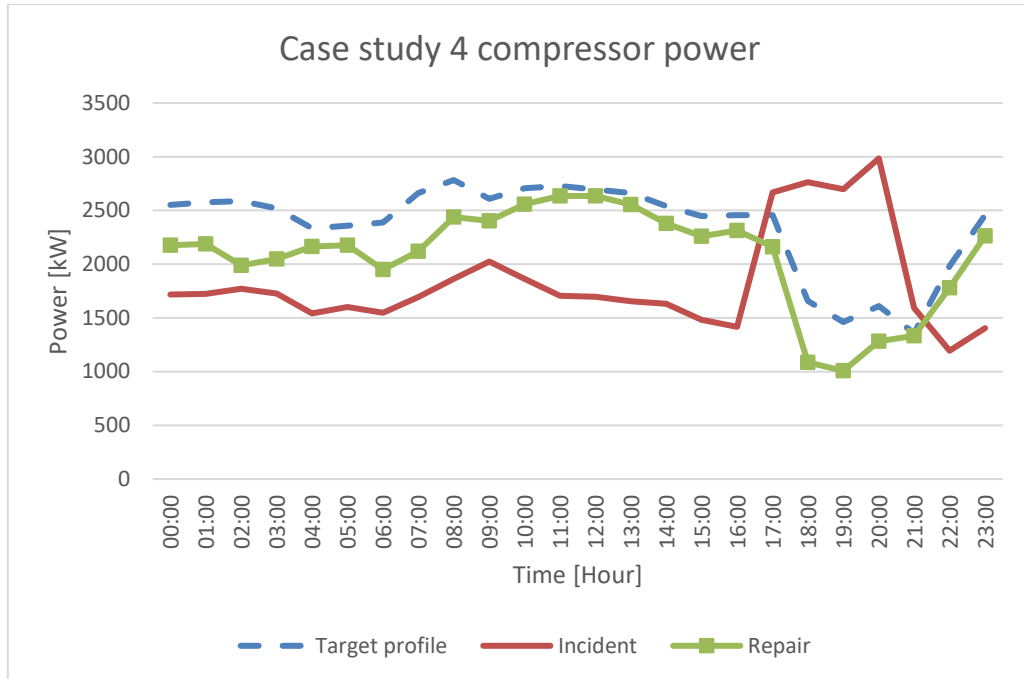


Figure 73: Case study 4 compressor power

From Figure 73 above, it is clear that the compressor power deviated significantly from the target profile from 18:00 until 22:00 where automatic valve control is expected. The method managed to identify a missed energy savings opportunity in the form of a 42% deviation from the target profile during that period. The deviation caused the calculated compressor power for level 43 to be an average of 632 kW higher from 18:00 until 22:00 than the target profile. The missed energy savings opportunity was identified by applying the developed method as a malfunction with the control system causing a loss of control, which reduced the savings achieved from 18:00 until 22:00.

After the cause was identified, the solution was determined, namely that the control system was reset. After the solution was implemented, the average compressor power was 317 kW less from 18:00 until 22:00 than the target profile. The average power demand reduction of 632 kW was attained from 18:00 until 22:00 by using the method. The calculated compressor power deviation from the target profile for the day of the incident and the day the solution was implemented is shown in Table 31 below.

Table 31: Case study 4 compressor power deviation comparison

Description	Deviation on incident (22 September 2021)	Deviation on repair (27 September 2021)
Total	-50%	-15%
During control period	42%	-27%
Outside control period	-52%	-12%

A deviation in the calculated compressor power for level 43s target profile was reduced from 42% over to 27% below the target profile from 18:00 until 22:00, as shown in Table 31 above. The missed savings opportunity from 18:00 until 22:00 was an average of 632 kW. The developed method assisted in identifying the missed energy savings opportunity and its cause, which led to a solution that could be implemented. The solution was deemed satisfactory and was validated, as it managed to increase the energy savings opportunity by 3 624 kWh per day by reducing the average compressor power by 632 kW for four hours. The missed energy savings cost was reduced by approximately R 2.5 million per year.

The results from the case study are used to determine if the study objectives were obtained. The objectives and a comment stating whether the objective was achieved and how are shown in Table 32.

