

The implementation of a dynamic air compressor selector system in mines

**M. H. P. van Niekerk
21646384**

Dissertation submitted in fulfilment of the requirements for
the degree Magister in Mechanical Engineering at the
Potchefstroom Campus of the North-West University

Supervisor: Dr R. Pelzer

May 2015

Abstract

Title: The implementation of a dynamic air compressor selector system in mines
Author: Mr M. H. P. van Niekerk
Supervisor: Dr R. Pelzer
Degree: Magister in Mechanical Engineering
Keywords: dynamic air compressor selector, DCS, compressor control, compressor, electricity, power savings, pressure set point

The generation of compressed air comprises 20% of the total electricity usage in the mining industry, although compressed air is often seen as a free source of energy. There are however significant costs associated with generating compressed air and maintaining a compressed air system. There are several methods to optimise the electricity used to generate compressed air. The focus of this study is on one of these methods – the implementation of a dynamic air compressor selector. A Dynamic Compressor Selector (DCS) system was developed to fulfil this purpose.

DCS is a system that combines demand- and supply-side management of a compressed air network. DCS calculates a pressure set point for compressors and schedules the compressors according to the demand from the end-users. End-users include shafts, plants, workshops and smelters. DCS takes all of the compressors and end-users into consideration while doing the calculations.

This dissertation focuses on the DCS implementation process and on the problems encountered by previous authors while implementing the DCS technology. Additional problems were encountered while the DCS technology was implemented. DCS was however still successfully implemented. This study will expand the implementation procedure to ensure that the technology can be implemented successfully in the future.

DCS was implemented at a platinum mine in South Africa where it was able to calculate pressure set points for the compressors. DCS was able to accurately match the supply of, and demand for compressed air closely, resulting in lower overall compressed air usage. DCS improved compressor scheduling and control, limiting compressor cycling.

Improved compressor scheduling and control resulted in significant decreases in the electricity used to generate compressed air at the mine. A target average evening peak clip of 2.197 MW was simulated, set and achieved. Evening peak clip power savings in excess of an average of 3 MW were achieved.

Acknowledgements

I would like to thank the following people for helping:

- First and foremost, I would like to thank my God for blessing me with the ability and endurance to complete this study.
- Prof. Eddie Mathews and Dr Marius Kleingeld for providing the opportunity to conduct this study, as well as the financial support to complete it.
- Thank you to TEMM International (Pty) Ltd and HVAC International (Pty) Ltd for the opportunity, financial assistance and support to complete this study.
- Dr Ruaan Pelzer, Dr Hendrik Brand, Dr Johan du Plessis, Dr Johann van Rensburg and Mr Tjaart Zwiegers for proofreading my dissertation and giving suggestions where required.
- SW van Heerden for assisting with developing DCS.
- Kobus van Tonder for assisting with the implementation of the project.
- All my friends, those who studied with me and as those who did not, thank you for your continued support throughout. We finally made it.
- My family, for their understanding and support throughout my studies. Without your continued support, this study would not have been possible.

Thank you all.

Table of Contents

Abstract.....	i
Acknowledgements.....	ii
Table of Contents.....	iii
List of Figures	v
List of Tables	vii
List of Abbreviations.....	viii
List of Measuring Units.....	ix
List of Terms	x
List of Symbols.....	xii
Chapter 1: Introduction, background and literature.....	1
1.1. Introduction	1
1.2. Context and background	1
1.3. Compressed air networks	4
1.4. Supply-side (compressors) overview	15
1.5. Shortcomings of existing control methods.....	24
1.6. Purpose of study	30
1.7. Dissertation overview	31
Chapter 2: The implementation of a dynamic air compressor selector	33
2.1. Introduction	33
2.2. What is DCS?	33
2.3. Input parameters.....	36
2.4. Implementing DCS.....	38
2.5. Simulation results.....	41
2.6. Practical problems faced during DCS implementation.....	44

2.7. Summary	62
Chapter 3: Results after the implementation of a dynamic air compressor selector	64
3.1. Introduction	64
3.2. Pressure set point control	64
3.3. Production and consumption flow	65
3.4. Overall flow reduction	69
3.5. Compressor scheduling	70
3.6. Electrical energy efficiency.....	73
3.7. Validation of study.....	75
3.8. Summary	75
Chapter 4: Conclusion and recommendations.....	77
4.1. Conclusion	77
4.2. Recommendations for further study	78
Reference list.....	80

List of Figures

Figure 1: Yearly electricity consumption in South Africa	1
Figure 2: Average yearly electricity price increase versus average yearly inflation rate	2
Figure 3: Eskom ToU schedule	3
Figure 4: Surface valve installation with an electric actuator.....	7
Figure 5: Standalone compressed air system	9
Figure 6: Compressed air ring feed system.....	10
Figure 7: Compressor inlet guide vanes.....	18
Figure 8: Volumetric efficiency of compressor when guide vane control is enforced	19
Figure 9: Compressor characteristic curve	20
Figure 10: Compressor system including blow-off valve.....	21
Figure 11: Control valve installation underground	26
Figure 12: Typical surface valve installation.....	27
Figure 13: Example of a control system implemented to control valves.....	28
Figure 14: Example of a control system implemented to manage compressors	29
Figure 15: DCS simulation to calculate compressor pressure set points	34
Figure 16: DCS simulation for the control of compressors.....	35
Figure 17: Mine compressed air surface layout.....	37
Figure 18: Proposed baseline profiles	40
Figure 19: Simulation results for running compressors.....	41
Figure 20: Flow comparison between baseline and simulation results	42
Figure 21: Power usage comparison between baseline and simulation results	43
Figure 22: Surface valve installation.....	45
Figure 23: Typical 24-hour compressed air profile for a single shaft.....	45
Figure 24: Typical optimised shaft set point	46
Figure 25: Shaft set point versus actual pressure with ramping function	48
Figure 26: Shaft set point not being lowered after peak production time	49

Figure 27: Schematic drawing of flow meter compared with a photo of flow meter	51
Figure 28: Actual installed Verabar® flow meter.....	52
Figure 29: Spiking flow meter	52
Figure 30: Shaft compressed air flow after fixing spiking flow meter.....	53
Figure 31: Compressor delivery flows before DCS start/stop privileges	56
Figure 32: Compressor delivery flow after DCS start/stop privileges	57
Figure 33: Incorrect pipe configuration (inadequate decrease in pipe diameter).....	58
Figure 34: Pipe diameter before replacing the pipe to the shaft.....	59
Figure 35: Shaft pressure versus set point before pipe replacement	59
Figure 36: Node variance function in DCS	60
Figure 37: Offset function in DCS.....	61
Figure 38: Pipe diameter after replacing the pipe to the shaft.....	61
Figure 39: Shaft pressure versus set point after pipe replacement	62
Figure 40: DCS calculated set point compared with shaft set points	64
Figure 41: Production flow versus consumption flow (mine data)	66
Figure 42: Production flow versus consumption flow (DCS data)	67
Figure 43: Compressed air network pressure.....	68
Figure 44: Flow profiles.....	70
Figure 45: Running compressors before DCS implementation	71
Figure 46: Running compressors after DCS implementation (DCS data)	71
Figure 47: Running compressors after DCS implementation (mine data)	72
Figure 48: Electrical energy efficiency achieved by DCS.....	74

List of Tables

Table 1: Compressor specifications	38
Table 2: Baseline profiles	39
Table 3: Simulated power savings.....	43
Table 4: Compressed air flow with spiking flow meter	54
Table 5: Summary of power savings achieved by DCS	74

List of Abbreviations

DCS	Dynamic Compressor Selector
DSM	Demand Side Management
ESCo	Energy Service Company
GPS	Global Positioning System
IDM	Integrated Demand Management
IT	Information Technology
OEM	Original Equipment Manufacturer
PID	Proportional Integral Derivative
PLC	Programmable Logic Controller
SCADA	Supervisory Control and Data Acquisition
SI Units	International System of Units
ToU	Time-of-Use

List of Measuring Units

gpm	Gallons per minute
K	Kelvin
kg/m ³	Kilogram per cubic metre
kg/s	Kilogram per second
kJ	Kilojoule
kJ/kg	Kilojoule per kilogram
kJ/kg·K	Kilojoule per kilogram kelvin
kPa	Kilopascal
kW	Kilowatt
kWh	Kilowatt-hour
m	Metre
m/s	Metre per second
m/s ²	Metre per square second
m ²	Squared metre
m ³ /h	Cubic metre per hour
mA	Milliampere
mm	Millimetre
MW	Megawatt
MWh	Megawatt-hour
Pa	Pascal
psi	Pounds per square inch
rpm	Revolutions per minute
-	Used when no specific unit is available

List of Terms

Blasting:	During the drilling shift of a mine, holes are drilled into the rock face after which explosives are placed in the holes and detonated. This is referred to as blasting.
Blow-off valve:	Compressor pressure relief valve to expel excess air and to prevent compressor surge.
Compressor cycling:	Excessive shutting on/off of a compressor.
Compressor house:	A building that contains one or more compressors. The compressors can be of different sizes or capacities. Each compressor will have its own outlet, but eventually all the compressors will supply air into the same manifold.
Compressor surge:	Surge is the reversal of flow inside the compressor, accompanied by high varying load on the bearings of the compressors. Surge occurs when the compressor cannot add enough energy in terms of compressed air to the system to overcome the resistance or backpressure. Surge results in high vibration in the compressor, higher operating temperatures and quick changes in axial thrust.
Electrical energy efficiency project:	Electrical energy efficiency projects aim to reduce the total power usage during weekdays from 06:00 to 22:00.
Function block:	A graphical language for PLC design that best describes the functions between input and output variables.
Inlet guide vanes:	Stationary vanes that are located at the inlet of the first stage of a compressor. The inlet guide vanes direct the flow of air into the compressor at the correct angle for efficient operation. It can also control the mass flow of the air through the compressor.

Internal tag:	A tag created in DCS that acts as a replacement for a SCADA tag. An internal tag will be created if calculations have to be done on SCADA tags or if fixed values have to be inserted.
Load shift DSM project:	Load shifting projects aim to shift electrical load from Eskom peak periods to Eskom standard or Eskom off-peak periods.
Peak clip DSM project:	Peak clipping projects aim to reduce electrical load during Eskom peak periods.
Performance assessment period:	A three-month period during which Eskom closely monitors the DSM project performance to ensure that the contracted electricity savings by the ESCo implementing the project were achieved. After the performance assessment period, the ESCo is relieved of its responsibility to achieve the electrical savings. It is then the mine's responsibility to ensure that the savings achieved during the performance period continues to be reached.

List of Symbols

A	Area [m^2]
c	Constant value [-]
$c_{discharge}$	Discharge coefficient of air, usually taken between 0.6 and 0.97 [-]
$Cost\ saving$	Monetary savings [R]
C_p	Molar specific heat at a constant pressure for air [$\text{J/kg}\cdot\text{K}$]
CV	Flow coefficient of valve [-]
Δp	Pressure drop across the valve [kPa]
d_h	Hydraulic diameter [m]
η_{comp}	Compressor efficiency [-]
η_{motor}	Motor efficiency, usually taken between 0.85 and 1 [-]
g	Gravitational acceleration [9.81 m/s^2]
h	Height of point above reference point [m]
$hours_{operating}$	Total number of operating hours for the compressor [hour]
k	Specific heat ratio, taken as 1.4 for air [-]
λ	Darcy-Weisbach friction coefficient [-]
l	Length of pipe [m]
$\dot{m}_{air}$	Mass flow rate of leaking air [kg/s]
n	Polytropic coefficient, taken as 1.4 [-]
p	Air pressure [Pa]
P	Electrical power usage by the compressor [kW]
p_1	Atmospheric pressure [kPa]
p_2	Compressor discharge air pressure (absolute) [kPa]
p_{in}	Inlet pressure of compressor [kPa]

p_{line}	Compressed air pipeline pressure at leak (absolute) [kPa]
p_{out}	Outlet pressure of compressor [kPa]
P_{saving}	Amount of electricity that can be saved [kW]
P_{waste}	Wasted electrical power [kW]
Q	Volumetric flow rate [m ³ /h]
ρ	Air density [kg/m ³]
R	Molar gas constant [0.287 kJ/kg·K]
$R_{per\ kW}$	Unit cost per kW of electricity [R]
T_1	Compressor inlet air temperature [K]
T_{in}	Inlet temperature of compressor [K]
T_{line}	Temperature in compressed air pipeline at leak [K]
v	Air velocity [m/s]
w_{comp}	Energy used by the compressor [kJ/kg]
$w_{comp,mech}$	Mechanical energy [kJ/kg]

Chapter 1: Introduction, background and literature

1.1. Introduction

Chapter 1 provides background information on the electricity situation in South Africa. It discusses compressed air networks and centrifugal air compressors, including the compressors' functions and performance. This section focuses on the supply- and demand side of compressed air.

Chapter 1 furthermore provides an overview on compressor control and discusses the previous control strategies for compressors in the mining industry. A purpose for this study is identified and discussed. Finally, an overview of this dissertation is provided.

1.2. Context and background

According to data collected by The World Bank, electricity consumption in South Africa has been increasing steadily for the last 40 years [1]. Figure 1 shows the increase in the electricity consumption in South Africa from 1971 to 2011.

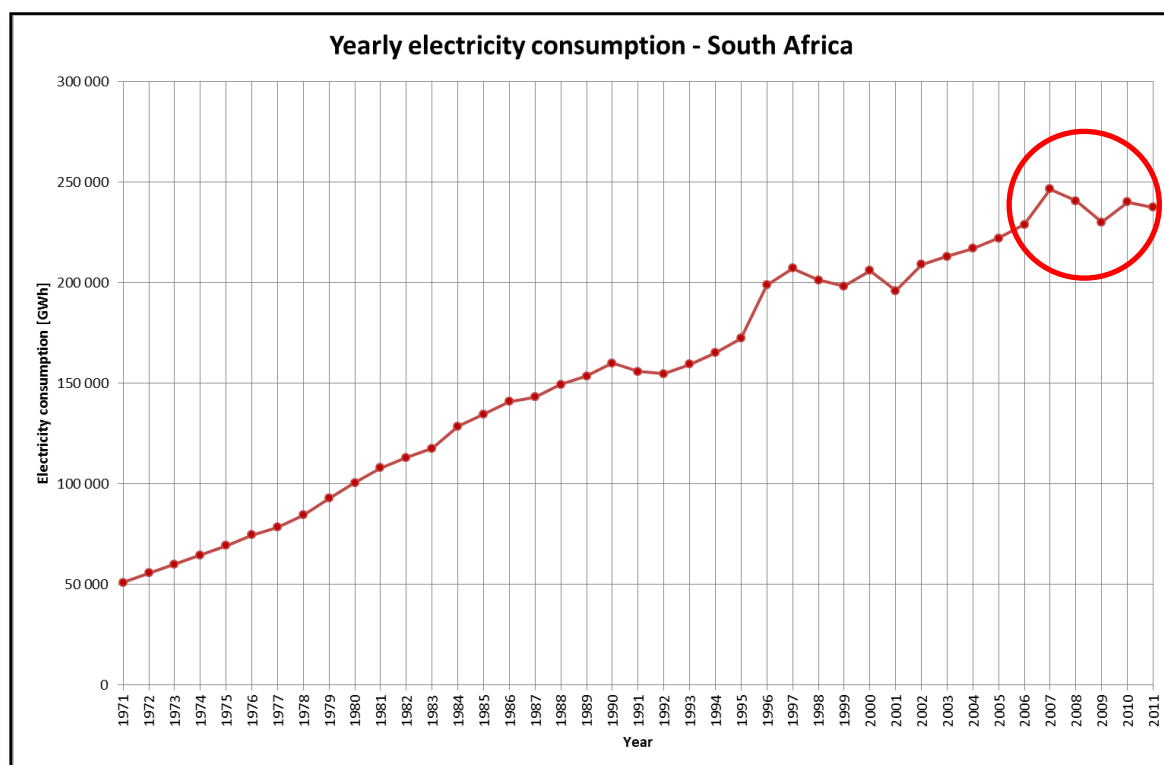


Figure 1: Yearly electricity consumption in South Africa ¹

¹ Adapted from [1].

It is evident from Figure 1 that electricity consumption in South Africa has been increasing steadily. From 2007 onwards, however, several interventions have been made to reduce electricity consumption.

The red circle in Figure 1 illustrates the impact of these interventions as well as the impact due to the weakening world economy. The weakening world economy has also caused a decrease in the demand for natural resources. Regrettably no more recent data has been published.

Eskom is South Africa's main electricity supplier, supplying around 95% of South Africa's electricity [2]. Figure 2 compares the average yearly price increase for electricity in South Africa with the average yearly inflation rate.

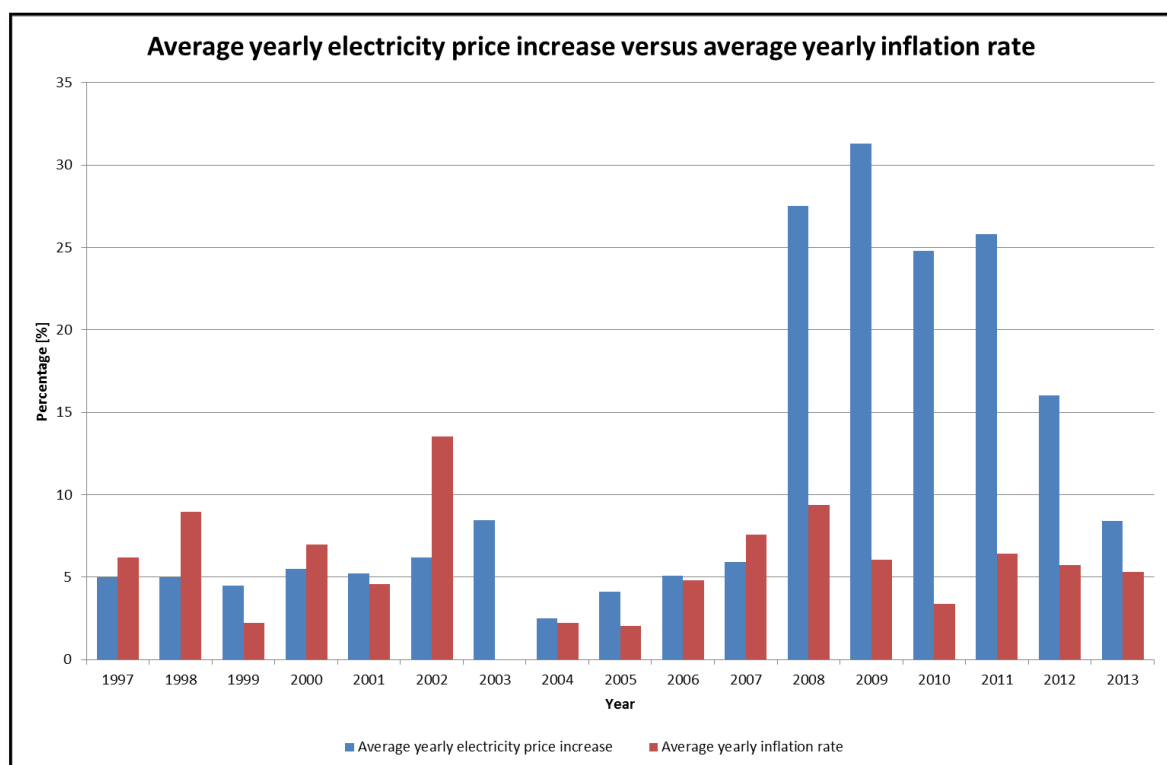


Figure 2: Average yearly electricity price increase versus average yearly inflation rate ²

As can be seen in Figure 2, the cost of electricity in South Africa keeps on increasing at a much higher rate than the inflation rate. The price of electricity in South Africa has increased significantly, with a spike in the percentage price increases since 2008. Eskom is enforcing methods to decrease the overall consumption of electricity in South Africa. One of these methods is Integrated Demand Management (IDM).

² Adapted from [3], [4].

Demand Side Management (DSM) is the implementation of certain measures in order to positively influence, control and reduce overall electricity consumption [5]. DSM is an initiative that falls under Eskom's IDM programme. Eskom structures some of its industrial electricity costs according to a time-of-use (ToU) schedule. The ToU schedule determines some of the different types of DSM project. Figure 3 shows the ToU schedule for Eskom electricity in South Africa.

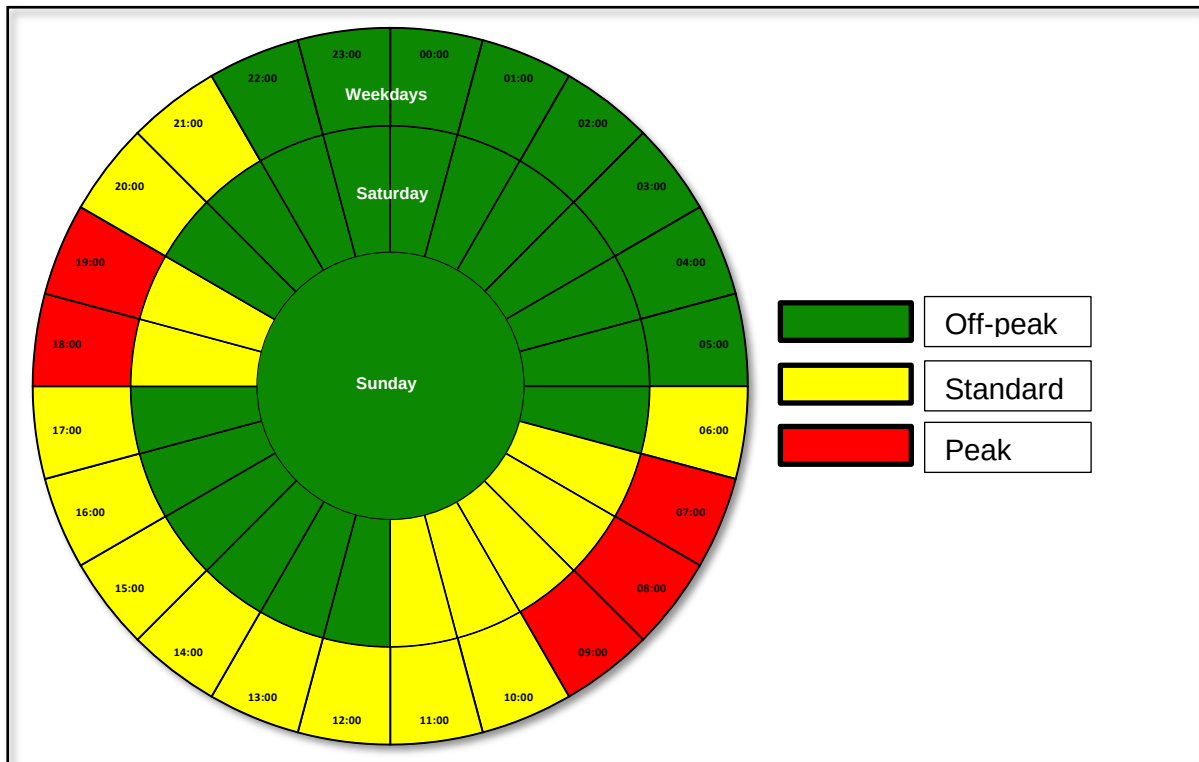


Figure 3: Eskom ToU schedule ³

Figure 3 shows the ToU periods for Eskom's Megaflex billing structure. As most mines use the Megaflex billing structure, it was used for this study. The Megaflex billing structure applies different electricity tariffs to different time periods. The main periods are peak periods, standard periods and off-peak periods.

The peak periods are the most expensive electricity periods. On weekdays, Eskom peak periods are between 07:00 and 10:00 and between 18:00 and 20:00.

During standard periods electricity is relatively expensive, but not as expensive as during the peak periods. On weekdays, Eskom standard periods apply to time periods between 06:00 and 07:00, between 10:00 and 18:00, and between 20:00 and 22:00. On Saturdays, Eskom standard periods are between 07:00 and 12:00 and between 18:00 and 20:00. Periods of the

³ Adapted from [3].

week that do not fall under peak or standard periods are off-peak periods. Electricity is the cheapest during off-peak periods.

The types of DSM projects that will be focused on is peak clip, load shift and electrical energy efficiency projects. Peak clipping projects aim to reduce the electrical load during the Eskom peak periods. Load shifting projects aim to shift electrical load from the Eskom peak periods to the Eskom standard or off-peak periods. Electrical energy efficiency projects aim to reduce the total power usage from 06:00 to 22:00 during weekdays.

The industrial and mining sectors in South Africa use about 60% of the maximum peak demand during Eskom peak periods [6]. Compressors use about 9% of the industrial demand. At some South African mines, compressors contribute up to 20% of the mine's total electricity cost [7]. Up to 80% of electricity costs can be ascribed to the life cycle cost of air compressors [8].

In Australia and some European countries, the generation of compressed air comprise about 10% of the total industrial electricity consumption [9], [10], [11]. In the United States of America, compressed air also accounts for up to 10% of industrial electricity consumption [9], [12]. Due to the high amount of compressors in use worldwide and also the inefficiency of compressors, compressed air is one of the most expensive energy sources in the world [9]. Thus, in order to save electricity it is necessary to reduce the amount of compressed air used in the mining industry.

1.3. Compressed air networks

A compressed air network in the mining industry typically consists of supplying users and demanding users. The supplying users are compressors, which are in compressor houses. The demanding users include plants, workshops and smelters. The supplying and demanding users are all connected by compressed air pipelines made of steel. The steel pipelines supply compressed air underground at the shafts to the mining levels and to the inside of the plants, workshops and smelters.

Mining shafts vary in size and in compressed air consumption. The consumption of compressed air per shaft can be in excess of 100 000 m³/h [13]. Compressed air is controlled during Eskom peak periods and mining off-peak periods to lower usage.

In the mining industry, compressed air is used mainly for rock drilling, but also for various other purposes [14]. Some of the smaller equipment that use compressed air underground

include loaders, venturi blowers, saws, pneumatic pumps, agitators, mechanical loaders, refuge bays, actuators and loading boxes [9], [13], [15], [16], [17].

Rather than using electric tools, compressed air is used to drive their pneumatic counterparts. Pneumatic tools are more compact, easier to move around and do not weigh as much as electric tools. Pneumatic tools can, furthermore, control torque, operate at different speeds and reach intended operating speeds. Compressed air can deliver energy with low levels of fluctuation, thus pneumatic tools will not be damaged when being overloaded by mine personnel.

A major reason for using compressed air in place of electricity to operate some mining tools is due to the safety benefits when working in areas with high amounts of water and gases [18]. Electrical machinery is not ideal when working in the high levels of methane gas found underground.

