Modernising underground compressed air DSM projects to reduce operating costs

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It all starts here ™

Abstract

Title:	Modernising underground compressed air DSM projects to reduce operating costs
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School:	North-West University, Potchefstroom Campus
Faculty:	Engineering
Degree:	Master in Mechanical Engineering

Growing demand for electricity forces suppliers to expand their generation capacity. Financing these expansion programmes results in electricity cost increases above inflation rates. By reducing electricity consumption, additional supply capacity is created at lower costs than the building of conventional power stations. Therefore, there is strong justification to reduce electricity consumption on the supplier and consumer side.

The mining and industrial sectors of South Africa consumed approximately 43% of the total electricity supplied by Eskom during 2012. Approximately 10% of this electricity was used to produce compressed air. By reducing the electricity consumption of compressed air systems, operating costs are reduced. In turn this reduces the strain on the South African electricity network.

Previous energy saving projects on mine compressed air systems realised savings that were not always sustainable. Savings deteriorated due to, amongst others, rapid employee turnover, improper training, lack of maintenance and system changes. There is therefore a need to improve projects that have already been implemented on mine compressed air systems.

The continuous improvement of equipment (such as improved control valves) and the availability of newer technologies can be used to improve existing energy saving strategies. This study provides a solution to reduce the electricity consumption and operating costs of a deep level mine compressed air system. This was achieved by modernising and improving an existing underground compressed air saving strategy. This improvement resulted in a power saving of 1.15 MW; a saving equivalent to an annual cost saving of R4.16 million.

It was found that the improved underground compressed air DSM project realised significant additional electrical energy savings. This resulted in ample cost savings to justify the implementation of the project improvements. It is recommended that opportunities to improve existing electrical energy saving projects on surface compressed air systems are investigated.

Keywords: Demand side management (DSM), energy efficiency, operating cost, mine compressed air system.

Samevatting

Titel: Modernisering van ondergrondse lugdruk “DSM” projekte om bedryfskoste te verminder
Outeur: C.J.R. Kriel
Promoter: Prof. M. Kleingeld
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Toenemende groei in die aanvraag na elektrisiteit dwing elektrisiteitsverskaffers om hulle elektrisiteitsopwekkingskapasiteit te vergroot. Verskeie projekte is geloods om die elektrisiteitsopwekkingskapasiteit te vergroot. Die finansiëring van hierdie projekte kan veroorsaak dat die elektrisiteitsprys bo die verwagte inflasieverhoging sal styg. Deur die elektrisiteitsverbruik te verminder word addisionele elektrisiteitsopwekkingskapasiteit geskep teen ‘n laer koste as die bou van nuwe kragstasies. Dit plaas die klem op strategieë wat elektrisiteitsverbruik verminder, gesien van beide die verskaffer en verbruiker se kant.

Die myn en industriële sektore van Suid-Afrika het ongeveer 43% van die totale elektrisiteit wat in 2012 opgewek is, verbruik. Ongeveer 10% van hierdie elektrisiteit wat deur die myn en industriële sektore verbruik is, was gebruik om lug saam te pers. Deur die elektrisiteitsverbruik van die lugdrukstelsels te verminder, kan daar ‘n merkwaardige afname in die verbruikerskoste bereik word.

Vorige elektrisiteitsbesparingstrategieë op myne se lugdrukstelsels was grotendeels suksesvol in terme van besparings, maar hierdie besparings was selde volhoubaar. Redes vir die wegkwyn van elektrisiteitsbesparings is onder andere hoë personeel omset, onvoldoende opleiding, gebrek aan onderhoud, stelselsveranderinge en so meer. Dit skep die geleentheid om bestaande elektrisiteitsbesparingsprojekte op myne se lugdrukstelsels te verbeter.

Die aaneenlopende verbetering van toerusting (soos verbeterde beheerkleppe), asook die beskikbaarheid van moderne tegnologie skep geleenthede om bestaande elektrisiteitsbesparingsprojekte op myne se lugdrukstelsels te verbeter. Hierdie studie fokus op die modernisering en verbetering van bestaande elektrisiteitsbesparingsprojekte van ondergrondse lugdrukstelsels.

‘n Bestaande elektrisiteitsbesparingsprojek op ondergrondse lugdrukstelsels is geïdentifiseer. Die bestaande projek is ondersoek en moontlike verbeterings is geïdentifiseer en gesimuleer. Uitvoerbare verbeterings is aangebring aan die bestaande projek. ‘n Bykomende 1.15 MW bespaaring, wat gelykstaande is aan ‘n jaarlikse kostebesparing van R4.167 miljoen, is verkry.

Dit is bevind dat die bykomende besparings die verbeterings aan die bestaande lugdrukstelsel geregverdig het. Daar word voorgestel dat verdere studies die moontlikheid ondersoek om bestaande bogrondse energieprojekte te verbeter.

Sleutelwoorde: DSM, energiedoeltreffendheid, bedryfskoste, ondergrondse lugdrukstelsel.

Acknowledgements

Philippians 4:13: “*I can do all things through Christ which strengtheneth me.*”

Everything I accomplish is not because of any ability I deserve, but through the glory of God. To God, Jesus Christ and the Holy Spirit all the glory for blessing me with a healthy mind and for giving me the strength to complete this dissertation.

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Nomenclature

List of units		
Symbol	**Description**	**Unit of measure**
h	Measure of time	Hour
s	Measure of time	Second
k	Denotes 1x10^{3}	Kilo
M	Denotes 1x10^{6}	Mega
G	Denotes 1x10^{9}	Giga
g	Measure of mass	Grams
m	Measure of distance	Metre
mm	Measure of distance (1m x 10^{-3})	Millimetre
N	Measure of force	Newton
J	Measure of energy	Joule
Pa	Measure of pressure	Pascal
W	Measure of power	Watt
A	Measure of electric current	Ampere
K	Measure of temperature	Kelvin
%	A fraction or ratio	Percentage
R	Measure of currency (South Africa)	Rand

List of symbols		
Symbol	**Description**	**Unit of measure**
C_p	Specific heat constant	[kJ/(kg.K)]
D	Inside diameter of pneumatic cylinder	m
d	Pneumatic cylinder – stem diameter	m
F	Force to be exerted	N
f	Friction factor [from Moody chart]	Dimensionless
g	Gravitational acceleration	9.81 m/s^{2}
h	Vertical distance from surface	m
k	Polytropic exponent	Dimensionless
L	The length of vertical pipeline	m
P	Power or pressure	W or Pa
R	Gas constant (Taken as 0.287 for air)	[kJ/(kg.K)]
S	Stroke length	m
T	Temperature	K
t	Time	s
V	Volume	m^{3}
v	Velocity	m/s
$\dot{V}$	Volume flow rate	m^{3}/s
W_e	Electrical power required to compress air	kW
X	Pneumatic cylinder – piston thickness	m

List of symbols – continued		
Symbol	**Description**	**Unit of measure**
Y	Cylinder length	m
$\dot{m}$	Mass flow rate	kg/s
π	Pi	Dimensionless
η	Efficiency	Dimensionless
ρ	Density	kg/m^3

Abbreviations

Symbol	Description
DSM	Demand Side Management
ESCO	Energy Service Company
GDP	Gross Domestic Product
IPP	Independent Power Producer
M&V	Measurement and Verification
NERSA	National Energy Regulator of South Africa
NSS	Network Slave Station
PID	Proportional-Integral-Derivative
PLC	Programmable Logic Controller
SCADA	Supervisory Control And Data Acquisition
TDP	Transmission Development Plan

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Chapter 1: Background

[1]

This chapter gives background regarding electrical energy supply and demand in South Africa. The need for demand side management (DSM) and the improvement of existing DSM projects are highlighted. This leads to the problem statement and objectives of this study. An overview of this document is also presented.

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[1] (*Figures and other information that do not contribute to the academic value of this dissertation will not be referenced in the bibliography. Footnotes will be used instead.)*

Howzit MSN News. (2013) *Eskom: Use less electricity!* [Online]. Available: http://news.howzit.msn.com. [Accessed: 12 September 2013].

1.1. Electrical energy supply and demand in South Africa

Research has shown that since 1971 worldwide electricity consumption has increased with an average of 3.5% per annum (IEA, 2012). As recent technologies became more and more reliant on electricity, this energy carrier has developed into an important aspect of modern human life. Electricity does not only play a major role in facilitating the human lifestyle, but it also contributes to the overall development of any country (Wolde-Rufael, 2006).

Gross domestic product (GDP) is a measure of a country's economy. GDP represents the value of all products and services produced and developed over a specific period. Should the GDP value increase over a period, an economic growth will be recorded for that time period (Kaliski, 2001). The fluctuation in the GDP value for South Africa during 2008-2012 is displayed in Figure 1 (Statistics South Africa, 2012).

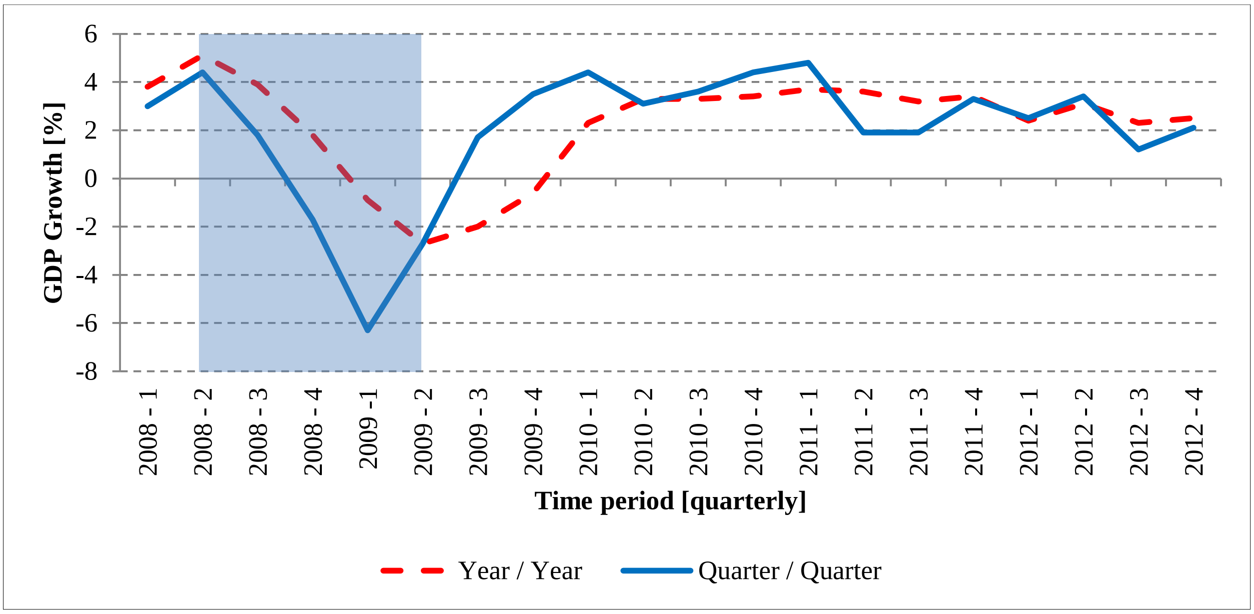

Figure 1: Growth in domestic product for South Africa (2008-2012).

Some experts are of the opinion that although the world experienced an economic recession during 2007–2008 (Taylor, 2009), electricity supply constraints were actually partly responsible for the negative economy growth experienced by South Africa during 2008/9 (Inglesi & Pouris, 2010). This belief is supported by the fact that load shedding was introduced as a quick solution to solve the problem of electrical energy demand exceeding the supply capacity of Eskom in 2008 (Inglesi & Pouris, 2010).

The day-to-day production and service delivery of all key sectors are dependent on a constant electricity supply. Key sectors influencing the South African GDP are (Statistics South Africa, 2012):

- mining industry,
- manufacturing industry,
- wholesale, retail and motor trade, and
- finance, real estate, business and government services.

Eskom is the main supplier of electricity in South Africa, generating more than 95% of the country’s electricity (Eskom, 2012b). In 2008 Eskom failed to meet the electricity demand of the country. Due to their dependence on electricity, all key sectors were directly affected. This resulted in damaging effects on the South African economy, as highlighted by the transparent light-blue block on the graph in Figure 1, for the period 2008-2 to 2009-1.

Electricity demand in South Africa has increased with over 50% since 1994. The factors that played a significant role in the increase in electricity demand were:

- economic expansion after sanctions were lifted in 1994 (Inglesi & Pouris, 2010),
- implementation of the free basic electricity policy in 2001 (Inglesi & Pouris, 2010), and
- the rural electrification policy of South Africa (Cecile, 1999).

Eskom implemented various projects to meet the increase in electricity demand. Some of these projects were implemented before 2008, but not in time to avoid electrical energy supply constraints. In 2005 Eskom launched a capacity expansion programme. The main aim of this expansion programme was to add 17 GW generating capacity to the national grid by 2018/19 (Eskom, 2012a).

Some of the strategies implemented by Eskom to expand the electricity generation capacity of the national grid included the following (Eskom, 2012a):

- building of new coal power stations,
- recommissioning of old coal power stations,
- building of new wind energy facilities,
- solar energy facilities, and
- independent power producers (IPPs).

Eskom experienced difficulties to remain on schedule with its capacity expansion programme. Boiler delays postponed the commissioning date of the Medupi power station from late 2012 to the end of 2014. Other challenges such as acquiring servitudes, managing employee dissatisfaction and dealing with poor scope definition contributed to overall project delays. Although precautionary programmes have been launched to manage these challenges, delays in the capacity expansion programme were inevitable (Eskom, 2012b).

Eskom had to launch various electricity demand reduction strategies to supplement the capacity expansion programme. These demand strategies entailed buyback agreements, residential power reduction programmes, the “power alert” system and DSM initiatives (Eskom, 2011).

The most familiar DSM initiatives are load shifting, energy efficiency and peak clipping (Palensky & Dietrich, 2011). Compressed air DSM projects related to this study are classified under energy efficiency DSM initiatives. Various specialists have different definitions for energy efficiency. All definitions point to the same conclusion namely: “doing more with less energy”. In the past, energy efficiency initiatives have successfully reduced the electricity demand in South Africa (Eskom, 2011).

Figure 2 shows the cost variation in Eskom’s average electricity supply cost from 1997 to 2012. The large price increase post-2008 was introduced to cover the expenses of the initiatives launched by Eskom to expand its generation capacity. The National Energy Regulator of South Africa (NERSA) has granted Eskom an annual electricity tariff increase of 8 % for 2013/2014 (Eskom, 2013).

Eskom have different tariff structures for different types of consumers. Most industrial customers (such as platinum and gold mines) are not on a fixed tariff structure. The electricity tariff depends on the time of use during the day, whether it is a weekday or a weekend and whether it is in the winter or summer months. Depending on the specific Eskom tariff structure, electricity tariffs during the winter months can be up to three times more expensive than in the summer months.

As a result of electricity cost rising above normal inflation rates, the cost to operate electrical equipment has increased significantly. The increase severely affected the South African mining industry to the extent that electricity cost has escalated to be one of the major expenses. For this reason strategies to reduce electricity usage in mines have become more prominent over the past decade.

During 2012 the South African industrial- and mining sector consumed 43.1% of the total electricity sold locally by Eskom (Eskom, 2012b). Studies have shown that compressed air systems are accountable for approximately 9% of the total industrial energy consumption in South Africa (Saidur *et al.*, 2010). Therefore, compressed air systems consumed approximately 4.3% (9125 GWh) of the total electricity sold by Eskom during 2012 (Eskom, 2012b).

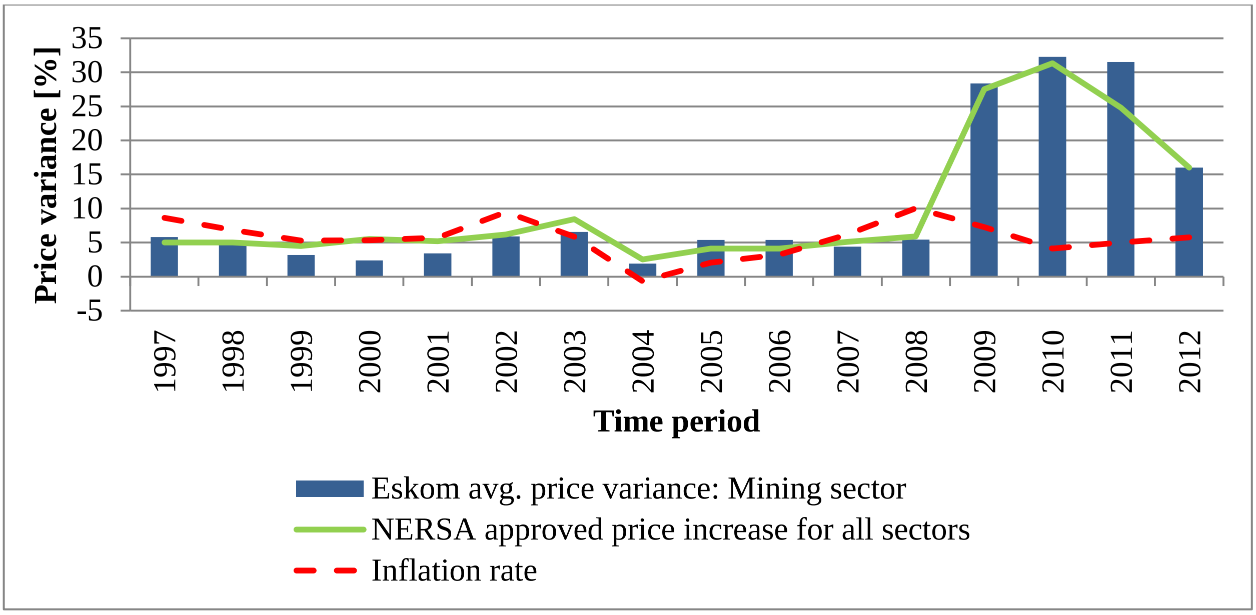

Figure 2: Electricity cost variance for the mining sector in South Africa (1997–2012).

Compressed air systems on deep level mines are vital for production and service delivery. System failure can result in radical production losses. Therefore, most industrial compressed air systems are overdesigned with ample spare capacity (Neale & Kamp, 2009). These redundancies amplify the feasibility for energy efficiency initiatives on compressed air systems.

By improving existing underground compressed air DSM projects with cutting edge technologies and expertise, the electricity demand of the country along with the operating cost of the client will be decreased. Therefore, the chance for another electrical energy supply constraint, like the one experienced in 2008, will be reduced.

1.2. Problem statement and objectives

Due to the imbalance between the electricity supply and electricity demand being experienced in South Africa, the need to reduce the electricity demand has escalated. With compressed air systems consuming a significant amount of electrical energy, various energy saving strategies have already been implemented on these systems. These strategies reduced the electricity demand, and the operating cost of these systems.

The development of cutting-edge technology, escalation in electricity cost along with system changes underline the feasibility of improving the underground compressed air saving strategies that already exist on deep level mines. The improvements will reduce the electricity consumed by compressed air systems even further. As a result operating cost will also be reduced.

The focus of this study will be on modernising and improving existing underground compressed air DSM projects to reduce operating cost on deep level mines. By improving these existing projects using cutting-edge technologies and expertise, the country’s electricity demand along with the client’s operating cost will be decreased.

1.3. Overview of this document

Chapter 1 provides the background regarding electrical energy supply and demand. The importance of electrical energy supply to ensure economic stability is presented. DSM projects are discussed and the need to modernise and to improve existing projects to reduce operating cost is highlighted.

Chapter 2 provides the foundation to improve an existing underground compressed air DSM project. An overview of the compressed air systems in the deep level mining industry, and the existing electrical energy saving projects already implemented on these systems are presented. An implementation procedure to modernise an existing underground compressed air DSM project is also proposed.

Chapter 3 provides the method that was followed to modernise and improve an existing underground compressed air DSM project. This method is explained using a case study.

Chapter 4 discusses the improved electrical energy savings that were achieved. A new method to measure the improvement in electrical energy savings is developed to verify the results.

Chapter 5 contains the conclusion of this study. Limitations to this study and recommendations for future studies are discussed.

Chapter 2: Concepts of compressed air in the deep level mining industry

[2]

This chapter provides the background to understand the modernisation and improvement strategy of an existing underground compressed air DSM project. Compressed air systems in the deep level mining industry are investigated and classified. Typical underground compressed air consumers are identified. Existing underground compressed air DSM projects are investigated and an implementation procedure for a typical modernisation and improvement strategy is presented.

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[2] Photo taken at a South African mine.

2.1. Introduction

The cost per unit [rand per megajoules (R/MJ)] of final energy for different energy carriers is displayed in Figure 3 (Yuan *et al.*, 2006). It is clearly visible that compressed air is one of the most expensive energy carriers. Despite the major cost implication of using a compressed air network, it is widely used in the mining sector. The ease of expanding compressed air networks and their reliability are some of the reasons why compressed air networks are popular energy delivery sources in deep level mines (Marais, 2012). Another reason why compressed air is used within the mining industry is because it poses no fire or explosion hazard (Yuan *et al.*, 2006).

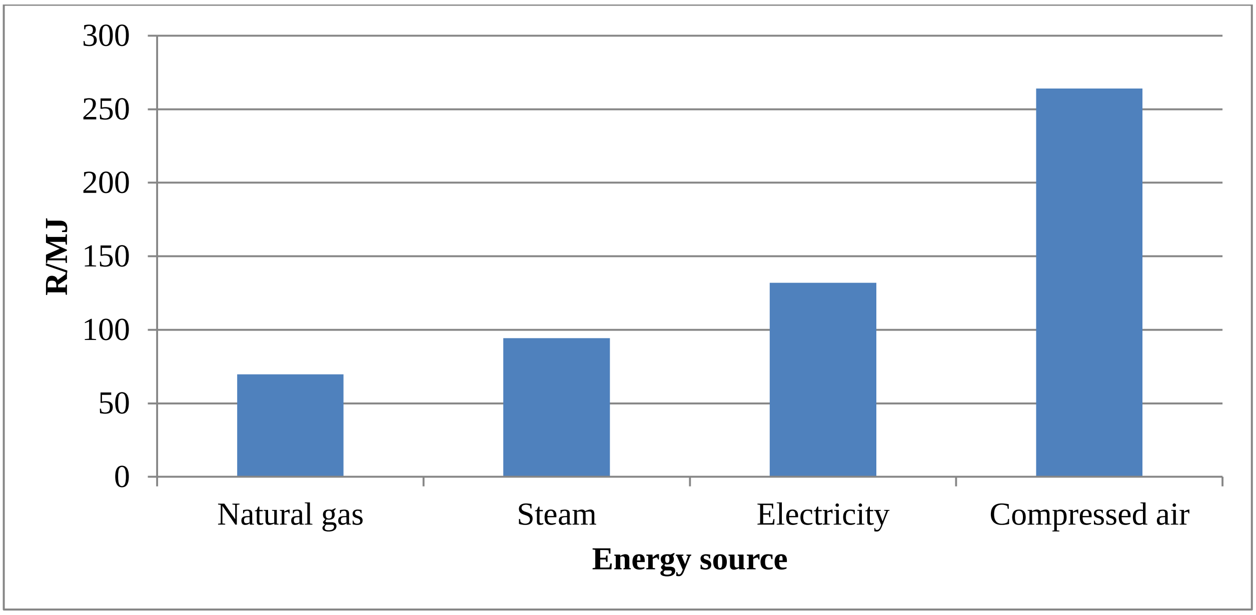

Figure 3: The cost per unit of final energy for different energy delivery carriers.

Various electrical energy saving projects have already been implemented on compressed air systems of deep level mines. This study focuses on improving existing underground compressed air DSM projects to reduce operating costs. An overview of surface compressed air systems in the deep level mining industry will be supplied as background to underground compressed air systems, which will be investigated in more depth later in this chapter.

2.2. Overview of compressed air systems in deep level mines

2.2.1. Selecting the appropriate compressed air supply source

Figure 4 shows the different types of compressors found in industry (Hongbo & McKane, 2008). Each type of compressor is ideal for a specific application.

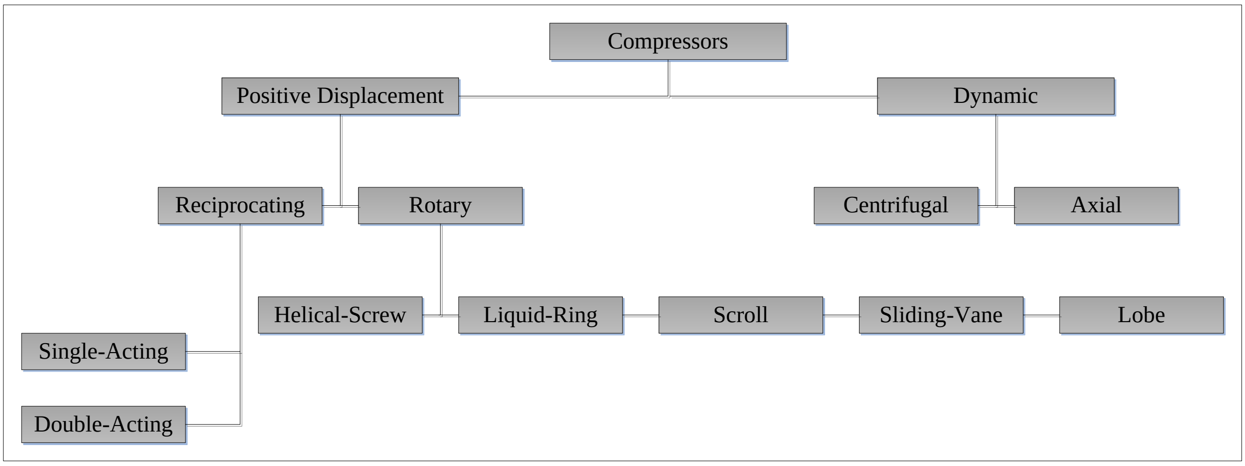

Figure 4: Classification of air compressors.

Each compressed air network should first be analysed before choosing an appropriate compressor as a compressed air supply source. Before a compressor is selected, the following parameters should be identified on the compressed air network (Greenough, 2000):

- volume of air required and at what pressure,
- quality of the air required (moisture content, dust particles, oil content etc.),
- effect of compressed air supply failure, and
- physical constraints, such as space available and the maximum allowable noise level.

A significant amount of compressed air can be consumed by the end-users of a compressed air network in the deep level mining industry. It was found that up to 5 000 tons of air could be consumed by a single mining shaft during a normal production day. Centrifugal compressors are mainly used to generate the compressed air due to their high flow rate generation capability.

The choke point (which is reached when the velocity through the compressor reaches Mach 1) is a limitation for maximum flow through a centrifugal compressor. On the contrary, the flow rate through other types of compressors (such as a reciprocating compressor) is limited by the cylinder size, number of cylinders, crankshaft rotation speed, and so forth. (Gallick *et al.*, 2006).

Figure 5 shows a multistage centrifugal compressor used to supply compressed air to a compressed air network in the South African gold mining industry. The installed capacity of a multistage centrifugal compressor found in the mining industry typically ranges from 1 MW to 15 MW. From personal experience it was found that compressors on typical mines are capable of supplying compressed air at 600 kPa at a flow rate from 30 500 m^3/h to 170 000 m^3/h.

Figure 5: Multistage centrifugal compressor used at a South African gold mine[3].

Steel pipes are mostly used to distribute the compressed air to the various demand sites. The 600 mm diameter pipeline displayed in Figure 6 is an example of compressed air distributed via a steel pipeline to a mining shaft.

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[3] Photo taken at a South African gold mine.

Figure 6: Steel pipe transporting compressed air to a mining shaft[4].

2.2.2. Compressed air networks

Platinum and gold ore are typically extracted using deep level mining activities. Platinum mines in South Africa are up to a 1 000 m deep whereas gold mines reach depths of 4 000 m (Seccombe, 2013). Two types of compressed air network were identified in the South African deep level mining industry:

1. standalone compressed air networks, and
2. integrated compressed air supplier networks.

Standalone compressed air networks consist of a single compressed air source that feeds only a limited number of consumers. Figure 7 displays a typical standalone compressed air network on a deep level mine. In the South African mining industry a typical standalone compressed air network could consist of a compressed air supply source, an ore processing plant and a mining shaft.

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[4] Photo taken at a South African gold mine.

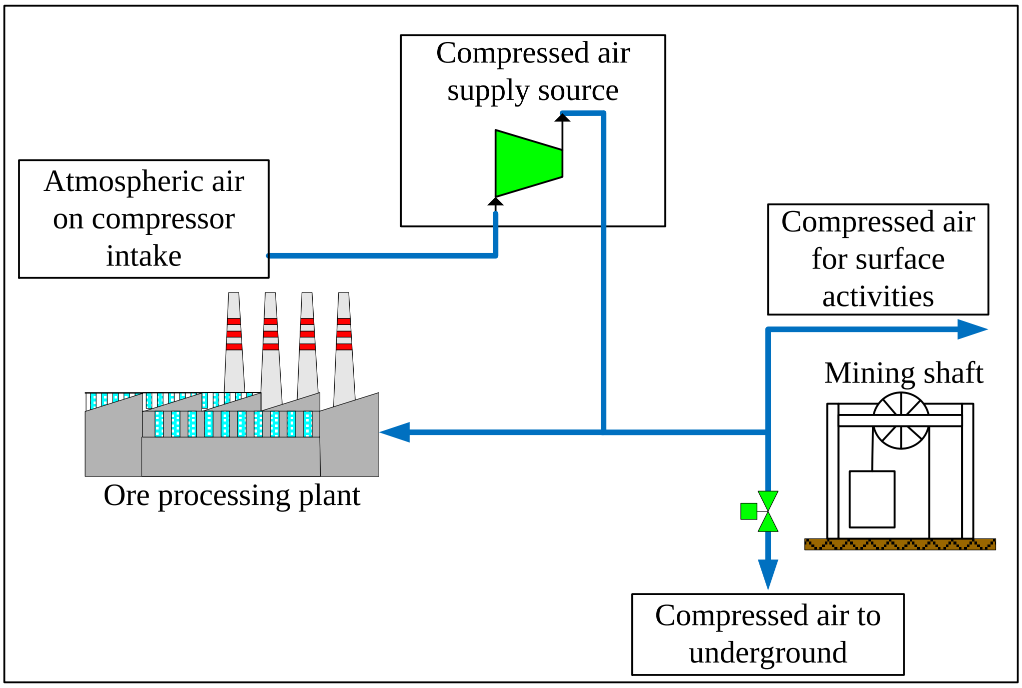

Figure 7: Standalone compressed air network.

Integrated compressed air supplier networks consist of more than one compressed air source. These compressed air sources are connected to one pipeline feeding various consumers. An advantage of these integrated compressed air supplier networks is that the air supply can be decentralised (Joubert, 2010). Should it happen that one consumer has a surplus of air, the air could be relocated to another consumer that is in need of compressed air at that point in time (Lodewyckx *et al.*, 2008).

Integrated compressed air supplier networks are the most common compressed air networks found in the South African gold mining industry (Joubert, 2010). An advantage of an integrated compressed air supplier network is that fewer compressors have to be installed to feed all the consumers in the area. It should be noted that the number of compressors required depends on the installed capacities of the compressors as well as the demand of the entire network.

The disadvantage of an integrated compressed air supplier network is that the network pressure is determined by the consumer with the highest pressure requirement. This can lead to an excess of compressed air supplied to other consumers. Strategies to eliminate this phenomenon are discussed later in this chapter. A typical integrated compressed air supplier network is displayed in Figure 8.

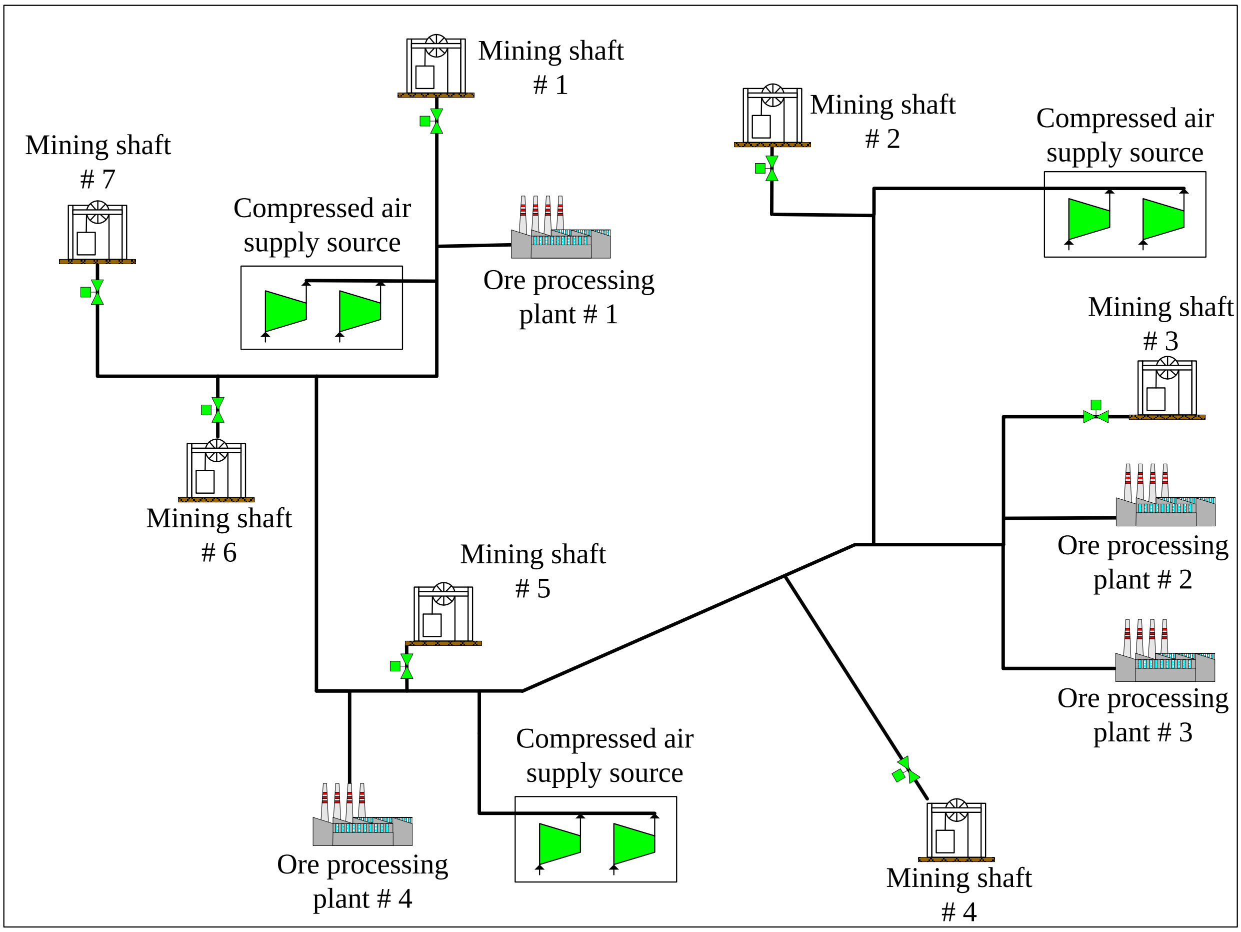

Figure 8: Integrated compressed air supplier network.