Table 32: Case study 4 objectives

Objective	Comment
Develop a method to identify missed energy savings opportunities	Achieved satisfactory. The method identified missed energy savings opportunities by using the critical parameter of total flow to the shaft
Develop a method to identify the cause of missed energy savings opportunities	Achieved satisfactory. The method identified the cause of missed energy savings opportunities by using the critical parameters of the downstream pressure and setpoint.

The identified causes of missed energy savings opportunities as identified in the literature review are shown in Table 33, together with the applicable one for this case study.

Table 33: Case study 4 validation

Case study	Interference with automatic control	High demand or unfavourable conditions	Infrastructure constraints or breakdowns	Control system problems
Case study 1	✓			
Case study 2		✓		
Case study 3			✓	
Case study 4				✓

3.6 Conclusion and discussion

The developed method was successfully applied to four case studies. The causes of missed energy savings opportunities in this study corroborate the reasons identified in the literature as the causes of missed energy savings opportunities. By implementing the developed method in each case study, missed energy savings opportunities were successfully identified together with the cause of the missed energy savings opportunities.

Solutions to the identified causes of the missed energy savings opportunities were obtained by successfully identifying the causes by applying the developed method. The solutions were implemented, and the critical parameters were compared to the target profiles once again. The developed method was successfully verified to identify and reduce missed energy savings opportunities and their causes by reducing the percentage deviation between the critical parameter and the target profile after the solution was implemented. The developed method was validated by quantifying the increase in compressor energy when missed energy savings were identified. The increase in compressor energy is a missed energy-saving opportunity. The developed method was validated by ensuring that the compressor energy was reduced after implementation.

The summary of the calculated missed energy savings opportunities that were reduced, together with the calculated cost, by implementing the developed method is shown in Table 34 below.

Table 34: Results summary

Case study	Missed energy savings reduced p.a. [MWh]	Missed cost savings reduced p.a.
Case study 1	1.67	R 3 million
Case study 2	3.38	R 5.5 million
Case study 3	0.33	R 1 million
Case study 4	1.32	R 2.5 million
Total p.a.	6.70	R 12 million

Chapter 4 Conclusion

4.1 Summary

The South African gold mining industry faces challenges that negatively impact its profit margins. The rise in labour costs, decrease in ore grade and increase in electricity costs all contribute to the steady decline in the profit margins of deep-level gold mines.

Compressed air networks remain a big utility expense for deep-level mines. Compressed air is used to perform numerous tasks to ultimately extract gold from underground working areas.

Numerous compressed air reduction initiatives have been implemented that reduce the energy costs of the mine. The initiatives aim to reduce the electrical cost of compressors by reducing the energy usage of said compressors.

However, there are challenges to the sustainability of energy reduction initiatives. Some of these challenges include:

- interference with automatic control,
- high demand or unfavourable conditions,
- infrastructure constraints or breakdowns, and
- control system problems.

These challenges affect the sustainability of energy savings projects negatively, which leads to missed energy savings opportunities. The literature contains solutions that reduce the missed energy savings opportunities after it has been identified; however, literature containing methods to identify missed energy savings opportunities in compressed air systems and to identify the cause thereof is lacking.

The objective of this study was to reduce missed energy savings opportunities for compressor energy savings projects. This was done by developing a method that identifies missed energy savings opportunities in compressed air systems and the cause thereof. Having identified the cause of the missed energy savings opportunities, solutions were implemented with knowledge from the literature.

Project savings cannot be sustained unless the technical requirements are met. Literature was used to identify what the technical requirements are for current compressor energy savings projects to achieve the desired energy savings. Target profiles for critical parameters were further

identified in compressed air systems to indicate whether the technical requirements for a compressor energy savings project were met. A deviation of 10% between the measured value and the target profile was deemed sufficient to identify missed energy savings opportunities and causes.

The case study methodology was applied due to the nature of a deep-level mine compressed air network. The developed method was implemented in four case studies. The method successfully identified missed savings opportunities and the cause of the missed energy savings opportunities for all four case studies. Solutions were implemented based on the cause identification method that successfully reduced the missed energy savings opportunities for all four case studies calculated at 6.70 MWh per year. The missed energy savings cost was reduced by approximately R 12 million per year.

4.2 Recommendations

A recommendation for future work is to develop a more generic method of identifying the day used for the target profile. The method used in this study was time-consuming and may be challenging to implement if in-depth knowledge of the specific project requirements is lacking. A method that does not rely on in-depth knowledge may be advantageous for time-consuming reasons.