Compressed air, however, has been found to be a less efficient option when compared to the electrical alternatives. This is mainly due to the high number of leaks occurring in older compressed air systems and the wasteful manner in which many compressors are being operated.

Several investigations have been done on compressors and compressed air at mines. These investigations showed that compressors are not always operated efficiently. Most mine perform centralised blasting; this means that all blasting is done on a fixed schedule. After blasting, cleaning usually takes place. During the blasting and cleaning shifts, less compressed air is required than during the drilling shift [6].

If the compressed air usage at shafts is lowered, the compressors have to supply less compressed air. A compressor can be switched off if the compressed air requirement is low enough. Electricity can be saved by switching a compressor off, or by just lowering the amount of air supplied by the compressor by throttling the inlet guide vanes of the compressor.

All the compressed air consumers and losses make up the demand side in a compressed air network. Control valves are sometimes installed at end-users to control and limit the compressed air supplied to a specific end-user. The valves will, usually, be controlled using a certain pressure set point. Therefore, pressure transmitters need to accompany the valve installation. Usually, flow meters will also be installed in order to monitor and quantify the amount of compressed air used by a specific end-user [19], [20].

1.3.1. Pressure set point control

Processing plants and smelters usually have constant high-pressure and low-flow compressed air requirements. Even if the shafts at the mine do not require high pressures, the surface air pressure will still have to be maintained at a high-pressure set point due to the plants and smelters.

The solution to this problem is isolating the plants, workshops and smelters from the compressed air network, thereby lowering the surface air pressure during the mining off-peak periods. Plants and smelters, however, still require compressed air. Therefore, smaller standalone compressors can be used at each of the plants and smelters to provide compressed air [21].

The pressure set point is calculated at the lowest maximum pressure requirement of the shafts. All the air-consuming equipment used by a mining shaft have a minimum required pressure that will allow for efficient operation. This pressure is specified by the original equipment manufacturer (OEM).

The pressure set point for the compressed air network is typically high during the drilling shift of the shaft, while the set point is lowered during the blasting and cleaning shifts. During mining off-peak periods, the pressure set point is gradually lowered until the pressure set point is at its lowest possible value. The pressure set point is then set at the lowest value [22].

A control method is required to control the compressed air used by the end-users. A good control method is to install isolation and control valves on the compressed air pipelines. Valves control the pressure after the valves, and thus reduce the amount of compressed air used by end-users. Valve control will be discussed in the section that follows.

1.3.2. Valve control

A typical control valve unit comprises a controllable valve, a controllable actuator, a programmable logic controller (PLC), a measuring device for control (for example, a pressure transmitter), and a medium to communicate with a central control system (for example, cables).

If a control valve is partially closed or throttled, the amount of compressed air flowing through the valve will be reduced. However, the amount the pressure can be reduced by is limited by specific parameters and design specifications of the compressed air network [20].

Closing the valve will result in a lower end pressure and less flow to the end-user. The correlation between pressure and flow rate can be seen in Equation 1.

$$Q = CV\sqrt{\Delta p} \quad 1$$

Where:

Q = volumetric flow rate [gpm];

CV = flow coefficient of valve [-]; and

Δp = pressure drop across the valve [psi].

The CV value is the volume of water in gallons per minute (gpm) at 60 °F that will flow through a valve at a pressure drop of 1 psi. Unfortunately, there is no SI equivalent for the CV value, therefore the volumetric flow rate and pressure drop have to be converted. To convert the volumetric flow rate from gpm to m³/h, multiply Q by 0.227. To convert the pressure drop from psi to kPa, multiply Δp by 6.895.

An electric actuator is typically used to control the valve. Pneumatic actuators are cheaper to install than electric actuators, but pneumatic actuators are also less reliable. If pneumatic actuators are installed and the system pressure is reduced by too much, the actuators will return to the fail-to-open position.

Pneumatic actuators will prevent the system pressure from being controlled at a specific pressure set point, even though the high pressure-requiring equipment is no longer operating [17]. An example of a typical installation of an electric actuator and a valve can be seen in Figure 4.

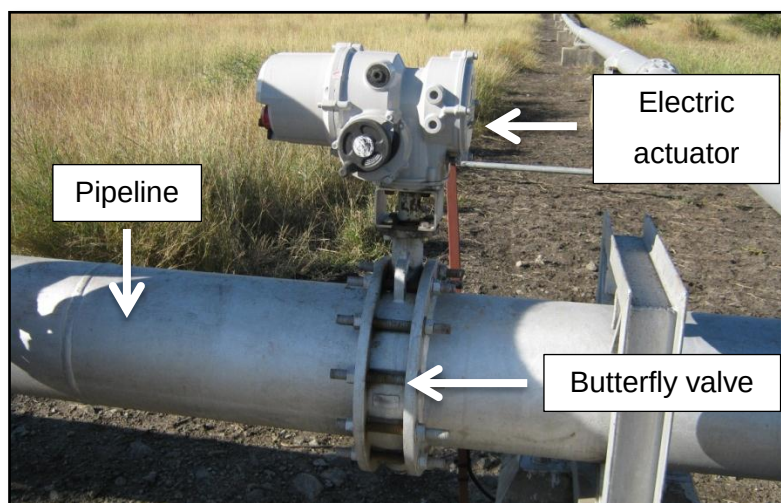


Figure 4: Surface valve installation with an electric actuator

The valves control the amount of air used by each of the end-users. This promotes power savings, because throttling back on the demand causes the system pressure to increase. This in turn provides the opportunity to also cut back on the compressed air supply, which will in turn save electricity. Firstly, the velocity of the air needs to be calculated. The equation to calculate air velocity is provided in Equation 2.

$$v = \frac{Q}{A} \quad 2$$

Where:

- v = air velocity [m/s];
- Q = volumetric flow rate [m³/h]; and
- A = area [m²].

From Equation 2 it is evident that the velocity of the air is dependent on the pipe diameter and the percentage that the valve is opened. An equation for Bernoulli's theorem to calculate the pressure after the valve can be seen in Equation 3.

$$\frac{v^2}{2} + gh + \frac{p}{\rho} = c \quad 3$$

Where:

- v = air velocity [m/s];
- g = gravitational acceleration [9.81 m/s²];
- h = height of point above reference point [m];
- p = air pressure [Pa];
- ρ = air density [kg/m³]; and
- c = constant value [-], c remains constant along any streamline in the flow.

From Equation 3 it is evident that the pressure is dependent on the velocity and the density of air. The valves control the amount of air used by each of the end-users. This helps to achieve power savings, because unnecessary compressed air will not be wasted.

1.3.3. Field instrumentation

Field instrumentation such as flow meters, valve actuators, pressure transmitters and so forth, are controlled and monitored by PLCs that are connected to a supervisory control and data acquisition (SCADA) system by a communication network. The cabling of the communication network is usually done with optical fibre and copper wire. Each mine and

each type of instrumentation has its own communication protocols for communicating over the communication network [19].

A pressure transmitter returns an electric current, measured in milliampere (mA). The electric current typically ranges between 4 mA and 20 mA. The current is a signal that describes the actual measured air pressure [23]. The PLC connected to the pressure transmitter is able to calculate the correct air pressure according to the current signal. Pressure transmitters are generic and not specific to a certain size compressed air pipeline. The pressure range that is measured must, however, be specified [19].

Compressed air flow can be measured either by a volumetric flow meter or a mass flow transmitter. A mass flow transmitter provides a more accurate description of the amount of compressed air used by the end-user than a volumetric flow meter does. A mass flow transmitter has to measure the temperature and pressure of the compressed air to calculate mass flow. These measurements can also be relayed to the PLC if required by adding a tri-loop splitter [19].

1.3.4. Types of compressed air network

There are primarily two types of compressed air network layouts utilised in the South African mining industry:

- **Standalone systems**

If only a single shaft or a single compressor house is present with interlinking pipelines, the system can be classified as a standalone system. This is typically a simple system with a predictable nature. An advantage of a standalone system is that changes in pressure or flow happen rapidly, thus maintenance on the pipeline can be done easily [15], [16].

The disadvantage of a standalone system is that it can be costly if there is more than one user needing compressed air because several compressors will have to be used with several pipelines. The whole system has to be shut down when maintenance on a compressor is required. Figure 5 shows a representation of a typical standalone compressed air system.

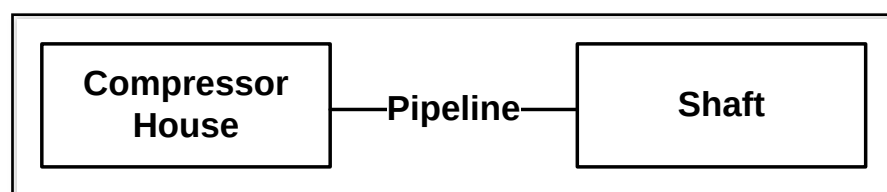


Figure 5: Standalone compressed air system

- **Compressed air ring feed systems**

In a compressed air ring feed system, there are several compressors and compressor houses as well as several compressed air end-users, all of which share a common compressed air pipeline. Control valves will typically be installed before the end-users to control the amount of compressed air used by the end-users.

Advantages of a compressed air ring feed system include [15], [16]:

- Sections of the compressed air ring can be isolated for maintenance on the pipeline or on a compressor without influencing the rest of the ring;
- More than one supply is available for compressed air;
- More control options are available; and
- Better compressor combinations can be operated.

The disadvantages of a compressed air ring feed system include [15], [16]:

- The compressed air network can be too large to do sufficient maintenance on the whole pipeline;
- It can take a long time before a pressure or flow difference at the end-users will be realised on the supply side; and
- One user's actions (such as opening or closing a valve) will influence all the other users in the network.

Figure 6 shows a representation of a simplified compressed air ring feed system.

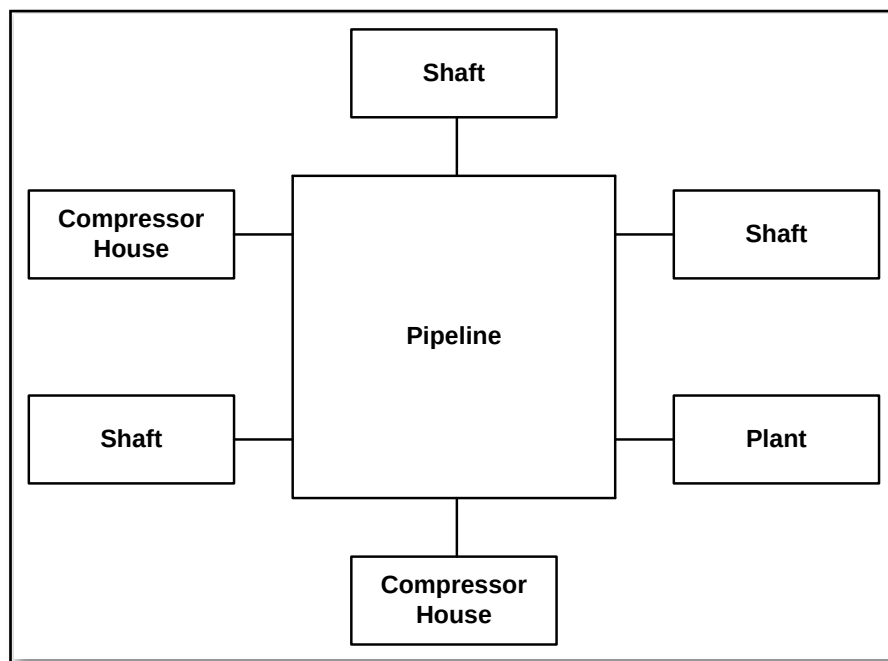


Figure 6: Compressed air ring feed system

The representation of a typical compressed air ring feed system in Figure 6 includes three shafts, one plant and two compressor houses. However, the plant would not usually form part of the overall compressed air network.

1.3.5. Compressed air pipelines

A common problem with compressed air pipelines is that pipelines are often undersized and therefore do not allow for the desired compressed air flow to reach the end-user. Undersized pipelines reduce the amount of compressed air flowing through the pipe and also reduce the end pressure due to frictional losses in the pipeline [24]. The pressure loss due to friction in the pipeline can be calculated with Equation 4.

$$\Delta p = \lambda \left(\frac{l}{d_h} \right) \left(\frac{\rho v^2}{2} \right) \quad 4$$

Where:

- Δp = pressure drop [Pa];
- λ = Darcy-Weisbach friction coefficient [-];
- l = length of pipe [m];
- d_h = hydraulic diameter [m];
- ρ = air density [kg/m³]; and
- v = air velocity [m/s].

Equation 4 shows that the diameter of the pipeline will influence the amount of pressure lost through a section of pipe. The pressure loss in a pipeline can cause significant wastage of compressed air because the pressure and flow delivered by the compressors will increase to compensate for too small pipelines.

These increases will, however, not solve the problem, because the pipeline will still choke the compressed air. It is important to select the correct diameter pipeline for the specific needs of the end-user regarding the velocity of compressed air through the pipeline.

The velocity of compressed air should never exceed 15 m/s, but a velocity of less than 10 m/s is the ideal velocity for compressed air. The velocity of the compressed air is restricted at 10 m/s to decrease the pressure drop through the pipeline. At 10 m/s, however, the compressed air can carry any dirt, water or debris to the drainage points or water traps in the system [24], [25].

The size of the pipeline should be designed to prevent a large pressure drop. This will be done by ensuring that the velocity of the compressed air in the pipeline is below or close to the ideal velocity. The lower the pressure drop through the pipeline, the lower the amount of power that will be required to generate compressed air. This will also decrease the amount of compressed air leaking out through leaks in the pipeline [24].

1.3.6. Loss of compressed air in compressed air networks

The cost of compressed air leaks is defined as the operating costs to compress the amount of air lost through air leaks. Leaks in the compressed air pipeline can waste significant amounts of compressed air, which in turn will waste electricity. Leaks can sometimes amount for up to 20–30% of a compressor's output [26], [27]. Leaks will also cause a pressure drop in the compressed air network, causing pneumatic equipment to function less efficiently [28], [29].

Compressed air networks usually have several leaks because the correct maintenance is not being done. Several components contribute to the amount of air lost through leaks. These components include system surface air pressure, temperature of the compressed air and size of the leak. Air leaks usually occur at bends, valves, couplers, welding joints, flanges, weak spots in the steel and other locations where additional components connect to the compressed air pipeline [17], [27], [28], [30], [31].

Rust in pipelines is the main cause of weak spots where air leaks happen. Rust occurs because carbon steel pipes are used instead of stainless steel pipes. Stainless steel pipes are too expensive to install in mine pipelines as the pipelines cover vast distances.

Air leaks are also caused when vehicles, large machinery and large animals travel over compressed air pipelines. Pipelines also just wear out over time [17]. Regular maintenance needs to be done on pipelines to ensure that leaks are minimised. The larger the air leaks, the more compressed air will leak out of the system. This will result in unnecessary financial losses and electricity wastage.

If the surface air pressure is reduced by using control valves to reduce the pressure delivered to the end-users, there will be a build-up of pressure in the system. The discharge pressures of the compressors are then decreased to compensate for the reduction of system pressure. The amount of electricity required to produce a certain amount of air can be calculated with Equation 5 [25], [32].

$$P = \frac{\dot{m} C_p T_{in} \left(\left(\frac{p_{out}}{p_{in}} \right)^{\frac{k-1}{k}} - 1 \right)}{\eta_{comp}} \quad 5$$

Where:

- P = electrical power usage by the compressor [kW];
 $\dot{m}$ = mass flow generated by compressor [kg/s];
 C_p = molar specific heat at a constant pressure for air [J/kg·K];
 T_{in} = inlet temperature of compressor [K];
 p_{out} = outlet pressure of compressor [kPa];
 p_{in} = inlet pressure of compressor [kPa];
 k = specific heat ratio of air [-]; and
 η_{comp} = compressor efficiency [-].

Equation 5 shows that there is a direct relationship between power usage, mass flow and outlet pressure of a compressor. If more flow is generated at a higher pressure, more power will be used.

The reduction in discharge pressure will result in the end-users consuming less compressed air, and less compressed air leaking out of the compressed air network through leaks in the pipeline [33]. The financial implications of air leaks can be calculated with Equations 6, 7, 8, 9, 10 and 11 [17], [30].

$$w_{comp,mech} = \frac{w_{comp}}{\eta_{comp}} \quad 6$$

Where:

- $w_{comp,mech}$ = mechanical energy [kJ/kg];
 w_{comp} = energy used by the compressor [kJ/kg]; and
 η_{comp} = compressor efficiency [-].

$$w_{comp,mech} = \frac{nRT_1}{\eta_{comp}(n-1)} \left[\left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} - 1 \right] \quad 7$$

Where:

$w_{comp,mech}$	= mechanical energy [kJ/kg];
R	= molar gas constant [0.287 kJ/kg·K];
T_1	= compressor inlet air temperature [K];
η_{comp}	= compressor efficiency [-];
n	= polytropic coefficient, taken as 1.4 [-];
p_2	= compressor discharge air pressure (absolute) [kPa]; and
p_1	= atmospheric pressure [kPa].

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

Where:

$\dot{m}_{air}$	= mass flow rate of leaking air [kg/s];
$c_{discharge}$	= discharge coefficient of air, usually taken between 0.6 and 0.97 [-];
k	= specific heat ratio, taken as 1.4 for air [-].
p_{line}	= compressed air pipeline pressure at leak (absolute) [kPa];
R	= molar gas constant [0.287 kJ/kg·K];
T_{line}	= temperature in compressed air pipeline at leak [K]; and
A	= area [m ²].

$$P_{wasted} = \dot{m}_{air} w_{comp,mech} \quad 9$$

Where:

P_{wasted}	= wasted electrical power [kW];
$\dot{m}_{air}$	= mass flow rate of leaking air [kg/s]; and
$w_{comp,mech}$	= mechanical energy [kJ/kg].

$$P_{saving} = \frac{(P_{wasted})(hours_{operating})}{\eta_{motor}} \quad 10$$

Where:

- P_{saving} = amount of electricity that can be saved [kW];
 P_{wasted} = wasted electrical power [kW];
 $hours_{operating}$ = total number of operating hours for the compressor [hour]; and
 η_{motor} = motor efficiency, usually taken between 0.85 and 1.

$$Cost\ saving = (P_{saving})(R_{per\ kW}) \quad 11$$

Where:

- $Cost\ saving$ = monetary savings [R];
 P_{saving} = amount of electricity that can be saved [kW]; and
 $R_{per\ kW}$ = unit cost per kW of electricity [R].

Using the equations above, the cost saving can be calculated when compressed air leaks are avoided. If this is done at a mine, the mine personnel will realise the amount of money that is being wasted. This might result in the mine personnel attempting to fix compressed air leakages as soon as the leaks are detected. As a result, mines could save substantial money each year when they monitor the cost of generating compressed air.

1.4. Supply-side (compressors) overview

There are several types of compressor that can be used in the mining industry, but the multistage centrifugal air compressor is the most common type. Multistage centrifugal compressors have intercoolers between the different stages. The intercoolers in the multistage compressor aim to obtain a polytropic compression exponent as close to one as possible [30].

Baseload compressors are compressors that will always be scheduled to run first; they will always have the highest priority and they will be run before other compressors in the system. When excess flow is required, trimming compressors are run in addition to the baseload compressors.

Compressors that can supply the amount of compressed air required during the mining off-peak periods are used as baseload compressors, while the rest of the compressors are used as trimming compressors.

Starting or stopping; loading or unloading; and throttling compressors are different control strategies that can be used. Starting or stopping compressors is the easiest form of control. Starting or stopping a compressor means that the compressor motor will be switched on or off completely [13], [34].

Loading or unloading a compressor will keep the compressor motor running continuously, but no compressed air will be generated because the coupling connecting the motor to the compressor will be disengaged.

A compressor is throttled by modulating the inlet guide vanes of the compressor, resulting in restricted inlet airflow [13], [34]. Throttling a compressor will help to control the delivery of compressed air, however, it will also reduce the efficiency of the compressor.

Unfortunately, not all compressors can be started or stopped regularly. Even if the compressors did have the capability to be started or stopped regularly, the mines sometimes do not permit it because mining personnel believe that starting and stopping compressors increases maintenance costs. The maintenance costs can sometimes be increased, but by stopping the compressors when possible, the electricity that can be saved can be more than the increase in maintenance costs.

When there are compressors that cannot be started or stopped regularly, the compressors would instead just be unloaded and loaded again rather than being stopped. When a compressor is unloaded, the motor is still running, the inlet valve is opened by a small percentage and the blow-off valve is fully open [13]. An outlet valve that allows the compressed air from the specific compressor to enter the compressed air system would also be closed when the blow-off valve is opened.

The type of control strategy used greatly affects the electrical energy efficiency of air compressors. Starting and stopping compressors completely when the need arises is the most electrical energy efficient control strategy. This will, however, have the largest effect on the motor and will also increase the amount of maintenance required on the compressor.

1.4.1. Inlet of compressor

By controlling the amount of air sucked in by the compressor, the amount of delivered compressed air can be controlled. For maximum efficiency the intake air of the compressor needs to be as clean as possible and cold enough.

Inlet air filters are installed to ensure that the intake air is clean. Filters remove particles and dust from the inlet air of the compressor [18]. These filters have to be replaced regularly,

because the filters cause a differential pressure when the compressed air passes through it. The dirtier the filters are, the higher the differential pressure is. By changing and maintaining the filters regularly, more efficient operation can be ensured [35].

The efficiency of the compressor will increase if the inlet air is clean – with no dust, moisture or other harmful element contamination. However, if the inlet air is not clean enough, contaminants will eventually build up on compressor components such as valves, impellers, vanes and rotors. Contaminant build-up will decrease the efficiency of the compressor.

Air quality is determined by the dryness of air and by its contaminant level. The air needs to be at an acceptable quality in order for the compressor to operate effectively. Treating the air beyond the minimum required dryness and contaminant level is unnecessary as it has no additional benefit [36]. The cooler the inlet air is, the denser it is. The density of the intake air will determine the ability of the compressor to deliver a higher mass flow and a higher pressure. High density air will be more efficient than low density air [37].

Occasionally, an additional compressor will be operated when the compressor efficiency decreases, resulting in unnecessary high electricity consumption. A better solution is to clean or replace the inlet air filters; however, this is not always done.

Inlet guide vanes are installed at the inlet of the first stage of a compressor. The main purpose of the inlet guide vanes is to change the direction of air entering the compressor. This is done to ensure optimum electrical energy efficiency. However, the efficiency is reduced when the inlet guide vanes of a compressor are closed too much resulting in the inlet flow of the compressor also being reduced.

The inlet guide vanes of the compressor controls the velocity, the angle of the velocity and the volume of air sucked in by the compressor. The inlet guide vanes of a compressor will typically be controlled by a controller, such as a PLC, and an actuator that is connected to the network and the compressor. Figure 7 shows a photo that was taken of a compressor's inlet guide vanes.

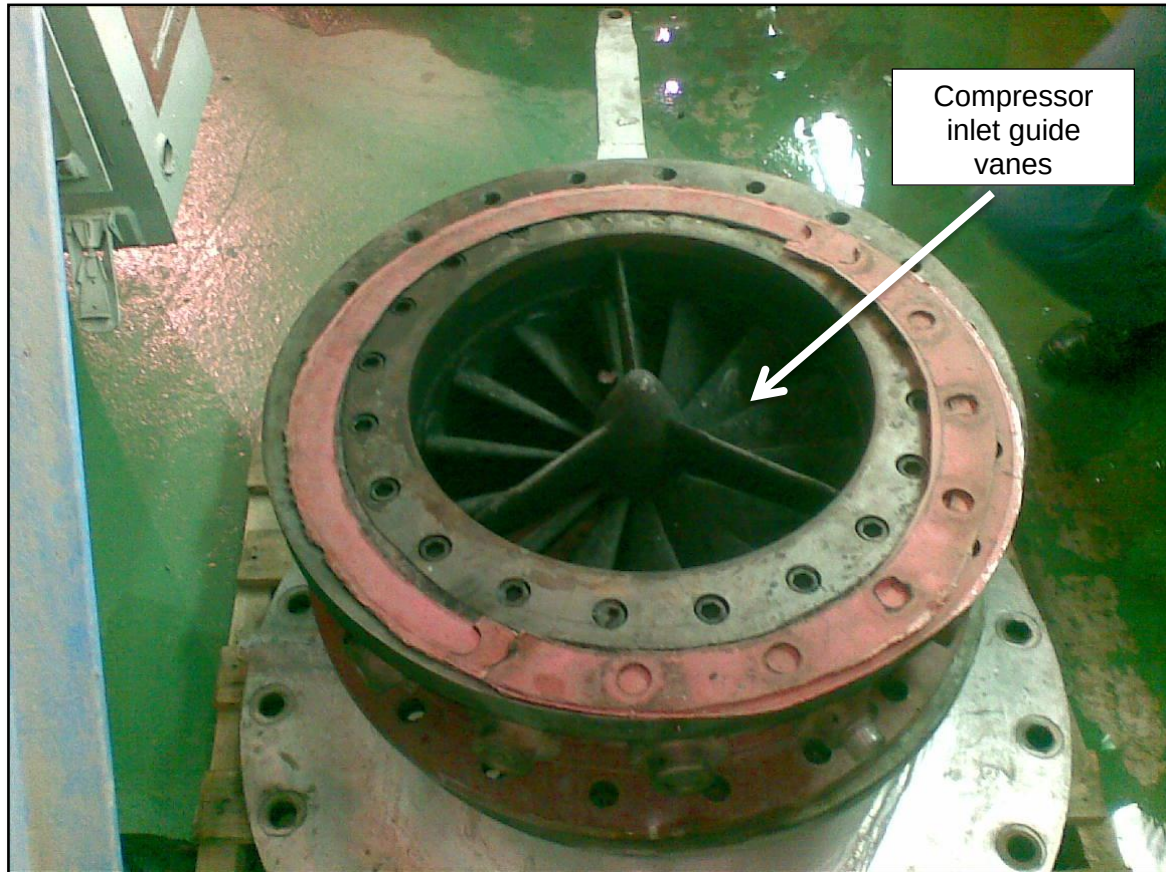


Figure 7: Compressor inlet guide vanes

If the demand for compressed air in the network decreases, there will be a pressure build-up upstream of the compressors in the compressed air network. The compressor will attempt to satisfy the pressure set point. If the delivery pressure of the compressor is higher than the pressure set point of the compressor, the guide vanes will start closing. This will result in a lower volume of intake air, which in turn will result in a lower delivery pressure and flow.

1.4.2. Surge control

Another control strategy is to throttle the compressors. Throttling is done when the flow delivered by the compressor is too much for the compressed air system, but the demand is still too high to completely unload or switch off the compressor.