2.2.3. Compressed air requirements

Compressed air is typically consumed by end-users in sections such as mining shafts and processing plants. Leaks on the compressed air pipelines also consume compressed air. The individual equipment and end-users consuming compressed air on a mining shaft will be discussed in detail later in this chapter. Table 1 shows the typical compressed air requirements of a mining shaft and a processing plant.

Table 1: Mining shaft and processing plant compressed air requirements.

Gold processing plant		**Mining shaft**	
Typical flow required [kg/s]	Typical air pressure required [kPa]	Typical flow required [kg/s]	Typical air pressure required [kPa]
0.1–0.9	500–700	8–40	200–600

The air pressure required by a processing plant is generally higher than the air pressure required by a mining shaft. However, the amount of air (mass flow) required by a mining shaft is significantly higher than the amount of air required by a processing plant (Joubert & Liebenberg, 2010). In processing plants, compressed air is mainly used to operate instrumentation devices.

By means of practical experience and by consulting relevant mine personnel, it was found that the compressed air requirements (pressure and flow) supplied to a typical deep level mining shaft largely depend on the following parameters:

- the type and quantity of equipment used,
- the depth of the mining activities,
- the condition of the compressed air network, and
- the daily operating schedule.

2.2.4. Underground compressed air consumers

It has already been mentioned that ore processing plants and mining shafts consume the majority of compressed air in the deep level mining industry. The focus of this study is on improving existing underground compressed air DSM projects. This section will therefore describe typical pneumatic equipment and compressed air applications used in a deep level mine.

On a typical deep level mine only a fraction of the compressed air is used on surface for maintenance, manufacturing and cleaning purposes. The majority of compressed air is consumed underground.

To understand the function of each underground compressed air consumer, one should first understand the ore mining procedure. Once the ore mining procedure is understood, one can understand the locations, importance and functions of each compressed air consumer underground. This information can be used to identify improvements on the existing compressed air saving projects. Figure 9 displays an underground layout of a typical deep level mine (Environment Canada, 2009).

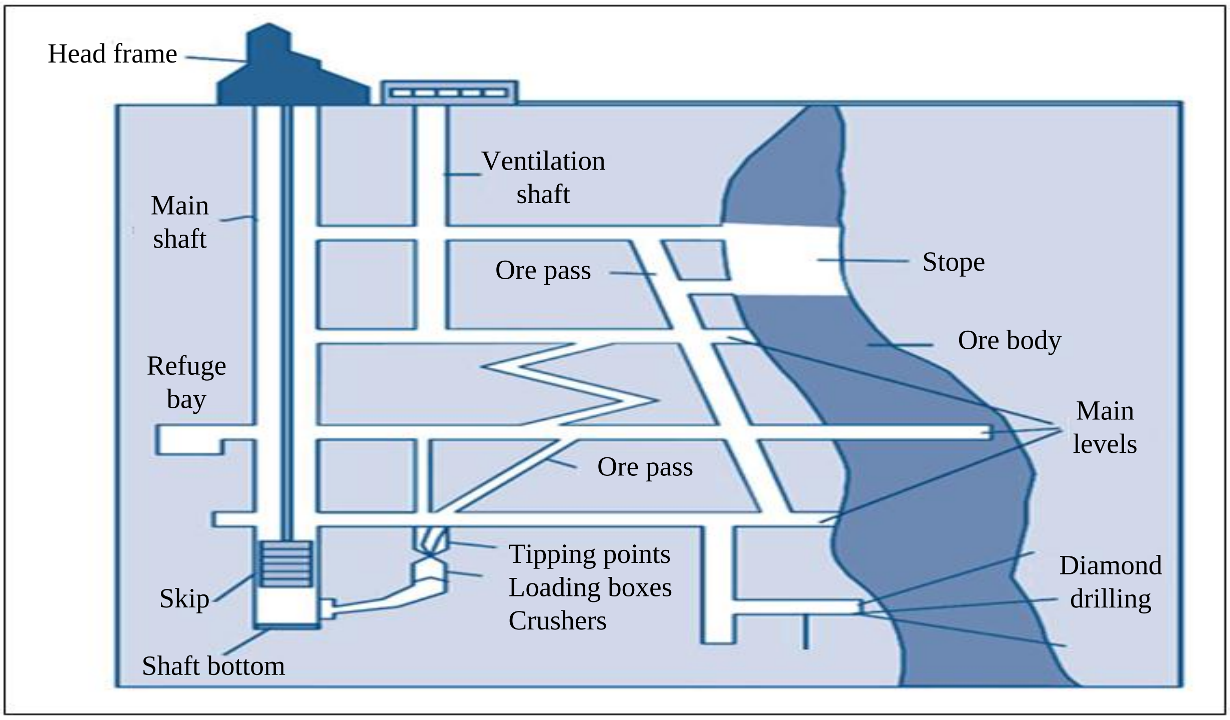

Figure 9: Underground layout of a typical deep level mine.

Pneumatic rock drills are one of the major consumers of compressed air underground. These drills are mainly used inside stope areas to drill holes into rock faces. Explosives, which are placed inside these holes, are used to break the rock faces into smaller pieces when the explosives are detonated. A deep level mine usually has more than one type of pneumatic drill, some of which are more suitable for production purposes; others are more suitable for development activities.

After the explosives have been detonated and the rock faces have been shattered into small pieces of rock (also known as ore), pneumatic loaders are used to collect the pieces of rock. These pneumatic loaders load the ore into hoppers that transport the ore to the nearest tipping bay. Both the pneumatic loaders and the hoppers are track-bound. As the ore is removed from the stopes, new tracks are installed for the pneumatic loaders to move forward.

Figure 10 shows a typical pneumatic drill mainly used for production activities. Figure 11 shows the loading action of a typical pneumatic loader.

Figure 10: Typical pneumatic rock drill[5].

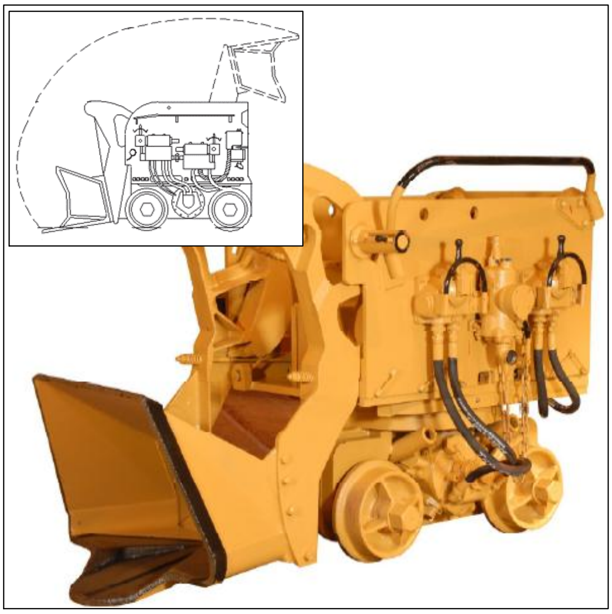

Figure 11: Pneumatic loader's loading action[6].

Track-bound locomotives transport the hoppers. Once the hoppers reach the tipping point, pneumatic cylinders are used to tip the hoppers, causing the ore to fall into the ore pass. The ore falls all the way down the ore pass into loading boxes located on the next level. Pneumatic cylinders open and close sliding doors fitted on the loading boxes. When these sliding doors open, the ore falls into another hopper to transport it to the next tipping point. This process is repeated to transport all the ore to the sump at the bottom of the shaft.

At the shaft bottom, loading boxes feed the ore into rock crushers that crush the ore into smaller pieces. The crushed ore is fed into skips, which are metal cages used to transport the ore. A winder located on surface winches the skips up and down the shaft to transport the ore to surface. Once the skips reach the surface, the ore is dumped into stationary hoppers. Conveyor belts or train trucks transport the ore from this point to the processing plants.

Apart from the tipping points and loading boxes, high-pressure ventilation doors also use pneumatic cylinders. These doors are used to seal off certain parts of a level to improve the efficiency of the

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[5] Tranter Rock drills. (2013) *S215 rock drill*. Roodepoort, South Africa. [Online]. Available: http://tranterenergyandmining.co.za. [Accessed: 02 July 2013].

[6] Trident SA. (2013) *Eimco 12AC rocker shovel*. Germiston, South Africa. [Online]. Available: http://www.tridentsa.co.za. [Accessed: 02 July 2013].

ventilation system through the mine. At some locations, locomotives transporting hoppers need to pass the ventilation doors to reach their destinations. Pneumatic cylinders are used to open and close the doors so that the locomotives can pass through. Figure 12 shows a typical pneumatic cylinder.

Figure 12: Example of a pneumatic cylinder[7].

Pneumatic cylinders do not consume large amounts of air (8-11 m^3/h) compared with other pneumatic equipment such as rock drills (190–320 m^3/h). However, the pressure pneumatic cylinders need to operate can be relative high (depending on the size of the cylinder and the force it has to exert; typically in the range of 400–550 kPa). The following concepts regarding pneumatic cylinders are explained in Appendix C:

- the volume of air consumed by a cylinder with one stroke,
- volume of air consumed by a pneumatic cylinder for a fixed time period, and
- the required cylinder diameter for a specific application.

In some gold mines compressed air is used to cool down the environment miners have to work in. This is commonly done using open-ended pipes (Van Tonder, 2010), although it is frowned upon and considered an inefficient method of cooling. As indicated in Figure 13 compressed air contributes approximately 6% to the total cooling in stopes (Bluhm & Biffi, 2001).

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[7] Thomasnet News. (2013) *NFPA air cylinders provides mounting flexibility*. Online product sourcing platform. [Online]. Available: http://news.thomasnet.com. [Accessed: 10 July 2013].

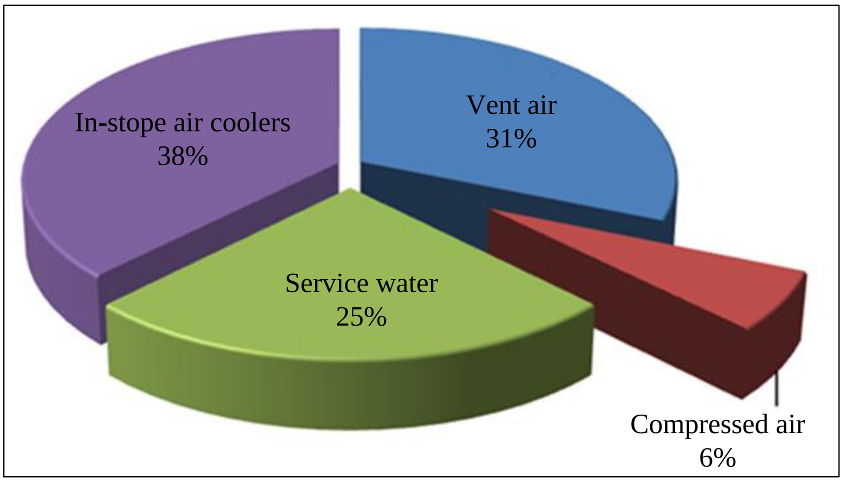

Figure 13: Components contributing towards stope cooling.

In the underground mining environment, various life-threatening dangers can occur: methane gas explosions, insufficient ventilation and rock deformation are just a few. A refuge bay is a safe place where miners can take shelter during an emergency. Figure 14 shows a typical layout of an underground refuge bay.

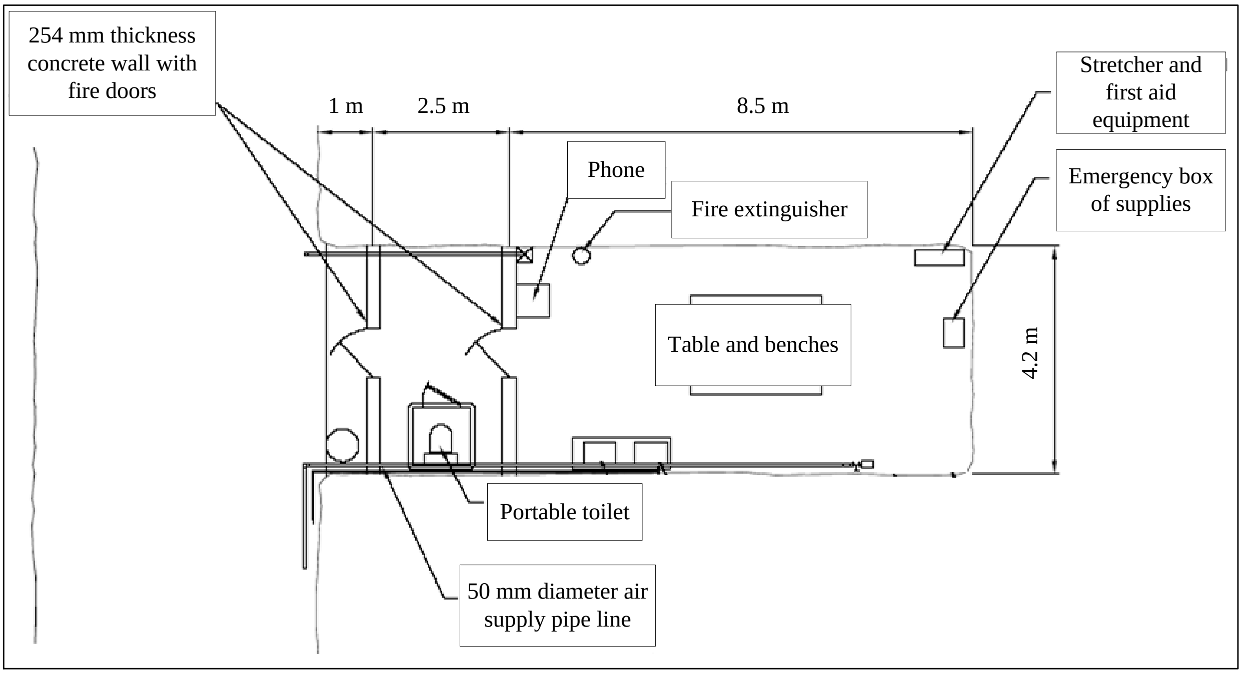

Figure 14: Typical underground refuge bay layout[8].

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[8] United States Mine Rescue Association. (2006) *Refuge station design and requirements*. Uniontown, USA. [Online]. www.usmra.com/.../refuge.../Refuge_Station_Design_Don_Peake.ppt [Accessed: 10 July 2013].

Underground refuge bays are supplied with compressed air through a 50 mm diameter compressed air pipeline and the refuge bays are usually pressurised to a pressure of 200–300 kPa. The positive pressure prevents toxic gases from entering the refuge bay. The required volume flow of fresh air that has to be supplied to the refuge bay is estimated at eighty-five litres per minute for every person occupying the refuge bay (Brake & Bates, 1999).

Typical compressed air requirements for selected underground compressed air applications discussed in this section are summarised in Table 2.

Table 2: Compressed air requirements of selected underground applications.

Compressed air application	**Compressed air consumption [m3/h]**	**Operating pressure [kPa]**	**Reference**
Pneumatic rock drills	190–320	400–620	(Tranter Rock drills, 2013)
Pneumatic loaders	348	480–860	(Trident SA, 2013)
Pneumatic cylinders	8–11	400–500	(Snyman, 2011)
Stope cooling	Site specific	Site specific	(Bluhm & Biffi, 2001)
Refuge bays	Eighty-five per person	200–300	(Brake & Bates, 1999)
Agitation	Site specific	400	(Marais, 2012)

2.3. Existing methods to reduce compressed air costs

2.3.1. Preamble

Various energy saving strategies have already been implemented on underground compressed air networks in the mining industry. Historical investigations indicate that the energy efficiency saving strategies yielded power savings of up to 2.2 MW on compressed air networks of deep level mines (Padachi *et al.*, 2009). In order to identify areas where the existing energy saving strategies can be improved, ample knowledge regarding the existing strategies is required.

On deep level mines, there are different mining activities during different periods of the day. Thus, compressed air requirements of mining shafts vary throughout the day. The daily underground operating schedule of a gold mining shaft during a typical production day would generally consist of activities such as drilling, charging up explosives, blasting, and sweeping (ore collection). Figure 15 shows the compressed air requirements during typical daily operation of a gold mining shaft.

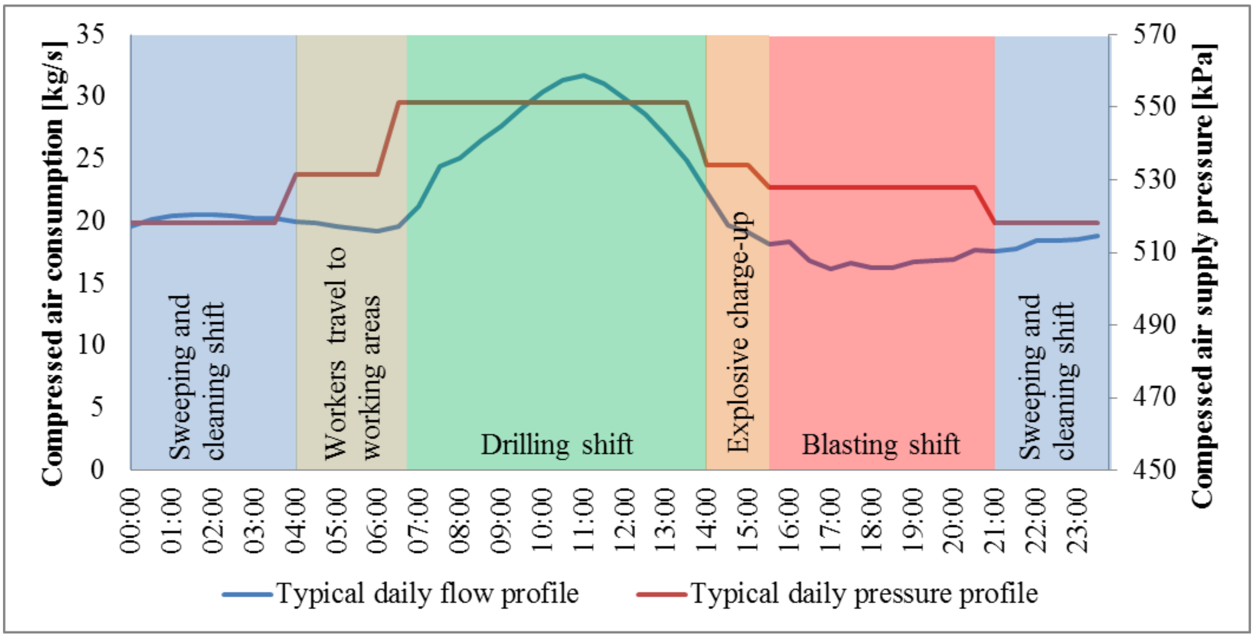

Figure 15: A typical operating schedule of a gold mine.

Mine workers start travelling from surface to their working areas from as early as 04:00. The path a mine worker has to travel to his workplace inside the stope areas was inspected during an underground site visit. A worker can take up to two hours to reach his workplace. This is due to the number of workers travelling, the availability of cages (the enclosure used to transport mine workers vertically down a mining shaft) and the distance to travel to their workplaces.

Once the worker has reached his workplace, work can commence and the drilling shift can officially start. During the drilling shift, pneumatic drills are used to drill 1.8 m deep holes into the rock face. Pneumatic drills are large consumers of compressed air during the drilling shift (Joubert, 2010).

During the explosive charge-up period, explosives are placed inside the holes drilled during the drilling shift. Figure 16 shows mine workers placing the explosives in the drilled holes. These explosives are usually wired to a centralised blasting panel, also known as a network slave station (NSS) box. The NSS box is manually activated by appointed mine personnel. Once activated, the explosives can be detonated remotely from surface. When all mine personnel have been evacuated, the explosives are detonated during the blasting period.

Figure 16: Explosives placed in the holes drilled during the drilling shift[9].

Due to the danger the blasting period poses, no mining activities are allowed during this period. As a result, the compressed air requirements during the blasting period are less than during any other period of the day. Compressed air consumers during this period are usually refuge bays, agitation tanks and system leaks.

After the blasting shift, the sweeping and cleaning period commences. From here onwards the daily production activities repeat itself. All underground compressed air consumers are supplied from one main pipeline feeding from the surface compressed air network. Consumers with the highest pressure requirement will determine the compressed air network-pressure set point at that time. Table 3 summarises compressed air consumers during the different production shifts.

Table 3: Typical compressed air consumers during various shifts.

Typical compressed air applications	Applicable production shift	Time of day
Pneumatic rock drills	Drilling shift	06:45–14:00
Pneumatic loaders	Sweeping and cleaning; drilling shift	21:00–14:00
Pneumatic cylinders	Sweeping and cleaning; drilling shift	21:00–14:00
Stope cooling	Sweeping and cleaning; drilling shift	21:00–14:00
Refuge bays	All	Continuous
Agitation tanks	All	Continuous
Network leaks	All	Continuous

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[9] Sobell, B., (2013) *Re-purposing an inactive mine site*. Colorado, United States of America. [Online]. Available: http://uteulay.wordpress.com. [Accessed: 23 July 2013].

Now that the typical daily underground operations found on a gold mine are known, the function of existing underground compressed air saving strategies can be investigated. The following topics will be investigated by a review of literature in the remainder of this chapter:

- existing energy saving strategies on surface compressed air networks,
- existing energy saving strategies on underground compressed air networks, and
- selecting a valve for a specific application.

2.3.2. Existing surface compressed air energy saving strategies

Recent studies have shown that energy saving strategies on the compressed air networks of deep level mines can be separated into two categories. The first category involves energy saving strategies on the supply-side of the compressed air network. These supply-side strategies are used to reduce the compressed air generation cost by improving the compressed air supply system’s efficiency. The second category involves the reduction in compressed air demand (Joubert, 2010).

Unmaintained, manually operated compressed air systems on deep level mines are usually overpressurised (Terrell, 1998). These compressed air systems are generally maintained at 600–700 kPa for the entire production day (Hongbo & McKane, 2008). Investigations have proven that a 20-50% energy saving potential is possible on these compressed air systems (Hongbo & McKane, 2008). An effective existing supply-side electrical energy saving strategy is to control the supply pressure of a compressor to a predetermined set point.

The supply pressure can be controlled by varying the compressor’s air intake volume. This can be achieved using various methods. One effective way of controlling the air intake volume of a compressor is by using a stator inlet vane controller. The volume of air taken in by the compressor is changed by varying the air intake angle using the inlet vanes (Lodewyckx *et al.*, 2008). By reducing the air drawn to the compressor, the electric power of the motor used to drive the compressor is reduced. This is evident from Equation 1 (Boles & Cengel, 2006).

Equation 1: Electrical power required to compress air.

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

Where:

W_e – Electrical power required by the motor to compress the air [kW]

$\dot{m}$ – Mass flow of the air being compressed [kg/s]

C_p – Specific heat constant $[\frac{kJ}{kgK}]$

T_{in} – Absolute inlet air temperature [K]

P_{out} – Absolute outlet pressure [kPa]

k – Polytropic exponent

P_{in} – Absolute inlet pressure [kPa]

η_c – Efficiency of the compressor [%]

η_m – Efficiency of the electric motor [%]

Controlling the supply pressure of a compressor to match the demand of the compressed air network also plays a significant role in compressed air demand reduction saving strategies. When the compressed air demand is reduced using these saving strategies, the required airflow through the compressor to maintain the supply-pressure set point can be reduced. As a result, electrical energy will be saved. Without compressor supply pressure control, electrical energy savings obtained from compressed air demand reduction saving strategies will be limited.

For the purpose of this study, the airflow through a leak in a compressed air pipeline is going to be compared with the airflow through an orifice. Due to the variance in the shapes of leaks found on a compressed air pipeline, this comparison is only for approximation purposes. Historical investigations have also used this comparison to describe the relation between system pressure and airflow through a leak (Snyman, 2011). Figure 17 shows an example of a leak found in the underground compressed air network of a South African gold mine.

Figure 17: A leak found on a compressed air pipeline[10].

From Equation 2 it can be seen that the flow through an orifice is directly proportional to the pipeline pressure (Boles & Cengel, 2006). Following this argument, the airflow through a leak in the compressed air pipeline can be reduced by reducing the pressure in the pipeline. Investigations have shown that leaks found on industrial compressed air networks can waste up to 30% of a compressor’s air output (Terrell, 1998).

Equation 2: Airflow through a leak.

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

Where:

$\dot{m}$ – Mass flow rate of air through leak [m^3/s]

$C_{discharge}$ – Discharge coefficient [0.6 for sharp edges, 0.97 for well-rounded edges]

k – Specific heat ratio of air. Taken as 1.4 [no unit]

P_{line} – Line pressure [kPa]

R – Gas constant. Taken as 0.287 [kJ/kgK]

T_{line} – Line temperature [K]

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[10] Photo taken at a South African gold mine.

The energy savings achieved by controlling the delivery pressure of a compressor to match the compressed air demand of the network can be summarised as follow:

- reduction in electrical power consumed by the motor driving the compressor,
- reduction in compressed air wasted due to system leaks, and
- reduction in pipe friction losses due to the lower flow rate.

A typical mine will have more than one compressor installed on an integrated compressed air supplier network. These compressors are interconnected and installed at strategic locations. Compressed air networks found in the South African deep level mining industry can have a total installed capacity of up to 85 MW (Schutte *et al.*, 2011).

Compressors are divided into two categories, baseload compressors and trimming compressors. In some ideal situations it is found that by operating a selected group of compressors, the required network pressure could be obtained. Baseload compressors can deliver the required airflow during low compressed air demand periods. These compressors would usually run throughout the day. Trimming compressors would then start and stop as the demand for compressed air changes throughout the day (Booysen *et al*., 2010).

The compressor-selection strategy is another supply-side energy saving strategy implemented in the deep level mining industry. Figure 18 displays a typical flow requirement profile of a ring-feed compressed air network. In this example there are five compressors that can supply compressed air to the network. The compressors have different air supply capacities. Compressor 1 and Compressor 2 are baseload compressors. The remaining compressors are trimming compressors.

Blow-off valves are used to release surplus air into the atmosphere when the compressor’s supply pressure gets too high. This safety control avoids compressor surge by keeping the compressor’s delivery pressure within safe operating boundaries (Berkele *et al.*, 2004). This method of avoiding compressor surge causes high energy losses (Booysen *et al.*, 2010). Implementing an efficient compressor-selection strategy along with inlet vane control will synchronise supply with demand; thus reducing the amount of blow-offs required. An efficient compressor running schedule is displayed in Figure 18.

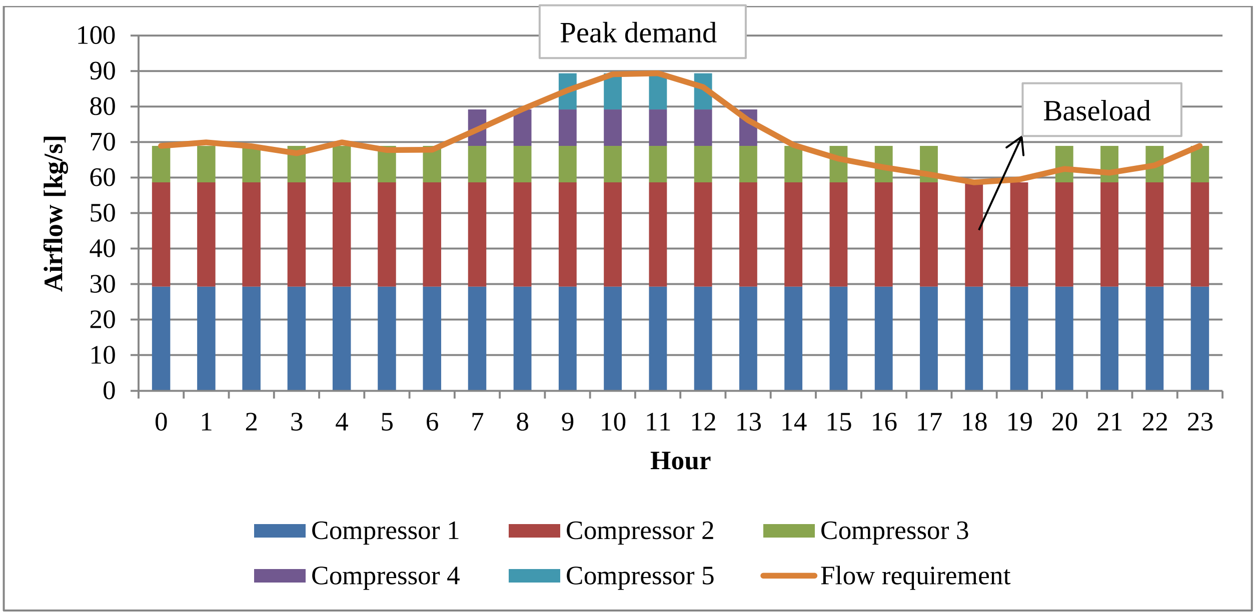


Figure 18: Efficient compressor selection for required airflow.

Other existing supply-side energy saving strategies found on compressed air networks in deep level mines include (Snyman, 2011):

- reducing the temperature of the compressor’s intake air,
- replacing old inefficient electric motors with more efficient electric motors,
- ensuring that the correct pipe sizes are used for the required flow range, and
- installing variable speed drives on the electric motors for compressor output control.

Some of the abovementioned supply-side energy saving strategies are more effective than others. The cost implications of the various saving strategies also differ. Each application should be investigated separately to identify the most suitable saving strategy. The focus will now shift from existing supply-side energy saving strategies to existing demand-side energy saving strategies.

Compressed air consumers on a ring-feed compressed air network (as discussed in Section 2.2.3) require different operating pressures. The compressed air network pressure is determined by the consumer that requires the highest pressure. Processing plants require a higher air pressure than mining shafts. If the processing plants and mining shafts are on the same compressed air network, the entire network needs to be pressurised to the pressure required by the processing plant.

An existing demand-side energy saving strategy is to divide the ring-feed compressed air network into a high- and low-pressure section (Joubert *et al.*, 2011). This can be achieved by installing control valves at strategic locations in the compressed air network. The processing plants can be supplied with compressed air from the high-pressure side and the mining shafts can typically be supplied from the low-pressure side.

By dividing the compressed air network into a high- and low-pressure section the following energy savings can be expected:

- reduction in pipe friction losses due to the lower mass flow on the low-pressure section,
- reduction in compressed air wasted due to system leaks, and
- as a result of the reduction in friction losses and leaks, a reduction in the electrical energy consumed by compressors.

2.3.3. Existing underground compressed air energy saving strategies

At a typical deep level mine, mining activities occur at various depths. As new technology develops, mining activities at greater depths become more feasible. A typical deep level mine will consist of various levels situated at different depths. A compressed air pipe will be located vertically in the shaft all the way down to the shaft bottom. At each level, a pipe will feed from the vertical pipeline supplying the level with compressed air.

Auto compression is the rise in compressed air pressure as a result of air being compressed by its own weight (Garbers *et al.*, 2010). Due to the effect of auto compression, the compressed air pressure at shaft bottom could differ from the compressed air pressure at surface. The air pressure gained at a certain vertical distance from surface can be calculated with Equation 3.

Equation 3: Calculating the effect of auto compression.

$$\Delta P = \rho g h$$

Where:

ΔP	–	Pressure gained due to the effect of auto compression	[kPa]
ρ	–	Density of air (at an average density of 1.05)	$[\frac{kg}{m^3}]$
g	–	Gravitational acceleration	$[9.81\,\frac{m}{s^2}]$
h	–	Vertical distance from surface	[m]

Pipeline friction losses can also affect the compressed air supply pressure on the various levels. The head loss due to pipeline friction is calculated with the Darcy-Weisbach equation (White, 2009). This equation has been combined with Equation 3 to compile Equation 4. The air pressure gained on various depths below surface, taking the effect of auto compression and pipeline friction losses into consideration, is calculated with Equation 4.

Equation 4: Air pressure gained at various depths below surface.