If it proves possible to create a generic method of identifying the day used for the target profile, it can be automated. By automating the target profile creation, time and resources can be saved. Automation of creating target profiles will lead to the solution being implemented on various sites in a shorter amount of time than it would with the proposed solution.

Future studies can include monitoring the target profiles created in this study automatically. Alarms can be created that can be sent to the responsible person if a value deviates from the target profile. Further research can be done on what the deviation percentage must be for each critical parameter. The deviation percentage of each critical parameter identified in this study to flag missed energy savings opportunities vary.

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APPENDIX A: PHYSICAL PROPERTIES OF AIR

As discussed in Section 1.3.2 the density of air is dependent on the pressure and temperature of the air. The density of air at different temperatures at atmospheric pressure of 1.10325 bar is shown in Table 35 below.

Table 35: Density of air at different temperatures at atmospheric pressure

Temperature of air [°C]	Density of air [kg/m ³]
-20	1.3958
-15	1.3687
-10	1.3426
-5	1.3175
0	1.2933
5	1.2699
10	1.2474
15	1.2257
20	1.2047
25	1.1845
30	1.1649
35	1.1459

40	1.1275
45	1.1098
50	1.0925
55	1.0759
60	1.0597
65	1.0439
70	1.0287
75	1.0139
80	0.99948
85	0.98549
90	0.97188
95	0.95865
100	0.94577
105	0.93323
110	0.92102
115	0.90913

120	0.89754
125	0.88624

APPENDIX B: TARGET PROFILES

The target profiles developed for Case Study 2 is shown in this section. The target profiles for level 43 are not added as these profiles did not assist in identifying the cause of the missed energy savings.

The target profile for critical parameter 1, total compressed air flow to shaft B, is shown in Figure 74 below.

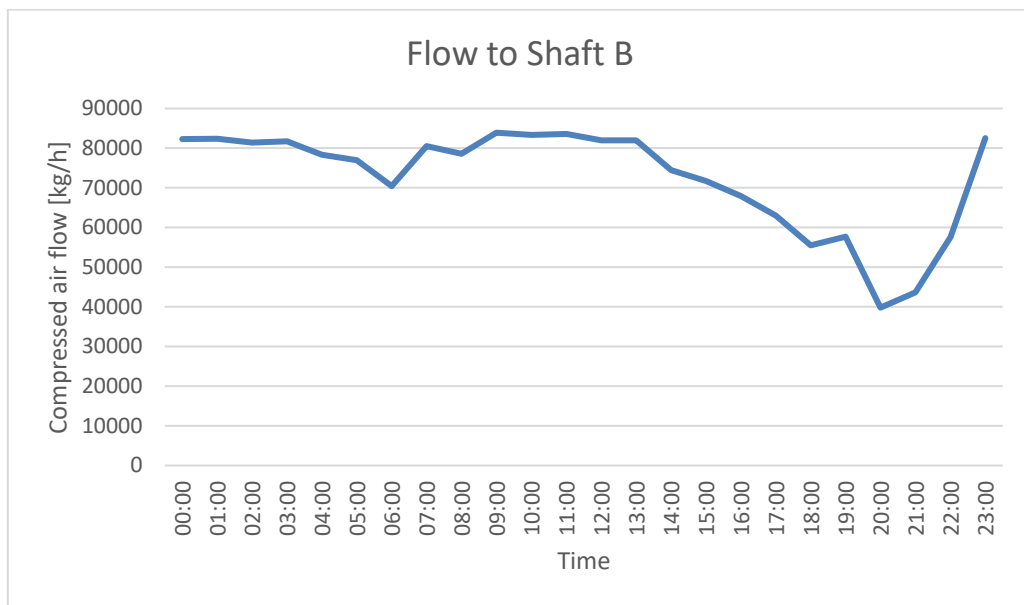


Figure 74: Target profile for Case study 2, critical parameter 1

The target profile for critical parameter 2, compressed air flow to level 41, is shown in Figure 75 below.