Different compressor makes, models and capacities will have different electrical energy efficiencies when throttling the compressors. Most compressors actually use less power when they are throttled. Compressors are, however, not as efficient when they are throttled as when they are operating at full capacity. Figure 8 shows a graph comparing the volumetric efficiency of a compressor against the inlet guide vane position.

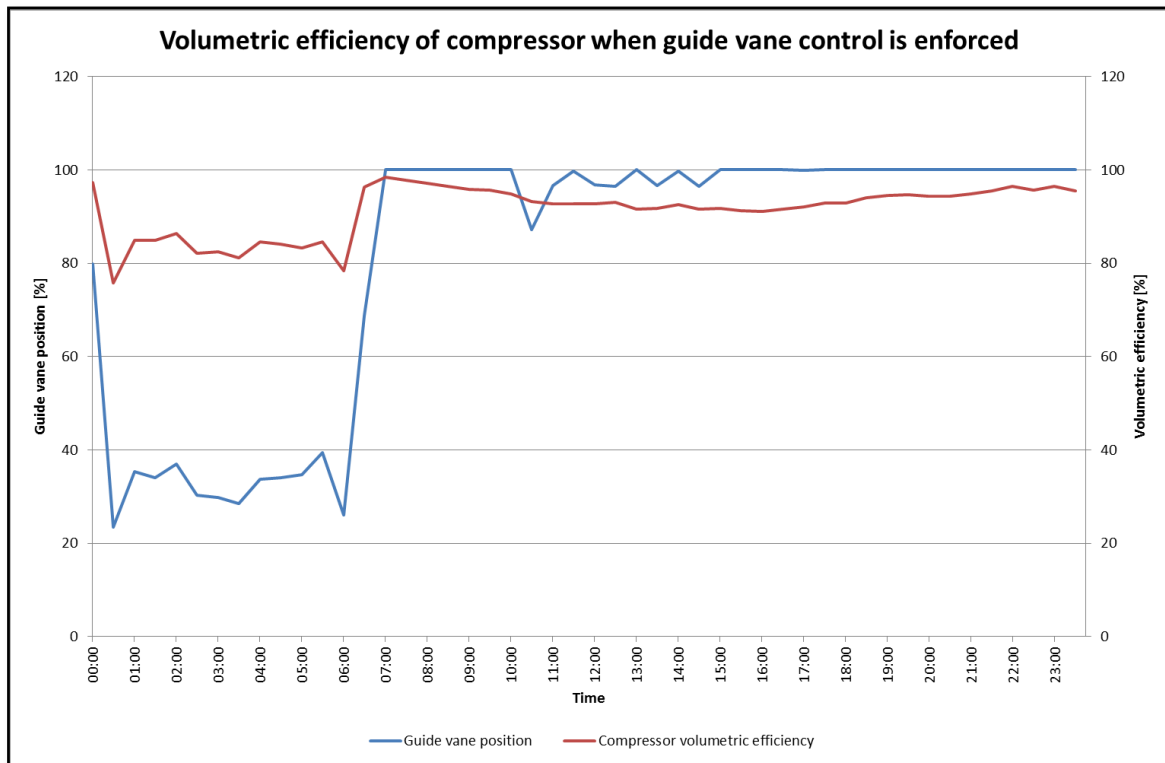


Figure 8: Volumetric efficiency of compressor when guide vane control is enforced

Figure 8 shows that when the inlet guide vanes of a compressor are closed, the volumetric efficiency decreases. Surge can, however, occur when a compressor reaches critically low flow ranges. Surge is defined as the reversal of flow inside a compressor accompanied by high varying load on the bearings of the compressor.

Surge can be defined as the reversal of flow inside a compressor, triggering a high varying load on the bearings of the compressor. Surge results in high vibration in a compressor, higher operating temperatures and quick changes in axial thrust.

Surge can damage the rotor seals, bearings as well as the compressor driver. Surge will also influence the complete cycle operation [38], [39]. Surge is usually prevented by means of a recycle loop that can be activated by a blow-off valve. A blow-off valve usually is a fast-opening valve used to prevent compressor surge [40].

Each make and model of compressor has a unique characteristic curve. This curve will show a compressor's stable operating region. A Moore controller will ensure that the compressor operates only in the safe operating region [15], [16]. This is done to prevent surge at all costs. Figure 9 shows a representation of a typical compressor characteristic curve.

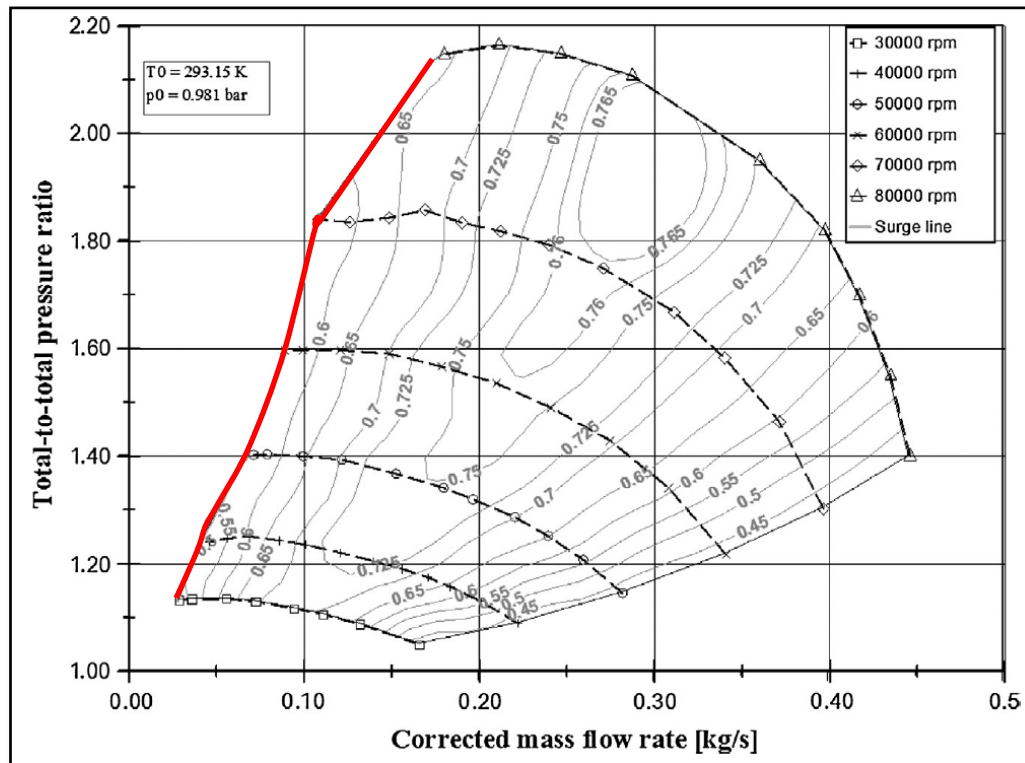


Figure 9: Compressor characteristic curve [41]

In Figure 9, the red line shows where surge will occur for the specific compressor. The surge line will be unique for each different type, make and size of compressor. Compressors should be operated as close to the efficiency lines as possible for safety and performance. This can be achieved through effective use of different control types. Pressure ratios and mass flow should be monitored.

A blow-off valve will vastly decrease the amount of air the compressor delivers into the system, because it is situated before the outlet of the compressor into the system. A blow-off valve is normally kept fully closed to allow all of the air that the compressor generates to enter the compressed air system. When the compressor blow-off valve is open, the efficiency of the compressor decreases significantly. The blow-off valve is, however, a powerful measure to reduce the possibility of surge occurring.

Figure 10 shows a simplified drawing of where in the compressor system the blow-off valve will typically be placed. The blow-off valve will typically be placed after the compressor outlet and before the compressed air enters the compressed air network, as shown in Figure 10.

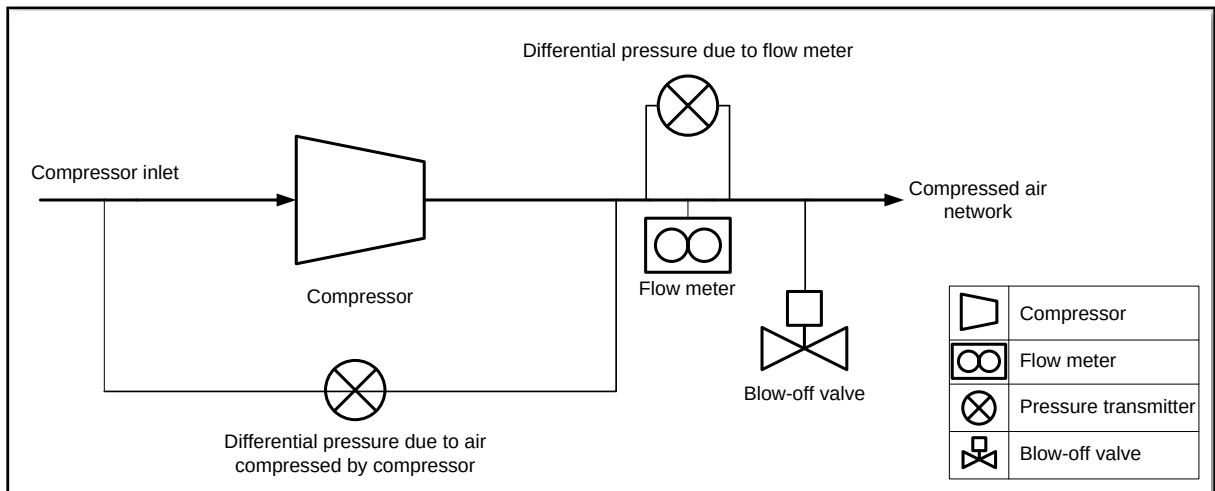


Figure 10: Compressor system including blow-off valve

In Figure 10 there is differential pressure from before the compressor to after the compressor. The differential pressure is due to the compressor sucking in air at atmospheric pressure and delivering it at the desired pressure, thus resulting in a gain in pressure. There is also differential pressure from before the flow meter to after the flow meter. The flow meter causes an obstacle in the compressed air pathway, resulting in pressure loss.

1.4.3. Matching supply and demand of compressed air flow

The supply of compressed air is driven by the demand in every compressed air network. Both the supply- and demand side will have to be monitored because both the system and the changes in the system are dynamic [42], [43]. Matching the compressors in a compressed air network with the required flow can result in significant power savings.

Less power will be required to generate compressed air because less compressed air will be wasted. By matching the supply flow to the required flow, about 10% of the power used by the compressor system can be saved [35], [44].

Compressors will have to be automated to control the compressed air supply according to the demand for compressed air. Compressor automation removes unreliable human manual control. By automating compressors, the matching of supply and demand flow can be improved [22]. Compressor automation is also dependant on the type of compressor and different instrumentation will be required to automate different individual compressor units [42].

If several compressors of the same make, model and operating capacity are present, the most efficient operation method is to run all compressors at full operating capacity, except

one. The one compressor that is not running at full operating capacity will then operate as the trimming compressor.

If compressors have different makes, models and operating capacities, it is more beneficial to individually control the compressors [42]. The individual control can be done by assigning a different pressure set point to each of the compressors.

By applying controls to the compressors as well as to the end-users, significant amounts of electricity can be saved. Proper control and monitoring of compressed air usage help to align the production and consumption of compressed air. Pressure, flow and power are the main criteria for control in a compressed air network [42].

Power is, because of the expensive electricity price, a very important control measure. Pressure is also required by the end-users to successfully operate its machinery, while the flow is also required to maintain a certain pressure set point. A compressed air flow usage, pressure set point and power baseline has to be created from these criteria in order to follow it when producing the compressed air [42]. The baseline is required to compare if the new control is actually an improvement.

Continually matching compressed air demand and supply effectively can become challenging due to the large number of losses present in many compressed air networks [45]. As mentioned in Section 1.3.6, there are several factors that can lead to the loss of compressed air. The compressed air will also have to be supplied at a higher pressure to overcome system losses, which will result in a higher flow rate for the compressed air.

1.4.4. Lowering the system air pressure

More often than not, compressors deliver compressed air at a higher pressure than the pressure actually required by the end-users. This is done to compensate for fluctuations at the end-users in the compressed air network [42].

Power can be saved by lowering the discharge pressure of the compressors. Lowering the system air pressure will also result in less compressed air leakages, because the amount of air leaking from the pipe is a function of the supply pressure in a compressed air system [27]. The correlation is shown in Equations 6, 7, 8, 9, 10 and 11 in Section 1.3.6.

Power savings will vary between different compressor makes and models and in different situations, but there will almost always be significant power savings, compared to the usual operating load, when the compressors are controlled efficiently and if power usage is taken into account [35].

Auto-compression is a term used frequently in the mining industry. Auto-compression takes place in deep-level mining shafts and is a term used when air is compressed by its own weight. Auto-compression is a beneficial factor in the deeper mines and the pressure increase of the compressed air can be calculated by Equation 12.

$$p = \rho gh \quad 12$$

Where:

- p = air pressure [Pa];
- ρ = air density [kg/m³];
- g = gravitational acceleration [9.81 m/s²]; and
- h = height of point above reference point [m].

A general guideline for auto-compression is that for every 1 000 m that the compressed air has to travel beneath surface, an increase of 11% relative to the pressure on surface will occur [46], [47]. In the gold mining industry, surface air pressure can be lowered significantly due to auto-compression.

Auto-compression allows the surface air pressure to be lower than the pressure required underground. A general guideline is that by reducing the surface air pressure in the compressed air network by 13 kPa, the electricity consumption by the compressors can be decreased by 1% [34], [48], [49], [50].

Auto-compression, however, does not happen often in platinum mines, since platinum mines are shallow when compared with gold mines. Platinum mining shafts are typically about 1 000 m deep. The shallow depth can cause problems when attempting to lower the surface air pressure of the compressed air network. This is because the pressure gain due to auto-compression cannot overcome the losses in the pipeline. The surface air pressure can, however, still be optimised for maximum electrical energy efficiency.

Unregulated users of compressed air in a compressed air network include leaks, pipes with open ends and users that have valves installed, but the valves are fully open or not controlled correctly. If the system air pressure is too high, these unregulated users will use up extra compressed air. This is called artificial demand [34], [51]. Artificial demand causes significant wastage of compressed air and electricity.

Surface air pressure can be lowered during mining off-peak periods. The compressors should supply the minimum required pressure to the end-users to not waste any electricity.

This means that the required pressure by the end-users will need to be optimised as discussed in Section 1.3.1.

To lower the surface air pressure, the discharge pressure of the compressors will have to be lowered. The discharge pressure will be determined by the pressure set point of the compressors. The compressors will be controlled by a controller that will control the inlet guide vanes and the blow-off valve of the compressor. The controller will typically be a PLC that is connected directly to the compressor.

All of the above-mentioned parameters influence the efficiency and the delivery flow of the compressors. It is, however, not realistic to expect a 100% efficient compressed air system. Regardless of what is done and implemented, the compressor and compressed air systems will never be fully efficient. This is because there will always be losses in the system that influences the efficiency.

1.5. Shortcomings of existing control methods

The need to develop a new dynamic air compressor selector system was due to several shortcomings with existing control methods. The existing control methods listed below were used before any dynamic air compressor selector systems were available, before the compressed air network was optimised and before the compressors were managed.

Several studies were done on existing control methods [6], [13], [15], [16], [19], [20], [22], [29], [45], [47]. Other existing compressor control methods provide individual control and power saving benefits, although a solution to integrate their benefits was lacking. The existing control methods are discussed in the section that follows.

1.5.1. Before dynamic air compressor selector systems

Before dynamic air compressor selector systems, several other manual interventions for controlling compressors were used. These methods, however, were inefficient and compressors were operated even when they were not required. These methods had several problems, including relying on human intervention, lack of real-time data, excessive compressor blow-off and incorrect compressor combinations [45]. These methods and their problems will be explained below.

- **Reliance on human intervention**

Compressors that are controlled manually are usually not controlled optimally. The control room operators will usually start or stop compressors according to a predetermined

schedule, instead of monitoring the demand and supply of compressed air in the compressed air network. This causes over- or undersupply of compressed air, resulting in inefficient operation.

- **Lack of real-time data**

A lack of real-time data causes serious problems when controlling compressors. Critical situations can arise, but due to the lack of real-time data, these situations will not be detected immediately by the control room operator or even by the control system. This will result in incorrect operation of compressors. Due to insignificant measuring equipment, mass flows and system pressure are not always known, even though it is important to monitor these parameters when controlling compressors.

Mass flow is an important measurement because it measures how much compressed air is used by each end-user. It is also important to monitor the pressure because if compressed air is supplied at a low pressure, some equipment might not function. It is important to have as many measurements as possible to prevent over- or undersupply of compressed air and to minimise electricity wastage.

- **Excessive compressor blow-off**

A compressor blow-off valve will open once the system pressure rises above the indicated set point, if guide vane control is not sufficient anymore, or to avoid compressor surge. Compressor blow-off is an ineffective control method, but it is better than cycling compressors or allowing a compressor to surge.

On odd occasions though, compressors operate for long periods with open blow-off valves. This results in wastage of compressed air and electricity. This operating method can sometimes not be avoided, due to the compressor setup at the mine and because surging has to be avoided. Opening the blow-off valve, however, has to be avoided as much as possible.

- **Incorrect compressor combinations**

Compressor combination is an important area of compressor control. By operating the correct combination of compressors all of the time, significant electricity savings will be realised. This, however, cannot always be done due to the way compressors are set up at the mine. In a compressed air network, operating the correct combination of compressors can often be a problem, especially if the compressed air network is several kilometres long.

In a compressed air network, the closest compressor houses have to supply compressed air to high-production shafts. This is, however, not always possible, because compressor

combinations do not always allow for this. If a compressor at every compressor house is operated, oversupply of compressed air will occur. It is also not efficient operating several compressors at partial load rather than operating fewer compressors on full load. This will also result in wastage of electricity. A compressor not running on its full electrical load decreases the efficiency of the compressed air system. This is because

1.5.2. Optimisation of air networks

Projects are implemented at mines to optimise the compressed air networks installed underground. A valve setup, the same as the valve setup shown in Figure 4 in Section 1.3.2, was installed where each of the level's compressed air pipelines tapped off from the shaft's main compressed air pipeline. Bypass pipelines were also installed over the isolation valve to allow compressed air to enter the shaft even when the main line isolation valve was closed. A bypass line is typically much thinner than the main compressed air line.

Control valves were installed on the bypass line controlling the amount of compressed air entering the shaft by adjusting the pressure of compressed air that was allowed through the valve. This setup was done because the control valves that would have to be installed on the main compressed air lines would have been too big. There is a direct relationship between valve size and valve cost. A smaller control valve is able to control the pressure better, with less fluctuation between pressures than the main compressed air line valve.

If the compressed air line is small enough and has low-flow requirements, a control valve can be installed on the main compressed air line without installing the bypass line setup. This is mostly done underground, because the flow requirements per level are significantly lower than the main compressed air pipeline's flow requirements.

This results in smaller compressed air pipelines, which means that the control valves are cheaper and easier to install. This also proved to be successful, as long as the pipeline did not require high flow rates. A control valve installed underground can be seen in Figure 11.

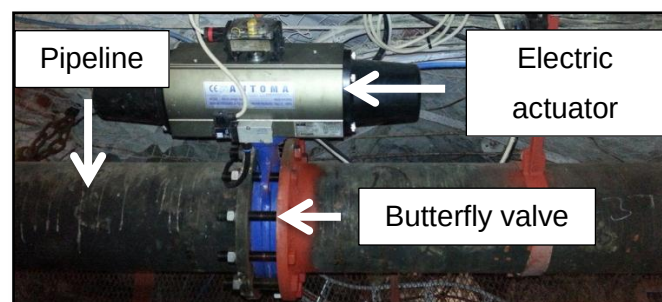


Figure 11: Control valve installation underground

It was realised that the same setup could also be installed on the surface, on the main compressed air line just before it enters the shafts. This resulted in a cutback on the usage of the compressed air usage of each shaft. Typically, the main compressed air line for a shaft would be at least 350 mm in diameter, but it could range up to 750 mm.

The bypass line would be a lot thinner; typically around 300 mm for a 600 mm main compressed air line, but this is would be dependent on the amount of flow required by the shaft during off-peak mining periods. A typical surface valve installation can be seen in Figure 12.

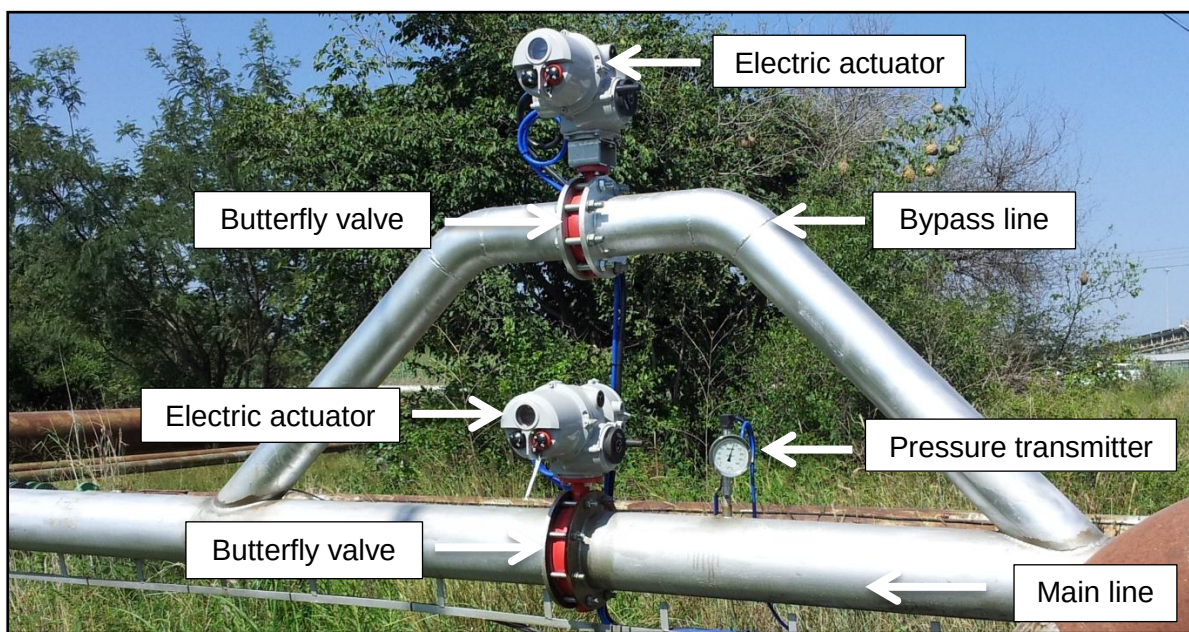


Figure 12: Typical surface valve installation

The valve setup would be controlled on a specific pressure. The pressure was set on a pressure set point for certain periods of the day. The pressure would be set at a high set point (above 600 kPa) during the mine drilling shifts, but could be set lower when drilling was completed and the blasting shift started. The minimum allowable pressure set point would be regulated by the type of instruments that were used during the specific shift.

The aim of the optimisation of air network projects was to firstly install isolation and control valves for each of the shafts. Afterwards, the pressure set points for each of the shafts were optimised for each hour of the day. By lowering the pressure set point for the shafts, air leaks were minimised and compressors used less power.

A control system was implemented with an easy-to-use graphical user interface that was used for controlling the valves. The control system was able to control surface valves as well as underground valves. An example of the control system can be seen in Figure 13.

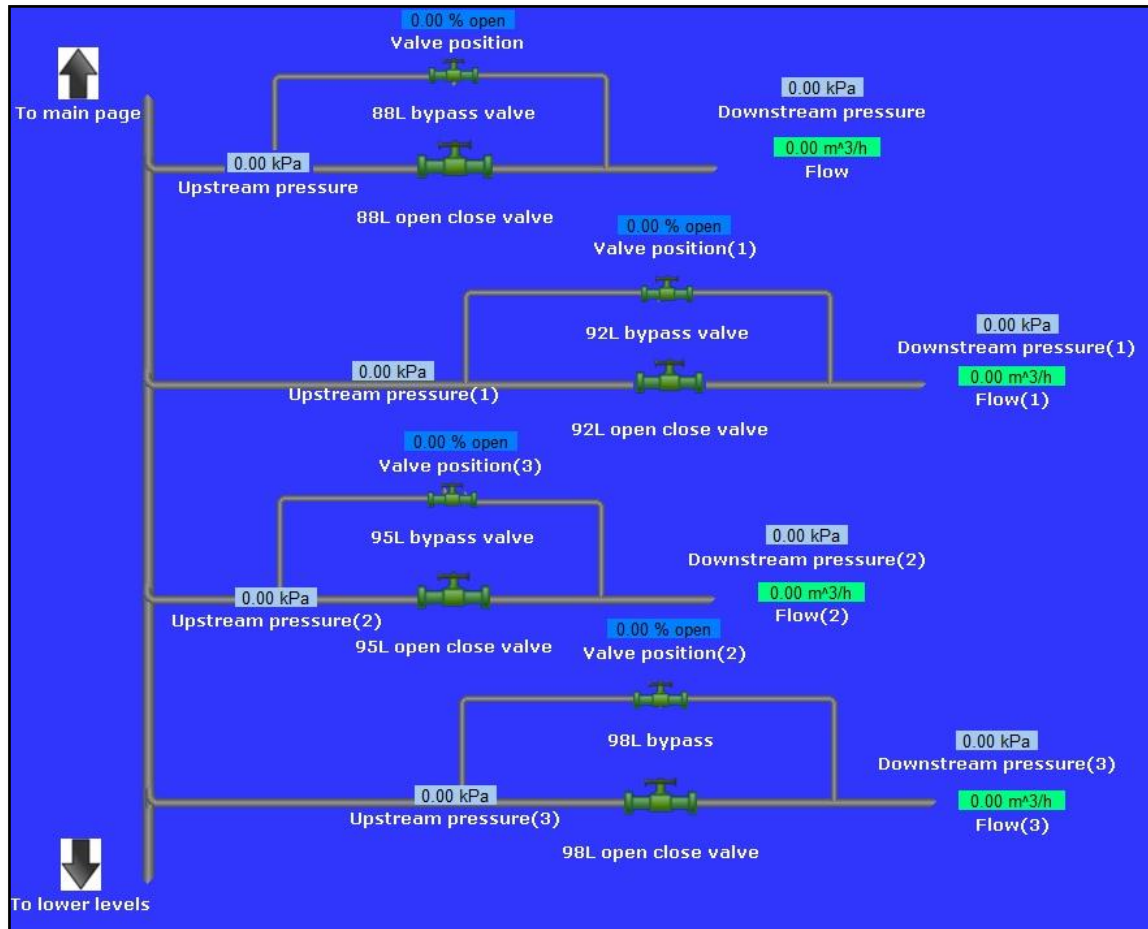


Figure 13: Example of a control system implemented to control valves

In industrial compressed air systems, compressed air leaks account for 10-30% of compressed air losses [52]. Excessive electricity consumption and poor system performance (such as the failure to supply required pressures) mostly resulted from compressed air leaks [13]. Therefore, another section of the optimisation of air network projects was to repair compressed air leaks. Electricity savings of up to 30% were obtained in some instances [17], [35].