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

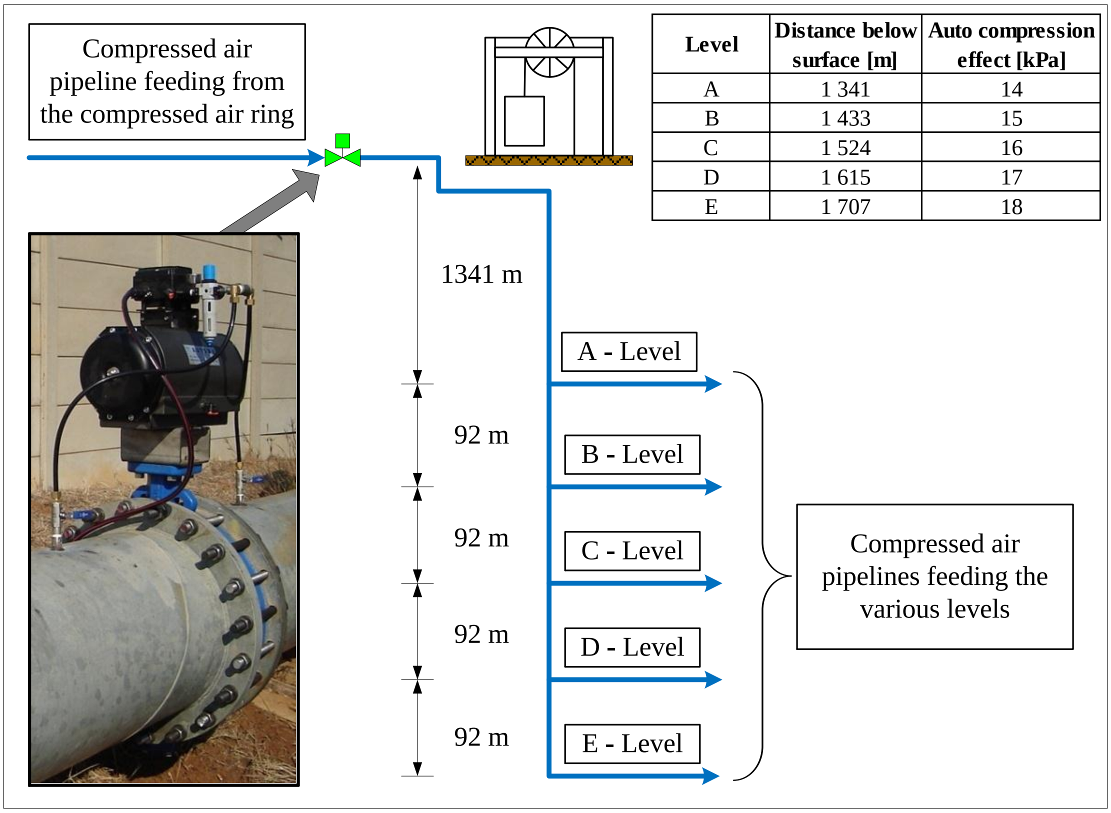
Where:

ΔP_{Total}	–	Air pressure gained at a vertical distance h from surface	[kPa]
f	–	Friction factor [from the Moody chart]	
L	–	Length of vertical pipeline	[m]
v	–	Flow velocity of the air	[m/s]
d	–	Inner diameter of the pipe	[m]

Due to different daily mining activities on a deep level mine (as discussed in Section 2.3.1), each level will require different compressed air pressures during different periods of the day. The different pneumatic equipment found on each level affects the pressure requirement of that mining level. The supply pressure required by a mining level depends on the consumer with the highest pressure requirement.

As the lifespan of the mine extends over time, the production activities on the various levels could change. This is due to the amount of gold available at various depths. As a result, the types of pneumatic equipment found on the levels will vary. For this reason, the pressure requirement of each level will change as time progresses.

A generally used underground compressed air consumption reduction strategy is to install a valve in the pipeline feeding the mining shaft. This valve is usually installed on surface just before the compressed air pipeline enters the mining shaft. For the purpose of this study, this valve will be referred to as the compressed air surface valve. Figure 19 illustrates a surface valve configuration along with the effect of auto compression, without considering pipeline friction losses.



Level	Distance below surface [m]	Auto compression effect [kPa]
A	1 341	14
B	1 433	15
C	1 524	16
D	1 615	17
E	1 707	18

Figure 19: Surface valve configuration and the auto compression effect[11].

The position of the surface valve is controlled to maintain the specified downstream pressure. Proportional-integral-derivative (PID) control is mostly used to control such a valve. The actual downstream pressure is measured with a pressure transmitter and serves as the process variable. The desired downstream pressure serves as the set point. The position of the surface valve is controlled according to the system error, which is defined as the difference between the process variable and the set point.

After measuring the downstream pressure with a pressure transmitter installed in the pipeline, the PID controller calculates the system error. Based on the magnitude of the calculated system error and the actual valve position, the PID controller calculates a new valve position to minimise the system error. The actual valve position is measured with a positioner installed on the actuated valve and serves as a feedback value. The actuator fitted on the control valve changes the position of the valve according to the newly calculated valve position.

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[11] Photo of a valve assembly taken at a South African mine.

E-Level in Figure 19 is 1 707 m below surface. Using Equation 4 it is estimated that the compressed air pressure at E-Level will be approximately 15 kPa higher than the surface compressed air supply pressure (pipeline parameters related to the case study were used in the calculation). For this reason the surface-pressure set point could be 15 kPa less than the required pressure on E-Level. This occurrence is displayed in Figure 20.

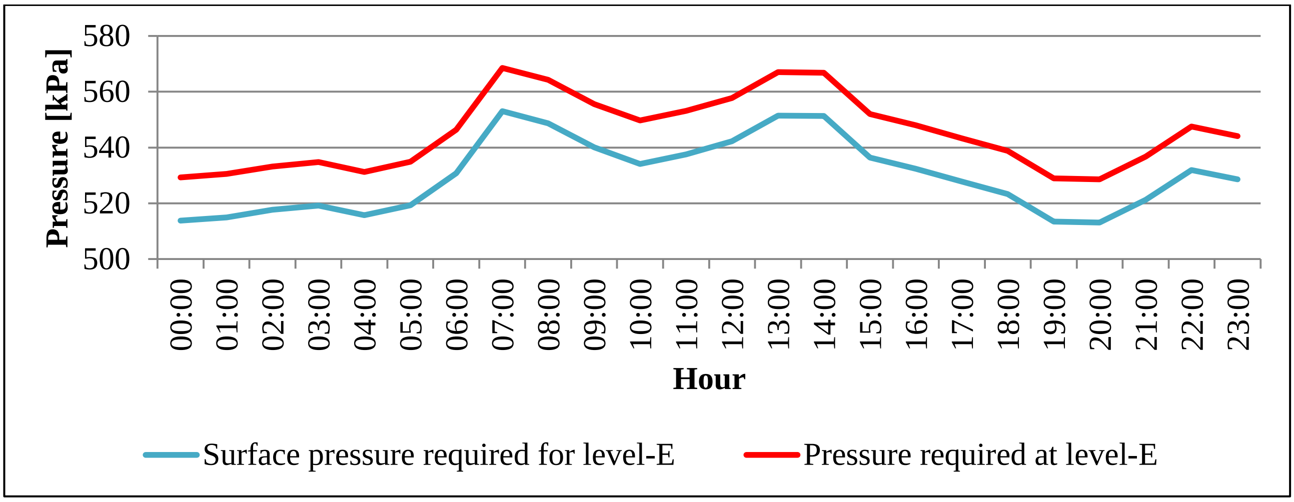

Figure 20: The effect of auto compression on the required surface pressure.

Similar to E-Level, the required surface pressure of each level can be determined by realising the effect of auto compression and pipeline friction losses. The required surface pressure for a specific time interval is determined by the level with the highest required surface pressure. If the required surface pressures of all the levels are plotted on a graph, the required surface-pressure set point can be determined. This occurrence is displayed on the graph in Figure 21.

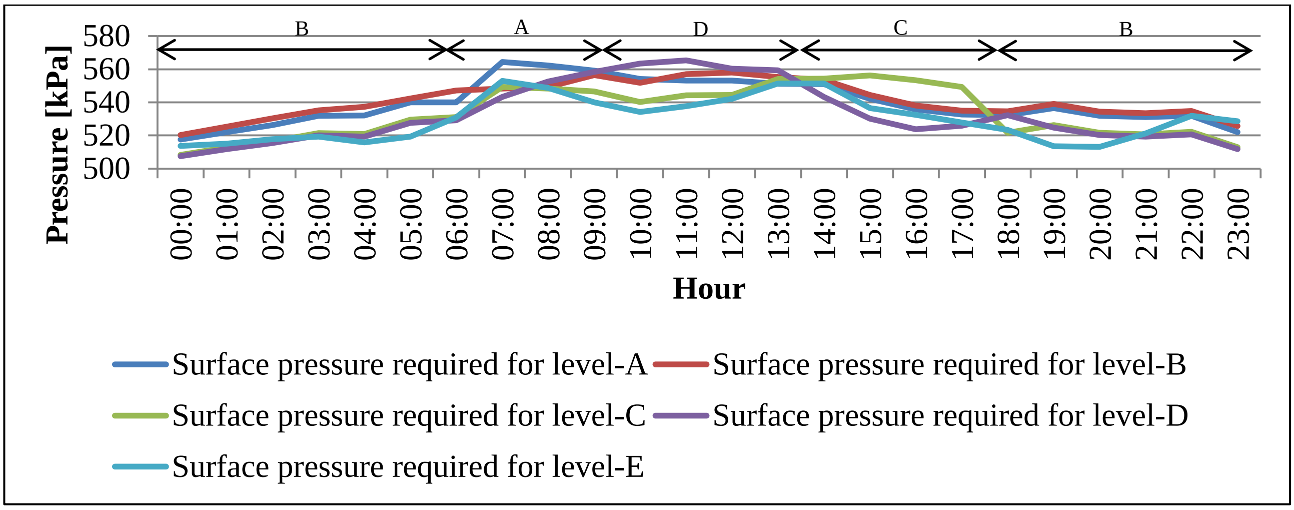

Figure 21: Surface supply-pressure set-point determination.

The minimum required shaft pressure can be maintained using the surface valve-control strategy. This strategy minimise the possibility of overpressurised air being supplied to the underground compressed air network. By keeping the surface supply pressure towards the mining shaft at a required minimum, the compressed air consumed due to leaks in the underground compressed air network will be minimised (as discussed in Section 2.3.2).

As already mentioned in Section 2.3.1, there are different mining activities on a deep level mine during different periods of a typical production day. This is applicable to each individual mining level. Thus, the various levels have different compressed air applications active during different time periods of the day. Another underground compressed air saving strategy is to install control valves in the pipelines supplying each level with compressed air.

These control valves are generally situated close to the main shaft and control the pressure of the air supplied to each level individually. Since compressed air pressure must be maintained, these control valves are controlled according to the pressure downstream of the valve. When the compressed airflow rate to a level suddenly increases, the valve would open to maintain the desired downstream pressure set point.

Alternatively, the control valve could be controlled to maintain a desired flow rate. However, this is not an indication of pressure available for the operation of equipment, but rather an indication of air usage. It is recommended that the flow rate on each level is monitored and an alarm activated should the flow rate exceed a certain set point. An investigation should be launched to determine the nature of this overconsumption.

Another existing underground compressed air strategy is to install isolation valves that isolate the compressed air pipeline feeding the stope areas. These valves are closed during non-drilling periods to avoid unnecessary compressed air being wasted in the stope areas. These valves are then manually closed by appointed mine personnel after each drilling shift. The mine personnel then reopen the valves at the start of the next drilling shift (Joubert, 2010).

2.3.4. Selecting the correct valve type

Depending on the applicable saving strategy and its objective, valves are often used to vary the flow and/or pressure of air. Valves are also used to isolate the compressed air supply in some applications. It is important to choose the correct valve for a specific application in order to achieve the desired objective and to maximise the lifespan of the valve.

The position of a valve can either be changed manually or with an actuator (actuators will be described in detail later in this section). A control device can be defined as a valve that manipulates the parameters of a fluid (such as air) to match a desired set point value. Control valves generally used in industry are displayed in Figure 22.

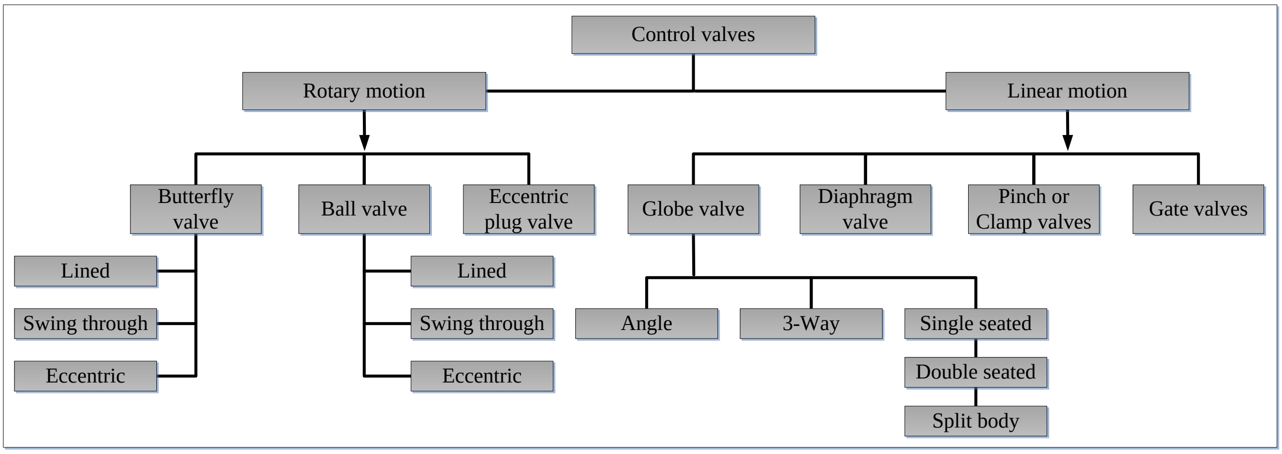

Figure 22: Typical control valves used in industry.

The different types of control valves can be categorised under three different types of standard flow characteristics. These flow characteristics can be defined based on the relationship between the flow rate through the valve and the valve opening (also known as valve travel) (PDHengineer, 2009). These standard flow characteristics are presented in Figure 23 and include (Fisher Controls International, 2005):

- quick-opening flow characteristics,
- linear flow characteristics, and
- equal-percentage flow characteristics.

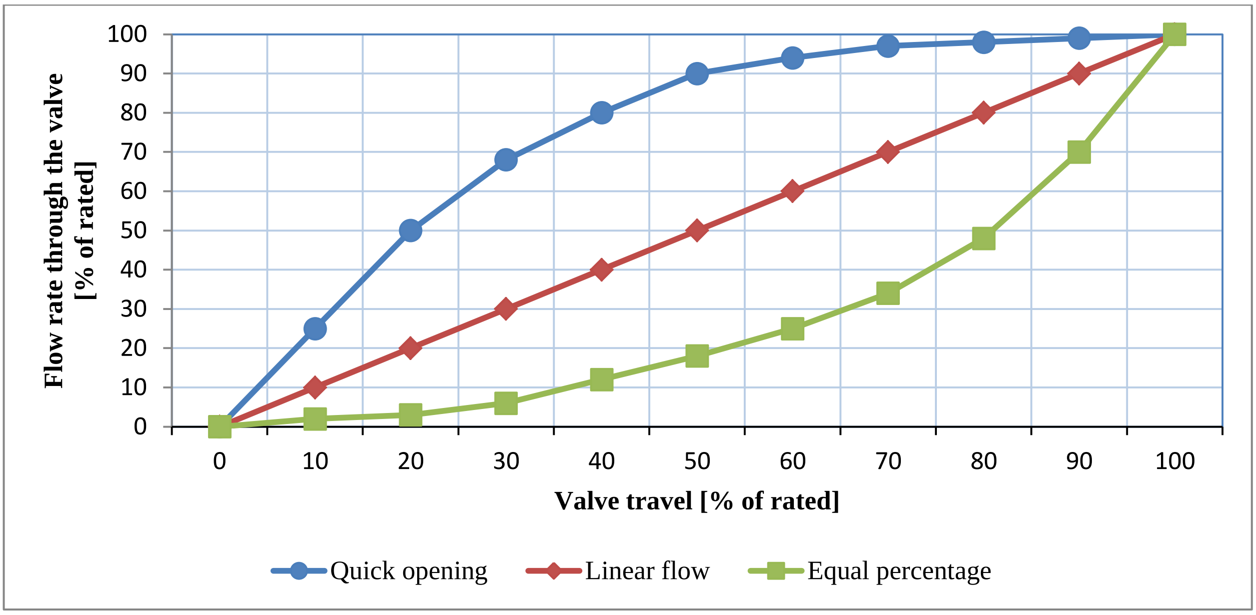

Figure 23: Standard flow characteristics of valves.

Valves have quick-opening flow characteristics if the maximum change in flow rate is achieved with minimal valve opening. Control valves with quick-opening flow characteristics are generally used in on/off applications where the maximum rated flow through the valve is needed as quickly as possible (Fisher Controls International, 2005).

Valves with linear flow characteristics produce flow rates through the valves that are directly proportional to the valve openings (percentage of valve travel). This type of valve is mostly used in applications where a constant change in flow rate is required (Fisher Controls International, 2005).

For a valve with equal-percentage flow characteristic, the change in flow rate through the valve is relatively small when the valve is near its closed position. The change in flow rate through the valve rapidly increases as the valve reaches its fully open position. Valves with these flow characteristics are ideal for pressure-control applications (Fisher Controls International, 2005).

There are various types of globe valves as indicated in Figure 22. Research has shown that single-seated globe valves are the most commonly used due to their ability to function in applications with stringent shut-off requirements (Fisher Controls International, 2005). Figure 24 displays a single-seated globe valve with cage-style trim ability.

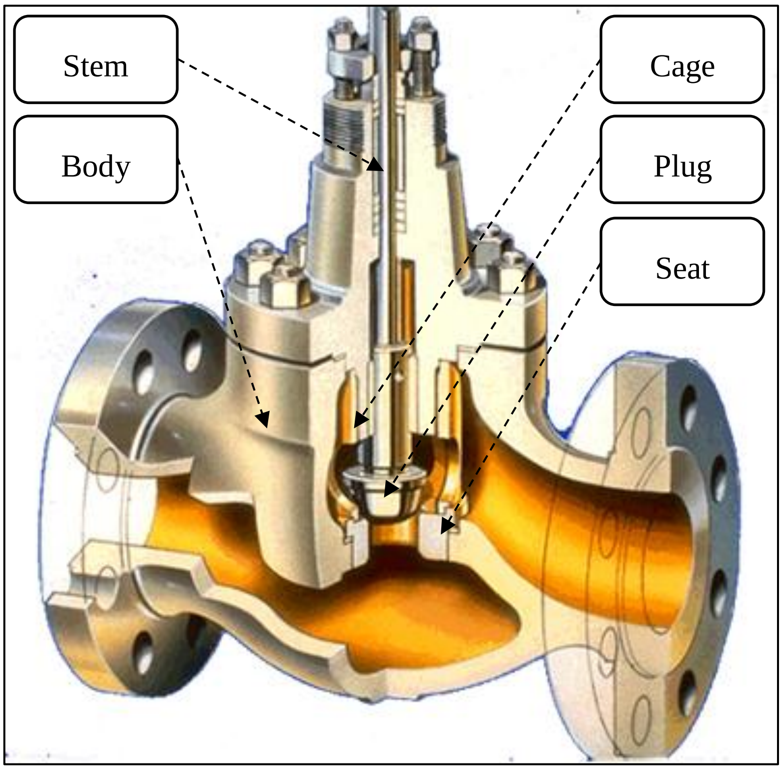

Figure 24: Single-seated globe control valve with cage-style trim[12].

Critical parts found within a single-seated globe valve are indicated in Figure 24. What makes a globe valve with cage-style trimming ability so unique is that different cages can be used to obtain the desired flow characteristic through the valve. Depending on the characteristic of the cage, it also reduces conditions such as noise pollution, flashing and erosion (Rahmeyer *et al.*, 1995). Figure 25 displays different characterised cages used to obtain different flow characteristics (Fisher Controls International, 2005).

Figure 25: Characterised cages for globe valve bodies.

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[12] Maylong Trading (Pty) Ltd. (2008) *Cage style globe valve*. Hong Kong, China. [Online]. Available: http://www.maylong-valves.com. [Accessed: 25 July 2013].

Although a globe valve with cage-style trim ability would be ideal to obtain certain flow characteristics for a specific application, this type of valve is expensive compared with a butterfly valve and a ball valve (Taljaard, 2012). Butterfly valves are known to provide an equal-percentage flow characteristic and are mostly used in throttling or on/off applications. When large pressure drops occur over the butterfly valve, large torque forces are required to change the position of the butterfly valve (Fisher Controls International, 2005).

V-notch ball valves also have equal-percentage flow characteristics. These types of valves are mostly used in shut-off applications. V-notch ball valves can also be used in pressure-control applications with a relatively small pressure drop over the ball valve. Ball valves and butterfly valves cause a small pressure drop over the valve when in the fully opened position (Fisher Controls International, 2005). Figure 26 displays a typical butterfly valve and a V-notch ball valve along with their critical parts (PDHengineer, 2009).

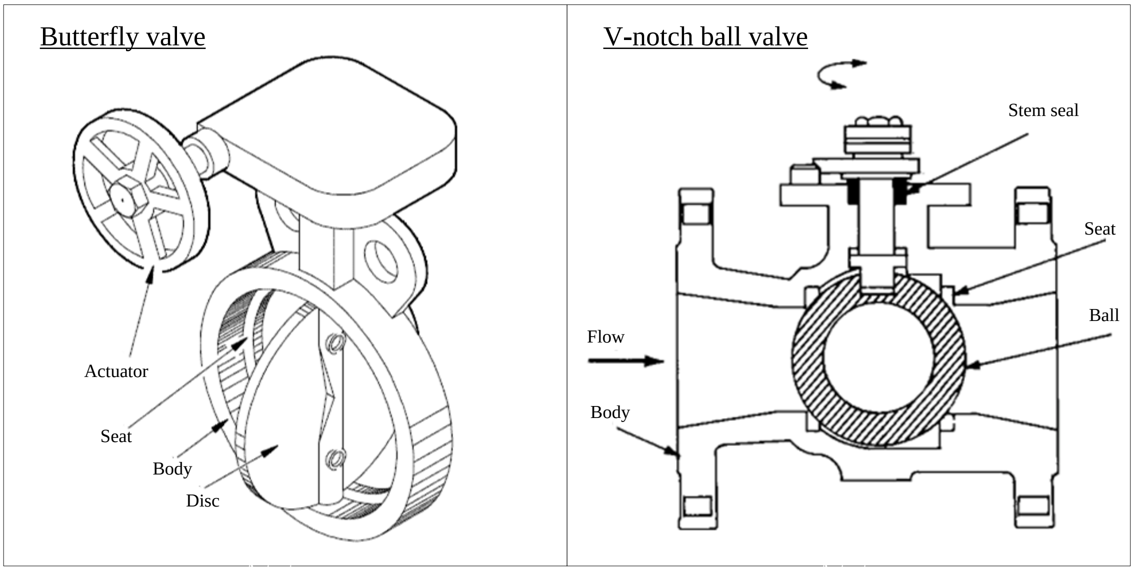

Figure 26: Butterfly valve and V-notch ball valve.

The valve together with all the components mounted on the valve body is called the control valve assembly. The control valve assembly generally consists of the following components (Fisher Controls International, 2005):

- valve body and its internal components,
- actuator,
- positioner, and
- limit switches.

An actuator is used to apply force to change the position of the valve. There are pneumatic, hydraulic, electric and manual types of actuators available. Each of these actuators has different advantages and disadvantages. Pneumatic actuators are the most commonly used actuators in industry and are less expensive than electric and hydraulic actuators. Electric and hydraulic actuators offer advantages where no air supply is available and where large forces are required to change the position of the valve (Fisher Controls International, 2005).

It should be noted that different types of pneumatic, hydraulic, electric and manual actuators exist. Figure 27 displays a rack and pinion electric actuator assembled to a butterfly valve. Figure 28 displays a diaphragm pneumatic actuator assembled to a globe valve.

Figure 27: Electric actuator - valve assembly[13].

Figure 28: Pneumatic actuator - valve assembly[14].

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[13] Beijing Haoli Valve Manufacturing Co. Ltd. (2013) *271D electric actuator butterfly valve*. Beijing, China. [Online]. Available: http://haolifa.en.alibaba.com. [Accessed: 25 July 2013].

[14] M.S. Engineering Works (2009) *Globe control valve assembly*. Ahmedabad, India. [Online]. Available: http://www.made-from-india.com/showroom/ms-eng. [Accessed: 25 July 2013].

The positioner is mechanically connected to a moving part of the valve to measure the position of the valve. The positioner receives the desired valve position signal from the PLC and compares it with the actual measured valve position. Depending on the type of actuator, the positioner regulates either the airflow (in the case of a pneumatic actuator) or the electric current (in the case of an electric actuator) towards the actuator to move the valve to the desired position.

In most energy saving applications a control valve assembly is used to control a specific parameter. As described in Section 2.3.3 this control is generally obtained using a PID control loop. It should be noted that the control valve assembly itself is one of several components in the control loop. Some equipment used in combination with the control valve assembly to obtain the desired control are (Taljaard, 2012):

- pressure transmitters,
- flow transmitters, and
- controllers such as PLCs.

Factors that should be taken into consideration when a valve is selected are (Booysen *et al*., 2011):

- type of medium applicable,
- flow parameter of the specified medium related to the application, and
- pressure parameter of the specified medium related to the application.

For the purpose of this study the type of medium is already fixed, namely air. The flow and pressure parameters will be different for each application and would typically depend on the location, time of day and the compressed air demand. A fourth constraint, which is valve cost, also plays a deciding factor in most situations. This constraint is also often the reason why the wrong valve for a specific application is chosen (Zappe, 1999).

When the correct valve type has been chosen, the correct valve size should be calculated. An oversized valve can lead to unnecessary expenses. A valve that is too small for its intended application could choke the system and production losses could occur. In a compressed air system, incorrect valve sizing could cause noise pollution and erosion damage to the internal parts of the valve (Emerson, 2012).

2.4. Project implementation procedures

2.4.1. Preamble

The primary goal of a DSM project could either be to change the pattern of the electrical energy used by the consumer, or to reduce the electrical energy consumption (Pelzer *et al.*, 2008). Energy efficiency DSM projects are implemented to reduce the electrical energy consumed by the consumer. This study focuses on underground compressed air DSM projects, which are classified as energy efficiency DSM projects.

Improving an existing DSM project will be seen as a separate, new project, and therefore normal project phases will be followed to successfully implement the proposed improvements. This section will focus on:

- typical project phases,
- project performance measurement strategies, and
- justifying improvements to existing DSM projects.

2.4.2. Typical project phases

Figure 29 displays typical project phases relating to a DSM project.

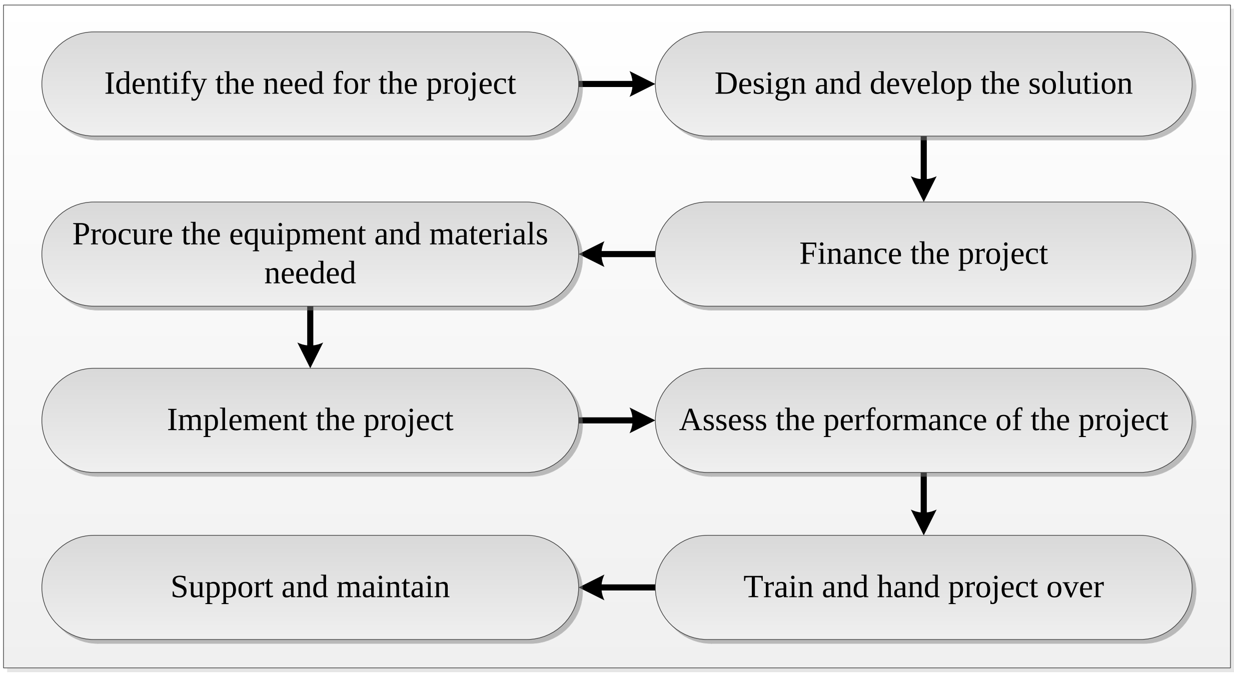

Figure 29: Typical project phases for a DSM project.

At first the need for improving an existing underground compressed air DSM project has to be identified. The feasibility of various improvement strategies also needs to be investigated. This can be done using simulations (where the expected improvement in electrical energy savings is simulated) and calculating implementation cost (where the cost to implement the various improvements is estimated).

Once the estimated improvement in electrical energy savings and the estimated implementation cost are known, a payback period can be determined. Figure 30 displays a graph that indicates the typical cash flow and payback period of a project. Based on the calculated payback period, an informed decision can be made on whether or not it would be feasible to implement the proposed improvements.

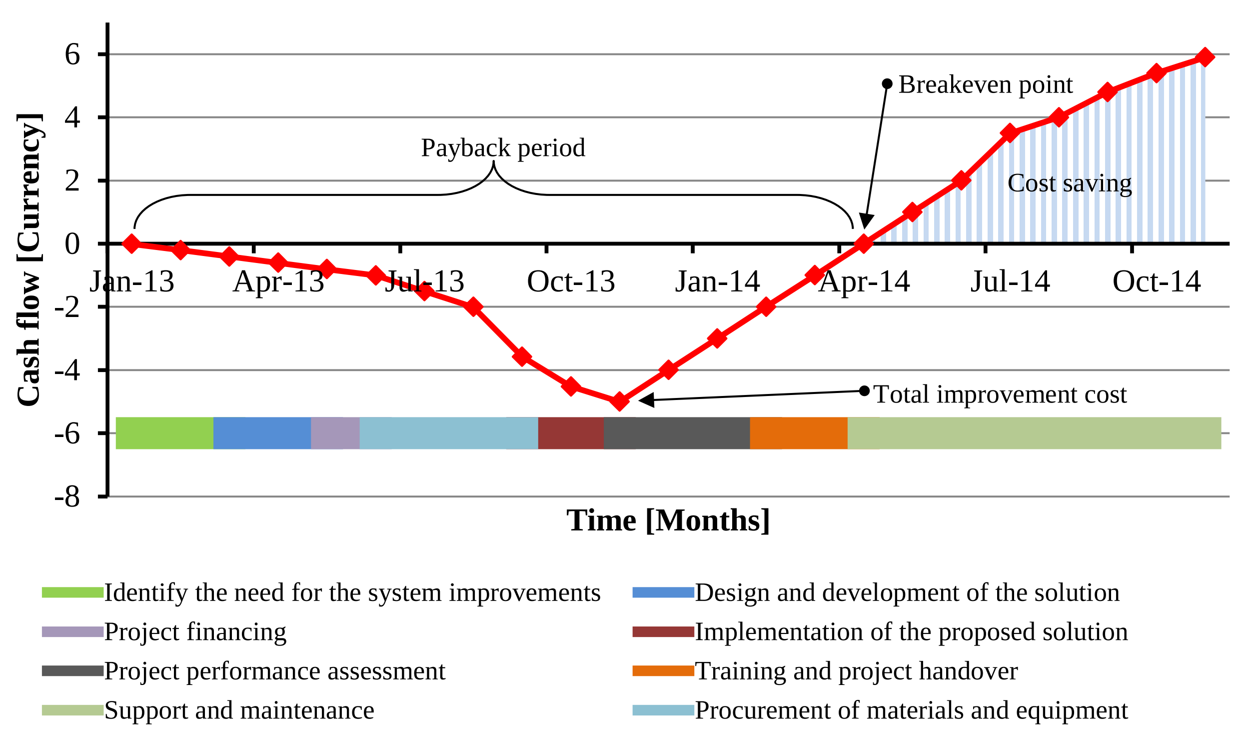

Figure 30: Graphical demonstration of a typical project cash flow and payback period.

2.4.3. Performance measurement strategies

The reduction in electrical energy consumption after a DSM project has been implemented has to be measured. By measuring the reduction in the electrical energy consumed, the project’s performance can be justified. This is done by comparing the electrical energy consumed after the project has been implemented with the electrical energy consumption before the project was implemented. The electrical energy consumed before the DSM project has been implemented is referred to as the baseline.

Baseline scaling compensates for any system changes, not related to the energy saving project, that could have changed the amount (normally measured in m^3/s) of compressed air consumed after the original baseline was constructed. There are various baseline adjustment methods in industry for different types of DSM projects. For the purpose of this study, one should only be aware that there are different types of scaling methods. Some scaling methods used in various DSM projects are energy neutral scaling, peak scaling and production scaling (Marais *et al.*, 2011).

The relationship between the compressed air system's electricity consumption and the production is understandable due to the number of pneumatic equipment used in the mining process. With the production baseline scaling method, the scaling factor is calculated based on the variance in production between the period when the original baseline was constructed, and the time of measurement. Figure 31 displays the daily power profiles of a typical compressed air DSM project.

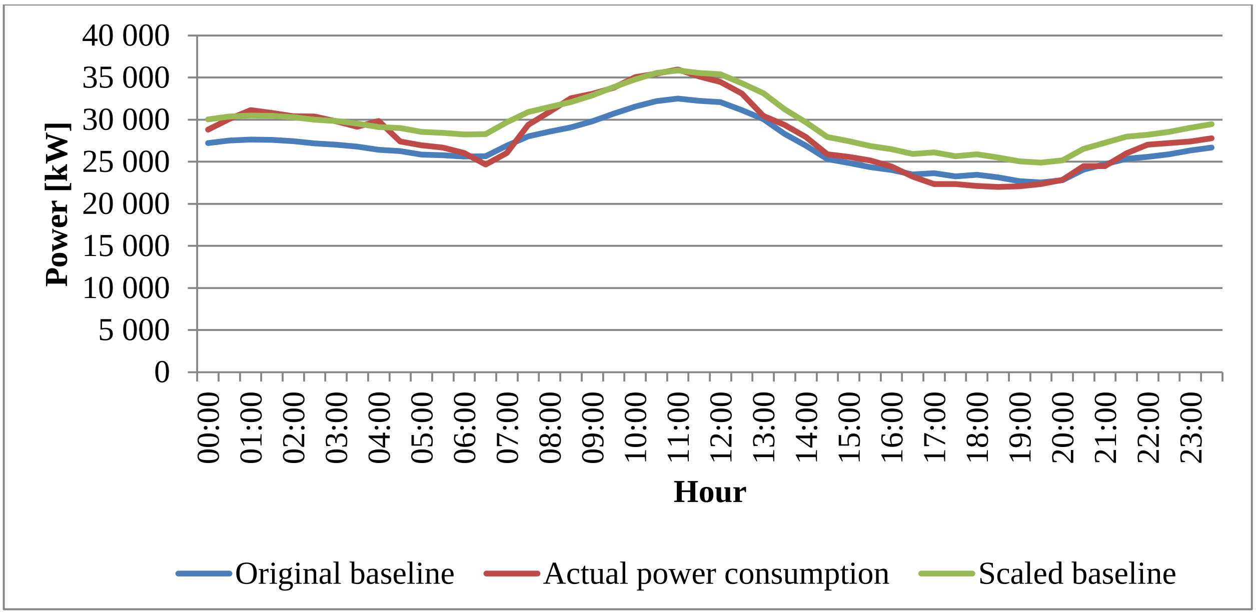

Figure 31: Actual power profile and baselines of a typical compressed air DSM project.