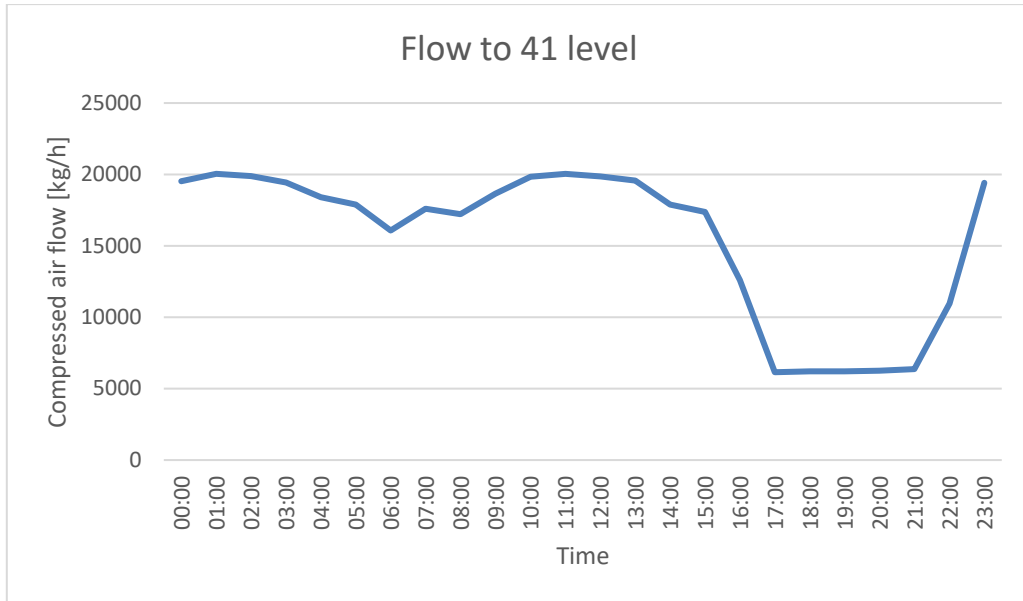


Figure 75: Target profile for Case study 2, critical parameter 2

The target profile for critical parameter 4, downstream pressure to level 41, is shown in Figure 76 below.

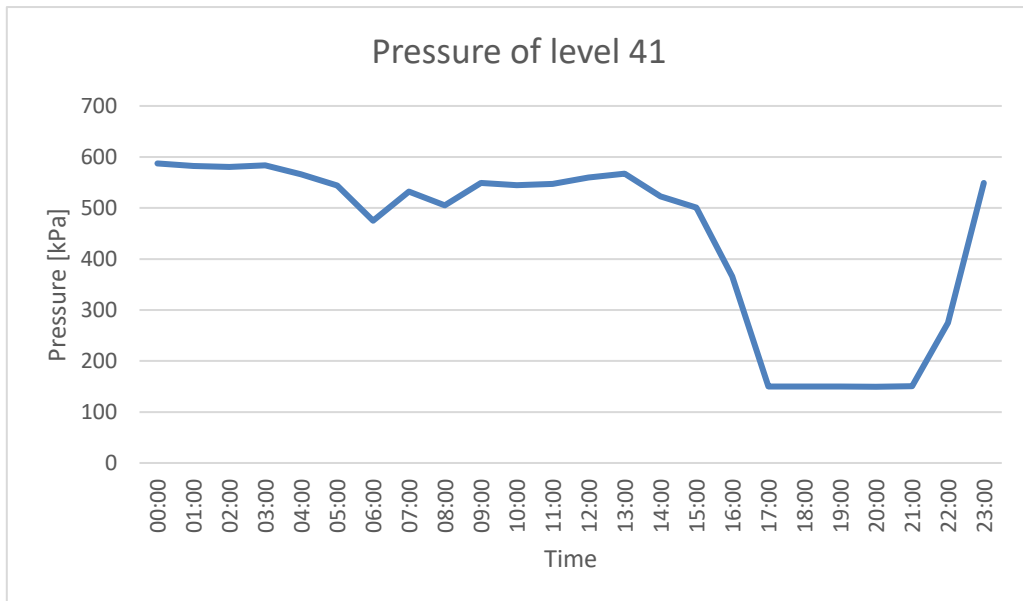


Figure 76: Target profile for Case study 2, critical parameter 4

The target profile for critical parameter 6, pressure setpoint of level 41, is shown in Figure 77 below.