1.5.3. Compressor management

Apart from the optimisation of air network projects that were performed, there were also compressor management projects. The aim of compressor management projects was operating the compressors as efficiently as possible by controlling the compressor outputs.

To achieve the required operation of the compressors, certain additional work was required. This included installing the correct instrumentation such as flow meters, pressure transmitters, positioners on the guide vanes and blow-off valves of the compressors, and any other instrumentation that helped to optimise and automate the compressor output.

After all the instrumentation was installed, the compressor had to be automated. To automate the compressors, the guide vanes and blow-off valves of the compressors needed to be automated. The automation controlled the amount and pressure of compressed air that was delivered by each of the compressors.

Surge needs to be prevented at all costs when controlling compressors. As mentioned in Section 1.4.2, surge can greatly damage compressors. All of this was done using a control system similar to the one used when optimising air networks. This control system, however, focused mainly on compressor management. An example of the control system used for the management of compressors can be seen in Figure 14.

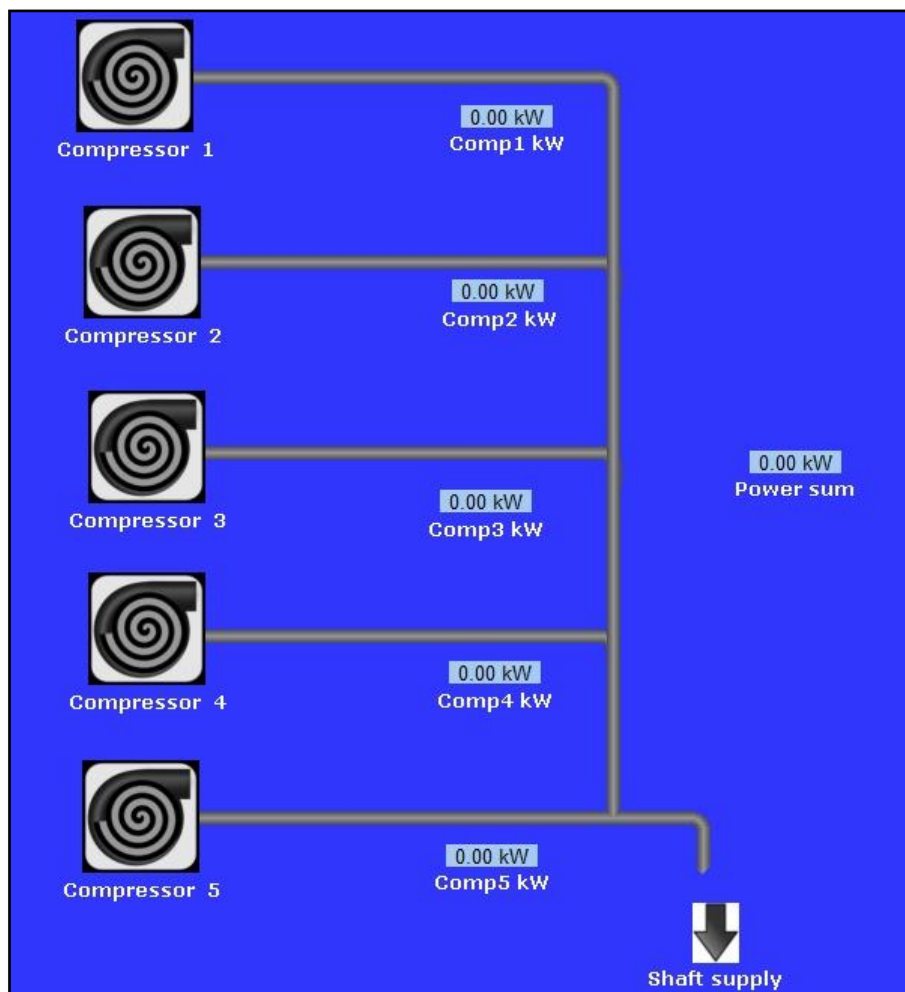


Figure 14: Example of a control system implemented to manage compressors

1.5.4. DCS development

Venter originally started developing the dynamic compressor selector (DCS) [21], [22]. Venter was responsible for all the mathematical calculations that were done by DCS. The original modelling and simulations was also developed by Venter. The calculations were done theoretically and were verified using simulations on different simulation software packages.

Venter only programmed DCS in Visual Basic .NET, which is a relatively easy programming language. Programs programmed in Visual Basic .NET cannot be given a graphical user interface that is usable in the mining environment.

Van Heerden eventually took over from Venter [53], [54]. Van Heerden transformed DCS from a mathematical program, which only did calculations, into a software package that could be used in the mining environment. Van Heerden created an easy-to-use graphical user interface that was accessible and usable in the mining environment.

During a study that was done by Van Heerden, several problems were identified while creating DCS. These problems included inaccurate field instrumentation, faulty valves, high-pressure set points and client IT policies. Van Heerden, however, only looked at the problems from a programmer's point of view. During the implementation of DCS that was done for this study, the problems Van Heerden identified were encountered, together with several other problems.

Van Heerden was only responsible for the software improvements required in DCS. Some of the problems could not be solved without proper project engineering experience; they could only be solved by combining project engineering experience with software development experience.

1.6. Purpose of study

As mentioned in Sections 1.3, and 1.5, control valves were installed to optimise the amount of compressed air each shaft used. Compressors were automated to optimise the amount of flow delivered by the compressors, as mentioned in Sections 1.4 and 1.5. These two systems, however, could not communicate with each other. The existing compressor management system could not optimise the compressors according to the end-user demand. This compressor management system only accepted fixed manual inputs.

Both of these controllers were static controllers, but in the mining industry, conditions and scenarios change constantly. For example, if the pressure set point of a shaft is raised, more compressed air will be required from the compressors at a higher pressure. An operator will have to manually adjust the static controllers to the new conditions.

The need was identified to develop a new dynamic air compressor controller. This new controller had to calculate the conditions continuously and it had to change its control strategy dynamically. The compressor controller had to take the amount of compressed air required by the end-users into account. The compressor controller would then also need to match the compressed air supplied by the compressors as closely as possible to the demand.

DCS is the compressor controller that was developed. DCS was tested extensively off-site, however, it still needed to be tested and implemented on an actual site. During implementation, the problems Van Heerden listed were encountered, together with several other problems.

The areas of focus for this dissertation will be the following:

- Discuss the control system;
- Investigate potential power savings;
- Simulate implementation possibilities;
- Implement the control system; and
- Discuss some of the challenges and limitations that were encountered during the implementation and how they were overcome.

The end purpose of this study is to determine whether DCS can successfully be implemented on a mine's compressed air system.

1.7. Dissertation overview

Chapter 1: Introduction, background and literature

Chapter 1 provides background information on the electricity situation in South Africa. It discusses compressed air networks and centrifugal air compressors, including their functions and performance. This section focuses on the supply- and demand side of compressed air.

Chapter 1 furthermore provides an overview on compressor control and discusses the previous control strategies for compressors in the mining industry. A purpose for this study is identified and discussed. Finally, an overview of this dissertation is provided.

Chapter 2: The implementation of DCS

Chapter 2 firstly explains what DCS is, and then provides the input parameters required to implement DCS. An investigation was done to see if the project was feasible. The investigation included determining a baseline profile and simulating the savings associated with a DCS implementation.

After the investigation was done, the project was implemented. During the project, several problems were encountered. The solutions to the problems were determined and data provided showing the validity of the solutions.

Chapter 3: Results after the implementation of DCS

Chapter 3 provides the detailed results after DCS was implemented and the results are discussed in detail. The chapter also shows verification of the data and provides validation of the study.

Chapter 4: Conclusion and recommendations

Chapter 4 is a conclusion to the study. Recommendations for further research on this topic are provided.

Chapter 2:

The implementation of a dynamic air compressor selector

2.1. Introduction

Chapter 2 firstly explains what DCS is, and then provides the input parameters needed to implement DCS. An investigation was done to see if the project was feasible. The investigation included determining a baseline profile and simulating the savings associated with a DCS implementation.

After the investigation was done, the project was implemented. During the project, several problems were encountered. The solutions to the problems were determined and data provided showing the validity of the solutions.

2.2. What is DCS?

DCS is a compressor controller that does compressor scheduling and calculates pressure set points for operating compressors. DCS dynamically calculates compressor priorities and pressure set points according to the compressed air demand. Because the scenario in a compressed air system changes continually, it is crucial to continually calculate new compressor priorities and pressure set points.

The calculations within the DCS system can be separated into different sections. There is a simulation for calculating the compressor pressure set points and a different simulation for calculating compressor priorities to control compressors. Even though these simulations are not directly linked, one will influence the other. The calculated pressure set points are provided to the compressors and it is used to control the inlet guide vanes and the compressor blow-off valves. This in turn results in the scheduling, starting and stopping of compressors.

Figure 15 shows a display of the simulation that was done for the compressed air network to calculate the compressor pressure set points. The orange nodes represent the end-users and the light-blue nodes represent the compressor houses. The green nodes represent the intermittent nodes and the grey blocks represent the pipes.

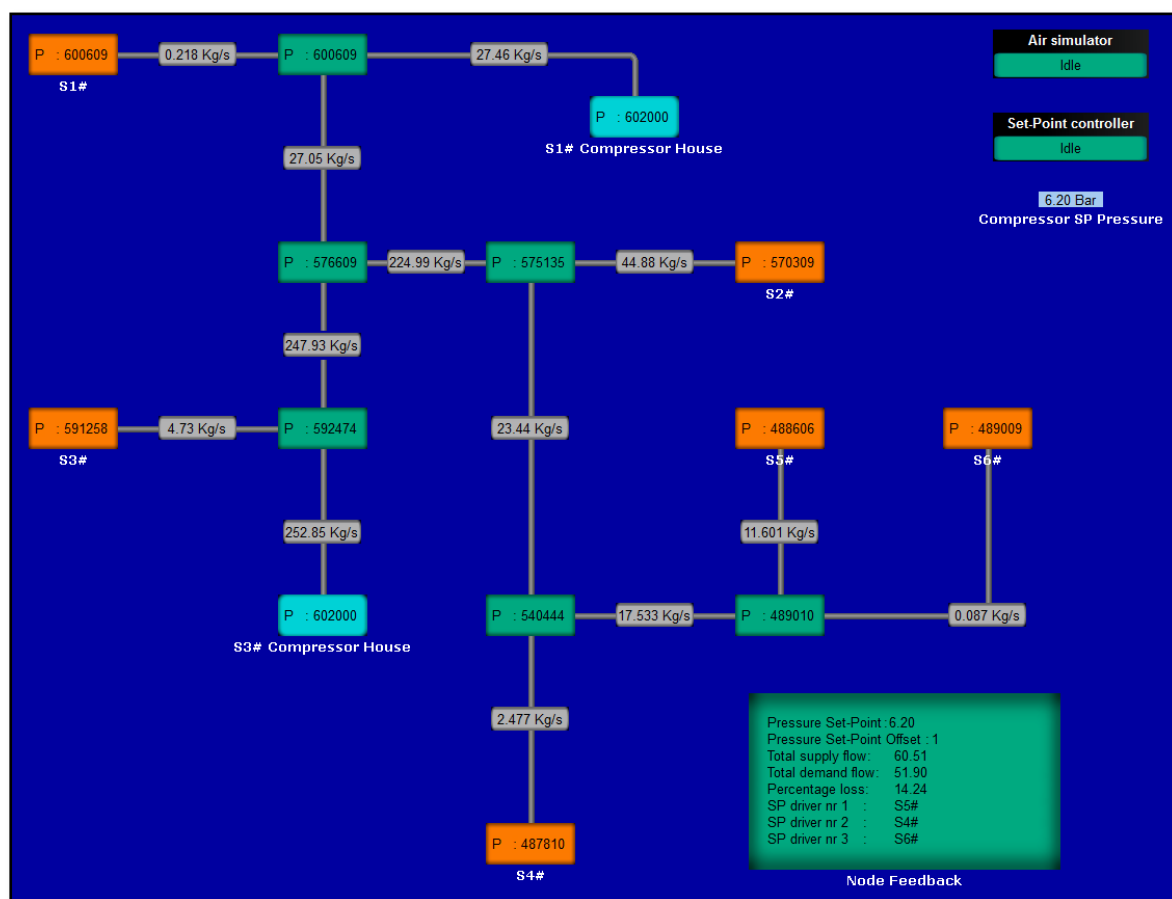


Figure 15: DCS simulation to calculate compressor pressure set points

The pressures that are displayed in the end-user nodes are calculated pressures and not actual measured pressures. This was the calculated pressure upstream of the control valve at the end-user. This was done to calculate all the changes in the network. It also allowed DCS to know the flow and pressure at any node in the network at any given time. The pressures displayed in the compressor house nodes, however, are the actual measured pressures.

DCS consists of an Air Simulator, a Set Point controller, a Node Feedback component, a Compressor Controller and a Compressor Prioritiser. All of the mentioned components will be discussed below.

The Air Simulator is responsible for all the calculations concerning network solving. It calculates all the pressures at the different nodes and the flows in the pipes [53]. The Set Point controller calculates the compressor set points by using the data calculated by the Air Simulator. Every half-hour the Set Point controller dynamically changes the compressor set point according to the pressure requirements [53].

The Node Feedback component automatically calculates the losses in the compressed air network. This is done by calculating a loss factor between the supply and demand compressed air flows. The loss factor is used in the calculations when DCS calculates the pipeline pressures and flows.

Figure 15 is a simulation of the compressed air network layout only. This section of the simulation was used to calculate the pressure set points for the compressors. A simulation was done to calculate which compressors would be scheduled to run and which compressors would be switched off to save electricity. A display of the actual simulation that was done for the control of the compressors can be seen in Figure 16.

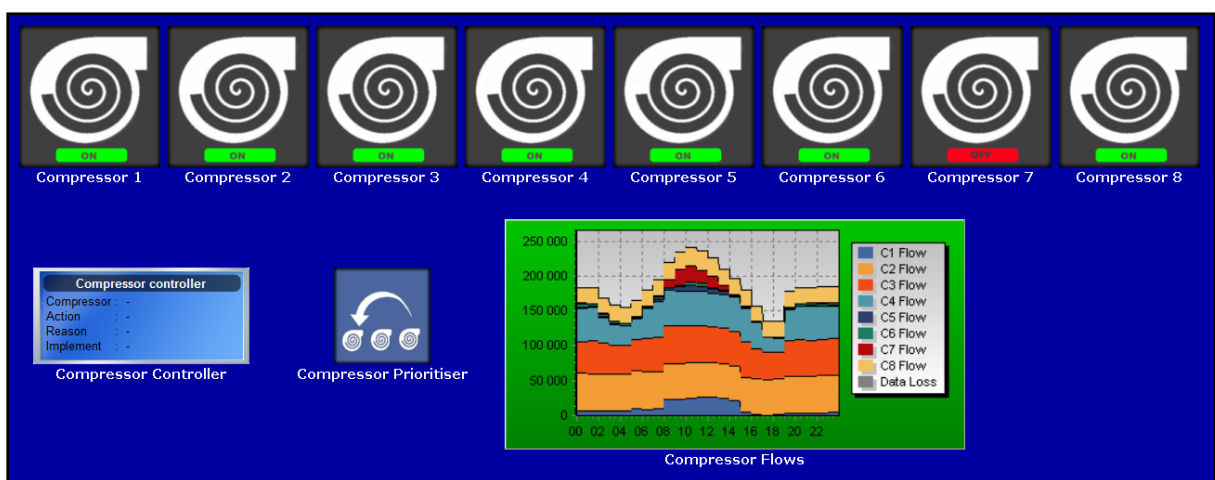


Figure 16: DCS simulation for the control of compressors

At a specific time during the simulation, the compressors with green notifications were running while the compressors with red notifications were switched off. The graph in Figure 16 shows the compressor delivery flows. As long as real-time data is available any of the compressor attributes can be drawn as a graph. This helps to monitor compressor operations easily.

The Compressor Controller in Figure 16 has the ability to start and stop compressors according to the flow and pressure requirements of the system. If automatic control is enabled, the Compressor Controller will automatically control the compressors in the most electrical energy efficient manner.

The Compressor Prioritiser calculates new priorities for the compressors according to the flow requirements in the system. It also calculates future priorities for the compressors according to the historical flow requirements of the system. The Compressor Prioritiser checks historical data for half-hour, one-hour and two-hour increments from the current time.

It then selects where the largest change in flow requirements were, and the priorities of that time will be the future priorities.

The future priorities are calculated to schedule the compressors in the correct combinations to make preparations for an increase or decrease in compressed air flow. The future priorities of the compressors are only an estimate. If the actual compressed air flow increase or decrease is more or less than the expected flow increase or decrease, another compressor can be started or stopped. This is why historical data is used.

The Compressor Controller was originally developed by Du Plessis [55]. The Compressor Controller was responsible for the scheduling and controlling the compressors. It was then upgraded by Van Heerden [53]. Van Heerden split the scheduling and control of the compressors into the Compressor Prioritiser and the Compressor Controller respectively.

2.3. Input parameters

Unfortunately, all of the information required to do the simulations was not available or easily accessible. The information required from the mine to implement DCS included the following:

- Compressor pressure set point [kPa];
- Compressor discharge mass flow [kg/s];
- Compressor delivery pressure [kPa];
- Compressor inlet guide vane position [%];
- Compressor blow-off valve position [%];
- Compressor running status [on/off];
- Compressor power [kW];
- End-user pressure set point [kPa];
- End-user pressure downstream of valve [kPa];
- End-user mass flow [kg/s];
- Pipe lengths and pipe diameters for the whole compressed air network [m]; and
- Bends for the whole compressed air network [°].

A surface layout of the compressed air network had to be obtained. If the pipelines were visible on Google Earth™, it could be used to plot the whole pipeline. If the pipelines were not visible, the whole pipeline had to be plotted with a GPS. All the pipe diameter and bend values had to be obtained or recorded in order to build a valid network. The pipe geometry was used to calculate the flow and pressure through the pipe. Figure 17 shows an example of a compressed air network layout that was done using Google Earth™.

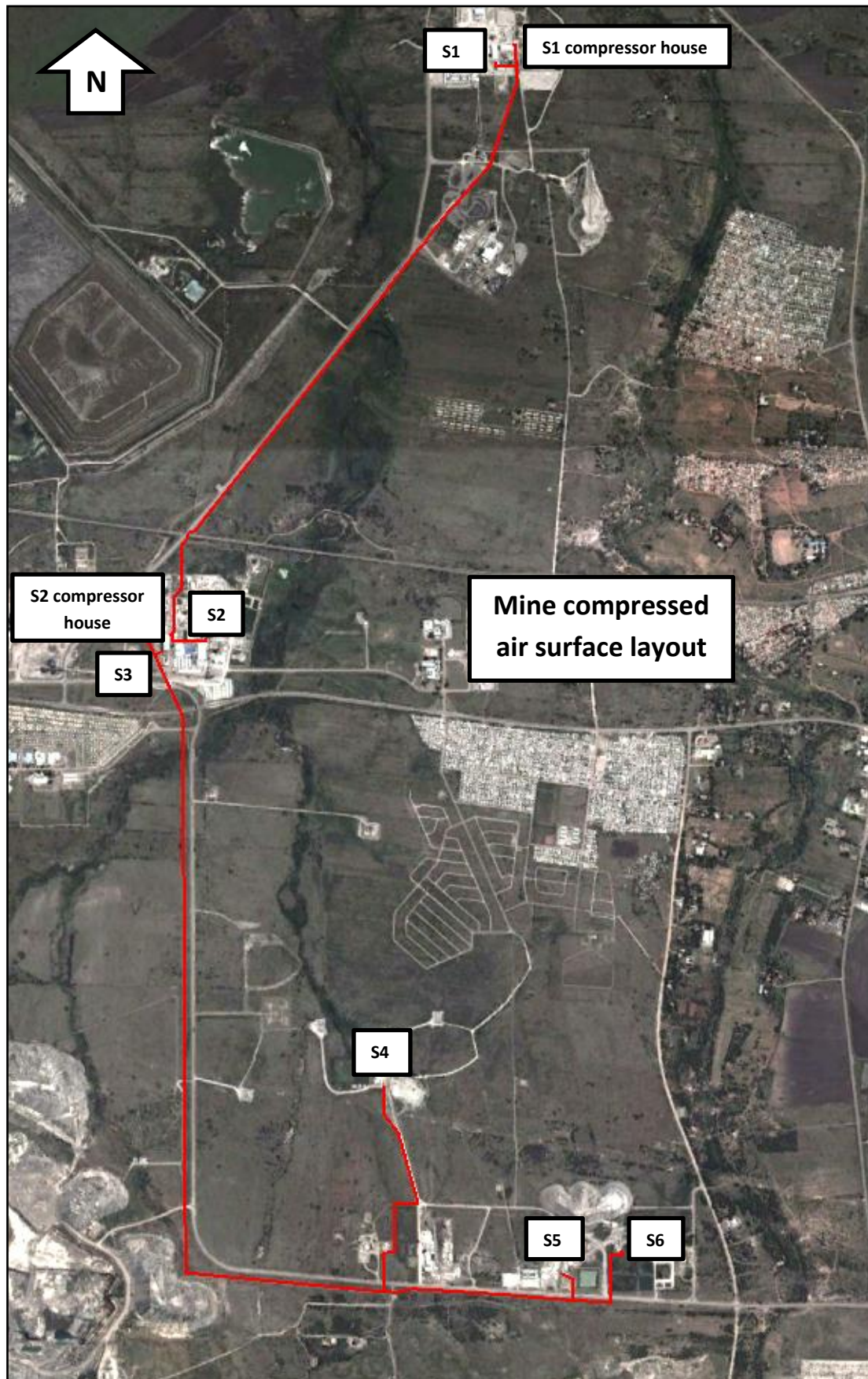


Figure 17: Mine compressed air surface layout

Another section of the data that was not already available was compressor delivery flows, because not all of the compressors had flow meters installed. Flow meters needed to be installed for DCS to function effectively. This delayed the implementation of DCS because DCS uses compressor delivery flow to schedule compressors. DCS could be implemented only after all the compressor delivery flow information was obtained.

Additional information that could also be helpful in the implementation of DCS includes:

- End-user pressure upstream of valve [kPa];
- Existing compressor priorities [1, 2, 3, ...];
- Existing compressor pressure set points [kPa];
- Valve open/close positions [%]; and
- Any other additional control constraints that are site-specific.

The additional information was not required for this implementation of DCS, but it makes DCS simulations more accurate and faster. The existing compressor pressure set points will also serve as backup pressure set points in the event that DCS fails to calculate pressure set points, or if it fails to write it to the compressors.

2.4. Implementing DCS

At the platinum mine used for this case study, the compressed air network consisted of six shafts and two compressor houses. Table 1 shows the compressors, their capacities and their location.

Table 1: Compressor specifications

Compressor number	Capacity [MW]	Compressor house number
1	4	1
2	5.1	1
3	5.1	1
4	5.1	1
5	1	1
6	1	1
7	4	2
8	4	2

The plants, workshops and smelters had standalone compressors catering specifically to their needs. This resulted in a lower required system pressure on average and also in a

simpler system. This study will not focus on the standalone compressors used at the plants, because they did not form part of the overall compressed air network.

Multistage centrifugal air compressors were used. For the purposes of this mine, multistage centrifugal air compressors were the most efficient and effective compressors to use. It was found through tests at various different mines that having a collection of smaller compressors are better for power saving than having only a few large (>5 MW) compressors. This is because smaller compressors can be switched on or off more frequently than large compressors. This means that when a compressor is no longer needed, it can be switched off.

Firstly, a baseline had to be determined for the implementation of the project. This was done by creating an average compressed air flow produced and an electrical power used profile for the compressors. Table 2 shows the proposed weekday baseline profile for the project.

Table 2: Baseline profiles

Time	Baseline power usage [kW]	Baseline compressed air flow [m³/h]
00:00	18 285	157 995
01:00	18 545	158 880
02:00	18 558	156 299
03:00	18 672	154 333
04:00	18 507	152 555
05:00	18 362	153 651
06:00	18 638	157 840
07:00	19 365	174 615
08:00	22 658	199 252
09:00	24 586	215 169
10:00	25 413	220 899
11:00	24 880	210 215
12:00	23 255	190 600
13:00	21 183	172 940
14:00	19 903	158 192
15:00	18 174	152 157
16:00	17 732	150 320
17:00	17 536	147 301
18:00	17 746	150 248
19:00	17 929	150 391
20:00	18 188	153 988
21:00	18 244	153 737
22:00	18 197	154 252
23:00	18 238	154 397

Table 2 shows the baseline profiles in hourly intervals. A graph is, however, a better representation of the baseline. Figure 18 shows a graphical representation of the baseline profiles for both the power usage and the compressed air flows.