From the power profiles displayed in Figure 31 it is visible that the scaled baseline is greater than the original baseline. This indicates a production increase since the original baseline has been constructed. The measurement process is conducted by an independent measurement and verification (M&V) team (Eskom, 2009).

2.5. Conclusion

In this chapter compressed air networks in the deep level mining industry were investigated and categorised. It was found that integrated compressed air supplier networks, with multistage centrifugal compressors as supply sources, are mostly used. The ore mining procedure was discussed to understand the functions of various underground compressed air consumers. The underground compressed air consumers were investigated and important information such as their compressed air requirements was discussed.

Existing compressed air DSM projects in the deep level mining industry were investigated. Information regarding important equipment used in these projects was presented. Typical project phases were presented and the measurement of electrical energy saving achieved was discussed. Information required to modernise and improve an existing underground compressed air energy saving project is now available.

Chapter 3: Research methodology and system design

[15]

In this chapter the method used to improve an existing underground compressed air DSM project will be presented. The simulated impact of the proposed improvements will be discussed.

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[15] Photo taken at a South African mine.

3.1. Introduction

One of the reasons why energy saving strategies are implemented on underground compressed air networks is to reduce operating cost. With the escalation in electricity cost, the viability to improve existing saving strategies has grown. However, it is important to investigate the feasibility of modernising and improving existing underground compressed air DSM projects before the projects are implemented.

Various project constraints could halter a modernisation and improvement strategy. An incorrect decision on whether or not to improve an existing savings project and which strategies to follow could result in inadequate additional energy savings and significant capital losses.

In this chapter an existing underground compressed air savings project will be identified along with methods to improve the project. A simulation model will be formulated to calculate the expected improvement in electrical energy savings. Following the calculation of expected improvement in electrical energy savings, the feasibility of the proposed improvements will be determined and the feasible improvements will be implemented.

The first step will be to identify existing underground compressed air DSM projects in the deep level mining industry. As mentioned in Chapter 2, platinum and gold mines are mainly considered deep level mines in the South African mining industry. Large underground compressed air networks are usually found on these mines.

3.2. Analysing the underground compressed air saving strategy

3.2.1. Identifying existing underground compressed air DSM projects

To commence with identifying existing underground compressed air DSM projects, the following information regarding various platinum and gold mines should be obtained:

- location,
- expected lifespan,
- production capacity, and
- details of relevant mine personnel.

Energy Service Companies (ESCOs) are often used to investigate, implement and test electrical energy saving projects. For this reason the consulting engineers' travel cost will increase the project improvement cost. The accessibility of the mine will also influence other project expenses such as equipment delivery cost. Therefore, the location of a mine can contribute to the feasibility of proposed improvements.

By comparing the estimated cost savings with the project improvement cost, a payback period can be calculated. The project improvements will not be feasible if the payback period exceeds the expected lifespan of the mine. Thus, the expected lifespan of the mine is an important piece of information that should be obtained during the early investigation phase.

The production capacity of the mine will be an indication of the size of compressed air network to expect. Opportunities for underground compressed air DSM projects will be higher for larger underground compressed air networks. Therefore, existing underground compressed air DSM projects would most likely be found on deep level mines with large production capacities.

Final confirmation as to whether or not an underground compressed air DSM project exists at a mine should be obtained by contacting relevant mine personnel. The investigation should persist if the following findings have been made:

- confirmation has been received that an existing underground compressed air DSM project has been implemented at the mine,
- location and life expectancy of the mine favour the possibility for improving the existing project, and
- necessary legal documents are in place to investigate the existing project.

3.2.2. Existing system operation

It is important that underground compressed air DSM projects should not affect production activities. If production is affected, significant income losses could occur. For this reason, any improvements made to an existing saving project must not affect production activities.

Information listed in Table 4 must be gathered before detailed investigations can start. This information should give the investigator a proper background regarding the existing system and which improvements would be possible without affecting production activities.

Table 4: Background information on an existing underground DSM project.

No.	**Description**	**Discussed in section**
1	Mining methods in use	2.2.4
2	The daily mining operating schedule	2.3.1
3	Underground layout	3.3.2
4	Locations with high compressed air usage	3.3.3
5	Compressors installed and their power demand	2.2.1

The underground layout of the deep level mine should give insight as to why certain equipment was installed at specific locations. It will also familiarise the investigator with the underground environment before a site visit is conducted.

Mining levels with high production outputs are generally synonymous with high compressed air usage. Locations to improve existing saving strategies could be pinpointed by identifying levels with high production outputs. Information regarding the mining methods used and the daily mining operating schedule could possibly provide information as to why certain energy saving strategies were previously implemented. The flow diagram displayed in Figure 32 summarises the operation analysis procedure to be followed.

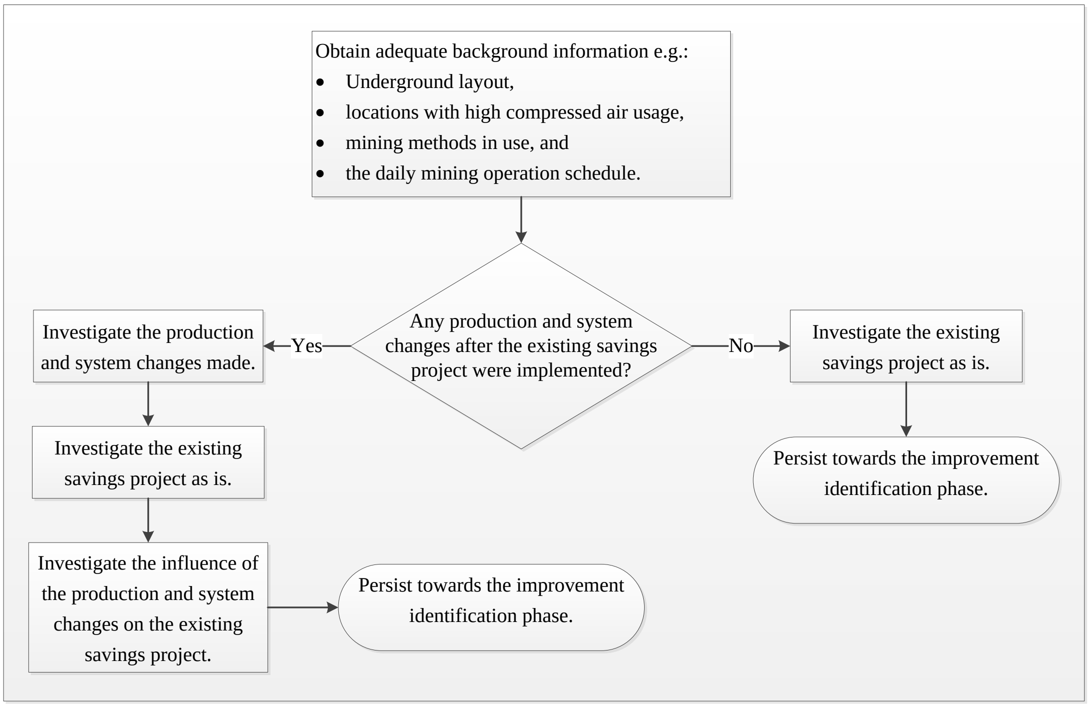


Figure 32: Existing underground compressed air DSM project operation analysis.

3.2.3. Analysing the performance of old projects

Electrical energy savings achieved by an underground compressed air DSM project are measured by comparing the actual electrical energy consumption with the electrical energy baseline (as discussed in Section 2.4.3). By analysing the performance of existing energy saving projects, valuable information can be obtained. Typical information that could assist in analysing an existing energy saving project is summarised in Table 5.

Table 5: Existing savings project performance information.

No.	Information description
1	Time elapsed after implementation
2	Electrical energy saving target for a typical production day
3	Scaling method used
4	Electrical energy savings achieved during performance assessment
5	Most recent electrical energy savings achieved

During the time that elapsed after the existing project has been implemented, technology related to control valve assemblies, communication networks and so forth could have improved. Situations which could have been a problem at the time of the previous implementation could now possibly be solved with new and improved technology.

It is important to know which type of scaling method was used to scale the electrical energy consumption baseline. This information could play a significant role when the achieved savings are analysed. While investigating existing projects related to this dissertation it was found that in most cases the measured electrical energy savings were inaccurate. The main reason for this phenomenon was because outdated baselines and scaling methods were used.

Due to the inaccurate measurements, electrical energy savings achieved by the existing saving projects could not be used as a parameter to analyse the possibility of improving existing projects.

3.3. Identifying solutions to improve the existing system

3.3.1. Preamble

The first objective of the methodology was to single out existing underground compressed air DSM projects that would be the most feasible to improve. The next step was to get familiar with the operating procedures of these projects and their environments.

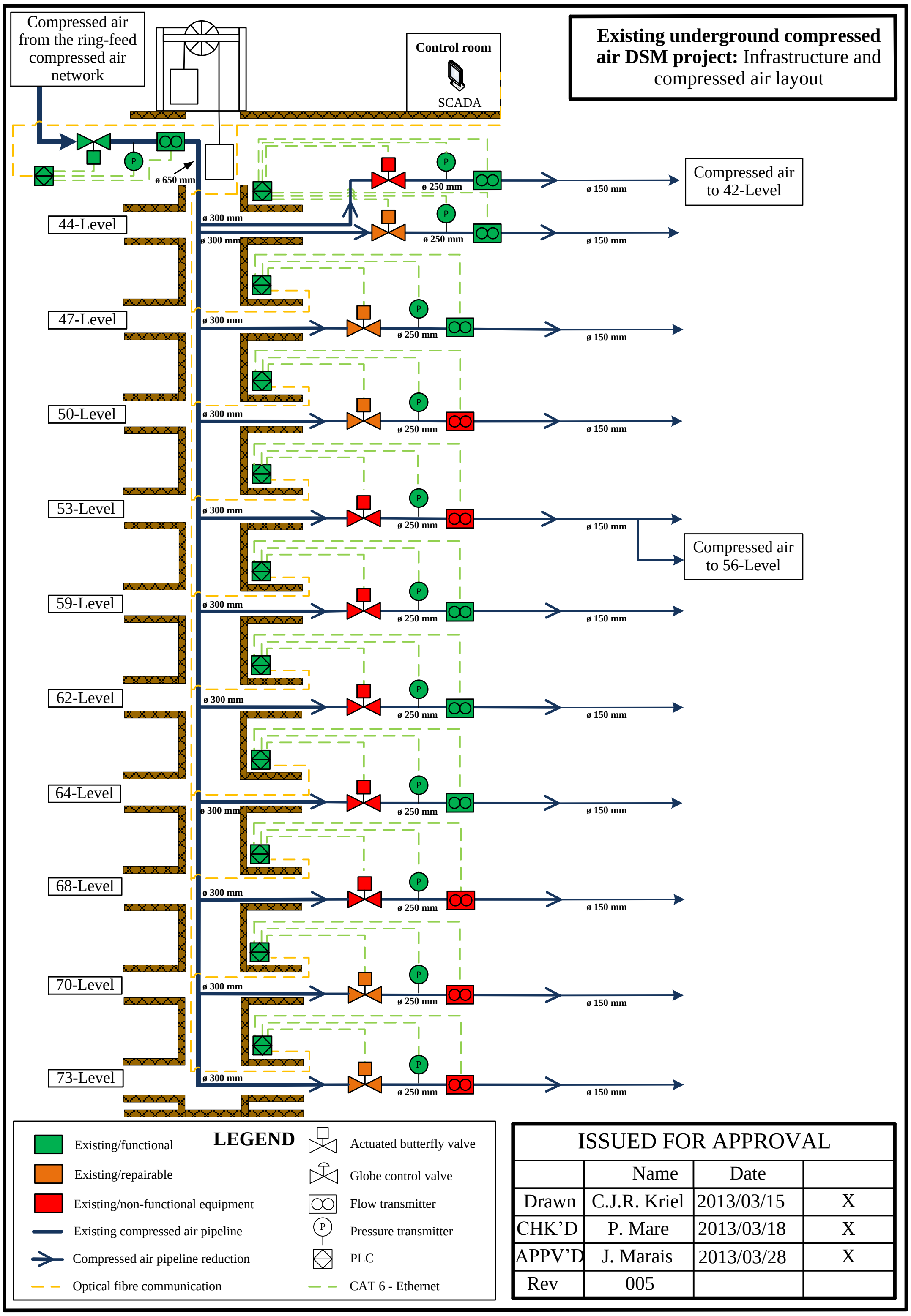
Thereafter, the underground compressed air network had to be investigated and the type of underground compressed air DSM project implemented at the mine had to be identified (Section 2.3.3 provides background regarding existing underground compressed air DSM projects). The equipment used in the existing savings project along with compressed air measurements at key locations had to be investigated. With the information obtained during these investigations, methods to modernise and improve the existing savings project could be identified.

3.3.2. Case study: background information

A deep level mine where a DSM project was implemented on the underground compressed air network will be discussed as a case study. This mine was selected because enough information was already available during the early investigation stage to identify the need for improvement. The mine will be referred to as *Mine A* because the name of the mine where this strategy was implemented may not be mentioned. Figure 33 shows the underground compressed air network layout with the existing equipment relating to the existing savings project found on Mine A. The existing DSM project was implemented in 2009.

The underground compressed air network at Mine A consisted of a 650 mm diameter pipeline situated vertically in the mining shaft. An actuated butterfly valve situated on surface controlled the supply pressure of the air feeding this pipeline. The valve was controlled via a PID control loop to maintain a desired downstream pressure set point (as explained in Section 2.3.3). The set point could be changed on the SCADA network.

The mining shaft had twelve active production levels from where ore was extracted. At the various levels, 300 mm diameter pipelines extracted compressed air from the vertically situated pipeline. The 300 mm diameter pipelines were horizontally placed and served as the main compressed air supply source towards the respective levels.



ISSUED FOR APPROVAL			
	Name	Date	
Drawn	C.J.R. Kriel	2013/03/15	X
CHK'D	P. Mare	2013/03/18	X
APPV'D	J. Marais	2013/03/28	X
Rev	005		

Figure 33: Existing infrastructure and underground compressed air layout

The 300 mm diameter supply line was reduced to a 250 mm diameter pipe approximately 100 m from where the compressed air was extracted from the vertical pipeline. An actuated butterfly valve had been installed on each compressed air supply line during the previous project, approximately 10 m after the pipeline reduction. These actuated butterfly valves were also controlled (via a PID control loop) to maintain a downstream pressure set point.

PID control was executed by a PLC that had been installed in the substations situated 40 m from the shaft on each level. Due to the functional limitations of the old PLC, the downstream pressure set point had been hard-coded on the PLC itself. As a result the downstream pressure set point could not be altered remotely from the surface control room. Should it have been necessary to change the downstream pressure set point of a specific level, a technician would had to go to the level-specific PLC and change the values on the PLC using the correct software.

Pressure transmitters had been installed downstream of all actuated butterfly valves during the previous project. The value measured by these pressure transmitters served as the PID control loop process variable. This process variable was critical for valve control. Flow transmitters had also been installed on the compressed air pipeline feeding the various levels. Similarly, a flow transmitter had been installed on surface in the compressed air pipeline feeding the mining shaft.

The flow transmitter installed on surface measured the total compressed air consumed underground. The flow transmitters installed on the compressed air supply line feeding the various levels measured the total compressed air consumed by individual levels. The sum of the values measured by the flow transmitters that had been installed on the various levels had to be more or less equal to the measured value of the flow transmitter installed on surface.

The existing underground compressed air DSM project had been implemented at Mine A two and a half years prior to this investigation. The saving project had been implemented by the mine itself. No formal documentation was available regarding the savings that had been achieved by the existing saving project.

The existing compressed air DSM project entailed controlling the supply pressure of the compressed air towards each level. Pressure set points had been determined based on the pressure requirement of each level. These pressure set points had been programmed into the PLCs.

By controlling the supply pressure of each level using the minimum required pressure during a specific time period, compressed air losses through system leaks and open ends had been minimised. By changing the supply pressure to the various levels during certain time periods of the day, the minimum required surface pressure could be reduced. For this reason the surface valve pressure set points had been recalculated and the newly calculated surface-pressure set points had been changed on the SCADA system.

3.3.3. Identifying areas for improvement

To identify areas for improvement on the existing underground compressed air DSM project the compressed air parameters (pressure and flow) measured at key locations on the underground compressed air system had to be investigated. All the existing pressure and flow transmitters in the underground compressed air system on Mine A are displayed in Figure 33.

It was found that all the existing pressure transmitters were in a working condition. Pressure data downstream of the butterfly valves were available on each level. On the contrary, some of the existing flow transmitters were not in a working condition. The flow transmitters installed on levels 50, 53, 68, 70 and 73 were all faulty and no flow data were available for these levels. Repairing or replacing these faulty flow transmitters was the area first identified to be improved.

Flow data for the individual mining levels are vital to accurately investigate the existing system and to further identify areas of improvement. The flow data is also needed to accurately calculate the expected improvement in energy savings. For this reason, portable flow transmitters were used on all the levels where compressed airflow data were needed. These flow transmitters were used to obtain data for a period of three months. With this data a true reflection of the average compressed air consumption per level for a typical production day could be obtained.

The next step was to determine if the existing underground compressed air DSM project was still functioning according to the original design. The primary objective of the existing compressed air DSM project had been to lower the supply pressure of the various levels during selected periods of the day. With pressure data available for all the levels, the functionality of the existing compressed air DSM project at Mine A could be determined.

With the most recent supply pressure data, an average daily pressure profile for each level could be constructed for a typical production day. The proposed pressure set points for each level were obtained from historical data. The actual daily pressure profile was then compared with the daily pressure set-point profile to determine if the pressure set point values were maintained.

It was found that the actual supply pressure profiles did not match the supply-pressure set point profiles for the majority of the levels. Figure 34 shows that the actual pressure profile of 68-Level did not match the supply-pressure set-point profile. This occurrence was found on all the levels except for 50-Level, which will be discussed later in this section.

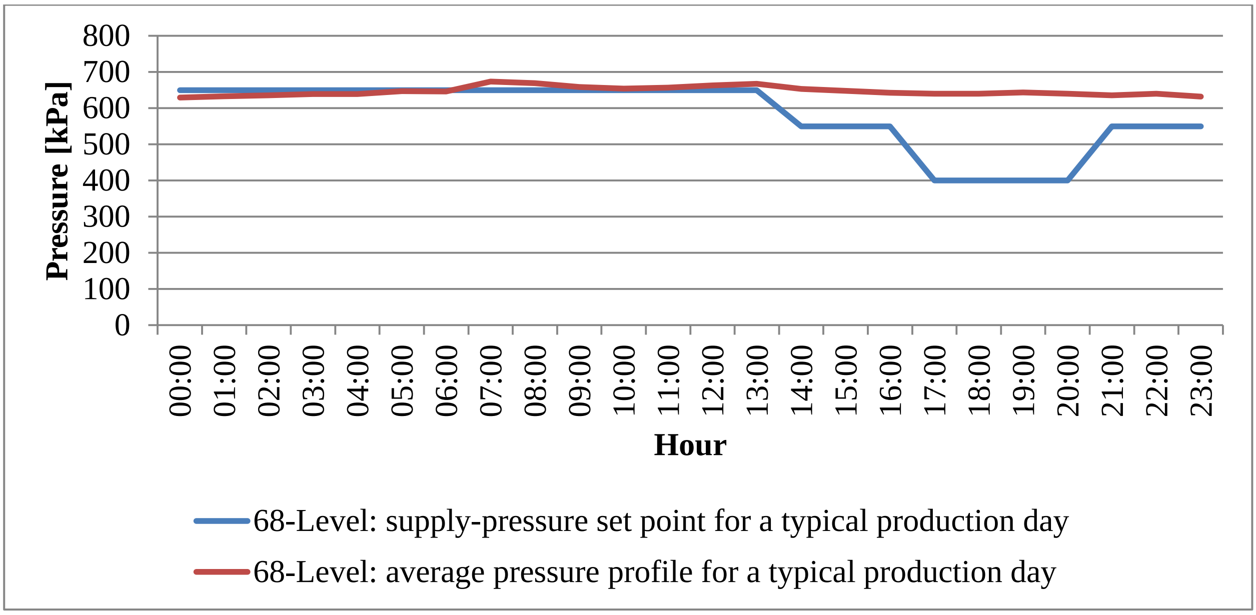


Figure 34: Actual pressure and pressure set-point profile for 68-Level.

Due to the lack of available data, it was not possible to determine the time period during which the supply-pressure set points had not been maintained. However, using the data available it was determined that the existing underground compressed air DSM project had not been functioning correctly for the year preceding the study. The supply-pressure control function on the various levels could be improved by re-establishing the supply-pressure control on each level.

Various reasons could be the cause of failing to maintain the proposed pressure set points. Based on the infrastructure and system control of the existing saving strategy, the following possible reasons were identified:

- communication failure between the PLC, positioner, actuator or pressure transmitter,
- communication failure between the PLC and the SCADA network,
- malfunctioning of the PID control loop executed by the PLC, or
- mechanical failure of the butterfly valve.

The communication links between the various pieces of equipment were tested. The possibility of a communication failure between the SCADA network and the PLC was eliminated because the pressure and flow data were logged on the SCADA network. This was also an indication that the communication network between the PLC, pressure transmitters and functioning flow transmitters was in a working condition.

With feedback from the valve positioner also logged on the SCADA network, it was possible to determine if the communication between the PLC and the valve positioner was still active. The valve position was logged as a percentage value on the SCADA system.

The valve position data was obtained and analysed. Each level’s butterfly valve position values were compared with the actual pressure and supply-pressure set-point profiles. Two phenomena were found on different levels:

1. the position of the butterfly valve changed when the downstream pressure set point changed, but with little or no effect on the actual downstream pressure,
2. the position of the butterfly valve did not change at all when the downstream pressure set point changed.

Describing Phenomenon 1:

The first phenomenon was found on levels 47, 50, 70 and 73. During a typical production day the downstream pressure set points of these levels were altered. The pressure set-point profile for a typical production day on 50-Level is displayed in Figure 35 and serves as an example.

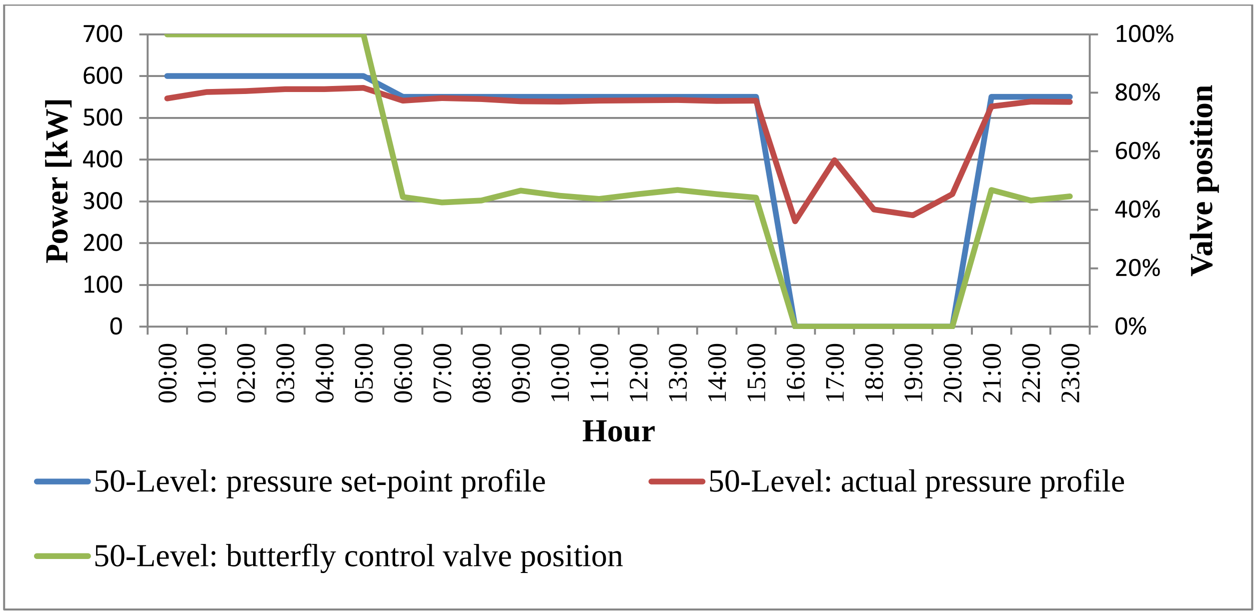


Figure 35: 50-Level butterfly valve position analysis.

From Figure 35 it is visible that when the actual supply pressure was below the set-point value, the position of the valve was fully open. When the supply-pressure set point was lowered to a value below the actual supply pressure, the position of the valve partly closed. When the supply-pressure set point was reduced to 0 kPa, the valve position changed to a fully closed position. This was an indication that the PID control loop was functioning correctly.

When the pressure set point was reduced to 0 kPa, the position of the valve changed to fully closed and a drop in downstream pressure occurred. The downstream pressure never reached the pressure set point of 0 kPa. This was an indication that there was most probably a mechanical problem on the butterfly valve that caused the butterfly valve to not seal properly.

When the butterfly valve on 50-Level was removed from the compressed air pipeline, it was found that the rubber seat was damaged due to extreme erosion. The damaged seat was the reason that the valve did not seal properly when it was in a fully closed position. Figure 36 displays a butterfly valve with a damaged seat due to erosion. The rubber seat could be replaced and the refurbished butterfly valve could be reused.

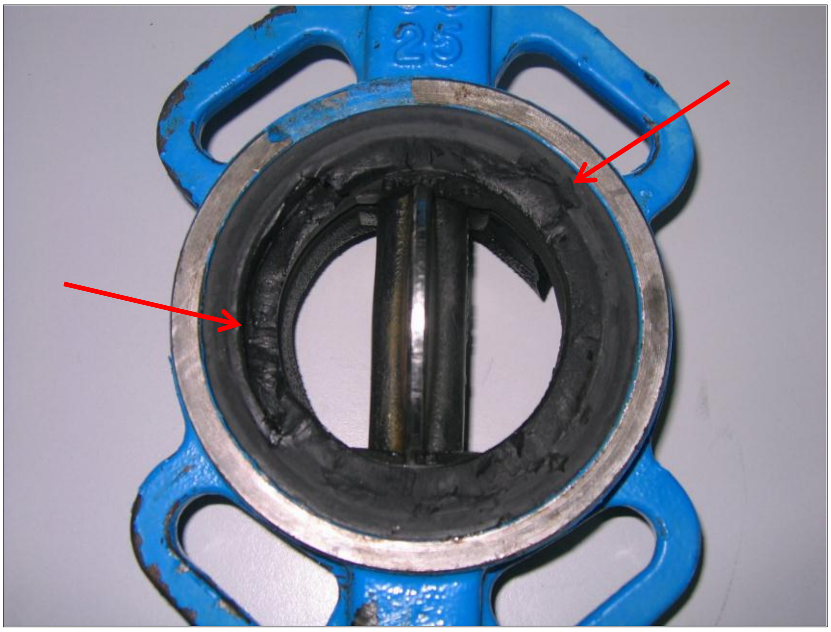


Figure 36: An example of a butterfly valve with a damaged seat due to erosion[16].

Describing Phenomenon 2:

The second phenomenon was found on levels 42, 44, 53, 59, 62, 64 and 68. When the pressure set points were lowered during the course of a typical production day, the position of the valves did not change. As a result the pressure set points were not maintained. Figure 37 shows this occurrence on 59-Level.

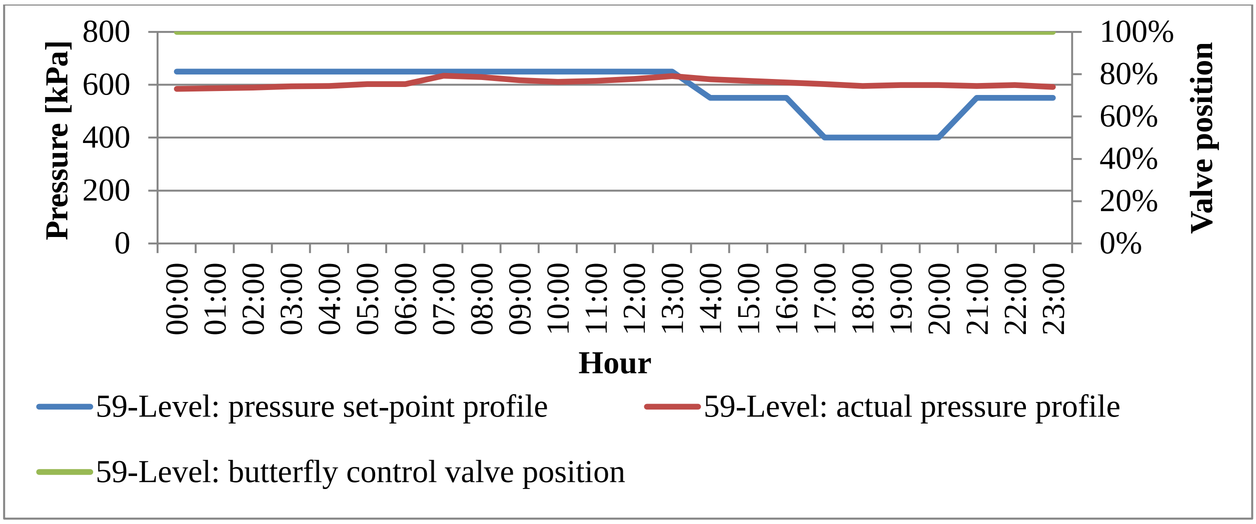


Figure 37: 59-Level butterfly valve position analysis.

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[16] Chemical Engineering World (2007) *Butterfly valve*. Engineering blog. [Online]. Available: http://chem-eng.blogspot.com/2007/02/butterfly-valve.html. [Accessed: 05 August 2013].

There could be various reasons for the butterfly valve position remaining in one position irrespective of the pressure set point. The following possible causes were identified:

- communication failure between the PLC and the related measurement equipment,
- communication failure between the PLC and the actuator,
- malfunctioning within the actuator or measurement equipment, or
- mechanical fault of the valve itself that prevents the disc from rotating.

After the valves on these various levels were inspected and tested during a site visit, the causes of this occurrence were found. It was found that all the valves, except for the valve situated on 47-Level, were mechanically damaged to such an extent that they could not be repaired. The discs were stuck in one position and all the electric actuators failed due to extensive overheating.

On 47-Level the communication link between the PLC and the actuator had been disconnected. Thus, the actuator could not be controlled to obtain the desired valve position. Except for a broken rubber seat that needed to be fixed, the existing butterfly valve on 47-Level could be reused.

It could be argued that the majority of failures mentioned were due to one main reason: the wrong valve type was used to execute the pressure control strategy. This argument is supported by the control valve research done in the literature survey (Section 2.3.4).

As mentioned in the case study background section (Section 3.3.2), the downstream pressure set point of each level could not be changed remotely from the surface control room. A technician had to go underground to the related PLC and change the set point manually using the related software. For this reason the downstream pressure set-point values had not been changed to compensate for alterations in the daily operating schedule.

A technician was only sent to change a downstream pressure set point of a specific level if the set-point value at that time was too low for a certain time interval. For this reason the most recent daily operating schedule of each level had to be investigated. New downstream pressure set points related to the most recent daily operating schedule had to be determined. Should it be found that the downstream pressure set points of the various levels could be changed, the required surface supply-pressure set point also had to be recalculated.

When a method is identified to re-establish the supply pressure control of each level, it should be noted that the downstream pressure set points should be controlled from the surface control room. The mine personnel should be trained on how to analyse the daily operating schedule for each level and how to determine the related downstream pressure set points. These set points should be recalculated and changed (if necessary) on a regular basis.

3.3.4. Methods identified to improve the existing system

Table 6 summarises the areas identified to improve the existing underground compressed air DSM project.

Table 6: Areas identified to improve existing compressed air DSM project.

No.	Area identified to improve
1	Re-establish the supply pressure control of each level.
2	Repair or replace all the broken measurement instrumentation.
3	Repair the broken butterfly valves.
4	Repair the communication network where necessary.
5	Use modernised equipment to enable the downstream pressure set point of each level to be changed remotely from the surface control room.
6	Re-evaluate the daily operating schedule of each level individually and recalculate the downstream pressure set points accordingly.
7	Recalculate the daily surface supply-pressure set points.

The most important area identified to improve is re-establishing the supply pressure control of each level. The primary reason for the supply pressure control failure on the various levels was due because the wrong control valve was selected. A butterfly valve type was selected to control the downstream pressure; most likely due to low purchase costs.

When a butterfly valve is used as a control valve in compressed air applications, large pressure drops could occur with the valve in a nearly closed position. This could cause extreme erosion damages to the seat and the disc of the valve, causing improper sealing when the valve is in a closed position (Emerson, 2012).

Although a butterfly valve has an equal-percentage flow characteristic (as described in Section 2.3.4), it was found that butterfly valves are more suitable for on/off applications than for downstream pressure-control applications. Should the damaged butterfly valves be repaired in order to re-establish the supply pressure control on the various levels, the same failure would occur; this would result in poor reliability.

A globe control valve could be specified with a specific flow characteristic to obtain the desired downstream pressure control without the effect of extreme erosion (Section 2.3.4). Although a globe control valve would be ideal for compressed air pressure-control application, this type of control valve is extremely expensive.