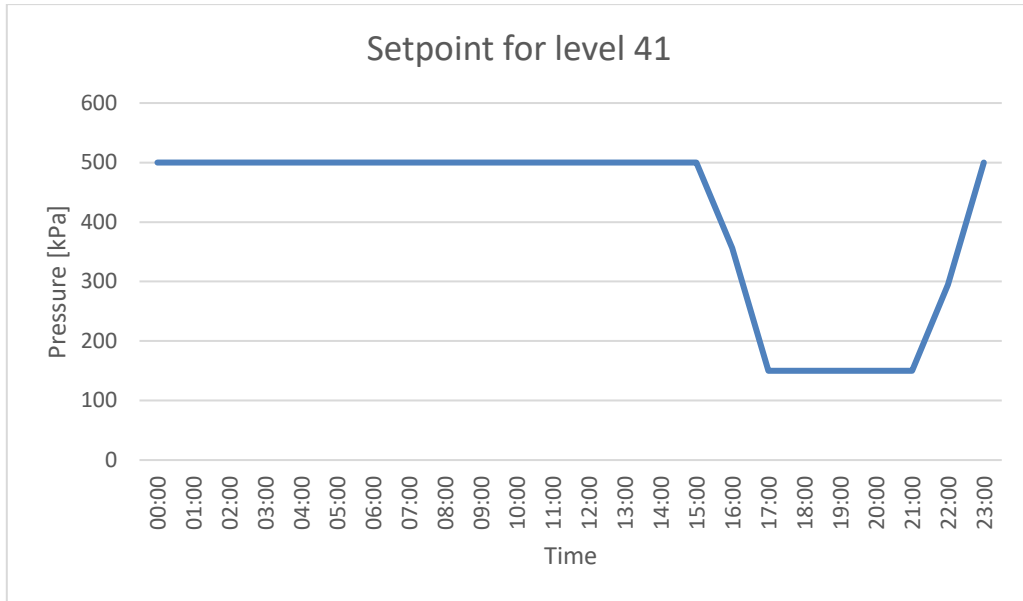


Figure 77: Target profile for Case study 2, critical parameter 6

The target profiles developed for Case Study 3 is shown in this section. The target profile for the shaft pressure is not included as this parameter did not assist in identifying the cause of the missed energy savings.

The target profile for critical parameter 1, total compressed air flow to shaft C, is shown in Figure 78 below.

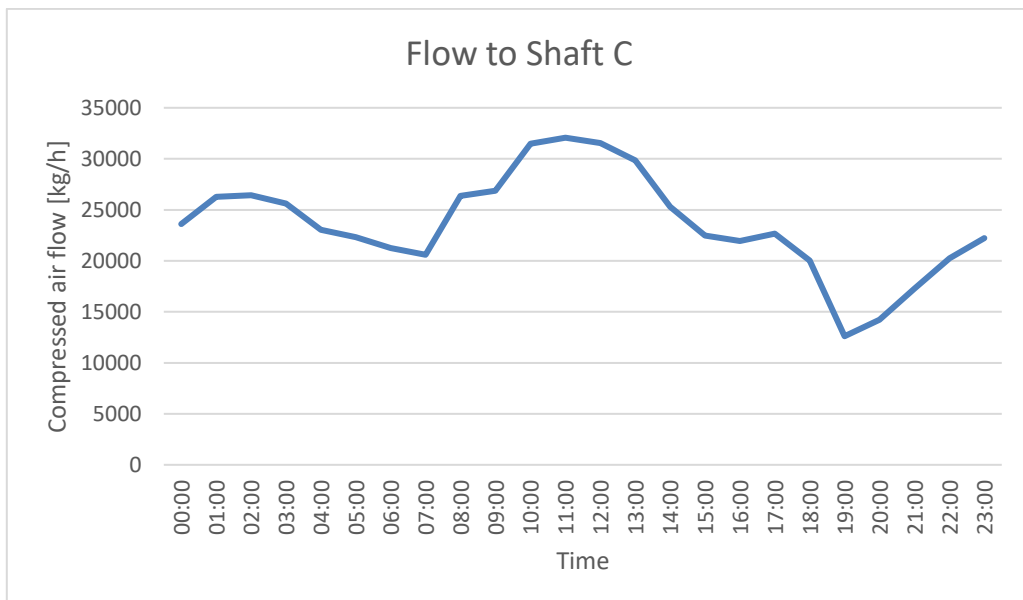


Figure 78: Target profile for Case study 3, critical parameter 1

The target profile for critical parameter 3, downstream pressure of the surface valve, is shown in Figure 79 below.