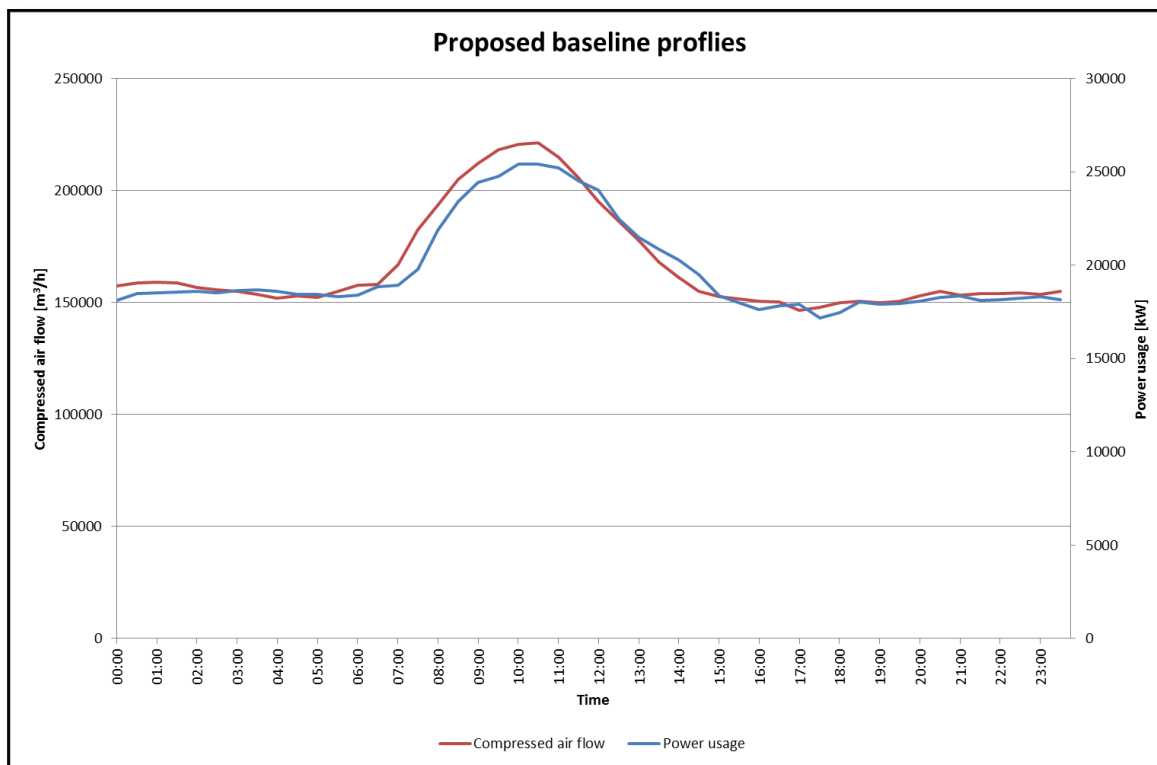


Figure 18: Proposed baseline profiles

The baseline profiles in Table 2 and Figure 18 consist of a compressed air flow and a power usage baseline. The shafts' compressed air usage formed the compressed air baseline. Only weekday power savings formed part of the project because of Eskom's Megaflex pricing structure. The data used to compile Table 2 and Figure 18 was obtained from the mine over a three-month period from before the implementation of the project.

Figure 18 also clearly shows that the peak production time of the specific mine was from 06:00 to 15:00 during weekdays. The peak production time is the period where the highest amount of compressed air and electricity is used.

This meant that for the mine there would not be significant power savings during the peak production time, but that there would rather be potential for power savings during the mining off-peak periods. The project was designed as an evening peak clipping project with a specified time of between 18:00 and 20:00 on weekdays, where the most significant power savings would be possible. The time-of-use pricing structure ensured that the evening peak savings would have the largest cost saving.

An Eskom DSM initiative funded the implementation of DCS at the platinum mine. The application for the project was approved and funding for the project implementation was received. A simulation to calculate exactly how much power savings would be possible and its results will be discussed in the next section.

2.5. Simulation results

A simulation had to be done to predict the savings that could be achieved by implementing DCS. This simulation would show how much the compressed air usage could be lowered, which would result in power savings.

The simulation was run using averages of actual data supplied by the mine before any changes to the electricity usage was made. The average flow data was used to predict the consumption during a typical day. Figure 19 shows the results regarding the number of operating compressors according to the DCS simulation.

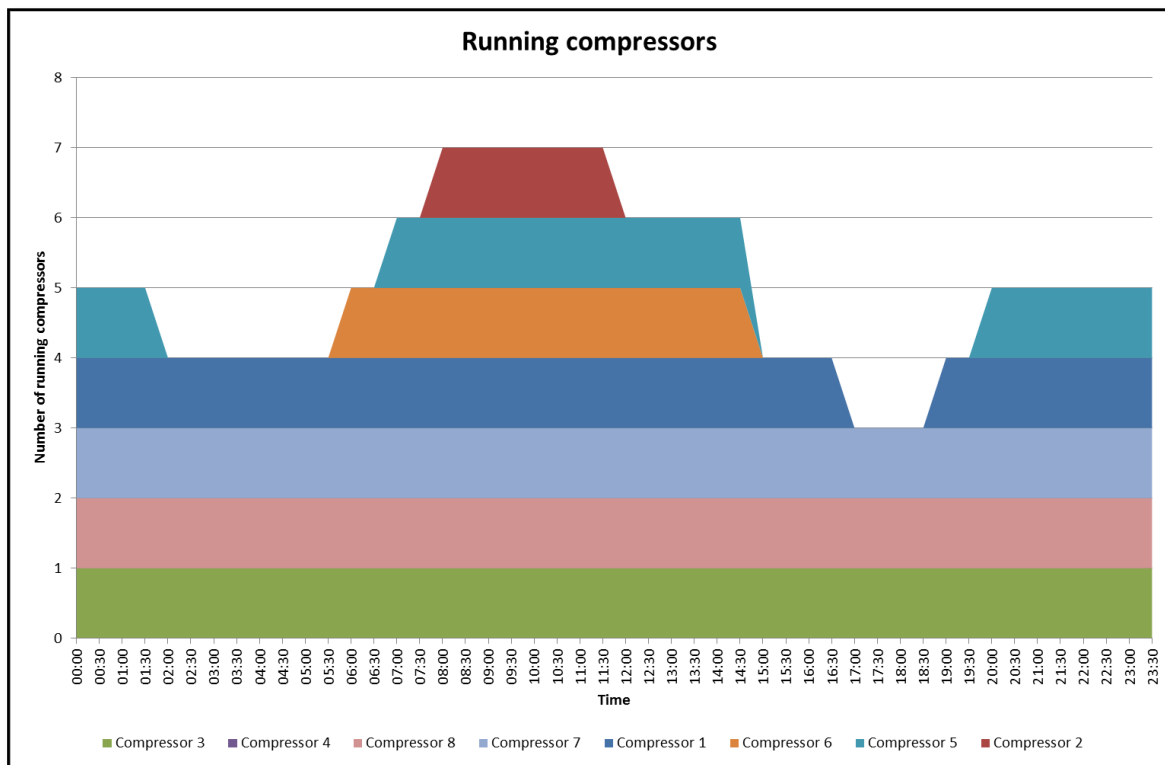


Figure 19: Simulation results for running compressors

In Figure 19, Compressor 4 is included in the legend, but not shown in the graph. This is because, according to the simulation, Compressor 4 would not be required to supply the required compressed air to the compressed air network.

Figure 19, however, only shows the number of running compressors, but without focusing on the flow or power usage. To have a better idea of the savings that could be possible, a comparison had to be made between the baseline and the simulation results for compressed air flow. Figure 20 shows the flow comparison.

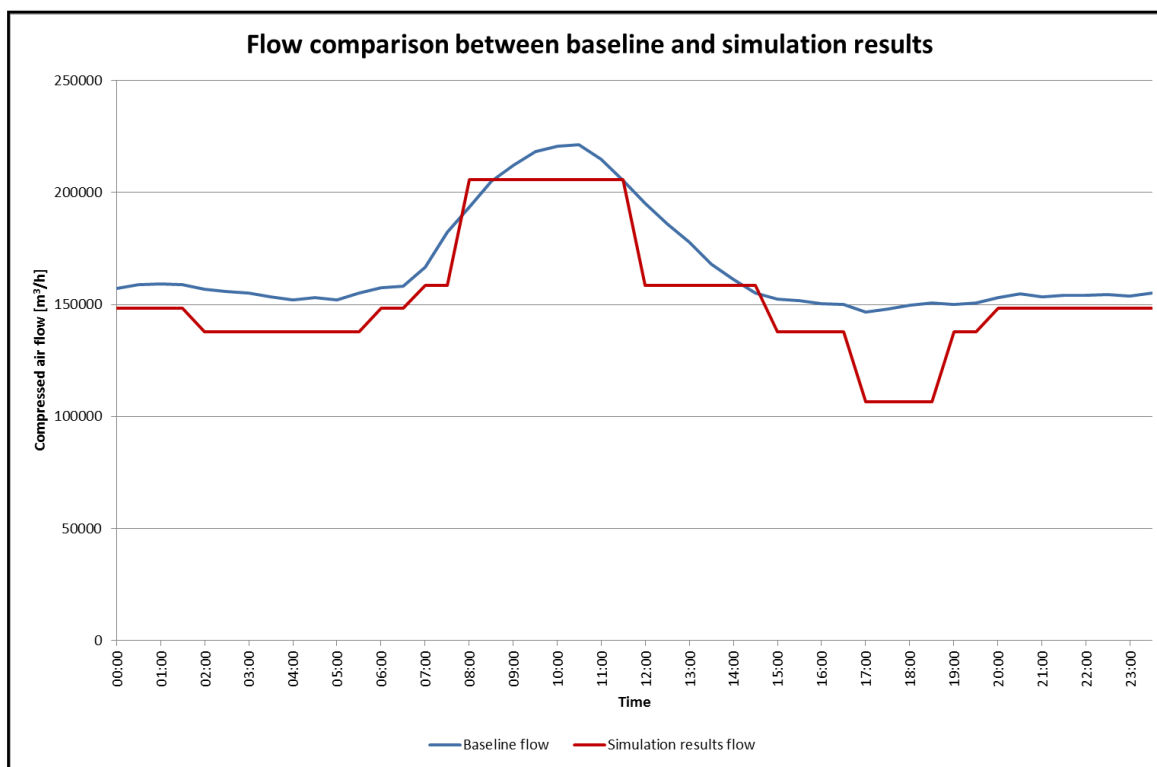


Figure 20: Flow comparison between baseline and simulation results

A comparison also had to be made between the baseline and the simulation results for power usage. Figure 21 shows the power comparison.

The project was designed as a peak clipping project, due to Eskom's Megaflex funding structures. At the time of submission, the evening peak time of between 18:00 and 20:00 was a critical time for Eskom with high electricity usage. This meant that at the time of submission, Eskom funded more peak clipping projects than any other types of project.

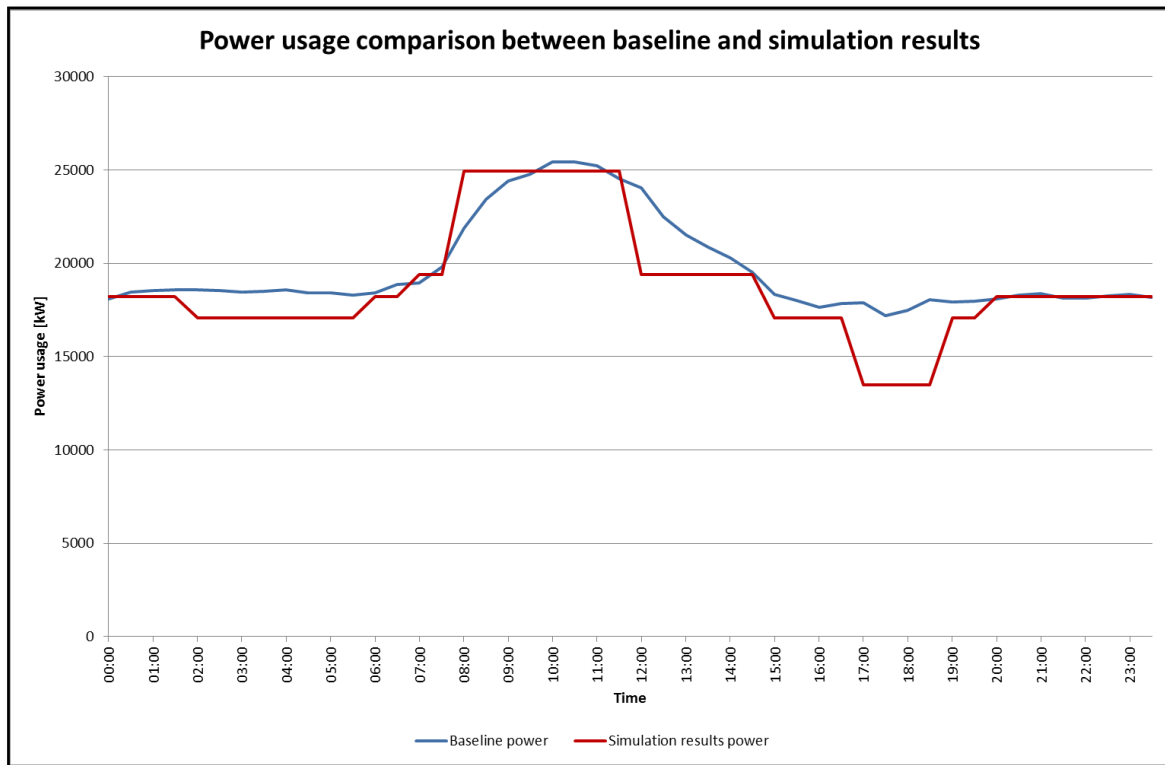


Figure 21: Power usage comparison between baseline and simulation results

Flow and power has a direct correlation to each other, resulting in both Figure 20 and Figure 21 having similar shapes. Table 3 shows a summary of the comparison between the baseline and simulation profiles.

Table 3: Simulated power savings

Time	Baseline power [kW]	Simulation power [kW]	Simulated saving [kW]
18:00	17 464	13 483	3 981
19:00	17 912	17 051	413
Average simulated power savings [kW]:			2 197

From Table 3 it can be seen that the simulation results clearly showed a reduction in power usage between 18:00 and 20:00. When the data from the baseline was compared with the results of the simulation, the simulation showed that an average evening peak clip of 2.197 MW was possible. This meant that a peak clipping project was feasible and had to be implemented.

2.6. Practical problems faced during DCS implementation

After determining that the project was feasible, the implementation of the project commenced. Van Heerden identified basic implementation problems while he was developing DCS into an easy-to-use graphical controller [53].

The problems Van Heerden identified included inaccurate field instrumentation, faulty valves, high-pressure set points and client IT policies. Van Heerden, however, only looked at the problems from a programmer's point of view. During implementation, the problems Van Heerden identified were encountered, together with several other problems.

The problems Van Heerden encountered, together with the additional problems that were encountered, will be discussed from a project implementation point of view. Solutions to the problems will be discussed and the result after the solution will be provided and discussed in the sections that follow.

2.6.1. Control valves

To enable the mine to control the compressed air used by the end-users, some valve installations were required. Firstly, an isolation valve had to be installed on the main line feeding the shaft. A bypass pipeline and valve also had to be installed. The isolation valve would be used to completely shut off the airflow through the main line and let all of the compressed air pass through the bypass line. The valve on the bypass line had to be a control valve. The control valve would control according to a pressure set point set by the shaft personnel.

The specifications of the main line isolation valve would be determined by the amount of compressed air used during the shaft's peak production periods. The pipe diameter would also affect the specifications of the isolation valve. The specifications for the bypass pipeline and the bypass valve would, however, be determined by the amount of compressed air used during the shaft's off-peak periods. A valve installation done at the mine used during the case study can be seen in Figure 22.

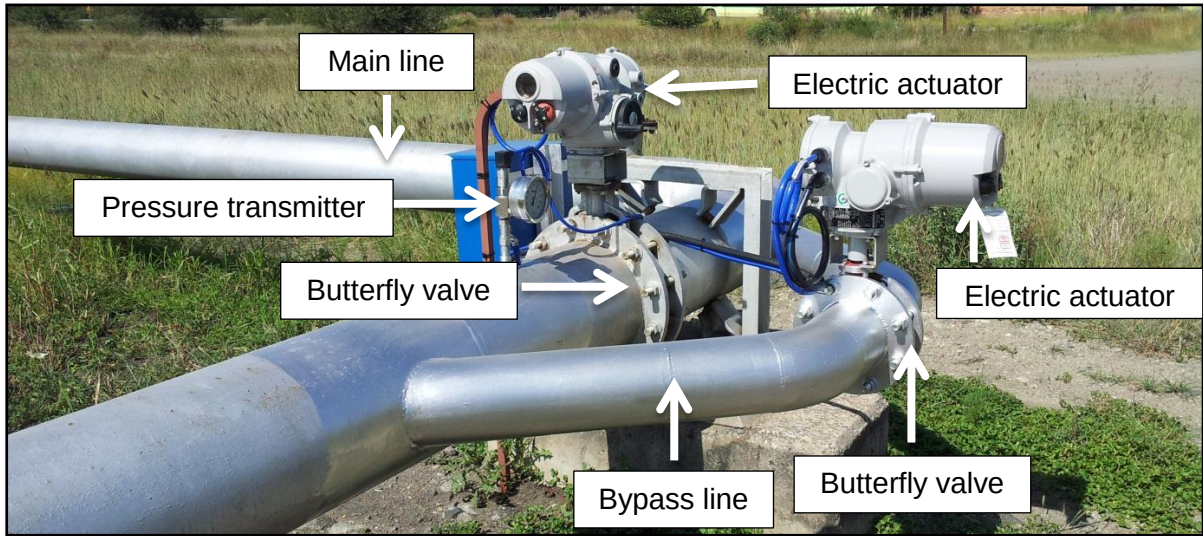


Figure 22: Surface valve installation

The pressure set point for each shaft had to be calculated as accurately as possible based on the actual pressure requirements to accurately supply the compressed air required by the shaft. The pressure set point would be calculated according to the amount of compressed air flow used by the shaft. The flow profile of the shaft was used to determine the periods of the day that the compressed air was being used. Figure 23 shows a typical 24-hour compressed air flow profile for a specific shaft.

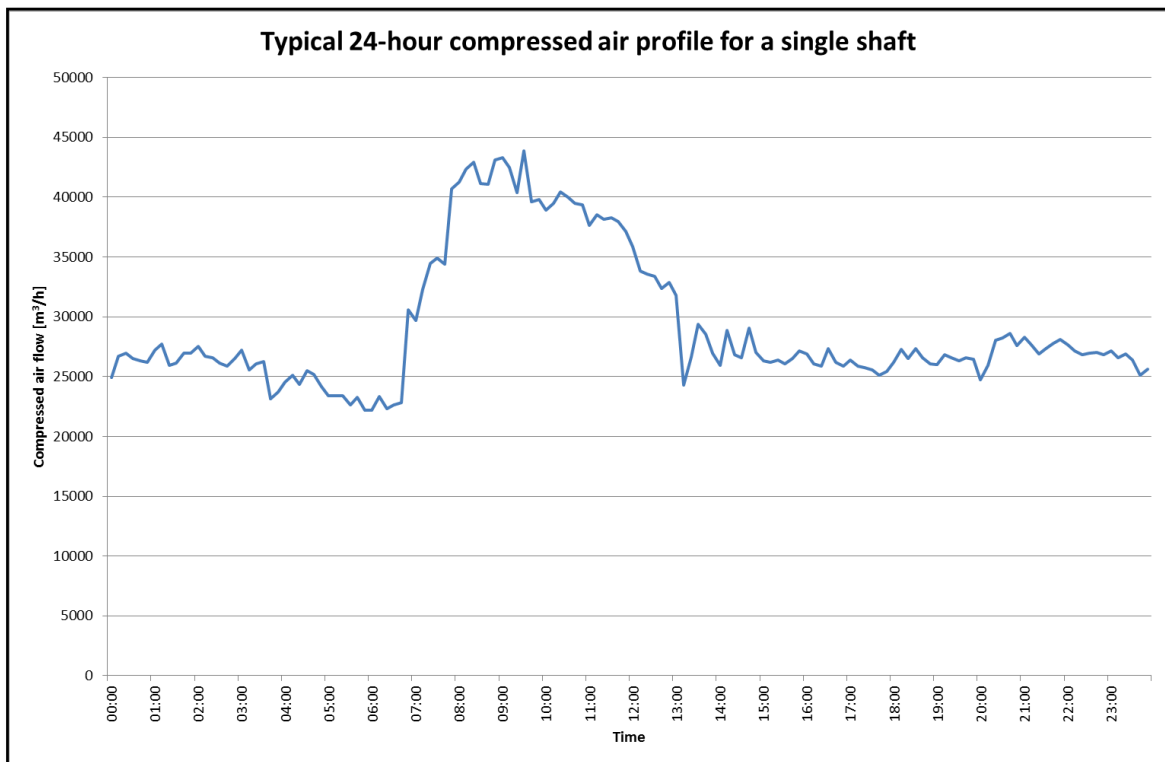


Figure 23: Typical 24-hour compressed air profile for a single shaft

The data used to compile Figure 23 was obtained from the mine. The data was for one day only. From Figure 23 it is evident that the peak production time for the shaft during the case study was between 06:30 and 12:00, which was the drilling shift. The pressure set point already had to be set higher at 05:30 to build up the backpressure in the compressed air network for when the drilling shift started. Also, the pressure set point was only set lower at 12:30 in case the drilling shift lasted longer than planned.

After 12:30 the pressure set point could be lowered. Between 13:00 and 16:30 blasting took place, resulting in low usage of compressed air. After 16:30, the cleaning shift started and compressed air was required again, although not as much and at not such a high pressure as required during the drilling shift. The pressure set point had to correspond with the compressed air usage for the shaft.

An easy, but time-consuming, method to calculate a pressure set point for a shaft was by estimating a pressure set point based on the flow profile of the shaft. The set point could then be lowered gradually until the minimum pressure required by the shaft, without influencing production or productivity, was reached. Figure 24 is a representation of a typical shaft pressure set point after it had been optimised.

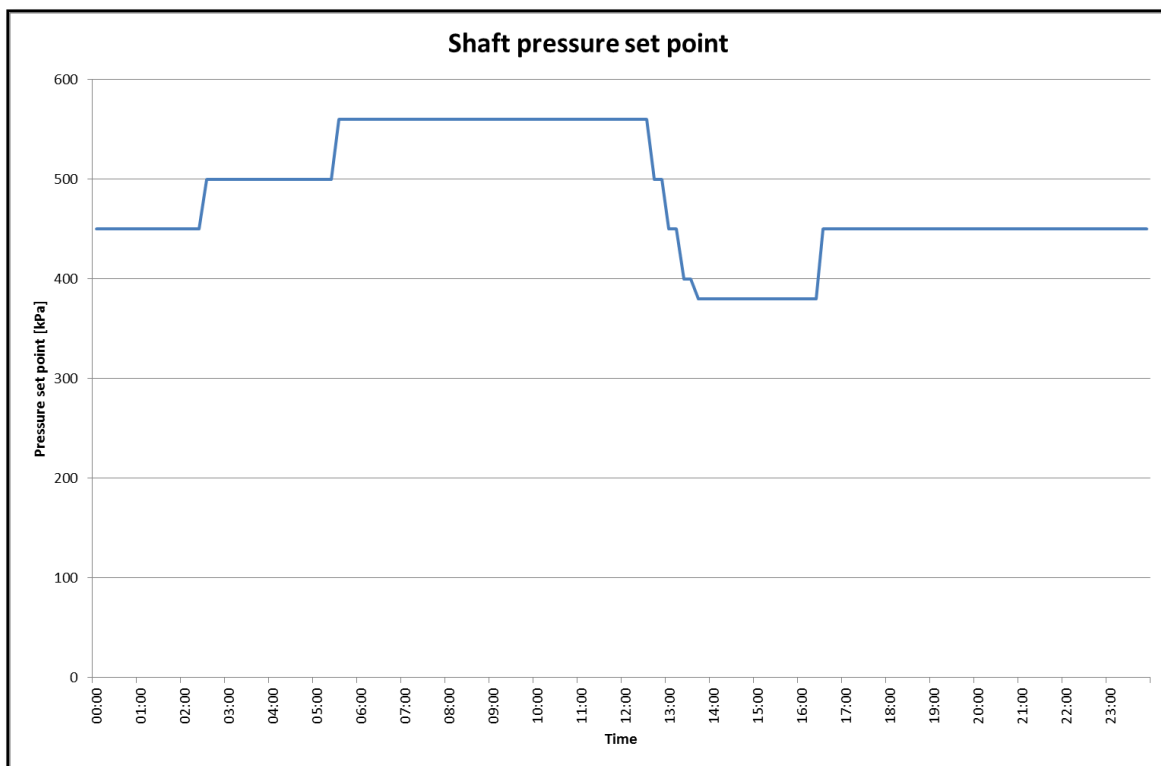


Figure 24: Typical optimised shaft set point

In Figure 24, the pressure set point was optimised according to the demand for compressed air from the shaft. The pressure set point was raised during the morning periods to accommodate the higher pressure requirements and to build up pressure in the pipeline. The pressure set point was then raised even more to accommodate the drilling shift.

After the drilling shift, the blasting shift took place during which a little compressed air was required. This meant that the pressure set point could be dropped significantly. After the blasting shift, the pressure set point was raised again to accommodate the cleaning shift.

The pressure set point was entered into a function block in the PLC, which would control the valves according to the pressure set point set using PID control loops. The function block had the functionality to set specific time intervals as peak intervals. This would keep the main line valve completely open, allowing the maximum available compressed air to enter the shaft. If the interval was set as an off-peak interval, the main line valve would be closed and the pressure would be controlled by the bypass valve.

A problem arose – there were faulty positioners on the valves that caused the valves to show that they were either fully open or fully closed, while they were actually 95% open or 5% open. This was easily fixed by recalibrating the positioners. The contractor who installed all of the valves was also responsible for the recalibration of the positioners.

2.6.2. Control on PLC level

Valve control is done at PLC level because it is the most empirical, modern form of control in the mining industry. The PLC had a backup battery that, in case of a power failure, would keep all installed programs and procedures saved on the PLC memory. This redundancy ensured that even when connection to the SCADA system was lost, control would still take place. The function block to control the valves was designed by mine personnel to comply with the mine's policies and standards.

After the implementation of the function blocks it was realised that when the valves are opened or closed completely without ramping the pressure set point up or down, the system pressure dropped or rose dramatically. This caused the compressors to struggle to compensate quickly enough for the sudden drop or rise in pressures, resulting in compressors stopping or starting unnecessarily. The pressure set point had to be ramped up or down to avoid this problem.

The function blocks in the PLCs were originally supposed to be able to take a minimum of 24 entries, at least one for each hour of the day. After implementation it was realised that the

function blocks only had a maximum of nine entries. The mine was responsible for creating the function blocks, but to comply with mine standards the original designs were not followed.

Because the function blocks could only take nine entries it caused problems when the pressure set point was manually ramped up or down. When the number of entries was higher than the maximum number of entries, the PLC went into its default state disabling all control.

To be able to take at least 24 entries, the function blocks would have had to be completely redesigned. This would have been time-consuming, which would then have delayed the project implementation. Instead, an easier and more efficient solution was found. A ramping function was added to the function blocks, enabling the control room operator to set the time it would take to change from one pressure set point to the next. This resulted in control as seen in Figure 25.