A rule of thumb for estimating the purchase cost of a globe control valve assembly is R1 000 per 1 mm inside diameter of the pipeline where the valve has to be installed. For example, if a globe valve has to be installed in a 200 mm diameter pipeline, the initial purchase cost of the valve would be approximately R200 000. A butterfly valve assembly for similar application would be approximately R15 000 [17].

It was mentioned in Section 3.2.2 that the production activities may not be affected by compressed air saving strategies. For this reason, the supply pressures of the various levels are not controlled during the drilling shift. The maximum possible supply pressures are supplied to the various levels during this period. A bypass configuration (as shown in Figure 38) is proposed as a possible solution to re-establish the pressure control on each level.

The bypass configuration will consist of a butterfly valve installed in the main pipeline and a globe control valve installed on the smaller diameter bypass pipeline. During the drilling period, the butterfly valve will be opened to supply the level at maximum pressure. During non-drilling periods, the butterfly valve will be closed and the supply pressure towards the level will be controlled by the globe valve installed in the bypass line.

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[17] Based on pricing obtained in 2013.

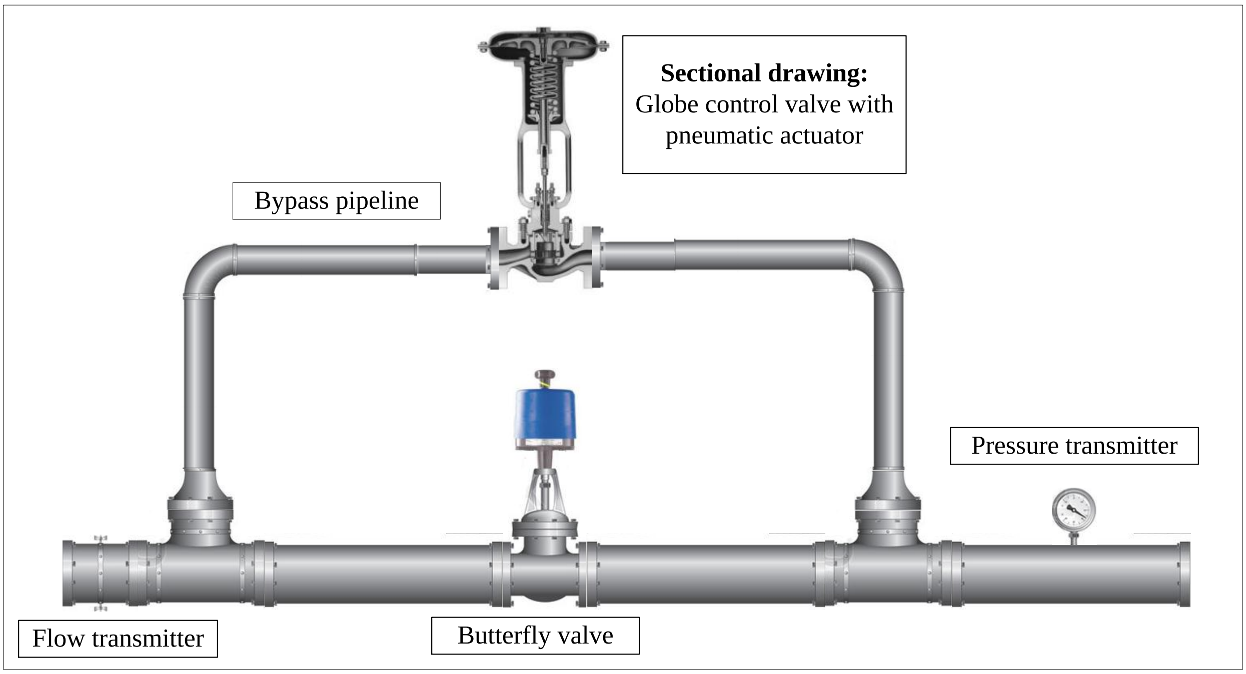

Figure 38: Globe control valve bypass configuration.

With this configuration, a smaller globe control valve will be needed to control the supply pressure and therefore the purchase cost of the globe control valve will be reduced. Although the main objective is to reduce the mass flow of air towards each level, the bypass globe control valve will be controlled to maintain the desired downstream pressure set point. This is due to safety and production reasons.

Should the globe control valve be controlled to maintain the desired flow rate, the valve will close should there be a sudden increase in compressed air demand. This will result in a pressure drop that could affect production. The pressure drop could also be a safety risk because it could affect the compressed air supply towards the refuge bays.

On the contrary, if the globe control valve is controlled to maintain the desired pressure set point, the valve will open should a sudden increase in compressed air demand occur. When more compressed air is extracted from the system, the pressure will drop and the globe valve will be opened by the PID control loop in order to re-establish the system pressure.

A sudden increase in compressed air demand can occur due to various reasons. The increase in the number of pneumatic equipment on a level due to production increases is one reason. Another reason is damaged pipelines causing significant leakages. By measuring the mass flow rate consumed by each level, an alarm could be set up on the control system indicating when the compressed air consumption on a level has increased above a certain limit.

In order to reduce the implementation costs of the improvement strategy, the existing butterfly control valve assemblies that are in a working condition can be reused. These valve assemblies can be installed in the main compressed air pipeline of the bypass configuration as indicated in Figure 38.

In order to be able to change the supply-pressure set point of each level from the surface control room, a modernised PLC has to be installed locally on each level. Necessary upgrades on the communication network will also have to be implemented.

3.4. Simulated impact of the proposed intervention

3.4.1. Preamble

The previous sections of this chapter focused on identifying an existing underground compressed air DSM project and identifying areas to improve the existing project to reduce operating cost. In order to determine the feasibility of the proposed improvements, the following information is required:

- estimated additional energy savings, and
- project improvement costs.

A simulation model can be used to estimate the additional electric energy that will be saved after the proposed improvements are implemented. The estimated additional cost saving resulting from the improved electrical energy savings can then be calculated. By comparing the expected additional cost saving to the improvement in implementation cost, the feasibility of the proposed improvements can be calculated.

This section focuses on the simulation model used to determine the expected additional electrical energy savings relating to the proposed project improvements discussed in Section 3.3. The project improvement cost will also be calculated and compared with the expected additional cost savings. The feasibility of the proposed improvements will be calculated and the expected payback period will be discussed.

3.4.2. Simulation procedure

A few steps were identified to compile an accurate simulation model to calculate the estimated improvement in electrical energy savings. These steps are summarised in Table 7.

Table 7: Procedure followed to formulate simulation model.

No.	Description
1	Identify, formulate and understand the problem
2	Determine which system data will be needed and collect it
3	Formulate the simulation model
4	Validate the simulation model
5	Perform the simulation and interpret the results

The first step was completed when the existing underground compressed air DSM project was investigated to identify possible areas for improvement (Sections 3.1–3.3). The required data to formulate the simulation model should be identified next. To determine the required data, one should be familiar with the mathematical equations that will be used within the simulation model.

It should be noted that the electrical motor that is connected to the compressor consumes electrical energy to power the compressor, which supplies compressed air to the network. The improvement in electrical energy saving will be justified by measuring the electrical energy consumed by the compressor motors, before and after the implementation of the proposed improvements.

In terms of the simulation model, the electrical energy consumption of the compressor motors after the implementation of the proposed improvements has to be simulated. This estimated electrical energy consumption can then be compared with the electrical energy consumption baseline to calculate the estimated improvement in electrical energy saving. The electrical energy required to compresses air can be calculated with Equation 1 (discussed in Section 2.3.2, but presented again for the ease of the reader).

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

Where:

W_e	–	Electrical power required by the motor to compress the air	[kW]
$\dot{m}$	–	Mass flow of the air being compressed	[kg/s]
C_p	–	Specific heat constant	$[\frac{kJ}{kgK}]$
T_{in}	–	Absolute inlet air temperature	[K]
P_{out}	–	Absolute outlet pressure	[kPa]
k	–	Polytropic exponent	
P_{in}	–	Absolute inlet pressure	[kPa]
η_c	–	Efficiency of the compressor	[%]
η_m	–	Efficiency of the electric motor	[%]

The simulation of the electrical energy improvement strategy on the existing underground compressed air savings project will be based on the following assumptions:

Assumption 1:

The total electrical energy consumed to supply the underground compressed air network of air is distributed between all the compressors connected to the compressed air network. To simplify the calculations, these compressors will be seen as one compressor supplying air to the underground compressed air network only. The calculations will be done using a compressor efficiency of 80% (the compressor efficiency is site specific and cannot be used as a constant value for other applications).

Assumption 2:

The inlet pressure (P_{in} in Equation 1) of the compressor will be atmospheric pressure (87 kPa absolute pressure). The compressor outlet pressure (P_{out}) will be the compressed air supply pressure towards the underground compressed air network. The mass flow ($\dot{m}$) that the compressor has to supply will be taken as the sum of mass flows consumed by all the individual levels. Assumption 1 and Assumption 2 are visually displayed in Figure 39.

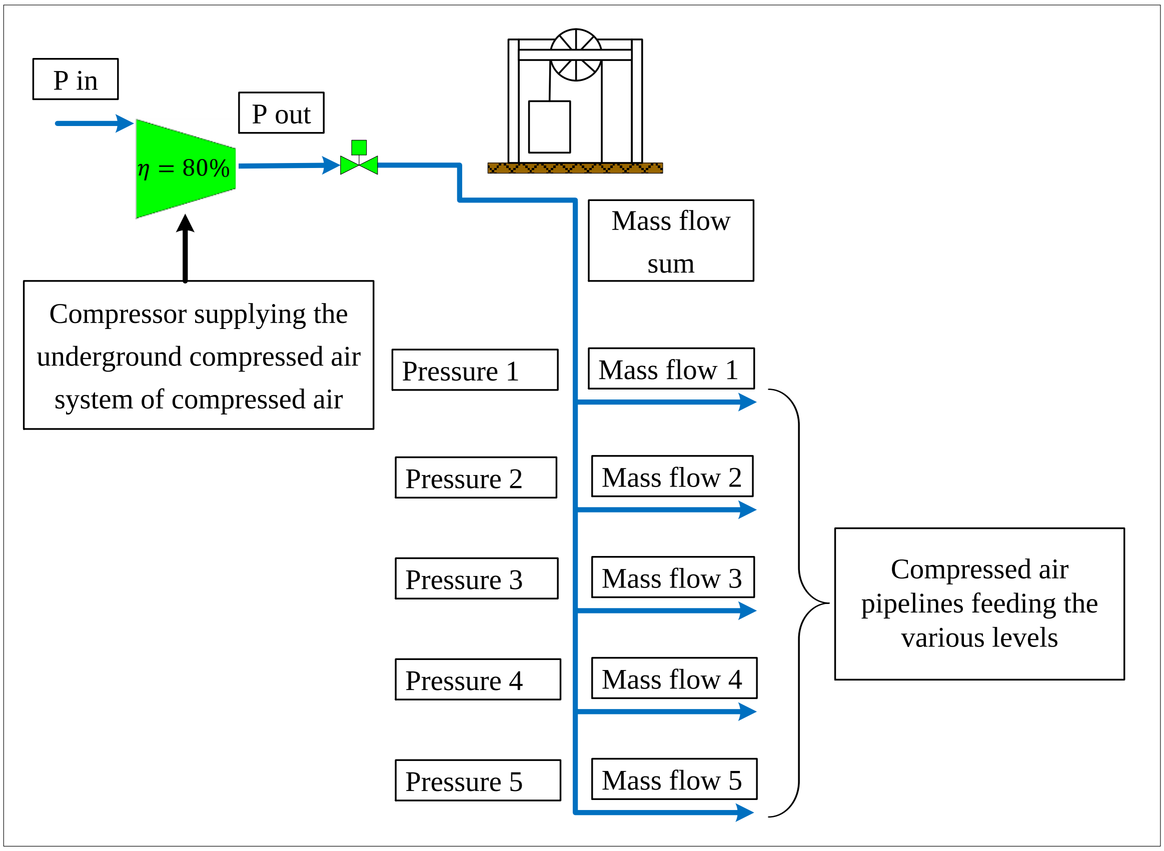

Figure 39: Schematic illustration of the simulation assumptions.

Following the assumptions and using Equation 1, the system data needed to formulate the simulation model can be identified. The required data can be obtained from the SCADA system on the mine. If the data is not available, portable measurement instrumentation devices have to be installed to obtain the required data.

After the data has been obtained, the data needs to be processed to average daily profiles for a typical production day. By applying Equation 1 to the data obtained, the electrical energy consumption baseline can be constructed. This simulated electrical energy consumption baseline will be used as the benchmark from where the improvement in electrical energy will be measured from in the simulation model.

For this case study the required data was obtained during the improvement identification stage discussed in Section 3.3.3. The required data and the reasons the data is required are displayed in Table 8.

Table 8: Data required to formulate a simulation model.

No.	**Data description**	**Unit**	**Reason for use**
1	Surface supply pressure.	kPa	To be used as the compressor outlet pressure.
2	Supply pressure of each level.	kPa	To determine newly proposed supply pressures for each level and a newly proposed surface supply pressure.
3	Mass flow of each level.	kg/s	To calculate the total shaft mass flow.
4	Shaft mass flow (if available).	kg/s	To verify the calculated shaft mass flow.
5	Actual electrical power consumption of all the compressors connected to the network.	kW	To calculate the average daily power baseline of the compressed air network for a typical production day.

The operating schedule, together with the types of pneumatic equipment found on each level, was investigated. The daily operating schedule, compressed air applications and the new proposed daily supply-pressure set points for each level are presented in Appendix A. By taking the newly proposed supply-pressure set points into consideration, an optimised surface supply pressure set-point profile can be constructed using Equation 4.

To be able to construct the proposed electrical energy profile, the expected daily compressed air mass flow at the newly proposed supply-pressure set points has to be simulated. This can be done using KYPipe, which is a simulation analysis model. KYPipe is used in industry to simulate real-life operations. Different compressed air network-related equipment such as variable pressure supplies, regulators, pipes and valves are used within the software to simulate a specific situation. Feedback is given through measurement devices such as simulated flow and pressure meters[18].

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[18] KYPipe. (2012) *Pipe2012: Gas (gas analysis)*. Products Overview. [Online]. Available: http://kypipe.com/gas. [Accessed: 12 September 2013].

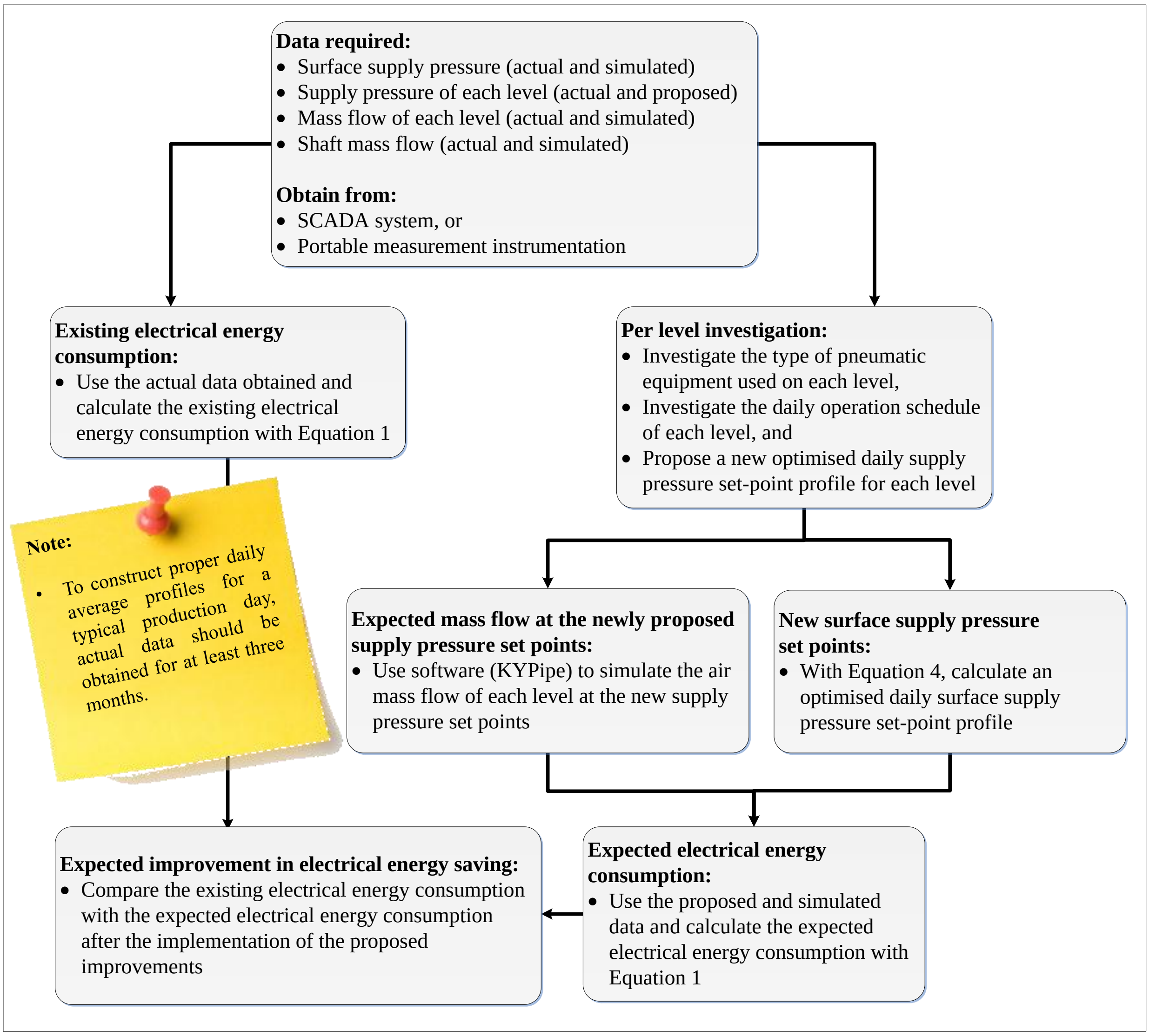
The KYPipe simulation results (the simulated compressed air mass flow values at the proposed supply-pressure set points) are presented in Appendix A. By using the KYPipe simulation results as part of the inputs to Equation 1, the expected electrical energy consumption after the implementation of the proposed improvements can be calculated.

The expected improvement in electrical energy savings can be calculated by comparing the electrical energy consumption baseline with the expected electrical energy consumption profile. Table 9 summarises the method used within the simulation model to calculate the expected improvement in electrical energy.

Table 9: Simulation model procedure.

No.	**Description**
1	Obtain the data required for a period of at least three months (data required in Table 8).
2	Compile daily average pressure, mass flow and power profiles for a typical production day.
3	Simulate the expected mass flow towards each level at the reduced supply-pressure set points.
4	Use Equation 4 to calculate the minimum required surface supply pressure profile.
5	Use Equation 1 to calculate the improved power profile with the minimum required surface supply pressure profile, and the total underground compressed air consumption profile (as calculated with KYPipe) inputs.
6	Compare the improved power profile with the electrical energy consumption baseline to obtain the expected improvement in electrical energy.

Figure 40 shows a flow diagram summarising the simulation formulating procedure.



Data required:
- Surface supply pressure (actual and simulated)
- Supply pressure of each level (actual and proposed)
- Mass flow of each level (actual and simulated)
- Shaft mass flow (actual and simulated)

Obtain from:
- SCADA system, or
- Portable measurement instrumentation

Existing electrical energy consumption:
- Use the actual data obtained and calculate the existing electrical energy consumption with Equation 1

Per level investigation:
- Investigate the type of pneumatic equipment used on each level,
- Investigate the daily operation schedule of each level, and
- Propose a new optimised daily supply pressure set-point profile for each level

Note:
- To construct proper daily average profiles for a typical production day, actual data should be obtained for at least three months.

Expected mass flow at the newly proposed supply pressure set points:
- Use software (KYPipe) to simulate the air mass flow of each level at the new supply pressure set points

New surface supply pressure set points:
- With Equation 4, calculate an optimised daily surface supply pressure set-point profile

Expected improvement in electrical energy saving:
- Compare the existing electrical energy consumption with the expected electrical energy consumption after the implementation of the proposed improvements

Expected electrical energy consumption:
- Use the proposed and simulated data and calculate the expected electrical energy consumption with Equation 1

Figure 40: Procedure to follow when formulating the simulation model.

3.4.3. Simulation validation

Although KYPipe is used in industry to analyse complex pipe networks, the application of the simulation software to this analysis must be verified to ensure that the results are accurate. An existing compressed air project, where the supply pressure towards a location is controlled using a control valve assembly, was identified. The following pressure-control strategy data was collected and is displayed in Figure 41:

- the daily supply pressure set-point profile,
- the actual daily supply pressure profile, and
- the actual daily compressed air mass flow.

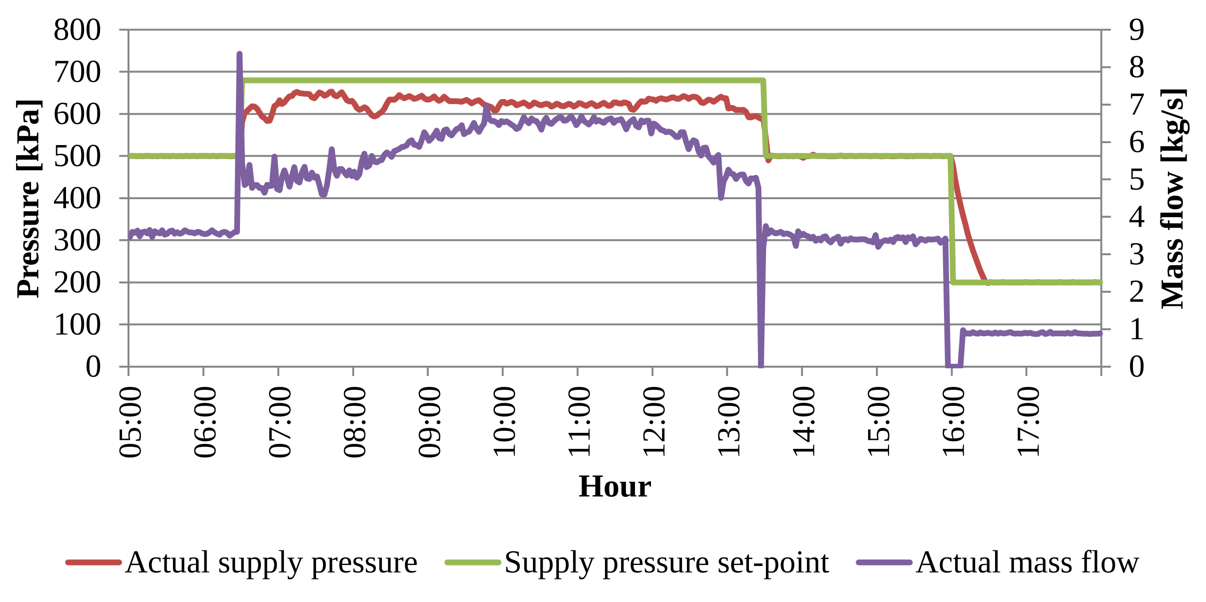


Figure 41: Control parameters of existing supply pressure strategy (KYPipe validation).

The average mass flow was determined for the period where the supply-pressure set points were 500 kPa and 200 kPa respectively. By using the average mass flow (during the period where the supply-pressure set point was 500 kPa) as an input value, KYPipe was used to simulate the mass flow for the supply-pressure set point being reduced from 500 kPa to 200kPa (at 16:00 in Figure 41). This result is displayed in Table 10.

Table 10: KYPipe validation result.

Set point [kPa]	**Ave mass flow [kg/s]**	**KYPipe results (mass flow [kg/s])**
500	3.5	Use actual value as input
200	0.9	1

It was found that the KYPipe-simulated mass flow was within 10% of the actual mass flow at a reduced pressure set point of 200 kPa. The KYPipe simulation results are presented in Appendix E.

The simulated mass flow values at the reduced supply-pressure set points are used within the simulation model to calculate the expected power profile. To validate the calculation method used within the simulation model, an existing standalone compressed air network will be considered. This standalone compressed air network consists of one multistage centrifugal compressor supplying compressed air to two mining shafts.

To validate the calculation method the following daily average profiles for a typical production day were obtained (using data for a period of three months):

- supply pressure profile of the compressor,
- supply mass flow profile of the compressor, and
- actual power consumption profile of the compressor.

By using the average supply pressure and mass flow profiles of the compressor for a typical production day as the input parameters for the simulation model, the theoretical power consumption profile of the compressor was determined. The theoretical power consumption profile was compared with the actual power consumption profile. This comparison is displayed in Figure 42.

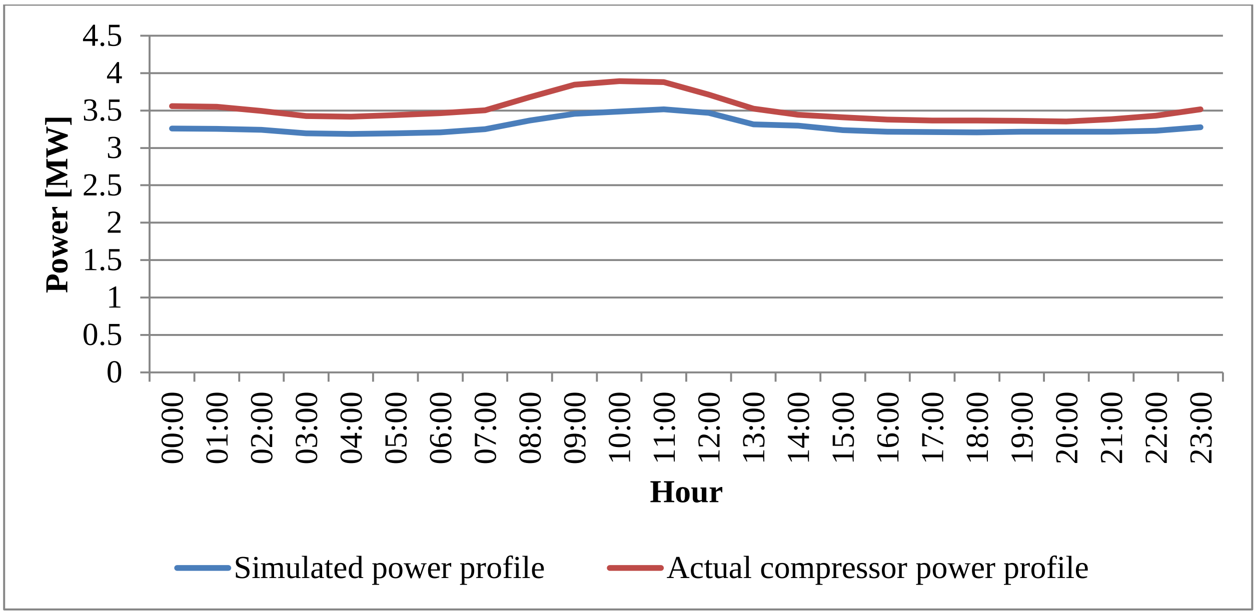


Figure 42: Validation of the simulation model.

It was found that the simulated power profile was on average within 10% of the actual power consumption of the compressor. Therefore, the simulation model can be used to simulate the expected improvement in electrical energy savings.

3.4.4. Calculated savings

Using the KYPipe simulation software, the expected compressed air mass flow at the reduced supply-pressure set points was simulated. These results are displayed in Figure 62 to Figure 64 in Appendix A. By comparing the simulated air consumption with the actual air consumption, the expected compressed air saving for a typical production day can be calculated. Figure 43 displays the results on a graph.

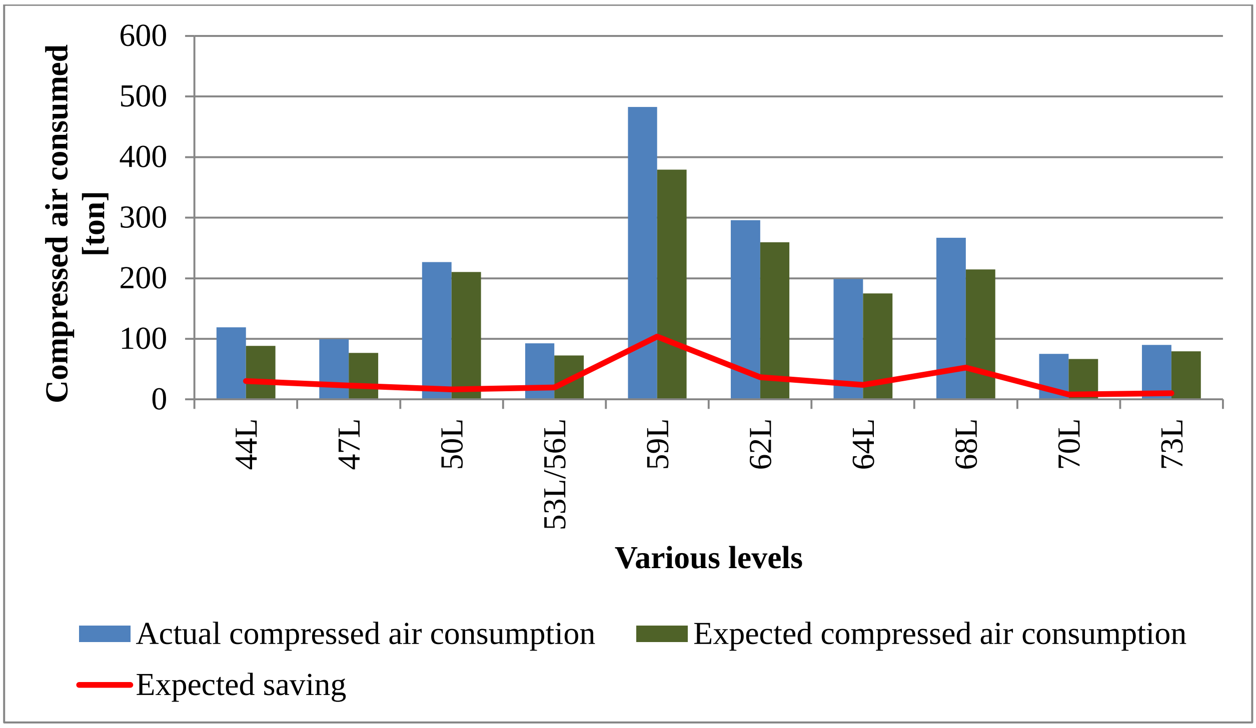


Figure 43: Compressed air saving per level for a typical production day.

The various levels can be prioritised according to the expected amount of compressed air to be saved for an average production day. From Figure 43 it can be noted that the lowest expected compressed air savings are from levels 70 and 73 respectively. The highest expected compressed air savings occur on levels 59 and 68 respectively.

Like any other project, the improvement and modernisation of an existing underground compressed air energy saving project would typically have a fixed budget. The implementation cost of the proposed improvements could exceed the fixed budget. In such a situation, one should investigate the feasibility of the proposed improvements on each level, especially the levels with low expected compressed air savings.

The expected reduction in surface supply pressure and total underground compressed air consumption are displayed in Figure 44. These results are based on the assumption that it would be feasible to implement the proposed improvements on all the levels.

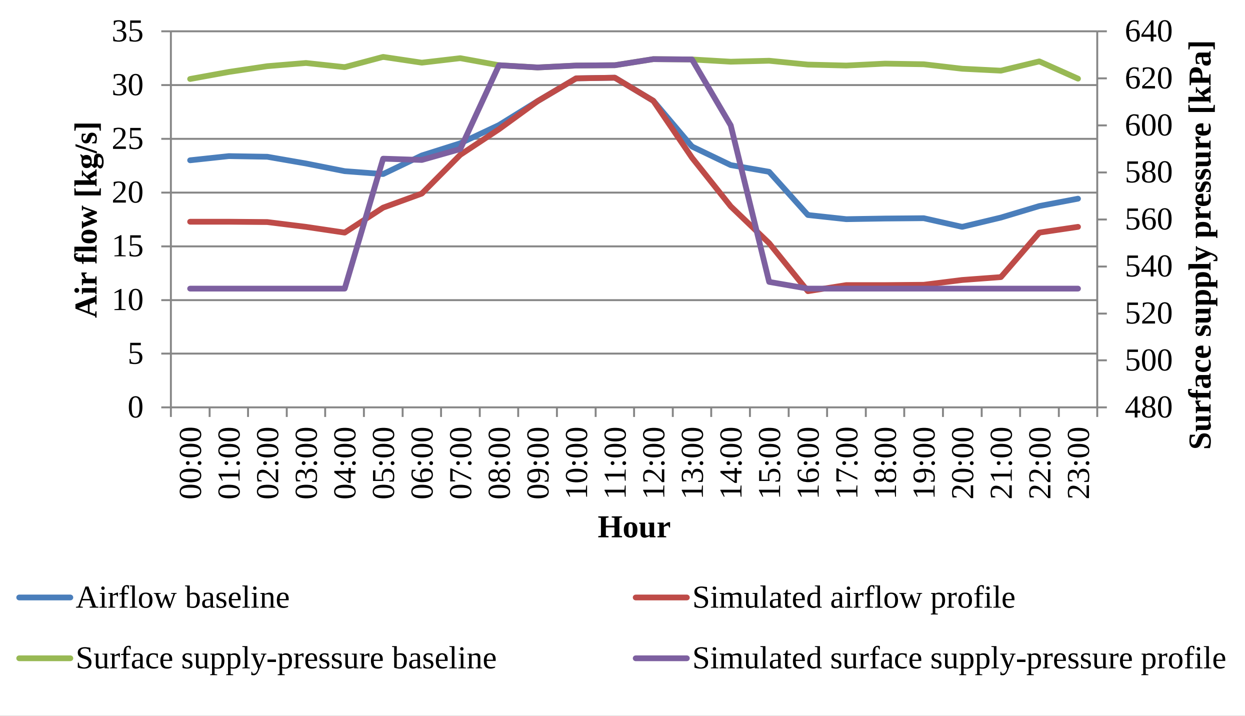


Figure 44: Compressed air supply measurements (implemented on all levels).

As previously mentioned, the production activities during the drilling shift must not be affected by the proposed improvements. For this reason, the supply pressure towards each level will not be controlled during the drilling shift. It is assumed that the compressed air consumption and surface supply pressure will stay unchanged during this period. This occurrence is visible between 07:00 and 13:00 in Figure 44.

With the simulation model formulated in Section 3.4.2 and using the data profiles in Figure 44 as input values, the electrical energy baseline and the expected electrical profile can be calculated. The difference between the electrical energy baseline and the expected electrical profile is the expected improvement in electrical energy after the improvements have been implemented. The electrical energy baseline and the simulated profile are displayed in Figure 45. These results are based on the assumption that the proposed improvements will be implemented on all the levels.