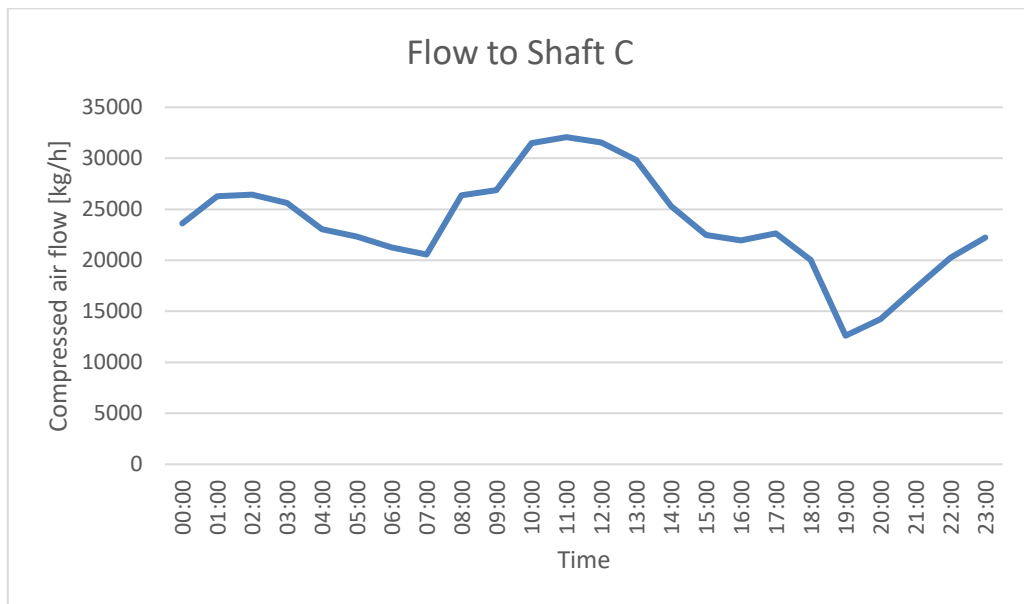


Figure 79: Target profile for Case study 3, critical parameter 3

The target profile for critical parameter 4, valve position of the surface control valve, is shown in Figure 80 below.

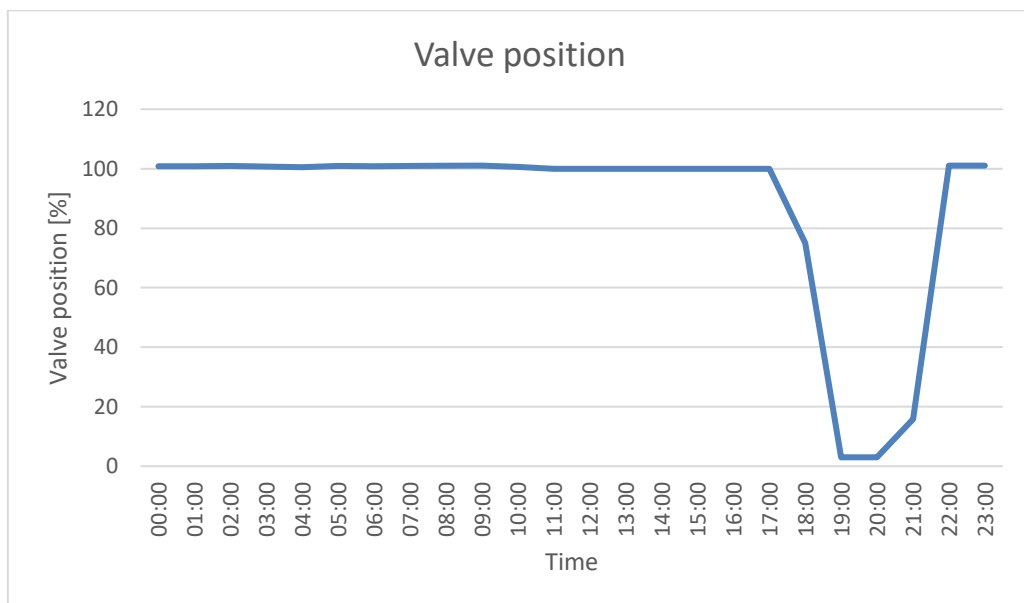


Figure 80: Target profile for Case study 3, critical parameter 4

The target profiles developed for Case Study 4 is shown in this section.

The target profile for critical parameter 1, total compressed air flow to shaft B, is shown in Figure 81 below.