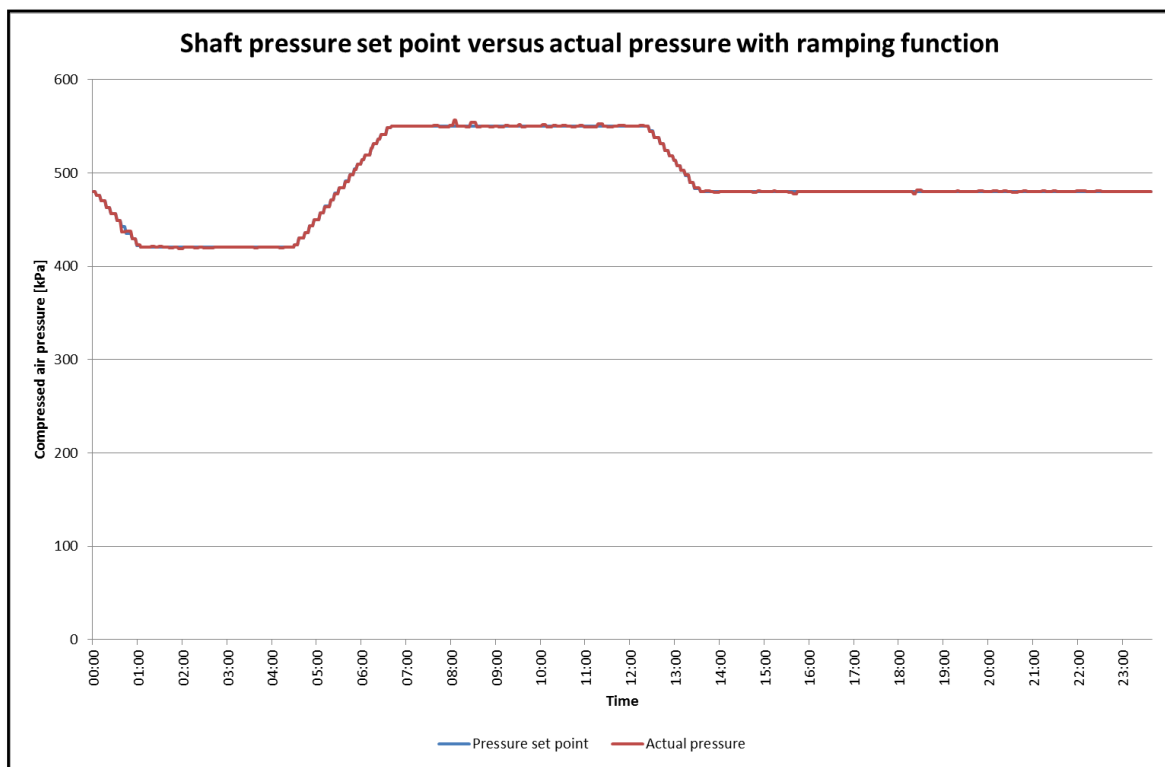


Figure 25: Shaft set point versus actual pressure with ramping function

Figure 25 was compiled using average data that was logged in DCS. The data was a total of five weekdays' data that was averaged and compiled into a 24-hour profile. With the ramping function in the function blocks, the valves closed gradually over a set time period. This

helped DCS and the compressors to register changes in the whole compressed air network before it became critical.

2.6.3. The impact of high valve pressure set points

DCS calculated the pressure set point for the compressors according to the pressure required by the shafts. However, as mentioned in Section 1.3.6, there were parameters that influenced the pressure that reached the shaft, causing pressure losses. These losses sometimes caused the compressors to operate at a higher pressure set point than necessary. The shaft's pressure set point had to be lowered after production periods to aid in creating an electrical energy efficient network.

The shaft's pressure set point was not lowered because the shaft personnel controlled the shaft pressure set point manually. Some of the shaft personnel were under the impression that the shaft pressure set point could not be lowered, even during off-peak periods. The mine personnel were afraid that lowering the pressure set point would cause the shaft to lose production. An example of where the pressure set point was not lowered after the peak production time can be seen in Figure 26.

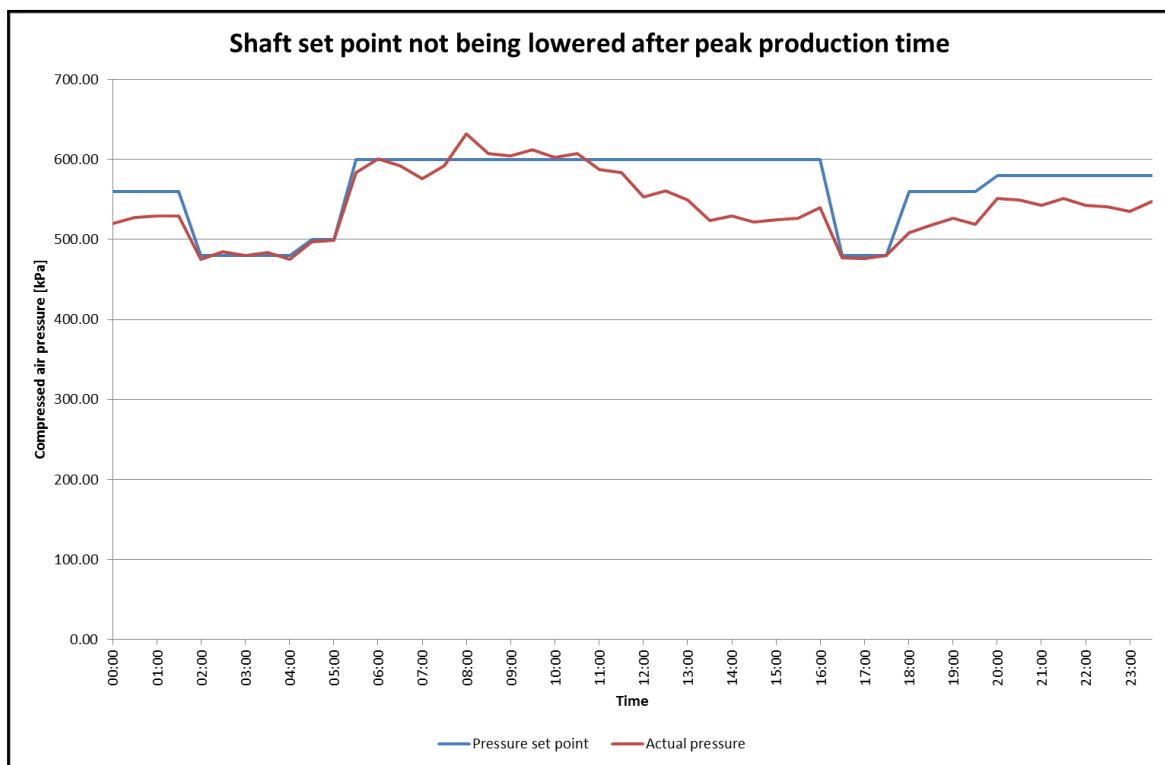


Figure 26: Shaft set point not being lowered after peak production time

Figure 26 was compiled using data that was obtained from the mine. The data that was used contained data for the average of weekdays for one week. In Figure 26 there is a point between 08:30 and 11:30 where the actual pressure rose above the pressure set point. This rise was because the pressure set point was set as peak time on the function block during peak production periods.

Setting the pressure set point as peak time on the function block caused both valves to remain fully open to allow maximum compressed air to the shaft. The shaft would receive the maximum pressure that was available at that point in the compressed air network.

A simple solution to the problem would have been to create pressure set points from historical data and then to manually add them to DCS instead of using the shaft's pressure set points. But, that would have caused DCS to be static instead of dynamic, which would make DCS similar to other existing controllers. DCS would then not be able to control the network in real-time.

Alternatively, another solution would have been to take the control privileges of the pressure set points away from the shaft personnel and rather let the personnel at the compressor control department control the pressure set points. Unfortunately, the mine did not want to take the control away from the shafts. The mine decided to keep the control of the pressure set points with the shaft personnel so that they could change the pressure set points as required by different situations or when a crisis arose.

2.6.4. Inaccurate field instrumentation

Inaccurate field instrumentation caused several problems during the implementation of DCS. DCS used the shafts' pressure set points and also their actual pressure to calculate pressure set points for the compressors dynamically.

Spikes occurred in the actual pressure readings when the pressure readings were inaccurate or when the pressure readings did not update quickly enough. It caused DCS to calculate inaccurate set points for the compressors.

If the pressure set points calculated by DCS were not accurate, the compressors would operate at pressure set points that would not supply the correct pressure to the shafts, which would result in loss of production or loss of potential power savings.

Flow meters used at the mining shafts on surface had to be mass transmounted flow systems. Using a mass transmounted flow system would be more accurate because it takes

into consideration that the characteristics of the compressed air would vary according to changes in the ambient temperatures on the surface.

The contractor that installed the surface valves used Verabar® flow meters. Figure 27 shows a schematic drawing of a Verabar® flow meter compared with a photo that was taken of an actual Verabar® flow meter before installation. The annotations on the flow meter schematic describe each part of the flow meter. It also shows the materials that each part of the flow meter is made from.

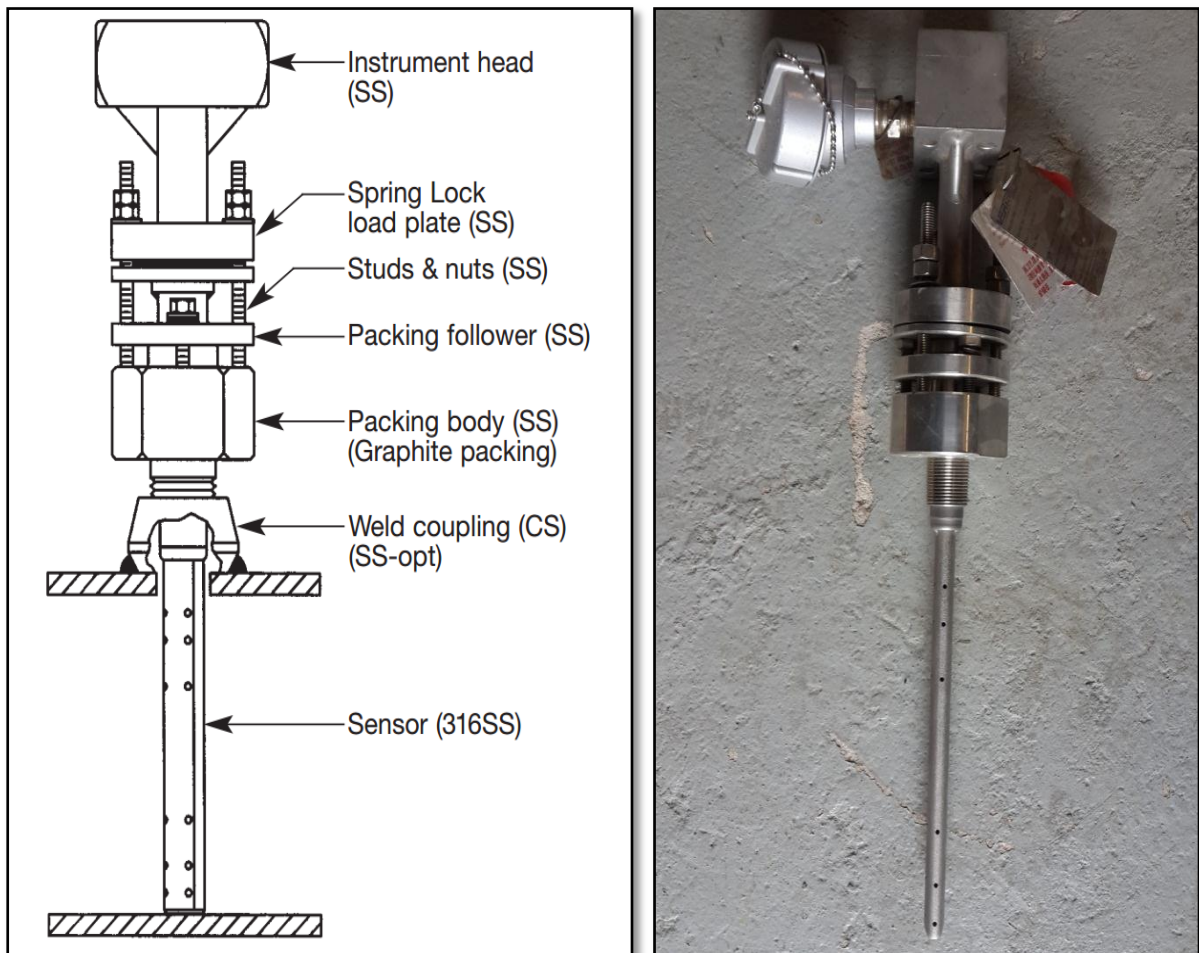


Figure 27: Schematic drawing of flow meter [56] compared with a photo of flow meter

Figure 28 shows a photo that was taken of an actual Verabar® flow meter after it was installed. The sensor part of the flow meter was installed into the pipeline, with the rest of the flow meter being outside of the pipeline.



Figure 28: Actual installed Verabar® flow meter

Compressed air flowing past the sensors of a flow meter causes a differential pressure over the sensors. A Verabar® flow meter uses this differential pressure to calculate the flow of the compressed air [54]. When the velocity of the compressed air is too low, it causes the differential pressure over the flow meter to be too low and the flow measurement will be inaccurate. Sometimes, it will cause a spike in measurements as indicated in Figure 29.

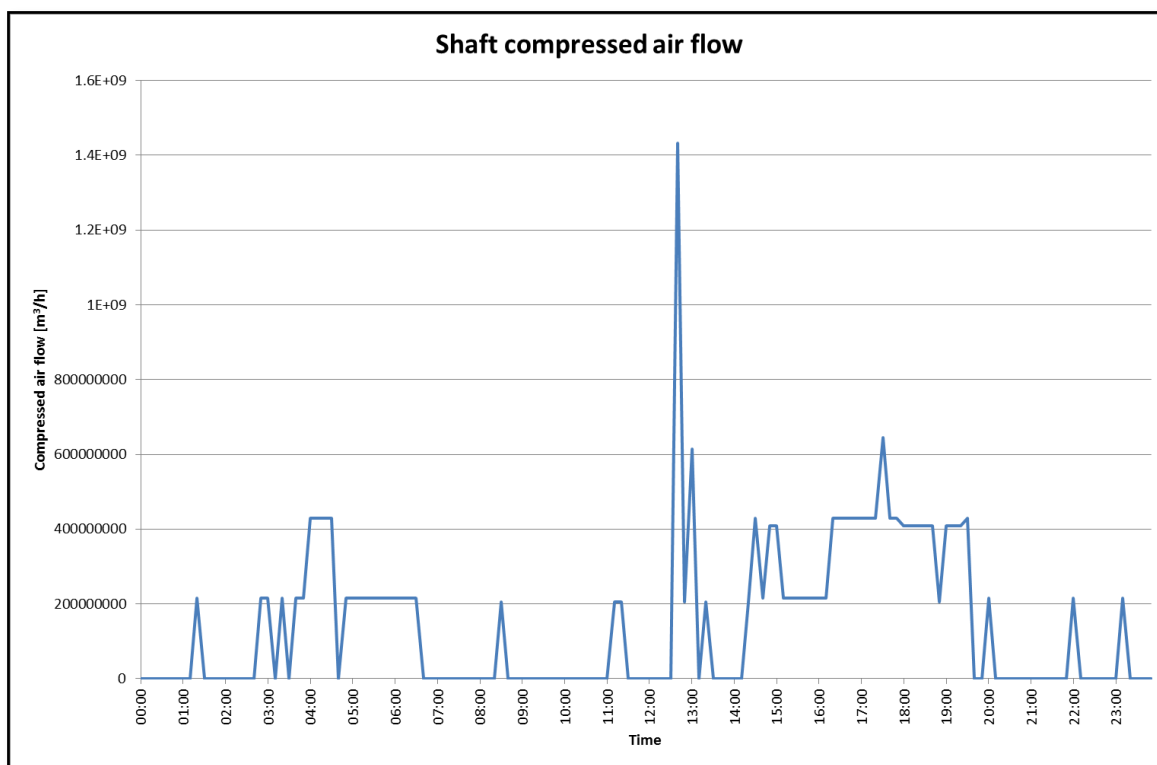


Figure 29: Spiking flow meter

Figure 29 was compiled using data obtained from the mine. The data that was used was for a weekday average for one month. To solve the problem of the spiking flow meter, a function needed to be written in an internal tag in DCS to restrict the flow measurement that DCS received. The function only changed the measured flow if it was unrealistically high. This then restricted the flow to the average peak-time compressed air flow for the shaft.

The best solution would have been to rather replace the flow meter, but mass transmounted flow meters cost about R80 000 each. This meant that it would not have been feasible to replace the flow meter. Figure 30 shows the compressed air flow of the shaft after the spikes in the flow was removed.

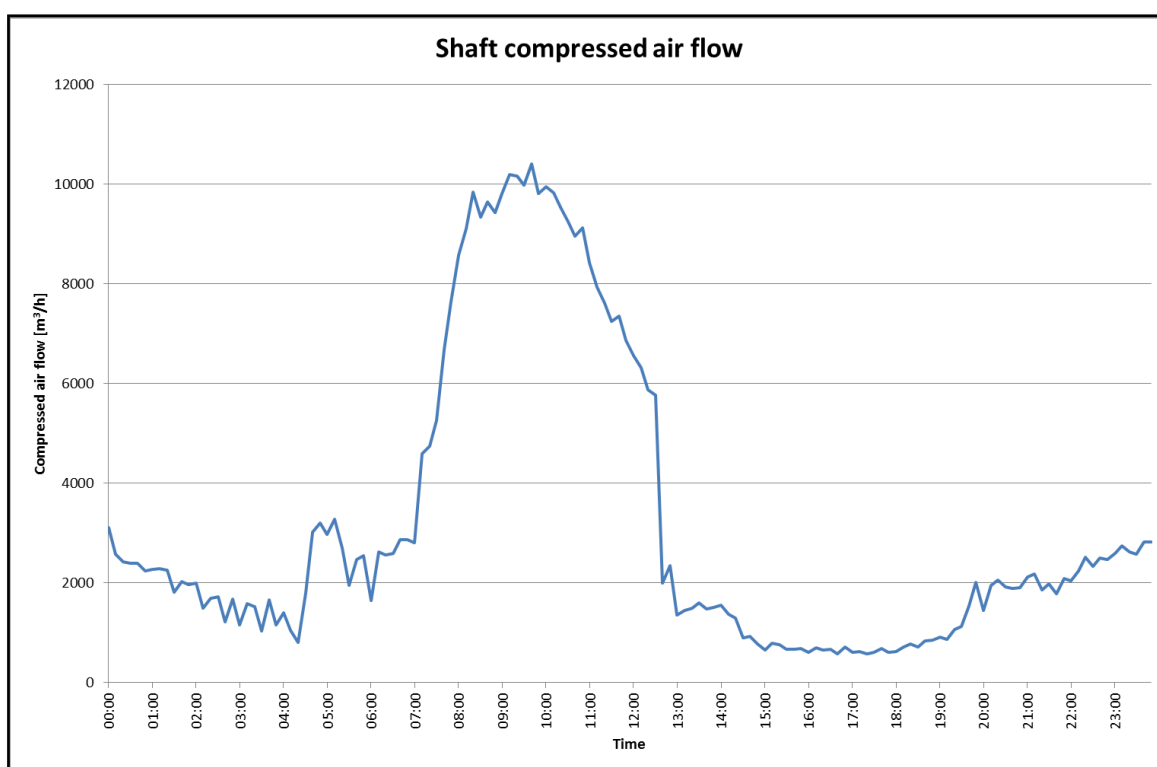


Figure 30: Shaft compressed air flow after fixing spiking flow meter

The data used to compile Figure 29 and Figure 30 can be seen in Table 4. The data was taken as an hourly average for one month's data. Only weekday data was used to compile the graph and the table, because weekend data did not give a valid representation of compressed air flow rates. Table 4 shows a comparison between the flow from before fixing, to after fixing the spikes.

Table 4: Compressed air flow with spiking flow meter

Time	Before fix: Compressed air flow [m³/h]	After fix: Compressed air flow [m³/h]
00:00	2 521	2 521
01:00	35 793 497	2 103
02:00	35 793 028	1 634
03:00	143 166 930	1 354
04:00	322 124 430	1 883
05:00	214 751 019	2 654
06:00	143 168 103	2 527
07:00	5 315	5 315
08:00	34 096 364	9 322
09:00	10 060	10 060
10:00	9 441	9 441
11:00	68 181 658	7 574
12:00	274 882 707	4 802
13:00	136 349 648	1 480
14:00	207 822 140	1 142
15:00	248 469 890	707
16:00	357 914 593	652
17:00	465 288 743	619
18:00	374 958 215	753
19:00	279 348 715	1 249
20:00	35 793 259	1 865
21:00	2 002	2 002
22:00	35 793 742	2 348
23:00	35 794 090	2 695

From Table 4 it can be seen that the flow profile was more stable and realistic when the spikes in the flow meter readings were removed; it was a critical fix that had to be made. The fix directly influenced the calculations of DCS, because every time a spike occurred, wrong set points were calculated for the compressors.

The easiest way to remove the spike was to create an internal tag with a function that limits the flow. The function will inspect the flow and if it is unrealistically high, it will substitute it with an average flow reading.

Other parameters that can cause field instrumentation to be less accurate are listed below:

- Dirt and water in the pipelines;
- Leaks around the measuring equipment;

- Vibration in the pipelines;
- Inaccurately specified field instrumentation;
- Varying temperatures; and
- Ineffective maintenance.

The power usage data was monitored and logged by a third-party company that was contracted by the mine. The company managed the electricity statistics for all the large electricity consumers of the mine. The electricity data was available for download from the company's on-site server. The electricity data was available in half-hour intervals for each day of the year.

One problem with a third-party company monitoring and logging the power data was that the data was not available in real-time and only as historical data. This caused problems during the implementation of DCS.

DCS used the compressors' power usage data to calculate efficiencies for each of the compressors. Without real-time data this could not be done. DCS, furthermore, calculated flow ranges for each compressor. The minimum and maximum flow at different pressures were logged and used for the scheduling of compressors.

The efficiencies calculated with the power usage data would have made DCS more efficient, but it was not a critical problem. The flow ranges that were calculated by DCS were the first controlling mechanism, while the power efficiencies were an additional controlling mechanism. The aim of the power efficiencies was to aid the scheduling of compressors.

2.6.5. Mine control constraints

To be efficient, DCS had to have enough control privileges to start and stop compressors. This meant that when a large compressor was running, but no longer required, a smaller compressor could be started and it could be switched with the larger compressor. It would also be able to start up compressors when the need for additional compressed air arose.

Control restraints of the mine, however, only allowed DCS to schedule compressors dynamically and to supply the compressors with a dynamic pressure set point. DCS did not have enough control privileges to start or stop compressors. This caused DCS to be less efficient than it could and should have been.

The mine controlled the starting and stopping of compressors and also the protection of the compressors by using a master controller. The protection of the compressors included surge control, start-up and shut-down sequences and compressor cool-down timeouts.

The master controller could accept commands from DCS regarding compressor pressure set points and priorities, but it would start or stop compressors according to its control parameters. This was an inefficient solution and it also limited the functionality of DCS.

Because DCS was not able to start or stop compressors, it caused one of the bigger compressors to supply varying flow when it kept on going into an idle state and back into an active state. If DCS had enough control privileges to stop or start compressors, the specific compressor could have been exchanged with a smaller one. Figure 31 shows the results for the period when DCS did not have control privileges. The red circles in Figure 31 highlight the areas where the flow of Compressor 3 kept on varying.

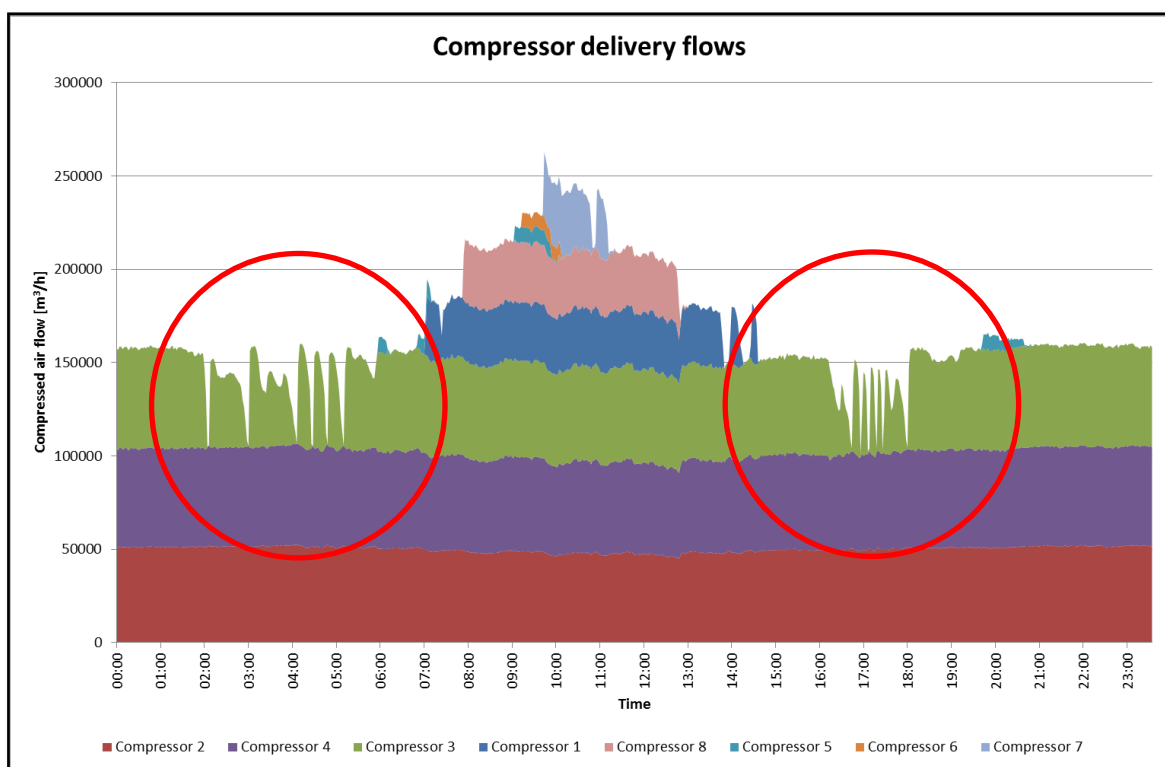


Figure 31: Compressor delivery flows before DCS start/stop privileges

The control of the master controller was changed to allow DCS to switch the priorities of the compressors when a large compressor was not required anymore. DCS would then switch the priority of the compressor that needed to be switched off to the lowest priority.

Switching the priorities resulted in exchanging the larger compressors for smaller compressors when it was possible. Exchanging the compressors in turn resulted in less compressor cycling and also in an overall reduction of the number of running compressors. The result can be seen in Figure 32.