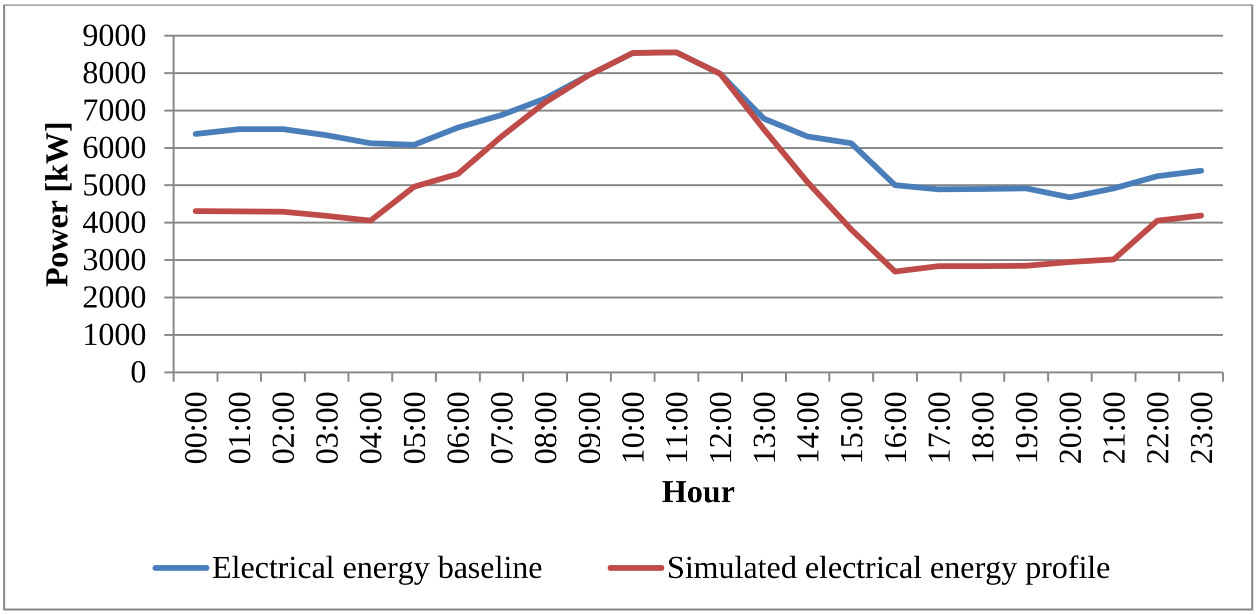


Figure 45: Electrical energy baseline and simulated profile (implemented on all levels).

The simulated improvement in power saving to the existing underground compressed air savings project implemented at Mine A is 1.34 MW. This improvement in electrical energy saving is for a typical production day. The expected improvement in electrical energy saving will result in an annual cost saving of R4.66 million. An average daily cost saving of approximately R10 000 will be achieved during the summer months, with an average daily cost saving of approximately R16 000 during the winter months.

The simulated improvement in electrical energy saving will have to be recalculated in the following situations:

- should it be found that the implementation cost of the proposed improvements exceeds the fixed budget and the proposed improvements cannot be implemented on all the levels, or
- simulated saving for a specific level does not justify the proposed improvements due to the high implementation cost.

The improvement in electrical energy savings was recalculated with the assumption that the proposed improvements will not be implemented on levels 70 and 73. The expected reduction in surface supply pressure and total underground compressed air consumption are displayed on the graph in Figure 46.

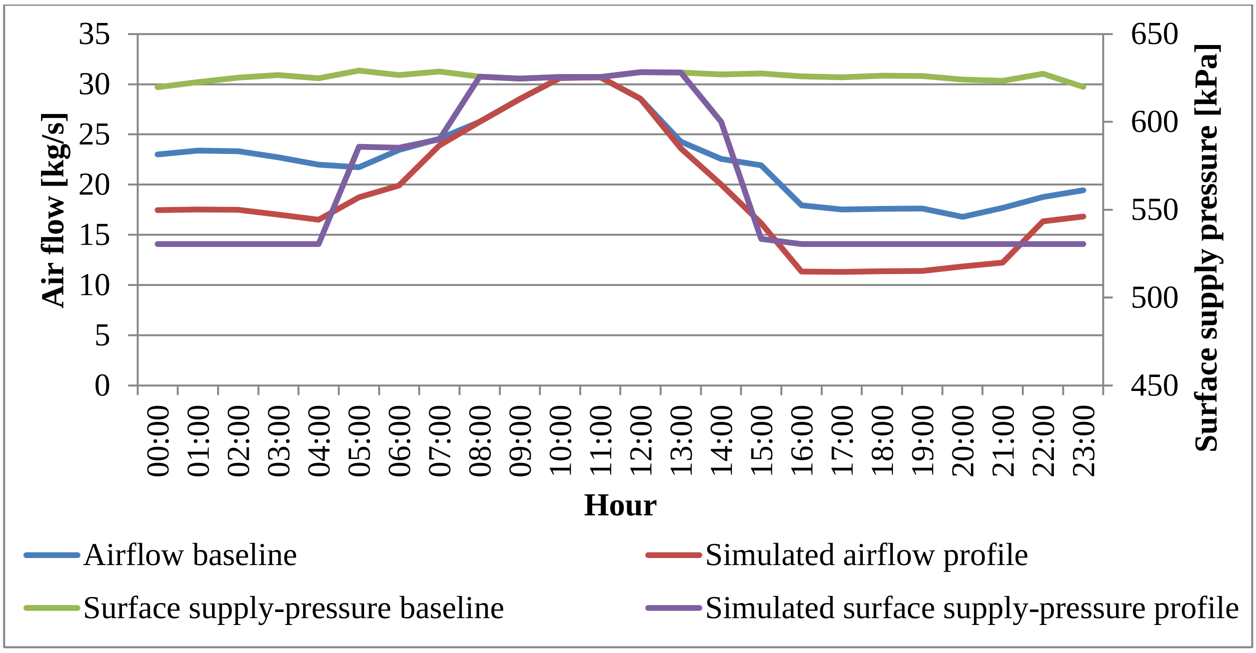


Figure 46: Compressed air supply measurements (excluding levels 70 and 73).

With the two levels with the lowest expected compressed air savings excluded from the simulation model, the electrical energy baseline and the simulated profile were recalculated. These recalculated profiles are displayed on the graph in Figure 47.

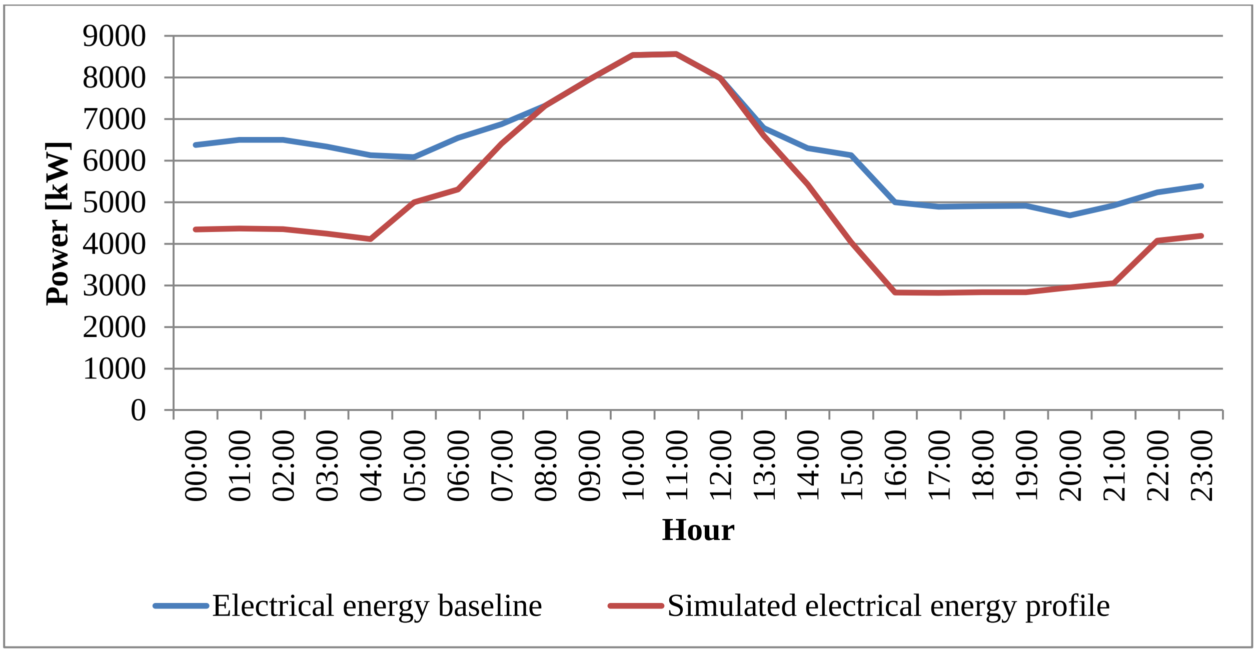


Figure 47: Electrical energy baseline and simulated profile (excluding levels 70 and 73).

The simulated improvement in power saving, without implementing the proposed improvements on levels 70 and 73, is 1.28 MW. This improvement in electrical energy saving is for a typical production day. This expected improvement will result in an annual cost saving of R4.45 million. An average daily cost saving of approximately R9 000 will be achieved during the summer months with an average daily cost saving of approximately R15 000 during the winter months.

3.4.5. Feasibility of improvements

During the previous section the estimated improvements in electrical energy savings were calculated for the following two scenarios:

1. proposed improvements implemented on all the levels, and
2. proposed improvements implemented on all the levels except levels 70 and 73, which are the levels with the lowest expected compressed air savings.

It should be noted that there are two types of expense that should be taken into account when the estimated project improvement cost is calculated. The first type of expense is fixed cost. Fixed costs stay unchanged irrespective of the number of levels to be improved and typically include, amongst others, medical, induction, travelling and training costs.

The second type of expense is the cost relating to the improvement of a level. This cost typically includes equipment and installation cost. For the purpose of this study, this type of expense will be referred to as the variable project cost. The estimated fixed project improvement cost is summarised in Table 16. The estimated variable project improvement cost is summarised in Table 17 with the total project improvement cost for both scenarios summarised in Table 18. These tables are presented in Appendix B.

It should be noted that additional costs such as software costs, consultant fees and other similar costs, were not taken into consideration when the total project improvement cost was determined. These costs could affect the payback period and should have been taken into consideration when the project had been investigated initially. These costs are not mentioned in this study due to company confidentiality.

The project improvement cost for Scenario 1 is estimated to be R6 388 400. With the cost saving related to the expected electrical energy savings for this scenario already calculated, the payback period is estimated to be thirty months. The project cash flow, payback period and the different project phases are displayed on the graph in Figure 48.

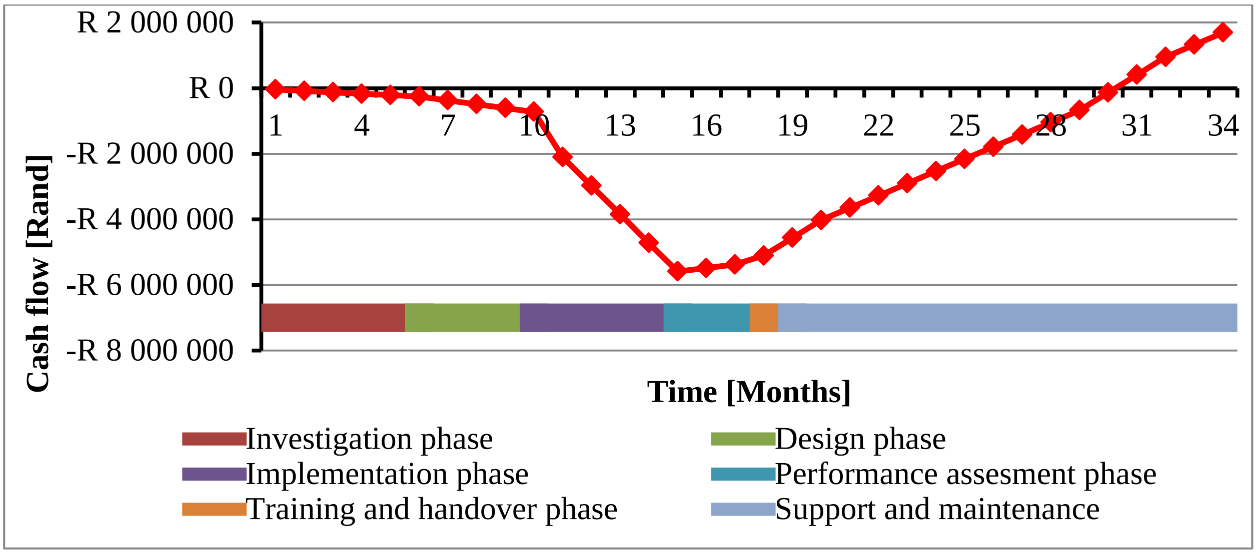


Figure 48: Estimated cash flow and payback period (implemented on all levels).

The total project improvement cost for Scenario 2 is estimated to be R5 362 000. With the cost saving related to the expected electrical energy savings for this scenario already calculated, the payback period is estimated to be twenty-eight months. The project cash flow, payback period and the different project phases are displayed on the graph in Figure 49.

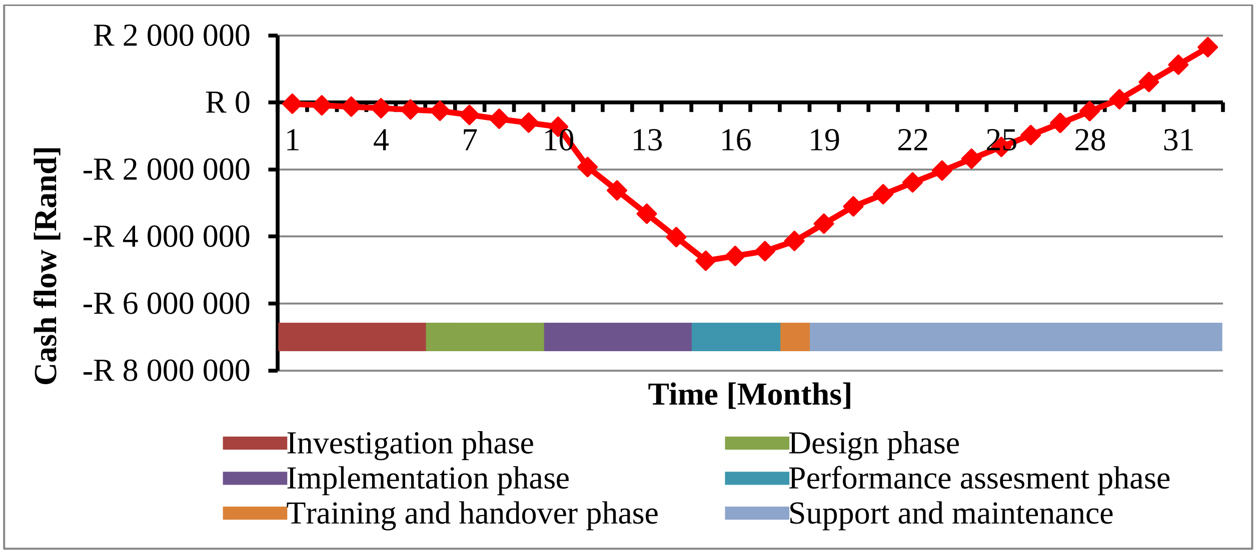


Figure 49: Estimated cash flow and payback period (excluding levels 70 and 73).

To determine the most feasible scenario, the differences between Scenario 1 and Scenario 2 must be investigated. The differences between these two scenarios are summarised Table 11.

Table 11: Differences between Scenario 1 and Scenario 2.

No.	**Description**	**Scenario 1: Improvements implemented on all the levels**	**Scenario 2: Improvements implemented on all the levels except levels 70 and 73**
1	Improvement in electrical demand cost	1.34 MW	1.28 MW
2	Implementation cost	R6.38 million	R5.36 million
3	Expected annual cost savings	R4.66 million	R4.45 million
4	Annual return on initial implementation cost	73 %	83 %
5	Client payback period	20 months	18 months

It will be feasible to implement the proposed improvements considering the cash flow and payback periods of the two scenarios. For both scenarios the capital that the client invested in the improvement strategy will be paid back within two years from when the improvements were first investigated. The annual return on investment for the two scenarios is between 73% and 83%. Based on annual return on investment, it will be more feasible to implement Scenario 2 (proposed improvements on all the levels except for levels 70 and 73).

It will cost approximately R1 million more to implement Scenario 1 (implementing the proposed improvements on all levels). Bearing in mind that this type of project generally has a fixed budget, implementing the proposed improvements on levels 70 and 73 could halt the project. Thus, the proposed improvements were implemented on all the levels except for levels 70 and 73.

3.5. Conclusion

In this chapter the method used to modernise and improve an existing underground compressed air saving strategy was presented. At first the project identification process was discussed. After an existing saving strategy was identified, valuable information that could be obtained by investigating the performance history of the existing saving strategy was discussed.

The existing saving strategy was investigated and possible areas to improve were identified. A simulation model was developed to calculate the expected improvement in electrical energy saving if the proposed improvements were to be implemented.

The cost to implement the proposed improvements was estimated. Based on the estimated cost prediction and the simulation results, the feasibility of the proposed improvements were calculated. The proposed improvement that was found feasible was presented.

It was found that by implementing the feasible improvements, an improvement in power saving of 1.28 MW could be expected. This will result in an additional annual cost saving of R4.45 million based on the 2013/14 Eskom electricity tariffs.

The method used to modernise and improve an existing underground compressed air energy saving project is now presented.

Chapter 4: Verification, validation and results

[19]

The additional electrical energy savings are justified. The M&V measurement technique is analysed. The results are compared with results obtained using a new measurement technique. The chapter concludes with the validation of the simulation results by comparing it with the actual measured results.

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[19] Adopted from: Technology Industry of Gold Mining [Online]. (2012) http://miningeducation.blogspot.com/2012/11/10-world-gold-mining-industries-biggest.html [Accessed: 05 September 2013].

4.1. Introduction

After an existing energy saving project was investigated, various improvements were proposed. With the help of the simulation model formulated in Chapter 3, the feasibility of the proposed improvements was determined and the feasible improvements were implemented. As part of the improvement strategy, equipment was used to improve and modernise the existing energy saving project. Figure 50 shows typical equipment used to improve the existing energy saving project.

Figure 50: Typical equipment used in the modernisation and improvement project[20].

Figure 51 displays a butterfly valve with an electric actuator installed within a compressed air pipeline feeding a level. A pressure transmitter installed as part of the modernisation and

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[20] Photos taken at a South African mine.

improvement project is also visible on the left-hand side of the butterfly valve. Additional benefits of the improved electrical energy savings project will also be discussed in this chapter.

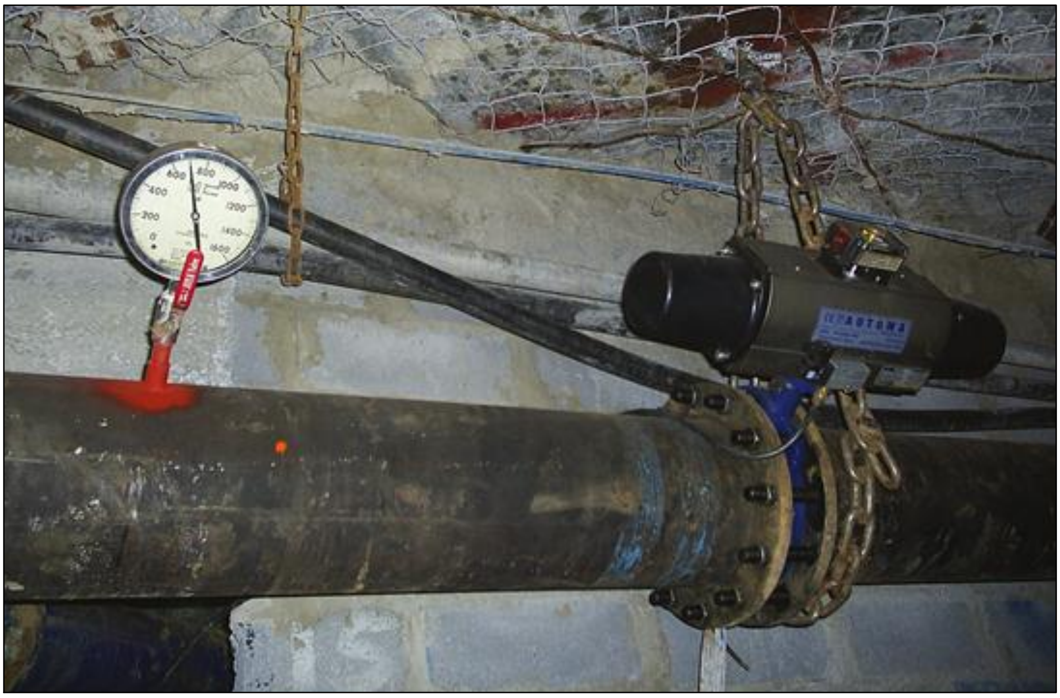

Figure 51: A butterfly valve and a pressure transmitter installed in a main pipeline.

4.2. Verifying the additional savings achieved

4.2.1. Preamble

In this section the method used by the M&V team to measure the improvement in the electrical energy saving will be analysed. The results will be compared with the expected improvement in electrical energy calculated with the simulation model.

Areas to improve the M&V measurement method will be identified. An improved measurement technique will be developed. The results of the new proposed measurement technique will also be compared with the simulated results. A conclusion will be made.

4.2.2. M&V measurement method and results

As already discussed in Section 2.4.3, a power consumption baseline is usually constructed before the energy savings initiative is implemented. After implementation, the actual power consumption is compared with the power consumption baseline to measure the savings achieved. Different baseline-scaling methods used to account for system changes after the construction of the baseline were also discussed in Section 2.4.3.

The underground compressed air network at Mine A is fed from a surface compressed air network. This surface compressed air network is an integrated compressed air supplier network as described in Section 2.2.2. This means that more than one compressed air supply is connected to a single pipeline feeding various compressed air consumers. The underground compressed air network at Mine A is only one of various compressed air consumers consuming air from the same network.

The entire network is supplied with compressed air from six different multistage centrifugal compressors, each with different install capacities. These compressors have a total installed capacity of 80 MW with an average operating load of 25 MW. Figure 52 displays two multistage centrifugal compressors, each with an installed capacity of 15 MW, supplying the compressed air network with compressed air.

Figure 52: Multistage centrifugal compressors located at Mine A[21].

Apart from Mine Shaft A, two other mining shafts together with three ore processing plants are consuming compressed air from the integrated compressed air supplier network. The M&V team constructed a 30-minute interval, average weekday power profile for all the compressors supplying the network with compressed air. This weekday average power profile was developed from data obtained for a period of three months before the proposed improvements were implemented. This weekday average power profile is the power baseline for this project and is displayed in Figure 53.

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[21] Photo taken at a South African mine.

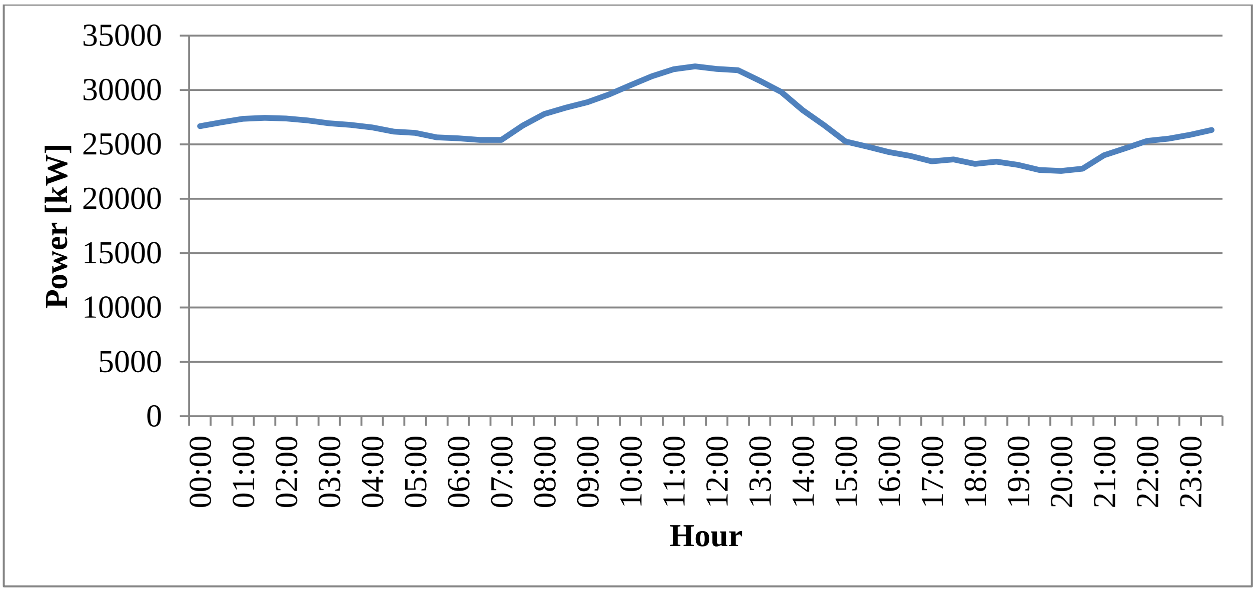

Figure 53: Weekday average power baseline profile.

Apart from the weekday average power baseline, a weekday average baseline was also developed for the total compressed air consumption of the network. This baseline was developed using flow data from the same time period the power data was used to develop the weekday average power baseline. The weekday average baseline for the network compressed air consumption is displayed in Figure 54.

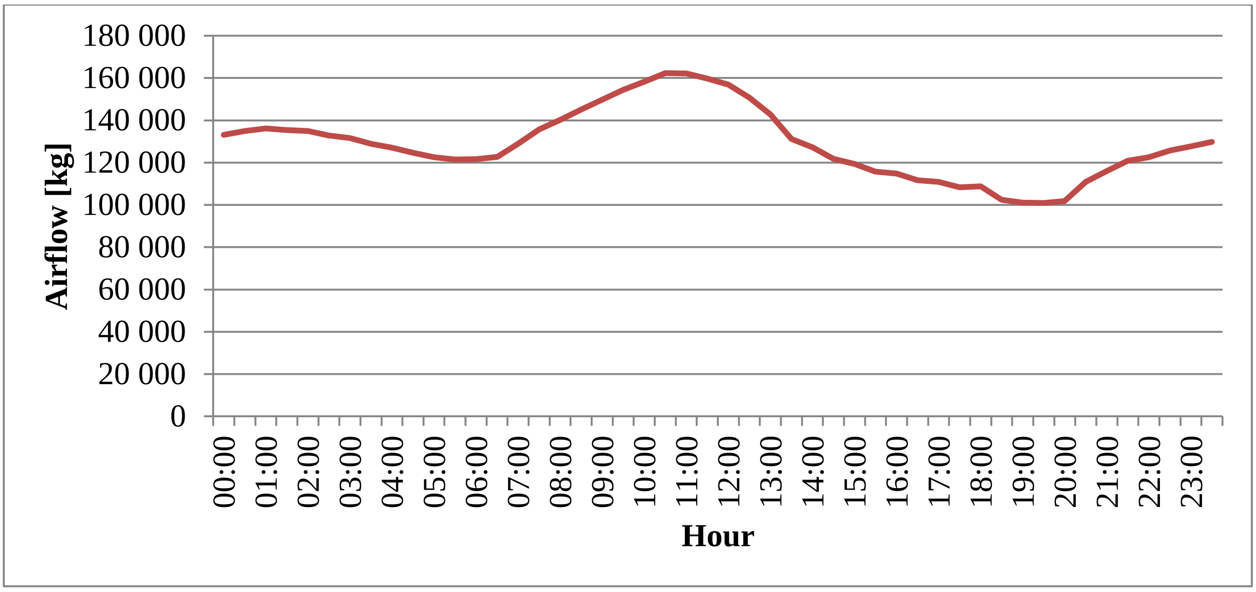

Figure 54: Total network compressed air consumption baseline (weekday average).

Due to the reasons mentioned in Section 3.3.4, the compressed air at the various levels will not be controlled during the drilling shift (which is from 09:00 until 12:00 for this application). Should the system stay unchanged, the compressed air consumption of each level should stay the same for the drilling shift after the proposed improvements have been implemented. If the compressed air consumed by the levels during the drilling shift change, it will not be as a result of the implementation of the proposed improvements.

The M&V team calculated the average relation between the total compressed air consumed and the total electrical energy consumed during the drilling shift for the entire network. The relation between the electrical energy and compressed air consumption is provided by Equation 5.

Equation 5: Relation between electrical energy and compressed air consumption.

$$y = 0.045x + 24534$$

Where:

y	–	What the electrical energy consumption per day would have been	[kWh]
x	–	Amount of compressed air consumed per day	[kg]

The regression model developed by the M&V team to determine the abovementioned relation is displayed in Figure 55.

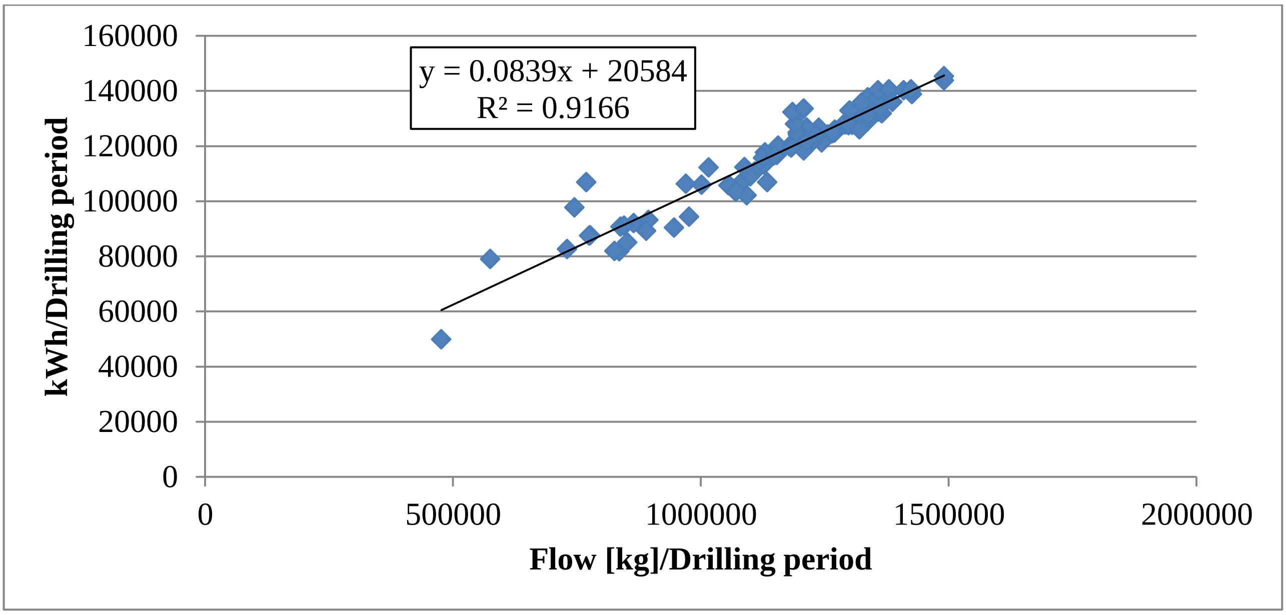

Figure 55: M&V regression model for the drilling period.

The relation obtained from this regression model should have been used to calculate the "what the electrical consumption per day would have been" value had the improvements not been implemented. It was found that this regression model was inaccurate. It was decided that this regression model will be updated using the latest data after the project performance assessment phase has been completed. The performance of the project will then further be justified using the updated regression model.

During the performance assessment phase the M&V team developed a different method to measure the improvement in electrical energy. The actual daily electrical energy consumption of the entire compressed air network was measured for a weekday. A scaling factor was calculated by comparing the actual power profile during the drilling shift with the baseline power profile for the same time period. The scaling factor was determined using Equation 6.

Equation 6: Baseline-scaling factor calculation.

$$Baseline\ scaling\ factor = \frac{x}{y}$$

Where:

y – Average electricity consumption during the drilling shift (baseline)

x – Average electricity consumption during the drilling shift (actual profile)

By comparing the scaled baseline with the actual power profile, the electrical energy saving due to the project improvement was calculated. The power profile baseline, the scaled power profile baseline and the actual power profile as measured by the M&V team for an average weekday during the performance assessment period are displayed in Figure 56.

It should be noted that the average actual power profile measured during the performance assessment period is much higher than the baseline power profile developed before the implementation of the proposed improvements. This could be because production has increased on the mines consuming compressed air from the network. For this reason the baseline was scaled to compensate for this phenomenon.

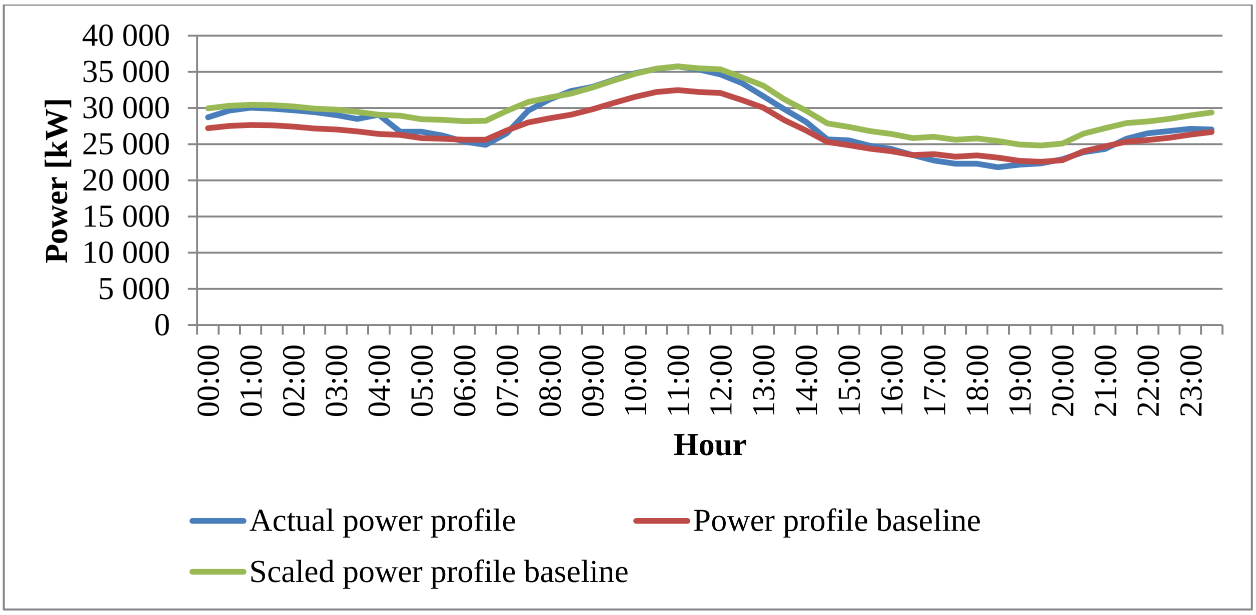

Figure 56: Power profiles (independent M&V team).