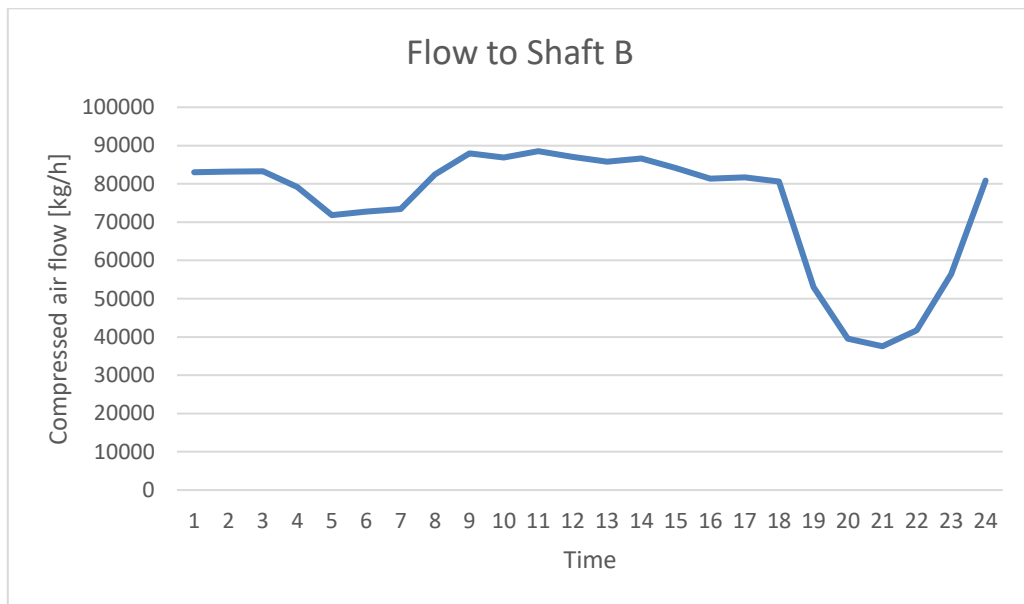


Figure 81: Target profile for Case study 4, critical parameter 1

The target profile for critical parameter 2, compressed air flow to level 43, is shown in Figure 82 below.

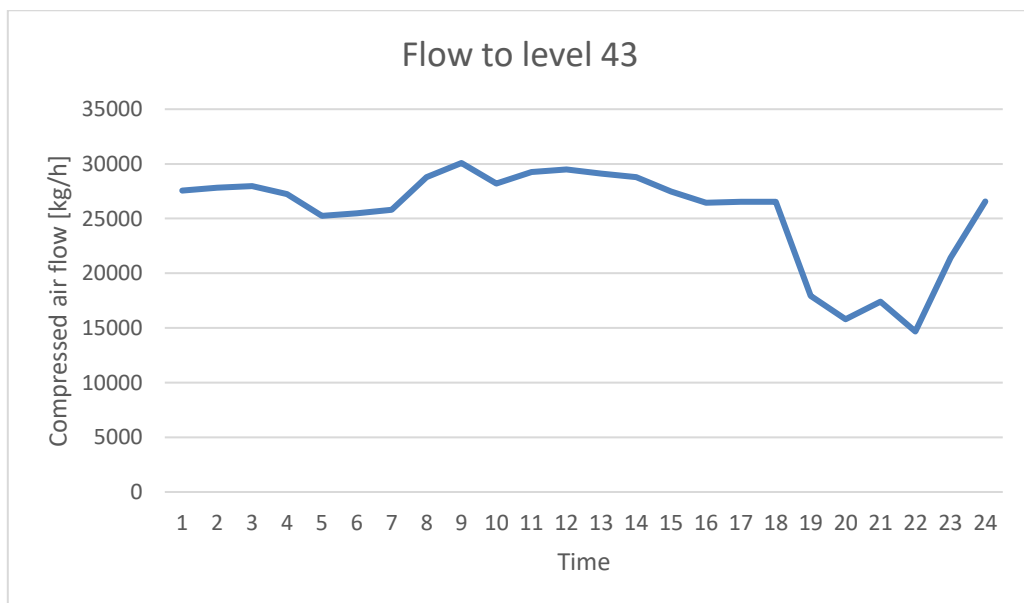


Figure 82: Target profile for Case study 4, critical parameter 2

The target profile for critical parameter 3, downstream pressure of level 43, is shown in Figure 83 below.