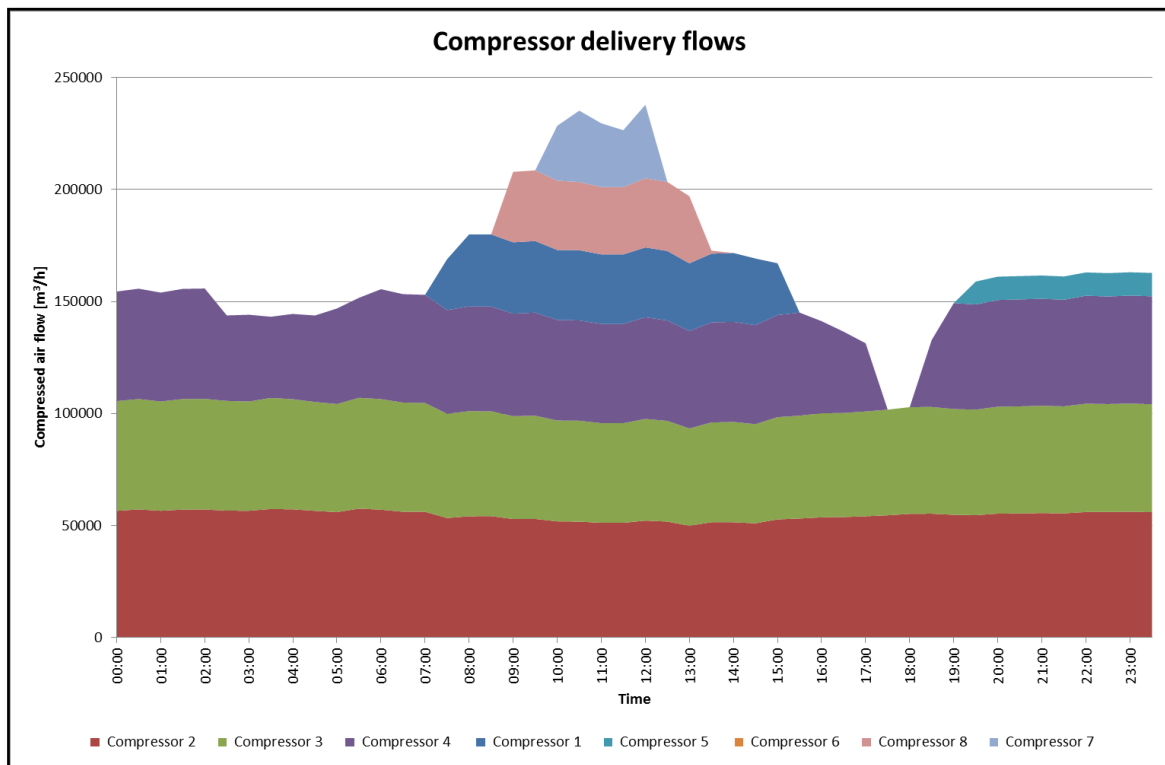


Figure 32: Compressor delivery flow after DCS start/stop privileges

Both Figure 31 and Figure 32 were compiled using data that was logged by DCS. The data used contained an average of one week's weekdays. When Figure 31 is compared to Figure 32, it can be seen that DCS clearly reduced compressor cycling and improved overall compressor control. Compressor 6 was included in the graph, but was not required to supply the required compressed air. This resulted in compressor 6 not showing on the graph.

2.6.6. Incorrect pipe configurations

Another problem was that the pipelines changed diameter without the proper pipework to support the decrease or increase in pipe diameter. This caused the simulation of DCS to be inaccurate and it also caused losses in the compressed air flow or pressure. Figure 33 shows an example of where the pipework was not done sufficiently.

Figure 33 shows the pipe diameter change that caused the pipe to choke the air at the narrowing, resulting in the desired compressed air flow rate and pressure not reaching the end-user. Even though some compressed air would still reach the end-user, the intended flow and pressure could not be achieved.

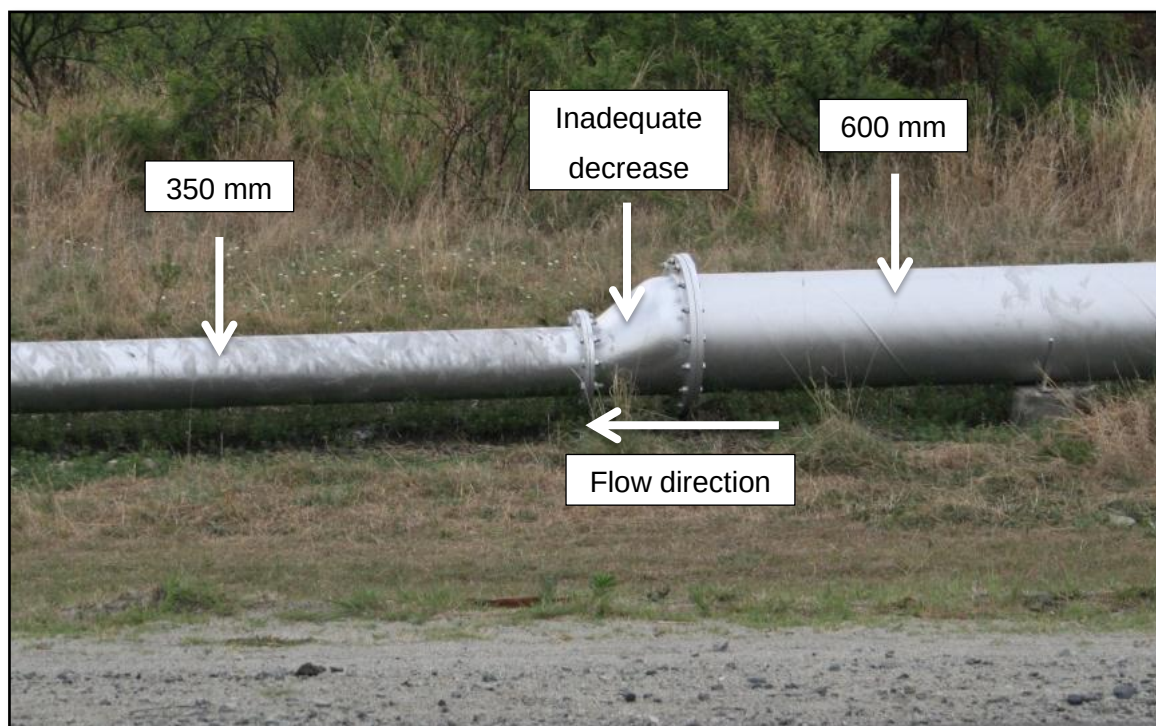


Figure 33: Incorrect pipe configuration (inadequate decrease in pipe diameter)

Incorrect pipe configurations also cause problems with DCS. DCS does not allow the connection of only two pipes to a node due to a constraint built into DCS. This means that a sudden decrease in pipe diameter, as shown in Figure 33, cannot be simulated accurately in DCS. The constraint is for verification purposes when building a simulation.

To compensate for these types of change in pipe diameter, a higher loss factor had to be entered into DCS when the setup was done. This would have made the DCS calculations more accurate, but it was not the best solution because it still would only have been a theoretic value. The best solution would have been to redo the pipework to ensure that the pipe diameter was consistent. Unfortunately, the mine did not want to work on pipelines unless there were leaks or similar problems with the pipeline.

The pressure set point would be set higher than required when the pressure of the shaft did not reach the intended pressure set point. On a specific shaft, there was a pipeline that did not meet the flow requirements and the compressed air that was required by the shaft did not reach it. The shaft was also too far away from a compressor house to reach the intended set point. The pipeline can be seen in Figure 34.

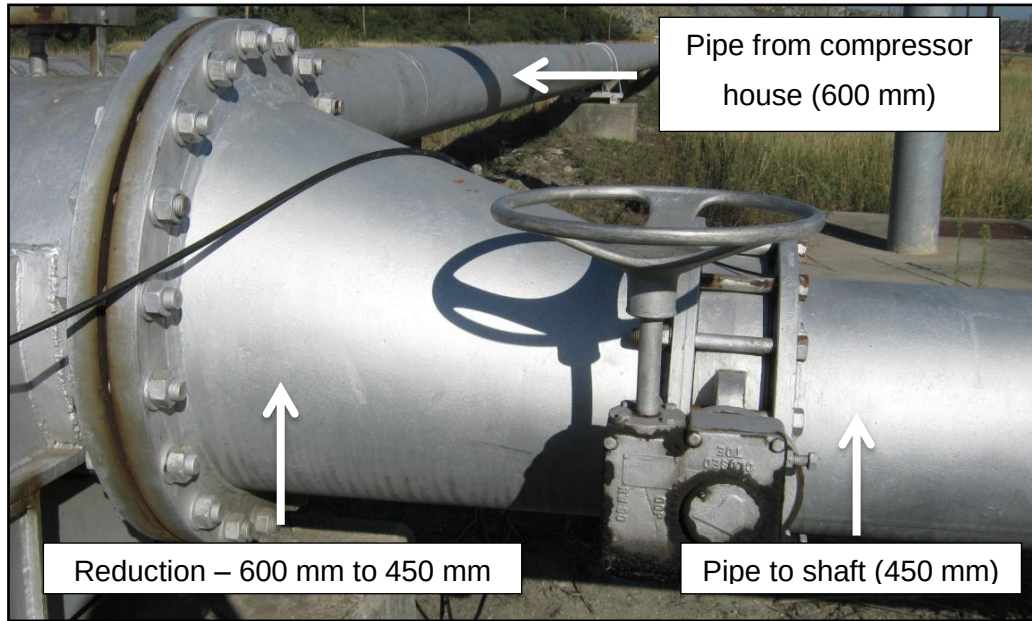


Figure 34: Pipe diameter before replacing the pipe to the shaft

The pipeline shown in Figure 34 was reduced to a pipe diameter that was too small for the compressed air requirements of the shaft. This caused the actual pressure of the compressed air that reached the shaft to be lower than the intended pressure set point. A representation of the problem can be seen in Figure 35.

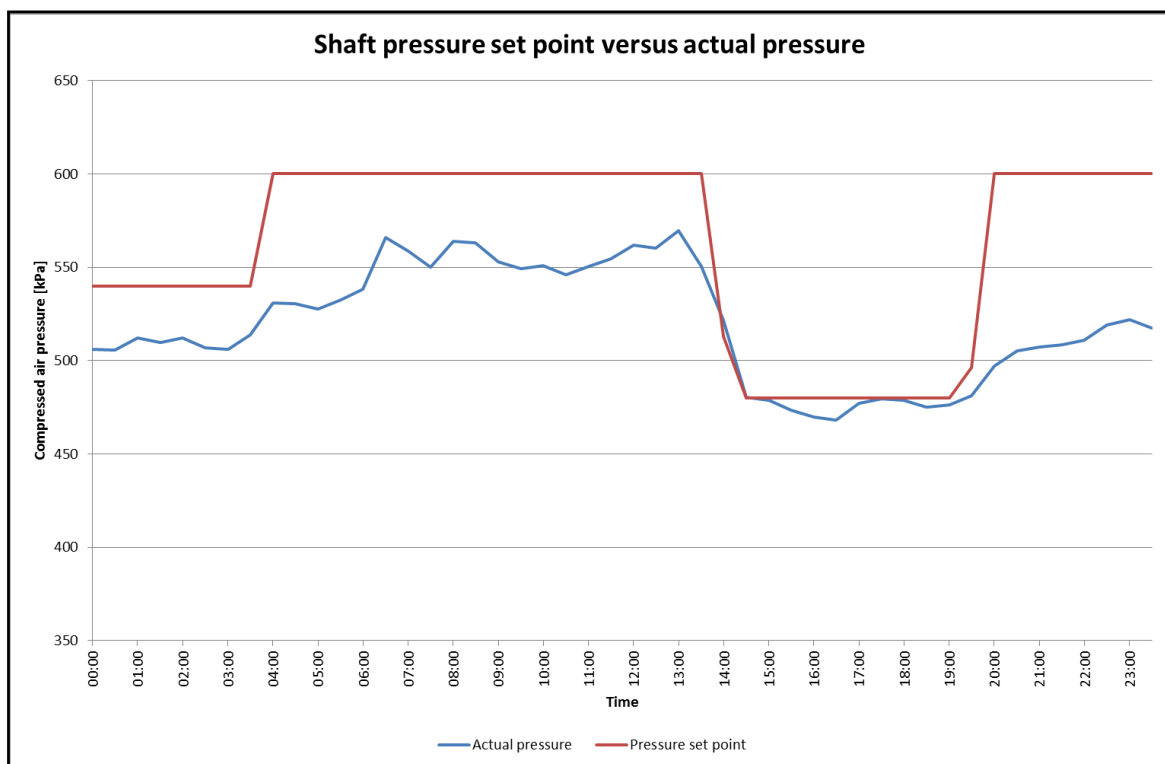


Figure 35: Shaft pressure versus set point before pipe replacement

The data used to compile Figure 35 was data that was downloaded from the mine's servers. The data was for one day only, but this was sufficient because most days followed the same pattern for the specific shaft. The intended pressure set point was not reached on most days.

To avoid the problem of the inadequate pipe diameters, a node variance feature was built into DCS. This enabled the compressor control department personnel to set a specific variance for the shaft. This was a good solution for the shaft.

For the compressors to supply the required compressed air pressure to the shaft, the compressors would have to operate at ± 700 kPa. This is an unrealistically high-pressure set point for compressors. The node variance function uses a percentage value that the pressure can differ from the set point. Figure 36 is a representation of the node variance function in DCS.

The screenshot shows a DCS configuration window for a node. The 'Description' field contains 'S5#'. Under 'Node type', 'Demand node' is selected. 'Pipes in' is '4B# to 4B Node' and 'Pipes out' is empty. The 'Pressure tag' is '506000.000/InternalTag S5# Pressure' with a unit of 'K Pa'. The 'Flow tag' is '7.644/InternalTag S5# Flow' with a unit of 'm^3/h' and an 'Edit_flo' button. The 'Set-Point pressure tag' is '540000.000/InternalTag S5# PressureSP' with a unit of 'K Pa'. The 'Node variance' is set to '5 / Fix', which is highlighted with a red rectangle.

Description	
S5#	
Node type ☐ Node ☐ Supply node ☒ Demand node	Pipes in 4B# to 4B Node
Pipes out	
Pressure tag 506000.000/InternalTag S5# Pressure	Unit K Pa
Flow tag 7.644/InternalTag S5# Flow	Unit m^3/h Edit_flo
Set-Point pressure tag 540000.000/InternalTag S5# PressureSP	Unit K Pa
Node variance 5 / Fix	Unit

Figure 36: Node variance function in DCS

The kPa and m³/h buttons as seen in Figure 36 are conversion factors built into DCS. The chosen unit will be the unit in which the values are received from the mine. These values are then converted to SI Units for calculation purposes.

A function was also built into DCS where the operator could set a pressure offset on the calculated pressure set point. By using this method, the shafts still received their required pressure and the compressors did not have to operate at unrealistic high pressures. The offset function in DCS can be seen in Figure 37.

The screenshot shows a software interface titled 'EditForm'. It contains several sections: 'Description' with a text field containing 'NodeFeedback 1'; 'Tags' with three fields: 'Set-point Tag' (541833 / Tag / InternalTag Temp Comp SP), 'Set-point write tag' (541833 / Tag / InternalTag SP Scaling), and 'Offset tag' (0 / Fix), which is highlighted with a red rectangle; 'Supply tags' with a list box containing 'InternalTag Production Flow (kg/s)'; 'Demand tags' with a list box containing 'InternalTag Consumption Flow'; and buttons for 'Add supply tag', 'Delete supply tag', 'Add demand tag', and 'Delete demand tag'. At the bottom, there is an 'InputFlow type' dropdown set to 'kg/s' and 'OK' and 'Cancel' buttons.

Figure 37: Offset function in DCS

The mine eventually replaced the pipe (shown in Figure 34) to remove the reduction in pipe diameter. Afterwards, the pipeline was a 600 mm pipeline that extended up to the shaft resulting in more compressed air reaching the shaft at a higher pressure. The replaced pipeline can be seen in Figure 38.



Figure 38: Pipe diameter after replacing the pipe to the shaft

After replacing the pipeline, the set point was also lowered during the mining peak production periods, but raised during the off-peak periods. Figure 39 shows the shaft's actual pressure compared with the new pressure set point after replacing the pipeline to the shaft.

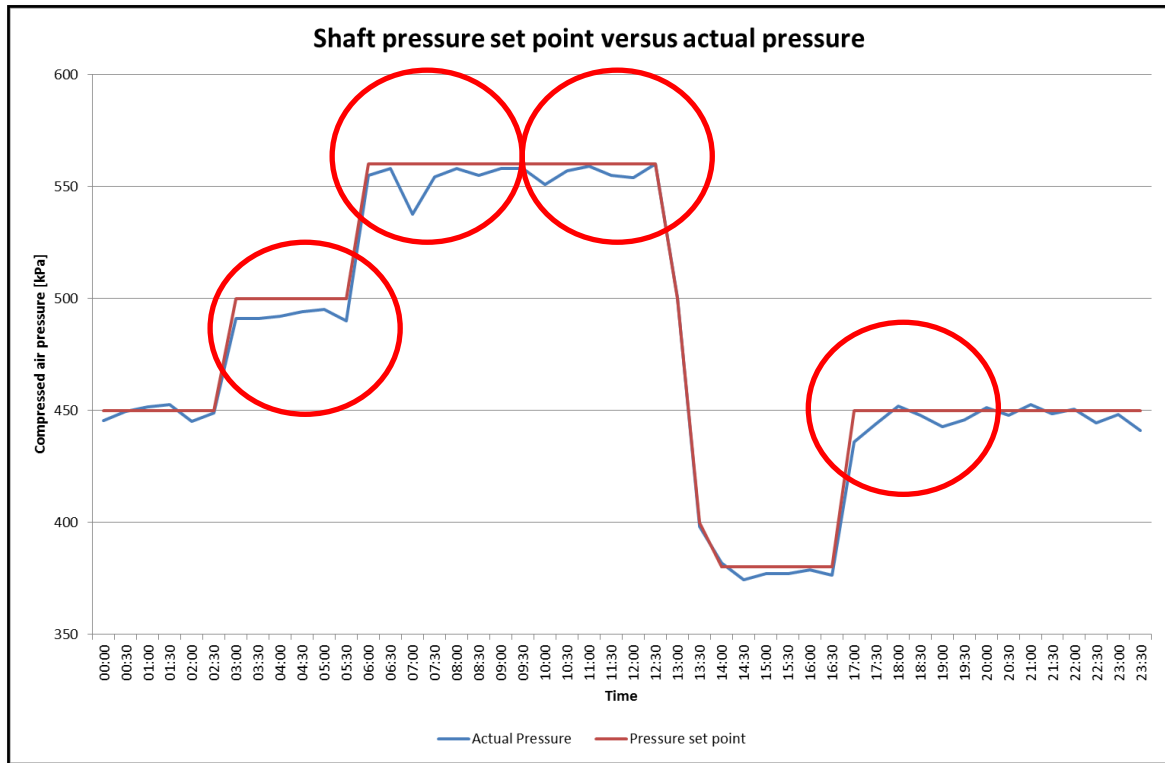


Figure 39: Shaft pressure versus set point after pipe replacement

Even though the pipeline was replaced, there were some instances where the actual pressure still did not reach the pressure set point. These instances are shown in the red circles in Figure 39. However, during other time periods, such as the mining off-peak periods, the actual pressure did reach the intended pressure set point.

This meant that the pipeline replacement was beneficial to the shaft, but that it was still not a valid solution to the problem. A possible solution that would have greatly benefited the shaft would have been to install a compressor closer to the shaft. This would have helped to increase the pressure that reached the shaft.

2.7. Summary

Chapter 2 explained exactly what DCS is. The chapter gave an overview of each of the different DCS calculations. After explaining what DCS is, all of the required, as well as additional helpful input parameters that was required to implement DCS were provided.

An investigation needed to be done to determine the feasibility of implementing DCS. This included generating a baseline profile and simulating possible power savings. After the baseline and simulation profiles were compared, it was seen that a project would be feasible and DCS was implemented.

While implementing DCS, several practical problems were encountered. These problems were solved as best as possible when taking into consideration mine constraints and the cost of repairing or replacing certain parts. The solutions to the problems, as well as the end-result after the solutions were implemented, were provided in this chapter.

Chapter 3:

Results after the implementation of a dynamic air compressor selector

3.1. Introduction

Chapter 3 provides the detailed results after DCS was implemented and the results are discussed in detail. The chapter also shows verification of the data and provides validation of the study.

3.2. Pressure set point control

One of the main tasks of DCS is to calculate pressure set points for the compressors to match the pressure required by the shafts. The pressure set points had to be calculated as low as possible, without affecting any mining operations. This proved successful after implementation. Figure 40 shows the results of a typical 24-hour compressor pressure set point profile as calculated by DCS after DCS was implemented.

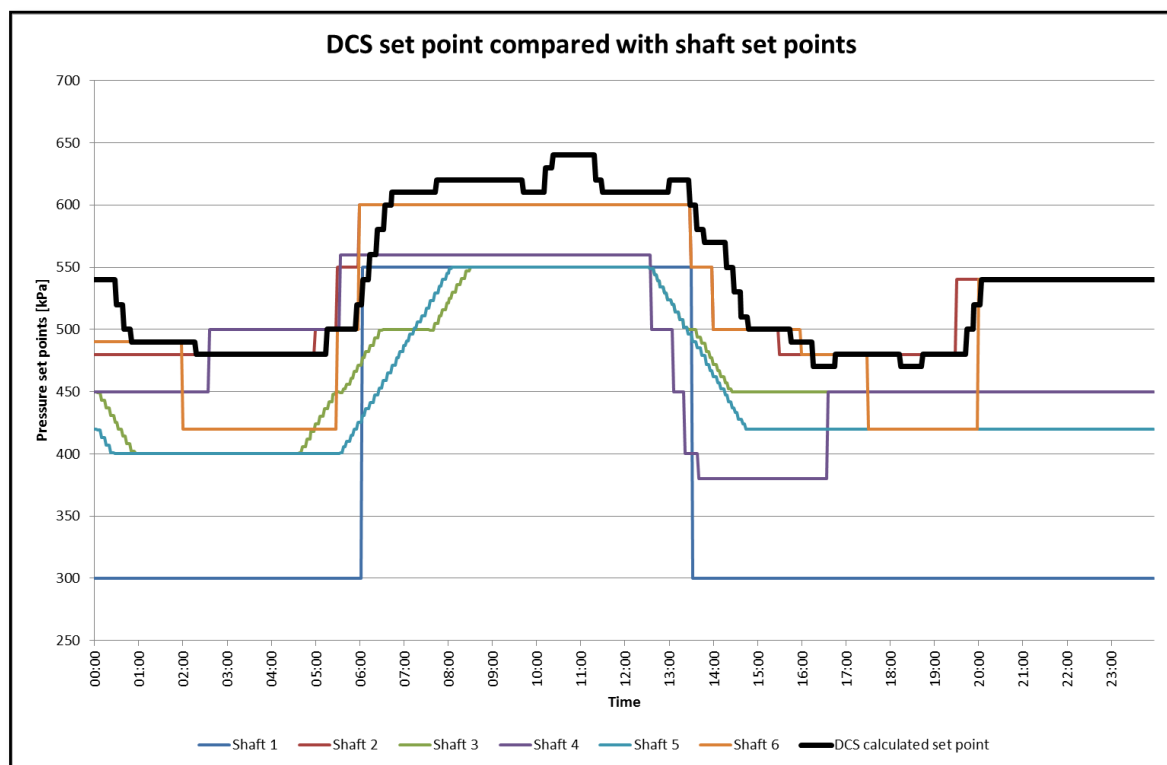


Figure 40: DCS calculated set point compared with shaft set points

The compressor pressure set point calculated by DCS and the pressure set points for the shafts were logged in DCS. The data was saved on the server that DCS was operating on. At the end of each day the data was sent to an off-site server. A database was created where the data could be viewed and downloaded when required. Most of the compressor data was available on the database.

Figure 40 shows that DCS did actually control the pressure set point for the compressors according to the actual pressures required by the shafts. DCS works on the principle of satisfying the pressure set point for the shaft with the highest pressure demand. This meant that Shaft 2 and Shaft 6 drove the compressor pressure set point for most of the day.

It is also clear from Figure 40 that the mining peak periods were reduced from 06:00 to 13:00 by implementing more accurate and more precise pressure set points for the shafts. The shafts' pressure set points were calculated and tested. DCS also optimised the compressor set points to match the required pressure by the shafts.

However, there were instances where the shaft pressure set points increased or decreased before DCS could raise or lower the compressor pressure set points. Examples of this can be seen in Figure 40 at 06:00 and 13:00. As mentioned, the pressure set points of the shafts were used to calculate the pressure set points for the compressors. The compressor pressure set points, however, needed to be ramped up or down to allow the compressors to adjust to the new set points.

When the compressor pressure set point was changed with 100 kPa, for example, the compressors would all start up in a few minutes in an attempt to satisfy the change in the compressor pressure set point. If the compressor set points were ramped up or down as shown in Figure 40, the compressors would be able to adjust to the change in compressor pressure set point and they would only start up when it was absolutely necessary.

3.3. Production and consumption flow

Another area that DCS focuses on is attempting to match the supply flow of compressed air from the compressors with the demand flow of compressed air from the shafts. Figure 41 shows that the production and consumption flows were matched at the mine. Figure 41 is a representation of the data that was logged by the mine.