In the previous chapter the simulation model indicated an expected improvement of 1.28 MW in power saving. After the proposed improvements were implemented on all the levels (except for levels 70 and 73), the M&V team reported an improvement in power saving of 1.57 MW. This is 0.29 MW more than estimated by the simulation model. Thus, the M&V measurement is within 25% of the simulated improvement.

By analysing the method used by the M&V team to measure the improvement in electrical energy saving, a few areas to improve the measurement technique can be identified. Firstly, the savings were justified by measuring the total electrical energy consumption of the entire compressed air network. But, the improvement strategy was only implemented on the underground compressed air network of Mine A (which uses approximately 30% of the total air consumed from the entire network).

Any changes influencing the compressed air consumption of the entire network would have an effect on the electrical energy consumption. This could include system changes on the other two mining shafts or even changes on the ore processing plants. These changes could have nothing to do with the improvement strategy on the underground compressed air network of Mine A. The discrepancy between the simulated results and the M&V results prompted further analysis. An alternative measurement method to quantify the impact of the system improvements was identified to determine if either the simulated model or the M&V methodology were inaccurate.

4.2.3. Developing measurement method and results

Areas to improve the technique used by the M&V team to measure the improvement in electrical energy savings were identified during the previous section. The measurements obtained from this technique were also discussed. In this section a new measurement technique will be developed to improve the measurement accuracy. The new technique will justify the improvement in electrical energy saving by considering only the compressed air consumed by Mine Shaft A.

To develop a new measurement technique, one should be familiar with the applicable data available. By investigating the M&V measurement technique discussed in the previous section, the data available to justify the electrical energy saving improvement was obtained. This data is summarised in Table 12.

Table 12: Data available to justify the improvement in power savings.

No.	Data description	Source	Unit	Symbol
1	Total network power baseline	M&V baseline report	kW	$P_{network\text{-}base}$
2	Total network air consumption baseline	M&V baseline report	kg/s	$F_{network\text{-}base}$
3	Total air consumption of Mine Shaft A	M&V baseline report	kg/s	$F_{shaft\text{-}base}$
4	Actual network power consumption	Instrumentation network	kW	$P_{network\text{-}actual}$
5	Actual network air consumption	Instrumentation network	kg/s	$F_{network\text{-}actual}$
6	Actual air consumption of Mine Shaft A	Instrumentation network	kg/s	$F_{shaft\text{-}actual}$

The new measurement technique has to justify the improvement in electrical energy savings based on the compressed air consumed only by Mine Shaft A. The first step in developing such a measurement technique is to calculate a power baseline ($P_{shaft\text{-}base}$) relating only to Mine Shaft A.

It can be argued that the total network power consumption reflects the total power needed to generate the compressed air consumed by the entire network. Therefore the total network power baseline ($P_{network\text{-}base}$) reflects the power needed to generate the compressed air consumed from the network during an average weekday ($F_{network\text{-}base}$). This argument can be made because these baselines were compiled with data from the same time period.

The total air consumption baseline ($F_{shaft\text{-}base}$) of Mine Shaft A was also determined with data from the same time period. With reference to the total network air consumption, the percentage of compressed air consumed by Mine Shaft A can be determined. Keeping in mind that the network power consumption reflects the power needed to generate the total compressed air consumed, the power needed to generate the compressed air consumed by Mine Shaft A can be justified. The power baseline ($P_{\text{shaft-base}}$) relating to the compressed air consumption of Mine Shaft A is calculated with Equation 7.

Equation 7: Power baseline calculation for Mine A.

$$P_{\text{shaft\_base}} = P_{\text{network\_base}} \times \frac{F_{\text{shaft}-\text{base}}}{F_{\text{network}-\text{base}}}$$

Where:

$P_{\text{shaft\_base}}$ - Power baseline for the shaft

$P_{\text{network\_base}}$ - Power baseline for the network

$F_{\text{shaft}-\text{base}}$ - Air consumption baseline for the shaft

$F_{\text{network}-\text{base}}$ Air consumption baseline for the network

The actual power profile relating to the compressed air consumption of Mine Shaft A can be calculated using the same principle. Data obtained for the period that the improvement in electrical energy savings have to be measured for (number 4-6 in Table 12) have to be used to calculate the actual power profile. The actual power profile relating to the compressed air consumption of Mine Shaft A is calculated with Equation 8.

Equation 8: Actual power consumption for Mine A.

$$P_{\text{shaft}-\text{actual}} = P_{\text{network}-\text{actual}} \times \frac{F_{\text{shaft}-\text{actual}}}{F_{\text{network}-\text{actual}}}$$

Where:

$P_{\text{shaft}-\text{actual}}$ - Actual power consumption for the shaft

$P_{\text{network}-\text{actual}}$ - Actual power consumption for the network

$F_{\text{shaft}-\text{actual}}$ - Actual air flow consumption for the shaft

$F_{\text{network}-\text{actual}}$ - Actual air flow consumption for the network

The same baseline-scaling method developed by the M&V team to scale the network power baseline is used to scale the power baseline ($P_{shaft\text{-}base}$) of Mine Shaft A. This scaling method is described in the previous section and the scaling factor is calculated using Equation 6. The power profile baseline, the scaled power profile baseline and the actual power profile for Mine Shaft A were measured using the new measurement technique for an average weekday during the performance assessment period. These results are displayed in Figure 57.

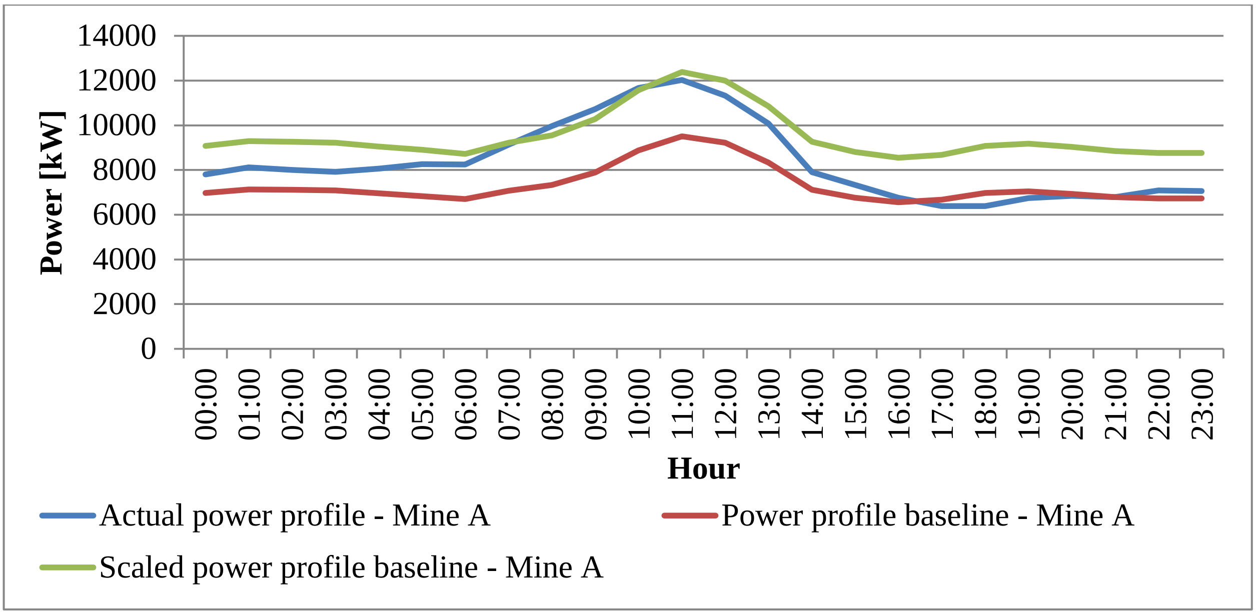

Figure 57: Power profiles (using new measuring technique).

The simulation model indicated an expected improvement of 1.28 MW in power saving. After the proposed improvements were implemented on all levels except for levels 70 and 73, the new measurement technique measured an improvement in power saving of 1.15 MW. This improvement is 0.13 MW less than estimated by the simulation model. The measurement results from the new measurement technique are within 10% of the estimated improvement in electrical energy saving.

4.2.4. Conclusion

Two measurement techniques were discussed in the previous two sections. The first measurement technique was used by the M&V team to measure the improvement in electrical energy saving during the performance assessment project phase. The second measurement technique was developed after possible areas to improve the M&V measurement technique were identified. The measurement results of these two measuring methods are summarised in Table 13.

Table 13: Results from the two measurement methods.

No.	Average weekday impact: M&V measurements [MW]	Average weekday impact: new measurement technique [MW]
Month 1	1.85	1.27
Month 2	1.41	1.23
Month 3	1.45	0.96
Average	**1.57**	**1.15**

If the results using the two measurement techniques are compared with the simulated result discussed in Section 3.4.5, it is found that the results using the new measurement technique is closer to the simulated results than the results using the M&V measurement technique. It should be noted that the results from the M&V measurement technique had an average overshoot of 25% compared with the simulated result. On the contrary, the results from the new measurement technique had an average shortfall of 10% compared with the simulated result.

To make a knowledgeable decision as to which measurement technique was the most accurate approach, the actual pressure control of each level had to be investigated. The initial proposed pressure-control philosophy (used in the simulation model to calculate the estimated improvement in electrical energy savings) was compared with the actual execution thereof. The pressure set-point profile and the actual pressure profile of 59-Level for a typical weekday are displayed in Figure 58.

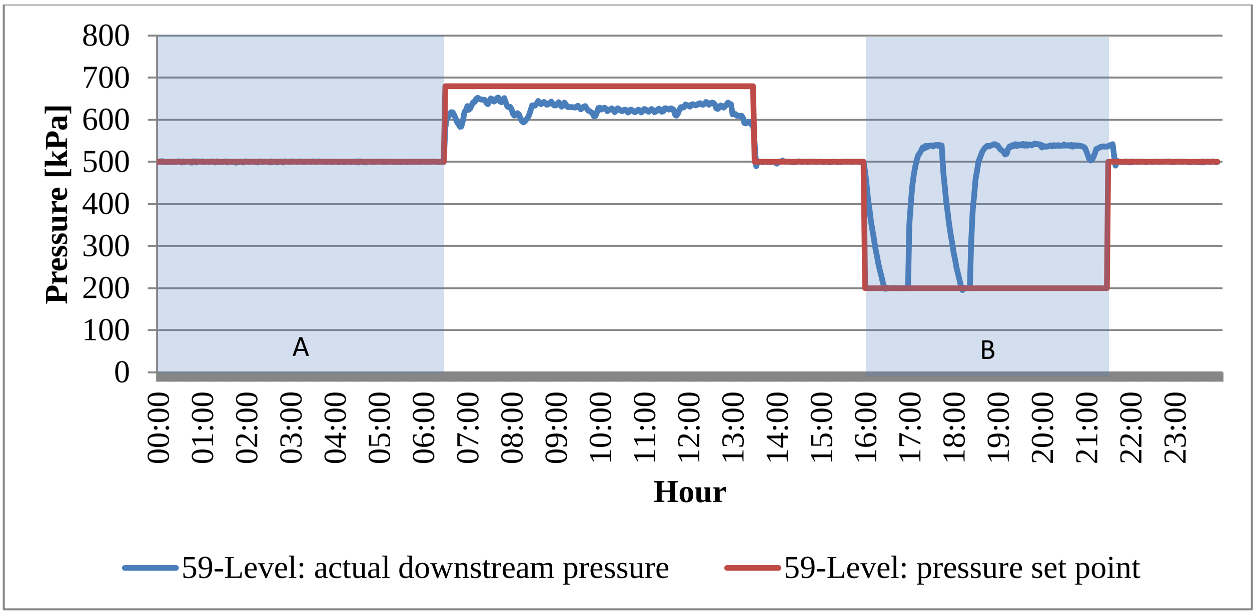

Figure 58: Pressure control execution on a typical weekday (59-Level).

Two different time periods during a typical production day were identified and are indicated with blue transparent blocks on the graph in Figure 58. During Time Period A the pressure control was executed without any deviations. During this time period the actual pressure was controlled according to the pressure set point. During Time Period B the actual pressure deviated from the proposed pressure set point. After further investigation into this phenomenon it was found that the control room operator manually entered pressure set points.

Further investigations indicated that afternoon sweeping (explained in Section 2.3.1) occurred on 59-Level during Time Period B. As a result, during this period locomotives were transporting hoppers loaded with ore to the tipping bays. The locomotives passed through high-pressure ventilation doors that were opened and closed by pneumatic cylinders. The tipping bays also operated using pneumatic cylinders to tip the hoppers. These cylinders were located downstream of the globe valve controlling the supply pressure towards the level.

With the pneumatic cylinders requiring a pressure of 400–500 kPa to operate, the control room operator had to manually override the pressure set point for production to proceed. This occurrence was not taken into consideration when the simulation model was formulated. In addition to this occurrence, the pressure set points proposed in the simulation model were altered during the commissioning project phase. Figure 59 displays a typical weekday where the pressure control was executed correctly on 62-Level.

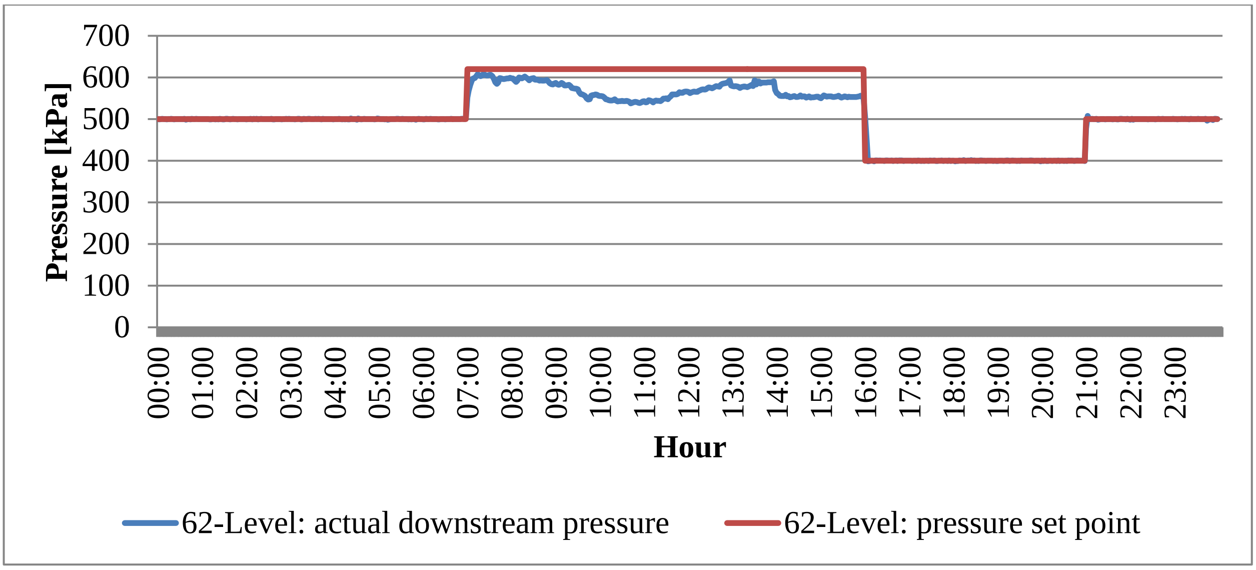

Figure 59: Pressure control execution on a typical weekday (62-Level).

As a result of overriding the pressure set point on 59-level almost every weekday (during the afternoon), it would be expected that the actual improvement in electrical energy savings would be less than the simulated result. This statement is supported by the fact that the proposed pressure set points were altered during the commissioning project phase. This occurrence can be noted by comparing the pressure set-point profiles in Figure 58 and Figure 59 with the pressure set points used in the simulation model (summarised in Appendix A: Table 15).

The conclusion can be made that the new measurement technique is a more accurate measuring technique than the original method used by the M&V team. This conclusion is based on the fact that the new measurement technique measured the improvement in electrical energy saving as 10% less than the simulation result. The M&V team measured the improvement in electrical energy saving as 25% more than expected.

4.3. Added benefits of the improved system

By controlling the supply pressure with a globe valve assembly instead of a butterfly valve assembly, the pressure control towards each level could be controlled with better accuracy. Due to the characteristics of the globe control valve, erosion does not damage the control mechanism of the valve to such extent as in the case of a butterfly valve. For this reason the required maintenance on the pressure-control system was reduced.

Using the upgraded communication network, the control room operator was able to change the supply-pressure set points of each level remotely from surface. This system improvement enables one to adjust the supply-pressure set-point profile of each level on a regular basis with more ease. By evaluating the supply pressure requirements of each level on a regular basis, the supply-pressure set-point profiles could be changed to adapt to any system changes.

Although the globe control valves were controlled to maintain a downstream pressure set point, the airflow towards each level was monitored with the newly installed flow measurement equipment. The compressed air consumption of each level on a typical production day had already been investigated. These values were programmed onto the SCADA network. If the flow rate towards a level exceeded the normal compressed air consumption set point, an alarm would notify the control room operator.

Various other system parameters were also monitored and logged on a local server. With this information available, fault finding in the case of control failure will be much easier. Some of the parameters monitored and logged are:

- flow rate towards each level,
- actual downstream pressure,
- downstream pressure set point, and
- valve position.

To monitor the condition of the compressed air network on each level, engineers do pressure drop tests on all the levels. These pressure drop tests are done on a day when there are no underground production activities (usually on an off-production weekend). During the pressure drop tests the underground compressed air network is supplied with a surface pressure of 450–550 kPa.

The shaft engineer accompanied by the relevant mine personnel travel to each level. At each level an isolating valve is closed and the time it takes for the pressure to drop (downstream of this isolating valve) to 0 kPa gauge pressure is measured. This time value is compared with values taken during previous pressure drop tests to determine the condition of the piping network on that level. If the time period for the pressure to drop is less than the previous readings, it is an indication that pipe leaks have increased, if the piping network on that level has not been expanded.

Without including the overtime salaries of the people involved with such a pressure drop test, it is estimated that a pressure drop test will cost approximately R12 000. This estimation is based on the following assumptions:

- it takes five hours to complete the test,
- the test is done on a Saturday between 11:00 and 15:00, and
- the 2012/2013 summer Eskom electricity tariffs are used.

With the pressure-control strategy implemented on the various levels, the supply pressure towards the levels is controlled according to a pressure set-point profile. The pressure set-point profile differs from level to level, but all the profiles have one characteristic in common. At a certain time period (which is usually after the drilling period), the pressure set point is reduced. This phenomenon is visible at 16:30 on the graph in Figure 60.

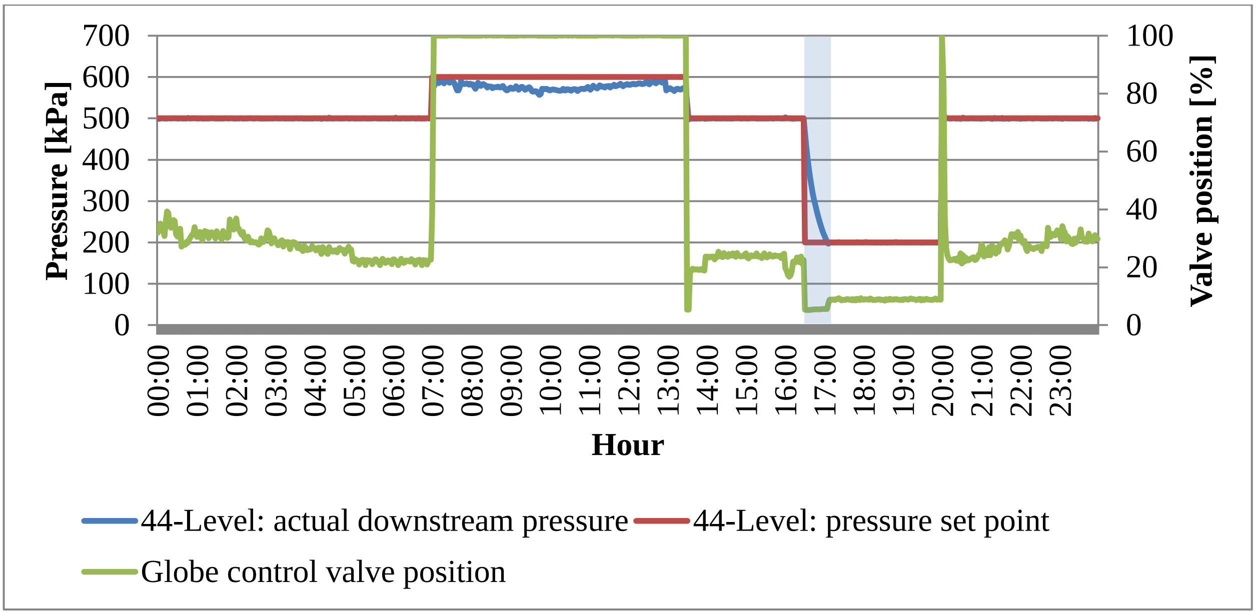

Figure 60: Pressure-control profiles for a typical production day (44-Level).

When the pressure set point is reduced, the position of the globe control valve is also reduced to achieve the desired downstream pressure. On the graph in Figure 60 it is visible that the position of the globe valve changes to a minimum of 5% when the downstream pressure set point changes from 500 kPa to 200kPa (indicated by the blue transparent block).

The time it takes for the actual downstream pressure to reach the pressure set point can be logged on the SCADA system. By comparing this time period to a predetermined benchmark, the condition of the piping network can be monitored. It should be noted that any system changes related to equipment consuming compressed air during this time period will affect the time at which the new pressure set point is reached.

If the time to reach the new pressure set point decreases compared with the predetermined benchmark, the compressed air consumed on that level during this period of the day has increased. The cause of this phenomenon should be investigated. If the number of pneumatic equipment or compressed air applications consuming compressed air during this time period remained unchanged, possible system leaks should be investigated.

By monitoring the condition of the compressed air pipe network on each level as described above, pressure drop tests can be done on a less frequent basis. This will result in additional cost savings for the mine. Major compressed air leaks will also be spotted sooner because the system is monitored more regularly.

4.4. Conclusion

The method used by the M&V team to measure the improvement in electrical energy savings was analysed. Areas to improve this measurement strategy were identified and a new measurement technique was developed.

The results of both techniques were compared with the results of the simulation model developed in Chapter 3. It was found that the results using the new measurement technique were more accurate than the results using the M&V measurement technique. The new measurement technique measured an average improvement in weekday power saving of 1.15 MW (annual cost saving of R4.37 million). This measurement result is within 10% of the simulated result.

Added benefits of the improved system include:

- more accurate supply pressure control,
- reduced maintenance,
- improved communication network, and
- additional system monitoring features.

Chapter 5: Conclusion

[22]

Objectives are reviewed. The correlation between the simulation results and the actual improvement in electrical saving are discussed. The study is concluded and recommendations for further studies are made.

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5.1. Study overview

In the past, various electrical energy savings strategies have been implemented on industrial compressed air networks. Studies have shown that energy efficiency projects implemented on the compressed air systems of deep level mines achieved power savings of up to 2.2 MW. These projects are not only reducing the electricity demand of the country, but are also helping to reduce the operating cost of compressed air systems.

With the cost of electricity rising well above inflation, the need to improve existing electrical energy saving strategies even further has increased in order to reduce the operating cost even more. Various existing energy saving strategies implemented on the compressed air networks of deep level mines have been investigated. This study focused on modernising and improving underground compressed air saving strategies to further reduce the operating cost.

A mine was identified where an existing underground compressed air DSM project was already implemented. The underground compressed air network at this mine was investigated by doing a detailed site investigation. Pressure, flow and power data were collected. Portable measuring instrumentation devices were installed where additional data were needed. The flow and power data were used to compile average 24-hour baseline profiles for a typical production day.

Possible areas to modernise and improve the existing compressed air DSM project were identified. A simulation model was then developed to simulate the proposed improvement in electrical energy when certain improvements to the system were considered. The proposed improvements were discussed with relevant mine personnel. Their inputs and expertise was used to determine the feasibility of the proposed improvements.

The proposed improvements were evaluated based on the expected improvement in electrical energy saving, the expected saving sustainability and the implementation cost thereof. Improvements that were found feasible were implemented on the existing underground compressed air saving strategy.

After the implementation of the improvements, the improved energy saving strategy was tested and monitored for three months. This three-month period is referred to as the project assessment phase.

An independent organisation, referred to as the M&V team, measured the actual improvement in electrical energy savings during the project assessment period.

The method used by the M&V team to measure the improvement in electrical energy saving was analysed. Possible areas to improve the original M&V measurement technique were identified and a new measurement technique was formulated. The improvement in electrical energy savings measured using the new measurement technique was compared with the simulated result.

5.2. Project conclusions

The M&V team measured an average improvement in power saving of 1.57 MW for mine working days during the project assessment period. This was approximately 25% more than the expected improvement in electrical energy saving calculated with the simulation model.

The new measurement technique measured an average improvement in power saving of 1.15 MW for mine working days for the same period. This was approximately 10% less than the expected improvement in energy saving.

It was found that the new measurement technique was a more accurate method of justifying the improvement in electrical energy saving. With an average improvement in power saving of 1.15 MW during mine working days, an annual cost saving of R4.167 million will be achieved (based on the 2013/2014 Eskom electricity tariffs).

The conclusion can be made that by improving existing energy saving strategies on the underground compressed air networks of deep level mines, the operating cost can be reduced significantly. With the continuous improvement of equipment and technology, areas to improve existing energy saving strategies will keep on growing. Existing energy saving strategies should be properly maintained and continuously upgraded to optimise the electrical energy savings achieved.

5.3. Limits to this study

Compressed air networks found in the deep level mining industry are large consumers of electricity. Operating costs can be reduced by improving existing electrical energy saving strategies already implemented on these networks. Although surface compressed air networks were investigated, this study focused on improving underground compressed air DSM projects to reduce operating cost.

The operating procedures of individual levels were analysed to determine the compressed air demand of each level for a typical production day. Improvements based on the control of the compressed air supply for each level were investigated. Improvements found feasible were implemented and tested. This study did not investigate possible improvements in the stope areas of the underground compressed air network.

5.4. Recommendations for future work

It was found that lack of maintenance, improved technologies and regular production changes magnify the possibility of improving existing underground compressed air saving strategies. These occurrences will most probably be found on existing surface compressed air DSM projects as well. For this reason, operating cost of compressed air networks in the deep level mining industry can be reduced even more by improving existing surface compressed air saving strategies.

Underground compressed air DSM projects can be improved even more by investigating areas where the demand side of the underground compressed air network can be improved. Valves that isolate the compressed air supply from the stope areas during the blasting shift should be investigated. These valves can automatically be closed when the NSS boxes are activated by mine personnel at the beginning of each blasting shift.

In this study it was found that equipment such as pneumatic cylinders are not large consumers of compressed air when compared to other compressed air consumers such as pneumatic drills. Equipment such as cylinders usually requires a high pressure to operate. The possibility of supplying these types of equipment with compressed air feeding from a pipeline before the pressure-control valve should be investigated. If the supply pressure towards a level is reduced, the supply pressure to these types of equipment will not be affected. As a result, the supply-pressure set points of the individual levels can be reduced even more during certain periods of the day.

It was found that operational activities often change on each level. For this reason the compressed air demand for the individual levels should also be analysed on a regular basis. It is recommended that a production analysis programme is implemented to monitor the system changes on each level. Appointed mine personnel should change the supply-pressure set points of each level accordingly to ensure optimal savings.

It is often found that mine personnel, such as control room operators, are relatively old people who have been working at the mine for a long period of time. These people are used to operate the compressed air network at a certain way. It is often difficult to convince these people to control the system on a different way they are used to. In order to ensure that the mine personnel have faith in the system changes, they need to be part of the project during the implementation phase.

The project objectives and technical details (such as why a globe control valve is installed to control the air pressure of a level) needs to be communicated to the mine personnel involved with the project. It is recommended that appropriate communication and motivation systems, which could help avoid any misunderstandings between the project engineers and the mine personnel, are investigated. By implementing a suitable communication and motivation system between the project engineers and the mine personnel, misunderstandings can be avoided and a more sustainable project will be ensured.

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Appendix A: Drawings, simulation results and set points

In order to optimise the daily pressure-supply set points of each level, the compressed air consumers of each level should be identified. The pressure requirement of each consumer and the time period during which the consumer will consume compressed air will also be required. This information is presented in Table 14. A simplified layout regarding the existing underground compressed air network and the different pneumatic equipment found is shown in Figure 61.

Table 14: Daily operating schedule - investigation summary.

Level 42		
Compressed air consumer	**Required pressure [kPa]**	**Time period in use**
Pneumatic rock drills	400–620	07:00–12:00
Refuge bays	200	Continuous

Level 44		
Compressed air consumer	**Required pressure [kPa]**	**Time period in use**
Tipping bays: pneumatic cylinders	400–490	20:00–07:00
High-pressure ventilation doors	400	20:00–07:00
Pneumatic rock drills	400–620	07:00–12:00
Refuge bays	200	Continuous

Level 47		
Compressed air consumer	**Required pressure [kPa]**	**Time period in use**
Tipping bays: pneumatic cylinders	400–490	20:00–07:00
Loading boxes: pneumatic cylinders	400–490	20:00–07:00
Pneumatic rock drills	400–620	05:00–14:00
Refuge bays	200	Continuous

Level 50		
Compressed air consumer	**Required pressure [kPa]**	**Time period in use**
Tipping bays: pneumatic cylinders	400–490	20:00–07:00
Loading boxes: pneumatic cylinders	400–490	20:00–06:00
Pneumatic rock drills	400–620	07:00–13:00
Refuge bays	200	Continuous

Level 53 / 56		
Compressed air consumer	**Required pressure [kPa]**	**Time period in use**
Tipping bays: pneumatic cylinders	400–490	22:00–07:00
Loading boxes: pneumatic cylinders	400–490	22:00–07:00
High-pressure ventilation doors	400	22:00–07:00
Pneumatic rock drills	400–620	07:00–12:00
Refuge bays	200	Continuous

Level 59		
Compressed air consumer	**Required pressure [kPa]**	**Time period in use**
Tipping bays: pneumatic cylinders	400–490	22:00–07:00
Loading boxes: pneumatic cylinders	400–490	22:00–07:00
High-pressure ventilation doors	400	22:00–07:00
Pneumatic rock drills	400–620	07:00–13:00
Refuge bays	200	Continuous

Level 62		
Compressed air consumer	**Required pressure [kPa]**	**Time period in use**
Tipping bays: pneumatic cylinders	400–490	17:00–07:00
Loading boxes: pneumatic cylinders	400–490	17:00–07:00
High-pressure ventilation doors	400	17:00–07:00
Pneumatic rock drills	400–620	07:00–14:00
Refuge bays	200	Continuous

Level 64		
Compressed air consumer	**Required pressure [kPa]**	**Time period in use**
Tipping bays: pneumatic cylinders	400–490	17:00–07:00
Loading boxes: pneumatic cylinders	400–490	17:00–07:00
High-pressure ventilation doors	400	17:00–07:00
Pneumatic rock drills	400–620	07:00–13:00
Refuge bays	200	Continuous

Level 68		
Compressed air consumer	**Required pressure [kPa]**	**Time period in use**
Tipping bays: pneumatic cylinders	400–490	17:00–07:00
Loading boxes: pneumatic cylinders	400–490	17:00–07:00
Pneumatic rock drills	400–620	08:00–13:00
Refuge bays	200	Continuous

Level 70		
Compressed air consumer	**Required pressure [kPa]**	**Time period in use**
Tipping bays: pneumatic cylinders	400–490	17:00–08:00
Loading boxes: pneumatic cylinders	400–490	17:00–08:00
Pneumatic rock drills	400–620	09:00–12:00
Refuge bays	200	Continuous

Level 73		
Compressed air consumer	**Required pressure [kPa]**	**Time period in use**
Loading boxes: pneumatic cylinders	400–490	17:00–07:00
Pneumatic rock drills	400–620	09:00–13:00
Refuge bays	200	Continuous

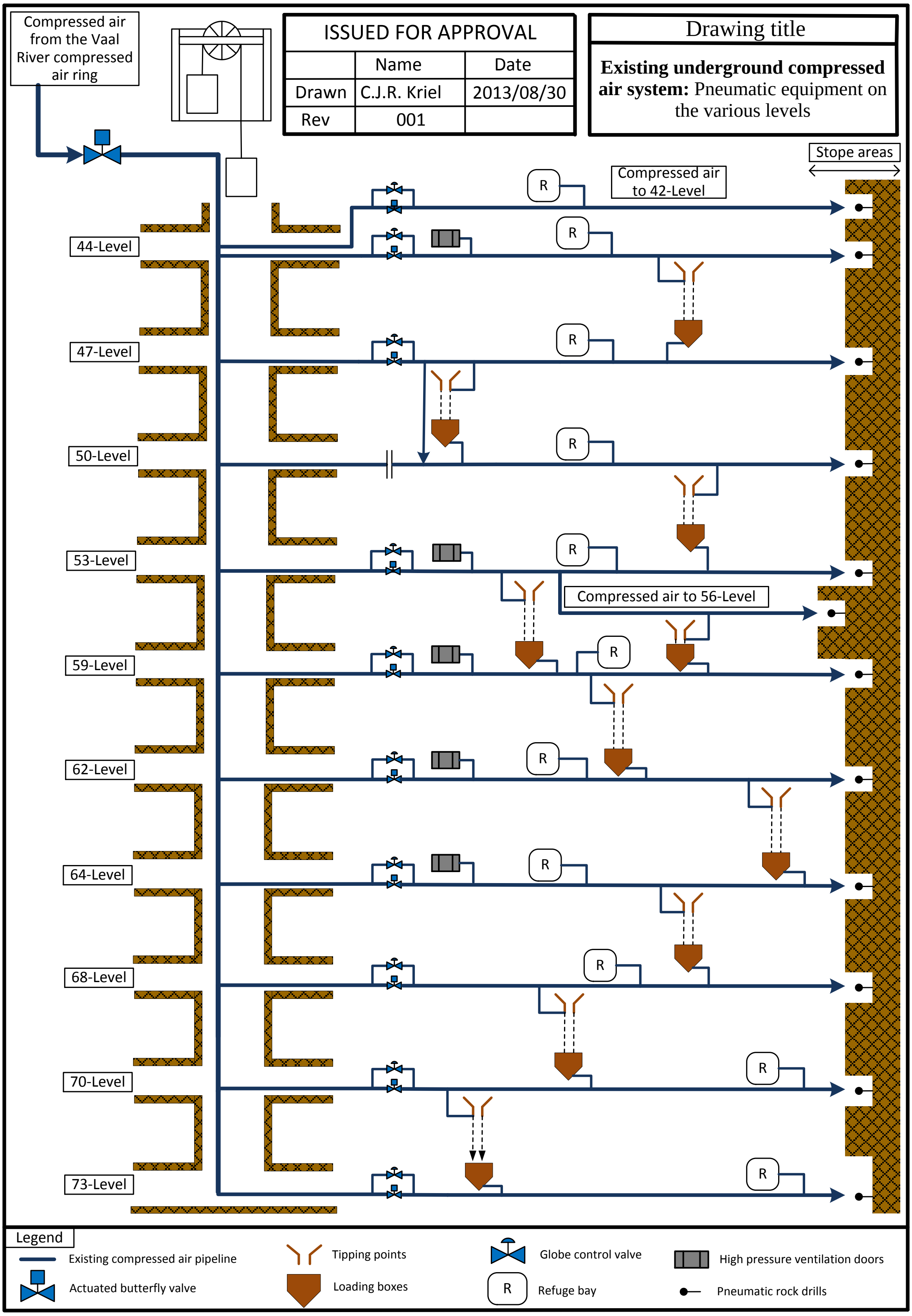

Figure 61: Existing pneumatic equipment found underground.