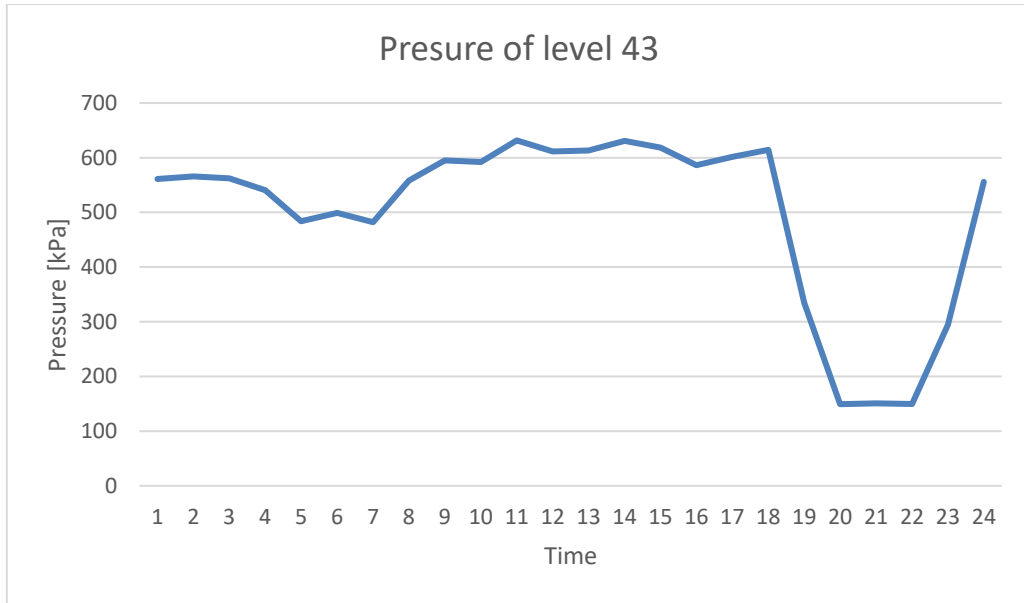


Figure 83: Target profile for Case study 4, critical parameter 3

The target profile for critical parameter 4, pressure setpoint of level 43, is shown in Figure 84 below.

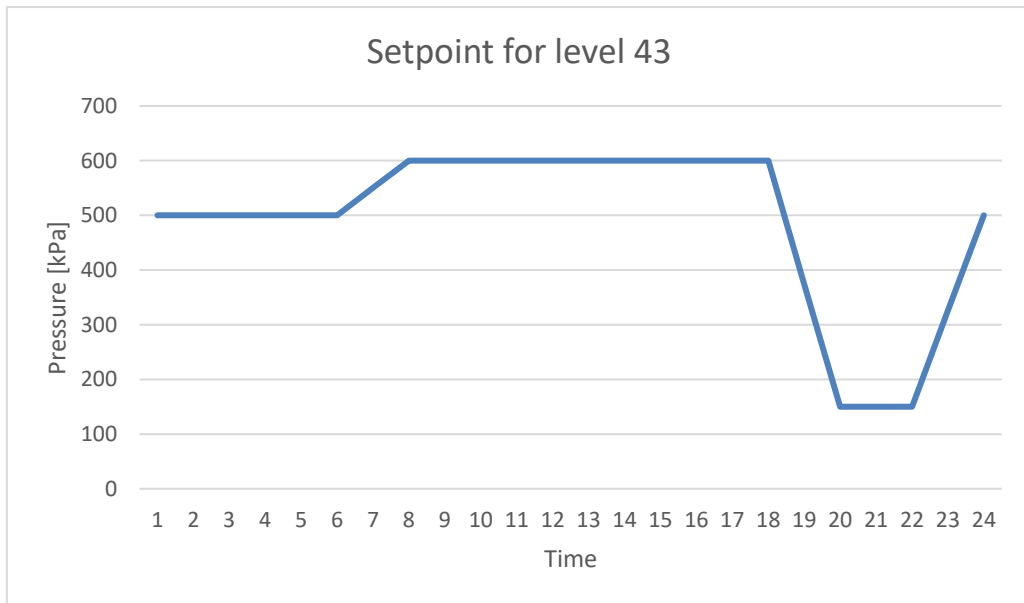


Figure 84: Target profile for Case study 4, critical parameter 4