With the different compressed air consumers identified on each level, along with the time period during which they are in operation, an optimised daily supply-pressure set point for each level could be constructed. The optimised daily supply-pressure set points for a typical production day for each level are displayed in Table 15. The minimum surface supply-pressure set point taking the effect of auto compression into consideration is also presented in Table 15.

Table 15: Optimised supply-pressure set points.

Optimised pressure-supply set points for the various levels [kPa] - Mine A									
Hour	**44 - L**	**47 - L**	**50 - L**	**53-L / 56-L**	**59 - L**	**62 - L**	**64 - L**	**68 - L**	**Proposed surface pressure**
	13.8	**14.8**	**15.7**	**16.6**	**18.5**	**19.5**	**20.1**	**21.3**	
00:00	500	500	200	500	500	550	500	500	531
01:00	500	500	200	500	500	550	500	500	531
02:00	500	500	200	500	500	550	500	500	531
03:00	500	500	200	500	500	550	500	500	531
04:00	500	500	200	500	500	550	500	500	531
05:00	500	601	573	500	500	550	500	500	586
06:00	500	600	541	500	500	550	500	500	585
07:00	620	627	547	636	634	644	652	500	632
08:00	611	621	545	631	629	634	647	669	648
09:00	601	614	539	621	617	625	633	658	637
10:00	599	609	539	618	611	619	628	654	632
11:00	607	617	541	621	614	621	630	657	636
12:00	615	620	542	627	622	629	636	663	642
13:00	500	626	542	550	633	640	646	668	646
14:00	500	610	541	550	500	628	500	500	609
15:00	500	400	500	550	500	550	500	500	533
16:00	200	400	400	200	200	550	500	400	531
17:00	200	400	400	200	200	550	500	400	531
18:00	200	400	400	200	200	550	500	400	531
19:00	200	400	400	200	200	550	500	400	531
20:00	500	500	200	200	200	550	500	400	531
21:00	500	500	200	200	200	550	500	400	531
22:00	500	500	200	500	500	550	500	500	531
23:00	500	500	200	500	500	550	500	500	531
Legend	**Extra pressure gained due to the effect of auto compression**								
	Drilling shift: No supply pressure control								
	Daily supply-pressure set point 1								
	Daily supply-pressure set point 2								
	Daily supply-pressure set point 3								

Figure 62 to Figure 64 display the simulated mass flow values (as calculated with KYPipe) at the different reduced supply-pressure set points as indicated in Table 15.

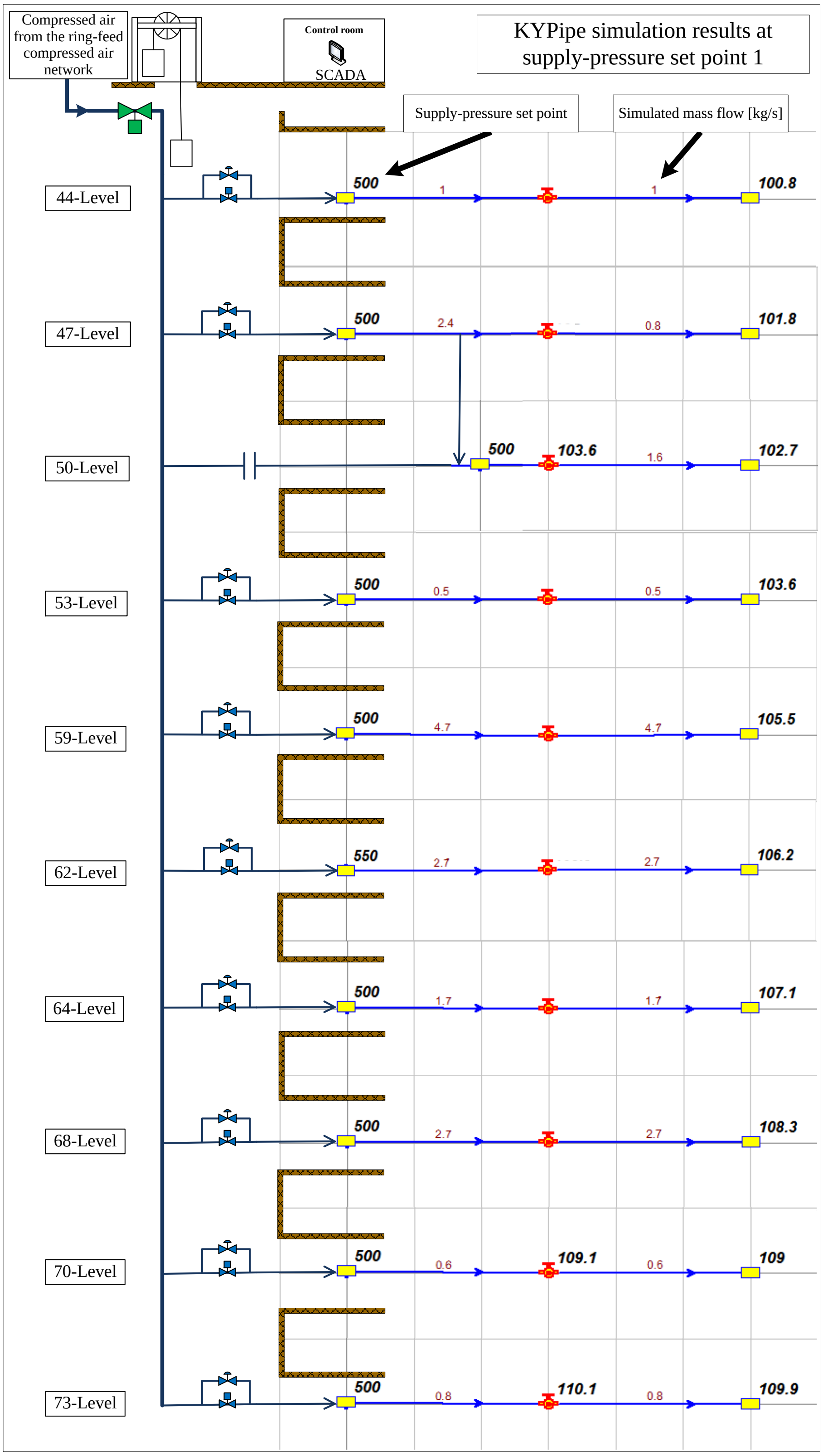

Figure 62: KYPipe simulation results at supply-pressure set point 1.

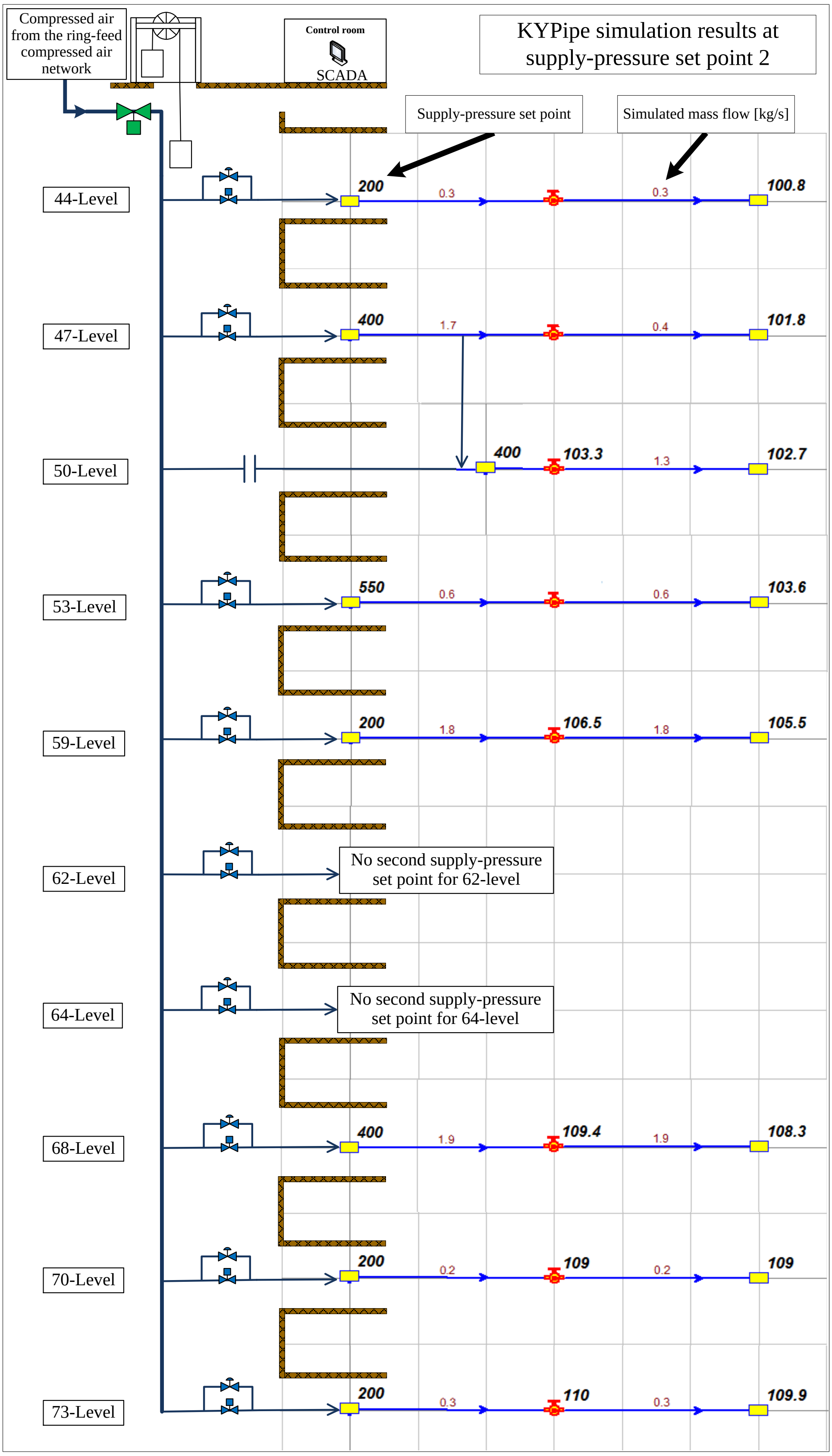

Figure 63: KYPipe simulation results at supply-pressure set point 2.

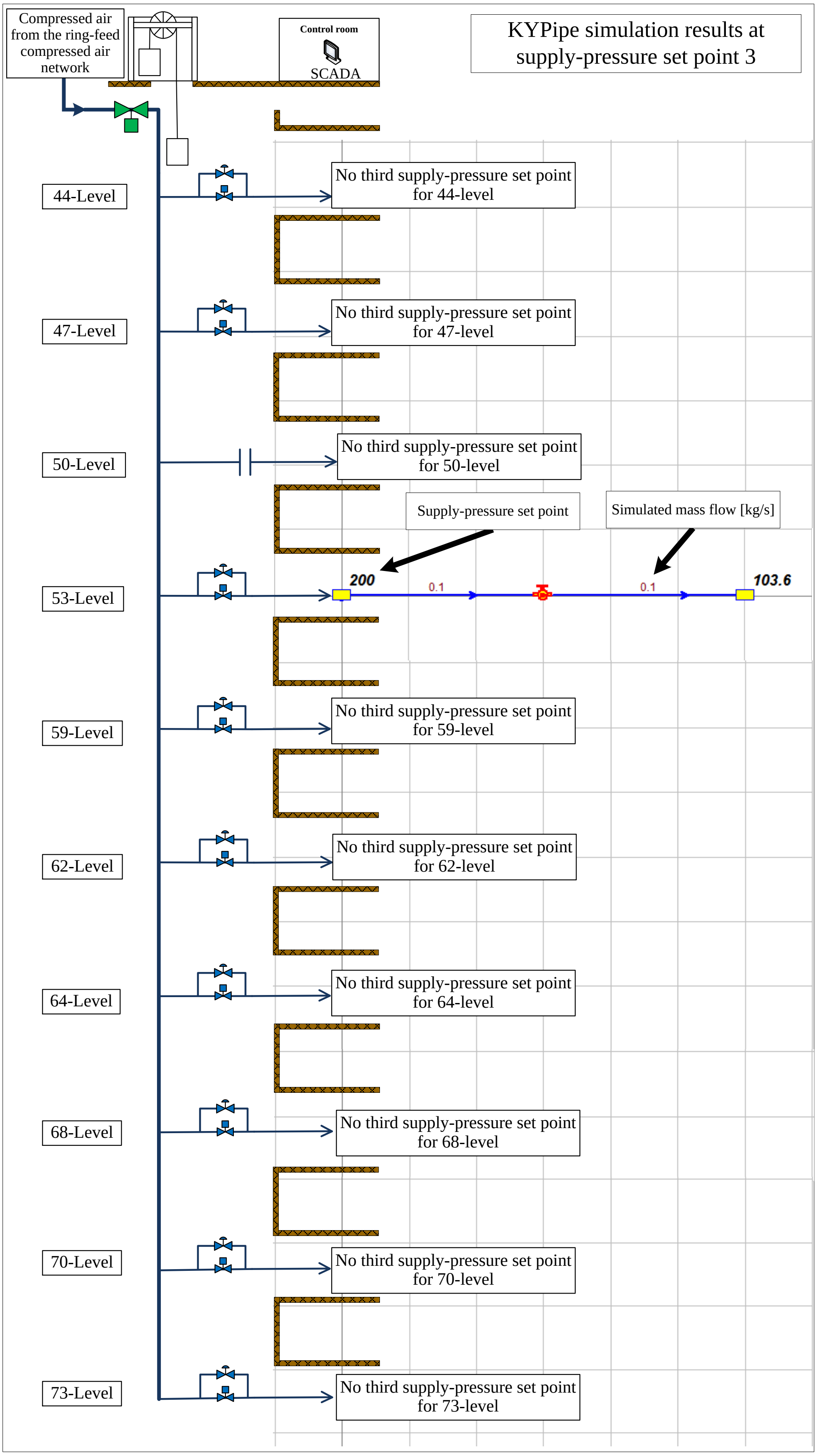

Figure 64: KYPipe simulation results at supply-pressure set point 3.

Appendix B: Estimated project cost

Table 16 shows the fixed improvement cost while Table 17 shows the variable improvement cost relating to the project used as a case study in this dissertation. Table 18 summarises the total project improvement cost for Simulation 1 and Simulation 2.

Table 16: Fixed improvement project cost.

Fixed improvement cost estimation: Mine A		
No.	**Item**	**Cost**
1	Modernisation and improvement investigation costs	R 255 000
2	Engineering	R 389 000
3	Detail design drawings	R 79 400
4	Preliminary and general (expenses which are incurred before work in producing the project deliverable commences)	R 533 000
Total overhead cost		**R 1 256 400**

Table 17: Variable improvement cost estimation per level.

Variable improvement cost estimation: Mine A		
No.	**Item**	**Cost**
1	PLC hardware	R 49 300
2	Cable and cable racks	R 25 800
3	Pipes, flanges and nipples	R 9 500
4	Globe control valve with pneumatic actuator and 4-20 mA position feedback	R 83 000
5	Refurbish old butterfly valve	R 7 800
6	Air drier	R 42 600
7	Compressed air mass flow meter	R 63 000
8	Installation cost	R 99 200
9	Commissioning	R 53 000
10	Verification and validation cost	R 80 000
Total per level improvement cost estimation		**R 513 200**

Table 18: Total improvement cost: Option 1 and Option 2.

Total improvement cost estimation- Mine A		
No.	**Item**	**Cost**
1	Fixed improvement cost estimation	R 1 256 400
2	Variable improvement cost estimation: per level	R 513 200
Simulation 1: Total cost to improve eight levels		**R 5 362 000**
Simulation2: Total cost to improve ten levels		**R 6 388 400**

Appendix C: Pneumatic cylinder calculations

Two strokes are presented in Figure 65. During the first stroke the piston is forced to the right-hand side forcing the stem to an outwards direction. During the second stroke the piston is pushed in the opposite direction pulling the stem back inside the cylinder. The cylinder completed a full cycle after both strokes have been completed. The symbols are explained as follow:

➢ D	-	The inside diameter of the cylinder
➢ d	-	The diameter of the stem
➢ F	-	The force exerted by the cylinder
➢ X	-	The piston thickness
➢ Y	-	The cylinder length

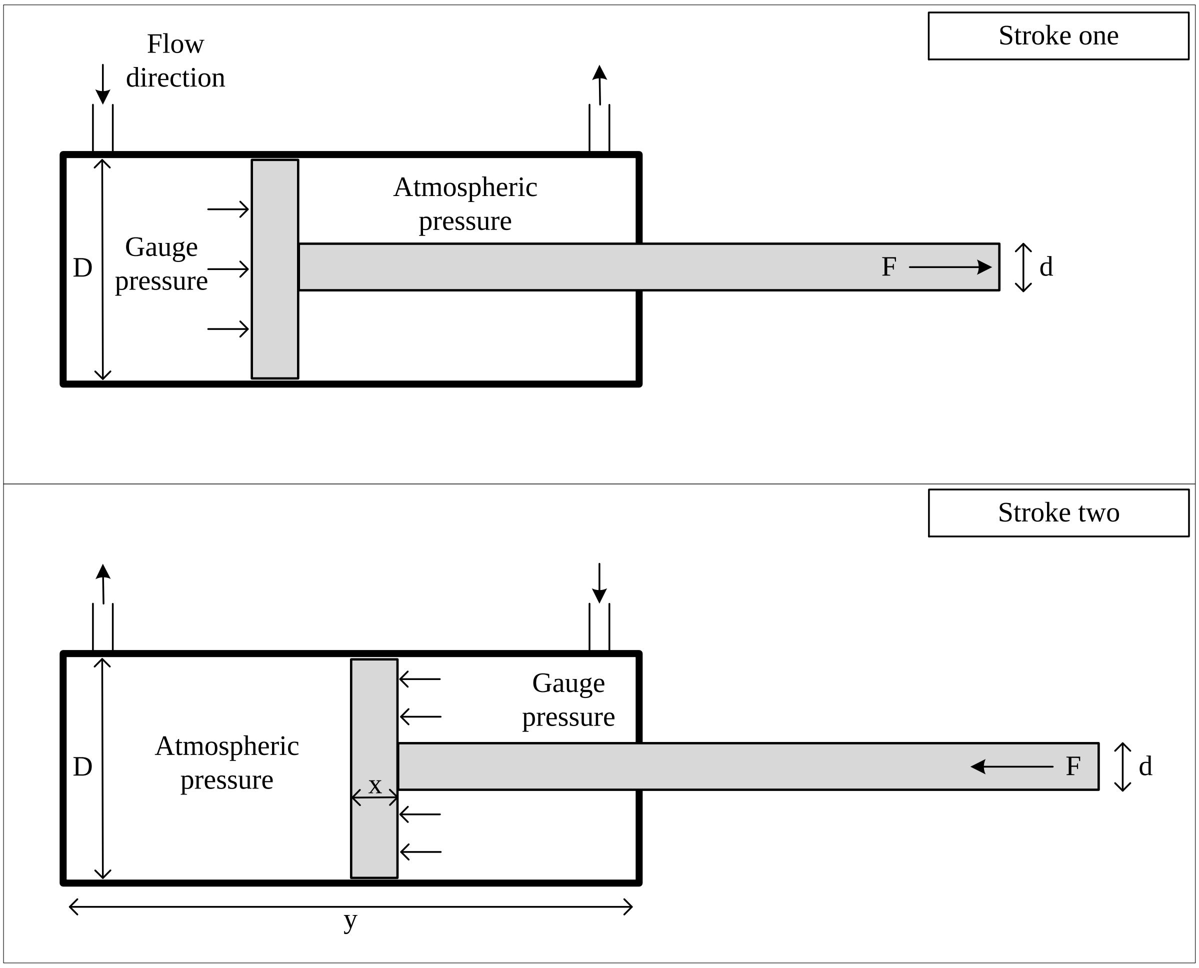

Figure 65: Pneumatic cylinder configuration - schematic diagram.

The volume of air consumed by a cylinder with one cycle can be calculated with Equation 9.

Equation 9: Volume of air consumed by a pneumatic cylinder for one cycle.

$$V = \left[\frac{\pi}{4}D^2(Y-X)\right] + \left[(\frac{\pi}{4}D^2 - \frac{\pi}{4}d^2)(Y-X)\right] \quad [m^3]$$

Where:

V – Volume consumed for a single stroke of length S [m^3]

D – Inside diameter of the pneumatic cylinder [m]

Y – Cylinder length [m]

X – Piston thickness [m]

d – Diameter of the stem [m]

Should it take the pneumatic cylinder a time period of t_s to complete one cycle, and the cylinder operates constantly for a time period T_p, the total volume V_T of air consumed during this time period is calculated with Equation 10.

Equation 10: Volume of air consumed by a pneumatic cylinder over a fixed time period.

$$V_T = V\frac{T_p}{t_s} \quad [m^3]$$

Where:

V_T – Total volume of air consumed for the time period T_P [m^3]

V – Volume consumed for a single stroke of length S [m^3]

T_P – Time period the pneumatic cylinder operates continuously [s]

t_s – Time period to complete one cycle [s]

Depending on the location where a pneumatic cylinder will be functioning, the pressure (P) supplied to the cylinder will mostly be in a specific range. The stroke length of the cylinder will depend on the specific application. By taking the supply pressure and the force (F) to be exerted into consideration, the diameter of the pneumatic cylinder (D) can be calculated using Equation 11.

Equation 11: Calculating cylinder diameter.

$$D = \sqrt{\frac{4F_{stroke\ one}}{\pi P}} \quad \text{Or} \quad D = \sqrt{\frac{4F_{stroke\ two}}{\pi P} + d^2}$$

Where:

D	–	Required inside diameter of the pneumatic cylinder	[m]
$F_{stroke\ one}$	–	Force to be exerted with stroke one	[N]
P	–	Pneumatic cylinder supply pressure	[kPa]
$F_{stroke\ two}$	–	Force to be exerted with stroke two	[N]
d	–	Diameter of the stem	[m]

Appendix D: Moody chart for calculating the coefficient of friction

Air pressure gained at various depths below surface is calculated with Equation 4. The friction factor of the pipeline is one of the input values to calculate this parameter with Equation 4. If the Reynolds number and the relative pipe roughness are known, the pipe friction factor can be obtained from the Moody chart, displayed in Figure 66.

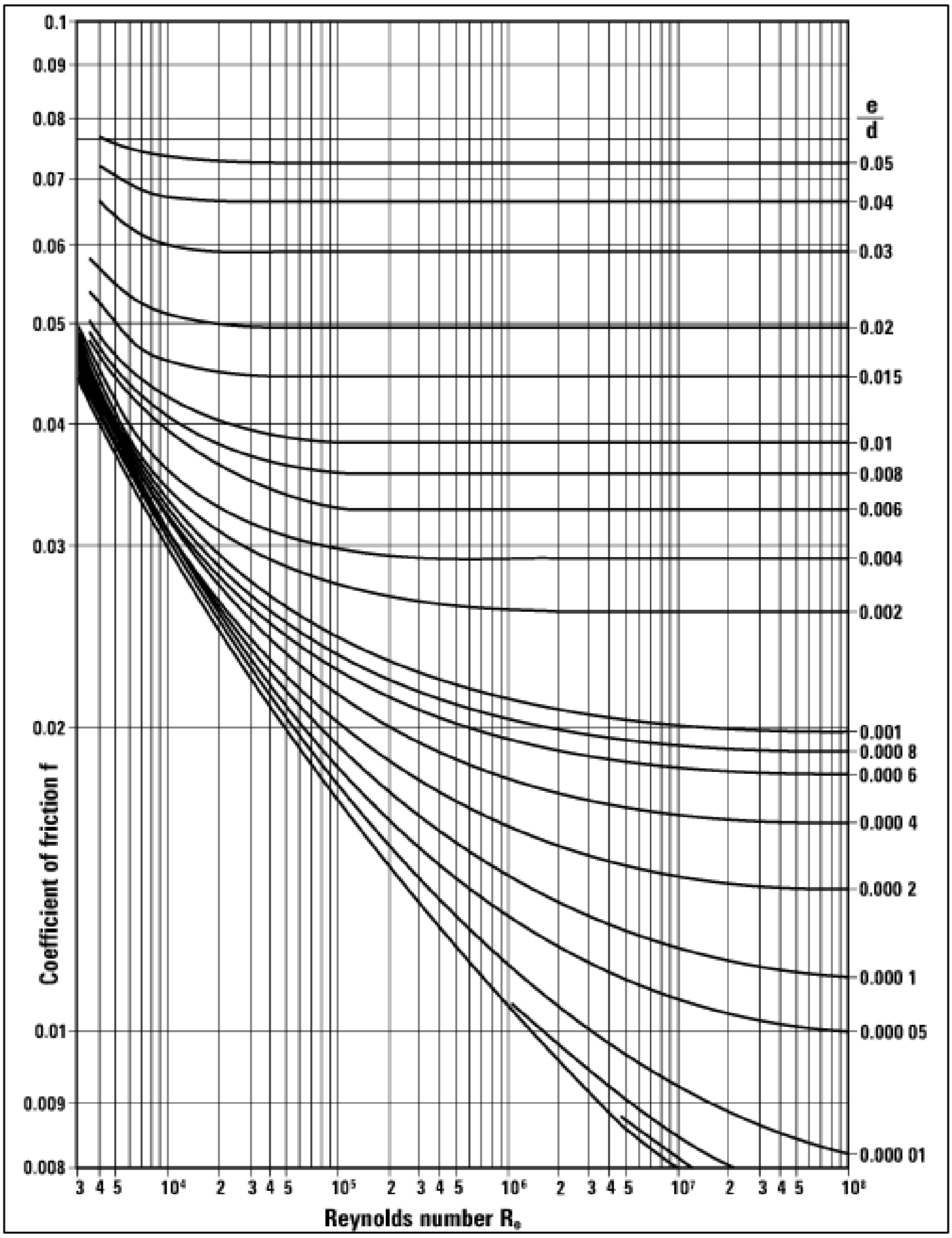

Figure 66: Moody chart.

Appendix E: KYPipe validation results

In Section 3.4.3 the KYPipe simulation method is validated by comparing a simulated mass flow with an actual mass flow measurement at a reduced supply pressure. Figure 67 and Figure 68 show the simulated mass flow results at the original supply-pressure set point and the reduced supply-pressure set point.

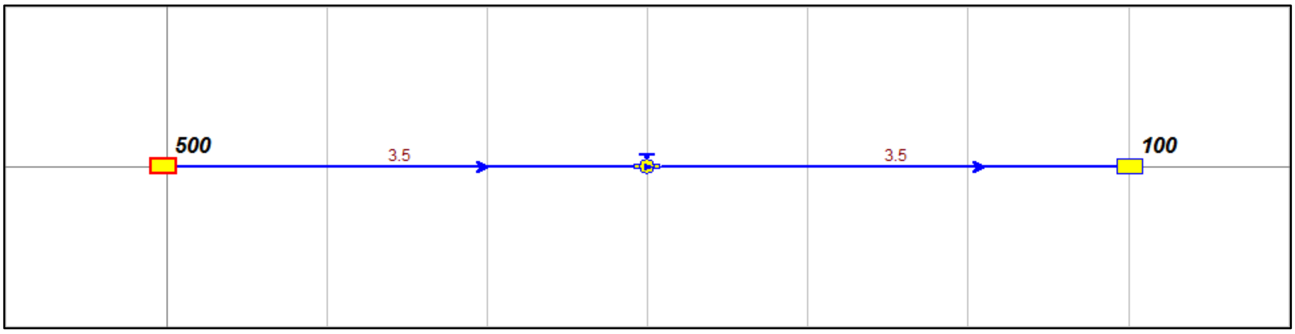

Figure 67: KYPipe simulation validation: result at original pressure set point.

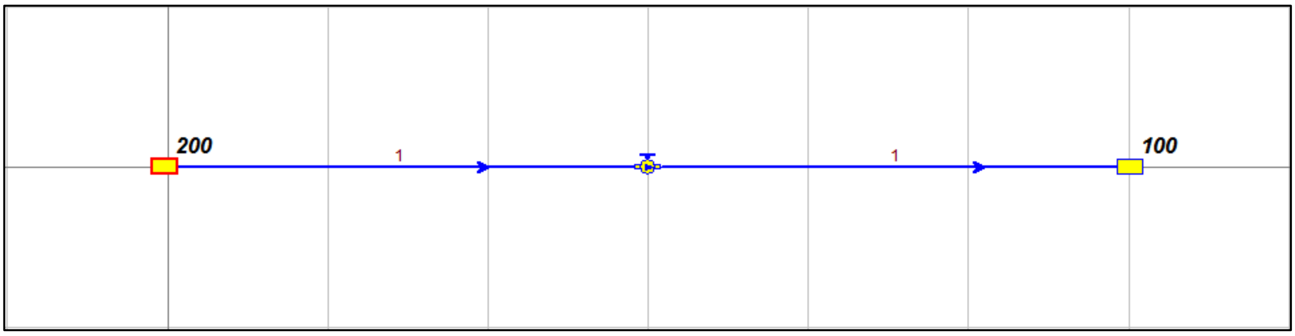

Figure 68: KYPipe simulation validation: result at reduced pressure set point.

Appendix F: Eskom tariffs

The Eskom tariffs indicated in Table 19 are according to the 2012/13 Megaflex tariff structure, for a 500 V to 6.6 kV voltage supply, within 300 km from the transmission zone.

Table 19: Eskom tariffs used for cost saving calculations.

Time of day	**Winter tariffs [c/kWh]**	**Summer tariffs [c/kWh]**
Off-peak	28.68	33.12
Standard	45.2	60.99
Peak	65.68	201.33

Figure 69 indicates the off-peak, standard and peak hours for Weekdays, Saturdays and Sundays.

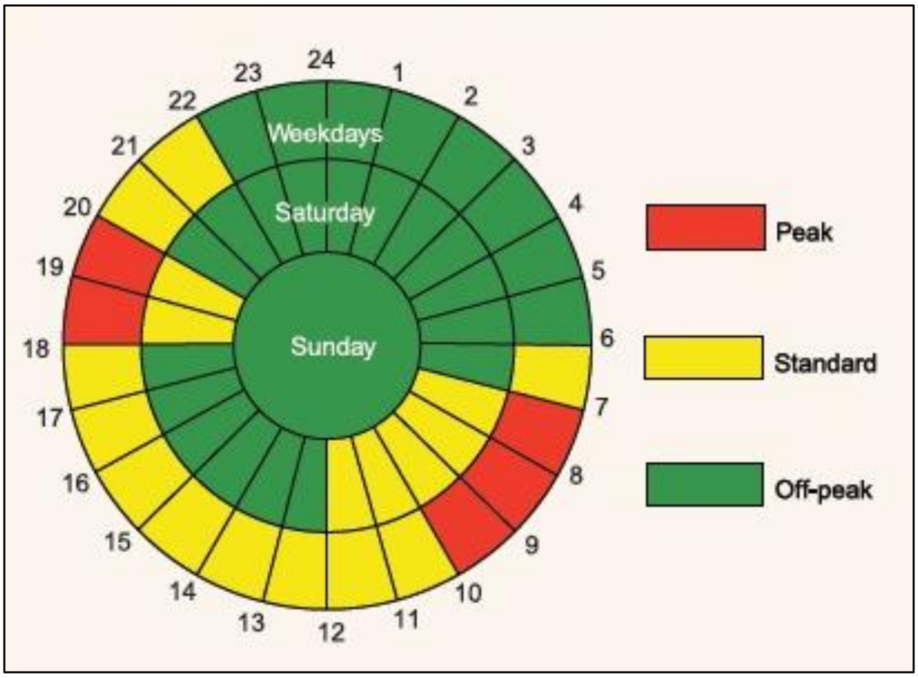

Figure 69: Eskom off-peak, standard and peak hour structure[24].

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[24] Turbo heat X changer [Online]. (2013) http://turboelement.com [Accessed: 16 April 2014].