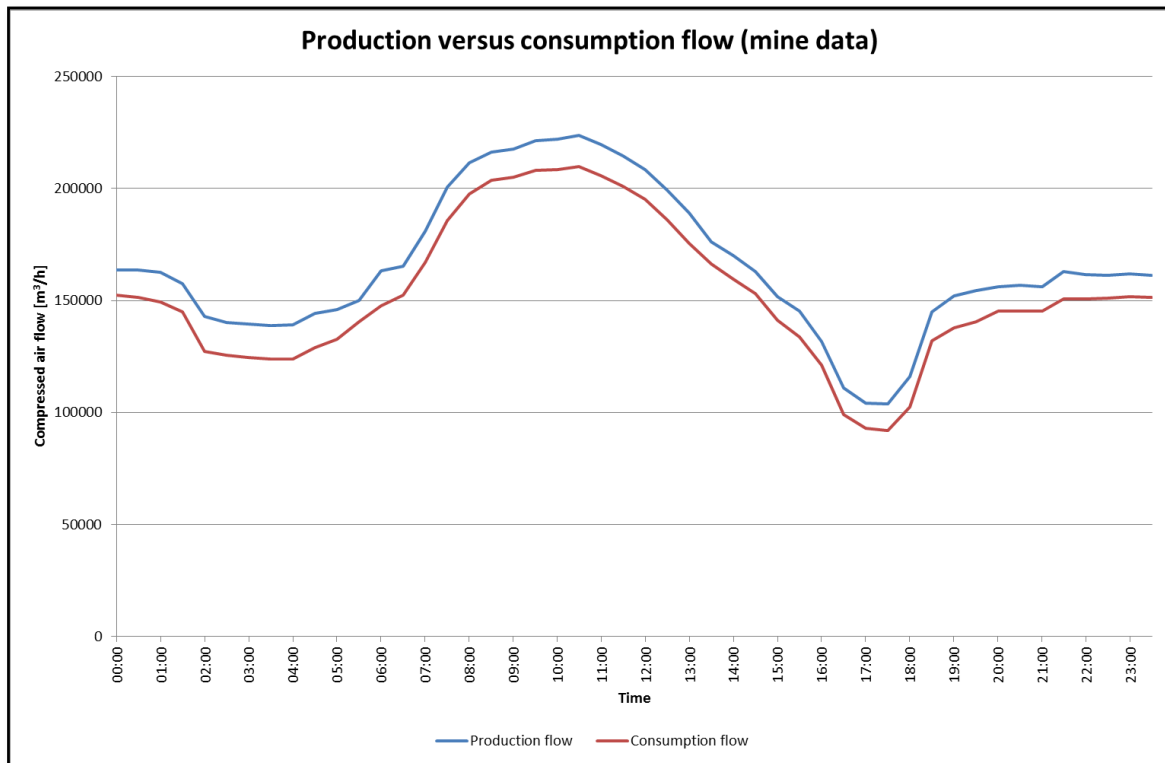


Figure 41: Production flow versus consumption flow (mine data)

The compressed air flows were logged by the mine and stored on an on-site server. There was a query tool as well as a trend tool installed on the server. The query tool was used to download data that was stored on the server in selectable time intervals. The trend tool could also be used to download the data, but a graph needed to be drawn before downloading could start. The trend tool was a quick and easy-to-use tool for viewing different properties of most components on the mine graphically.

Due to losses in the compressed air system, the compressors needed to supply more compressed air into the compressed air system than compressed air that were used by the shafts. The loss of compressed air was due to leaks in the pipeline, debris and water in the pipeline, as well as the total length of the pipeline. This meant that instead of attempting to match the supply of and demand for compressed air completely, the difference between it should rather have been kept as small as possible and as consistent as possible.

To verify the data, the data logged by DCS was compiled into a graph. This is a valid verification method because the data was logged on different servers using different methods of logging. The DCS data was available in real-time, while the data logged by the mine was only available as historical data. The graph compiled with DCS data can be seen in Figure 42.

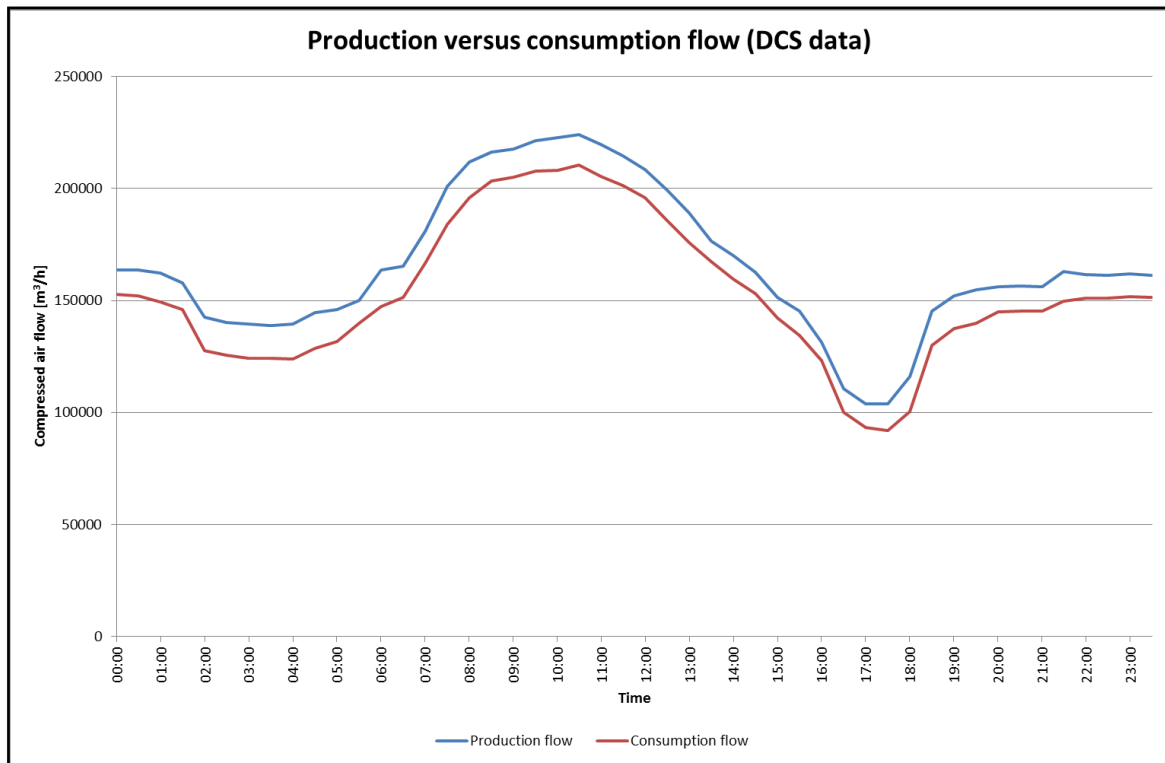


Figure 42: Production flow versus consumption flow (DCS data)

When comparing Figure 41 with Figure 42, it can be seen that the data logged by the mine and the data logged by DCS were the same. This was verification that any one of the sets of data could be used when calculating the efficiency of DCS in terms of matching the production flow with the consumption flow.

Automating the compressors formed part of the total study. The automation included installing pressure and flow transmitters. Because the flow transmitters at the compressors were only installed during the implementation of the project, there was no data available of the compressed air flow before project implementation. This meant that a comparison between production flow and consumption flow before DCS implementation could not be made.

By matching the supply and demand for compressed air, a more electrical energy efficient solution could be created at the mine. The demand for compressed air was dependent on the supply of compressed air, as shown in Figure 41 and Figure 42.

In systems where DCS does not control the compressed air supply, the supply can be a lot higher or lower than the demand. This will cause pressure fluctuations in the compressed air network. The compressed air network pressure can be seen in Figure 43. The red circles in Figure 43 shows where the fluctuations occur.

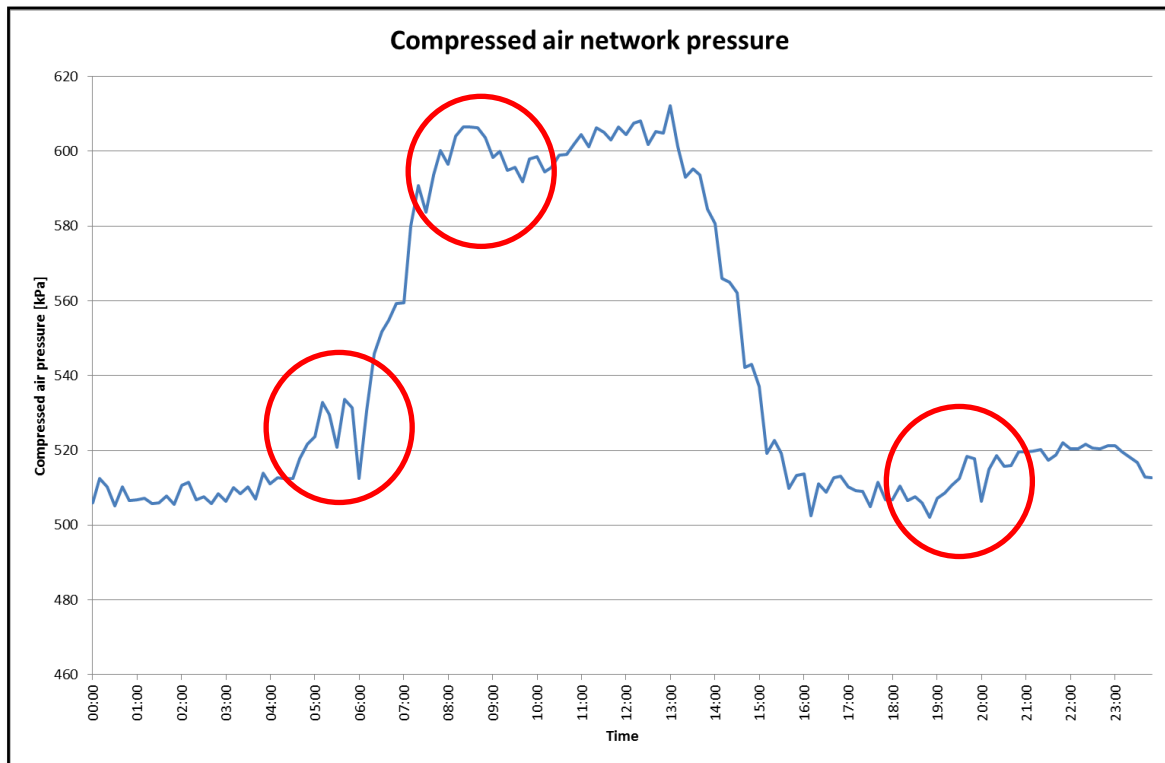


Figure 43: Compressed air network pressure

As shown in Figure 43, there were not many fluctuations in the network pressure after DCS was implemented. The only fluctuations that were recorded were around 06:00, 09:00 and 20:00.

The reason for the fluctuation at 06:00 was that most surface control valves were opened when the mine started producing at 06:00. This meant that most of the control valves were opened to allow more compressed air to flow to the shafts. The sudden increase in demand caused some fluctuations as seen in the first red circle in Figure 43. After the dip in system pressure, the compressors adjusted and raised the pressure up to the required pressure.

The second fluctuation was at around 09:00 as shown in the second red circle in Figure 43. The reason for the fluctuation was that the drilling shifts of the larger shafts started at 09:00, causing another increase in the demand for compressed air. After the fluctuation, the compressors adjusted again and the system pressure stabilised.

The third fluctuation, as shown in the third red circle in Figure 43, was caused at the end of the Eskom evening peak time. The control valves were optimised to allow the minimum required compressed air through to the end-users between 18:00 and 20:00. However, after 20:00 the control valves were opened slightly again. This caused the small fluctuation as seen in the third red circle in Figure 43.

The three fluctuations were small when taking the whole compressed air system, as well as the size of the system in terms of pipeline lengths and compressed air usage, into consideration. The largest fluctuation, which was the first one at 06:00, was only a drop of 20 kPa. This was small considering that the system operated at pressures of between 500 kPa and 620 kPa. To avoid the fluctuations, all the end-users pressure set points had to be optimised and ramping functions had to be added to all the set points.

3.4. Overall flow reduction

The performance assessment period of a project is a three-month period during which Eskom closely monitors the DSM project's performance. This is done to ensure that the contracted savings are achieved. After the performance assessment period, the company implementing the DSM project is relieved of its duties to achieve the contracted savings. The mine is then responsible to ensure that the savings achieved during the performance assessment period continues to be reached.

To be able to be as electrical energy efficient as possible, DCS had to lower the amount of compressed air produced by the compressors. This would enable the compressors to work less, which meant that some compressors could be switched off, resulting in power savings. The flow profiles for two months and the simulation results compared with the baseline flow profile can be seen in Figure 44.

The flow profiles for May 2013 and August 2013 in Figure 44 were compiled using the compressed air flow data for the shafts. The data was averaged and selected to include only weekday data.

The four flow profiles that are shown in Figure 44 are the baseline period flow profile, the simulation results flow profile, the May 2013 flow profile and the August 2013 flow profile. May 2013 was chosen because it formed part of the performance assessment period of the project. August 2013 was chosen to determine if DCS was still beneficial to the mine after the performance assessment period.

Only these specific months were chosen to simplify the graph and to show that DCS kept on performing as predicted. When the actual results in Figure 44 for May 2013 and August 2013 were compared with the simulation results, it was seen that the simulation was accurate.

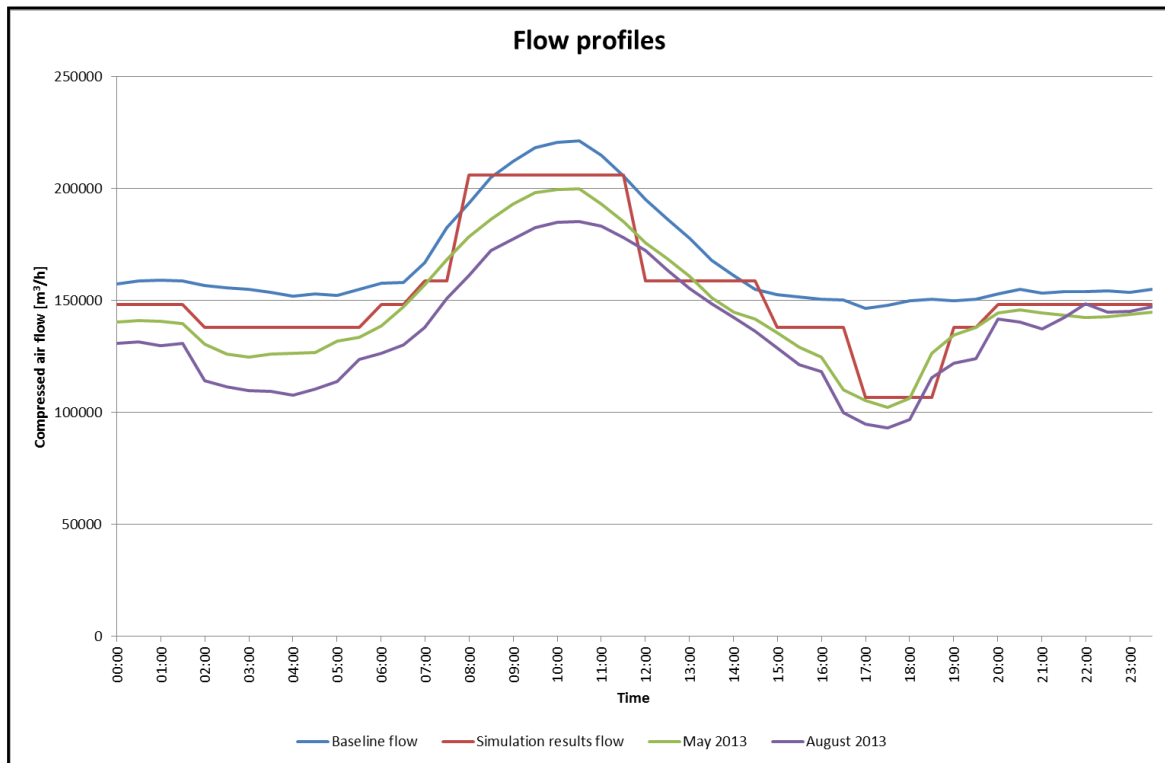


Figure 44: Flow profiles

The reduction of compressed air usage was done successfully as shown in Figure 44. The installation of the surface control valves at the end-users helped to lower the amount of compressed air used by the shafts during the mining off-peak periods of the day. DCS optimised the compressor delivery flow to fit the flow requirements of the shafts, which resulted in an overall reduction of compressed air usage.

3.5. Compressor scheduling

Another main task of DCS was to schedule compressors according to the required flow by the shafts. This resulted in better compressor control. Fewer compressors were running, which meant less electricity was used and less maintenance was required on the compressors. The compressors were also cycling less and more consistent control was achieved. Figure 45 shows the compressors that were running before DCS had been implemented.

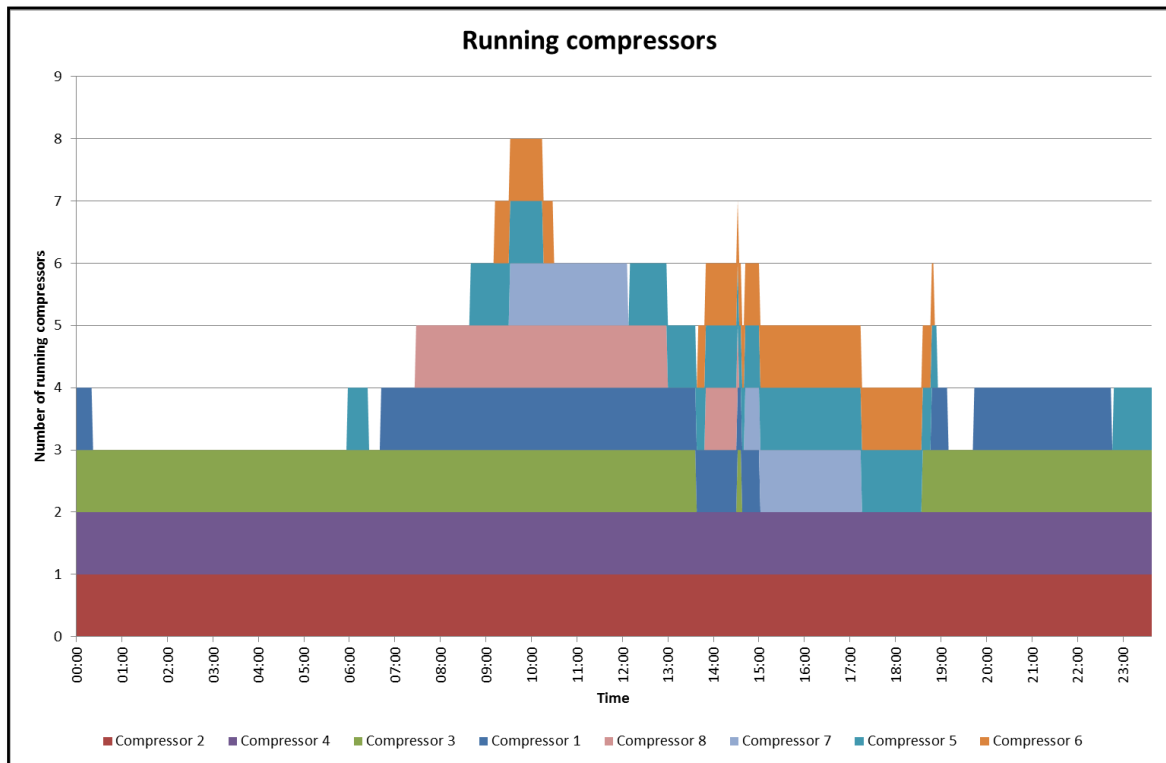


Figure 45: Running compressors before DCS implementation

Figure 46 shows the compressors that were running after DCS was implemented.

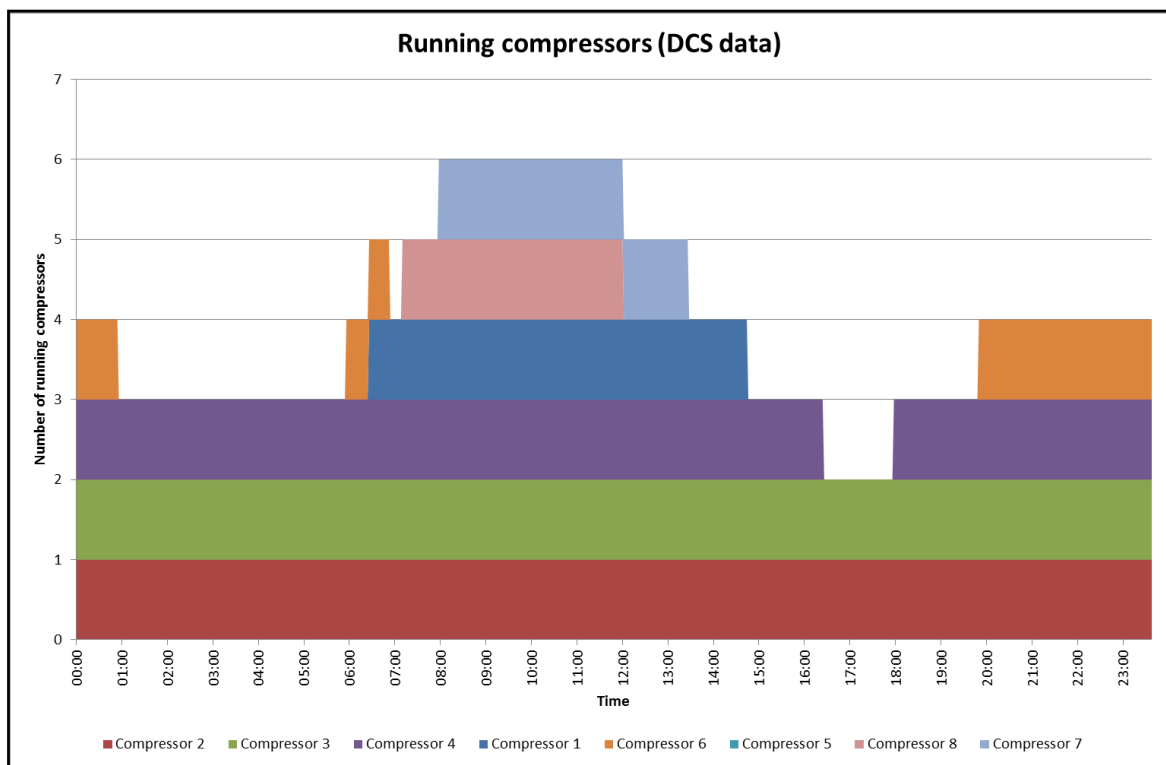


Figure 46: Running compressors after DCS implementation (DCS data)

It is evident from Figure 45 that the compressors were not running optimally. There was a high frequency in compressor cycling, which has potential negative long term effects for the compressor parts.. The mechanical parts of the compressors experienced more strain due to starting and stopping. Because of ineffective control, all eight of the compressors were also running at certain periods of the day.

The running statuses of the compressors were logged by DCS as well as by the mine. Duplicate sets of data were available, which meant that verification could be done. The data used to draw the graph in Figure 46 was logged by DCS. Figure 47 shows the number of running compressors as was logged by the mine and downloaded from the mine's servers using the query tool.

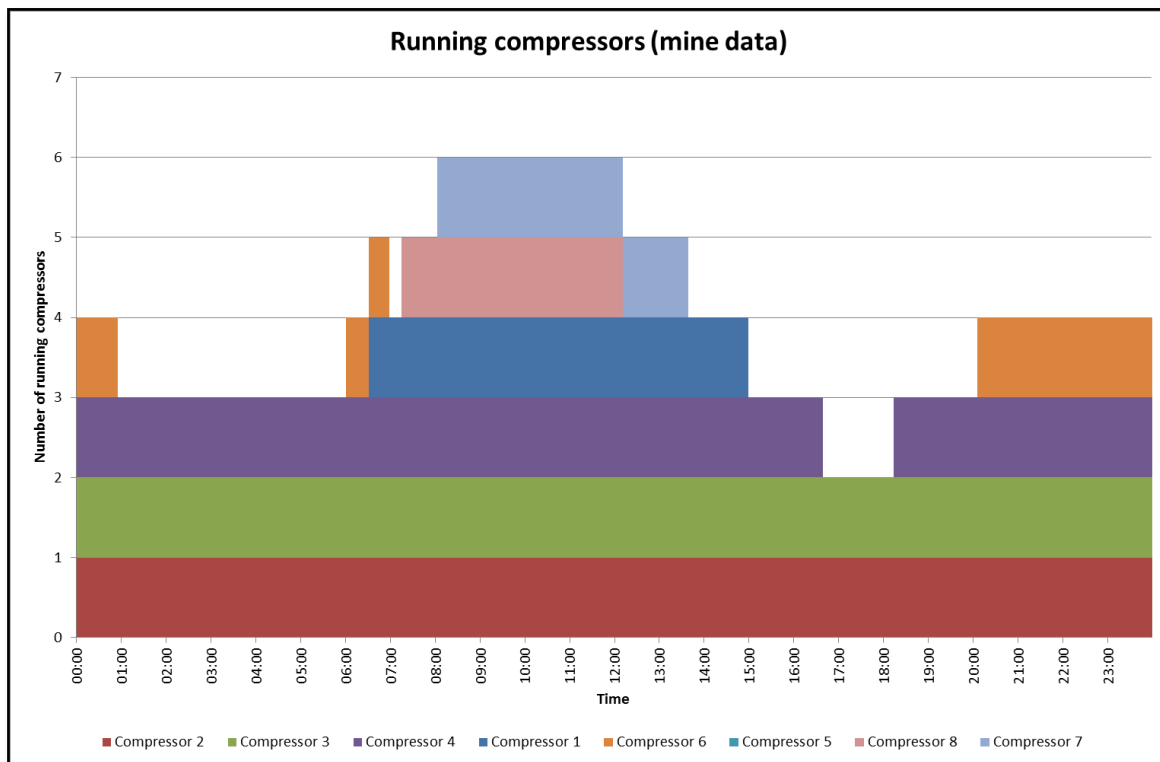


Figure 47: Running compressors after DCS implementation (mine data)

The data used to compile Figure 45, Figure 46 and Figure 47 were weekday averages for a month's data. A clear reduction in the running of compressors between 16:30 and 20:00 can be seen in Figure 46 and Figure 47.

Even though a compressor had to be started at 18:00, there were still less compressors running between 18:00 and 20:00 than before the DCS implementation. Most compressors could be switched off between 16:30 and 18:00, because that is when the blasting shift of the mine occurred. During the blasting shift, a small amount of compressed air was still

required. When the cleaning shift started at 18:00, there was an increase in the required compressed air again.

During the mine peak production periods, which stretched from 06:00 to 14:00, fewer compressors were run overall. Compressor cycling was also reduced during the mine peak production periods. Figure 46 and Figure 47 show that DCS improved compressor control, limiting the number of stops/starts per compressor. DCS also lowered the overall number of compressors used to supply compressed air to the end-users, which resulted in power savings.

When comparing Figure 46 and Figure 47, it can be seen that the data logged by the mine and the data logged by DCS were the same. This is a valid verification of data because the data sets were logged on different servers using different logging methods.

The DCS data was available in real-time, while the data logged by the mine was only available as historical data. The verification of the data showed that both the data logged by the mine and the data logged by DCS could be used to measure the efficiency of DCS in terms of compressor scheduling.

3.6. Electrical energy efficiency

Due to the funding structures at the time of project submission, this project was submitted to Eskom as an evening peak clipping project. A comparison of power profiles for May 2013, August 2013, the simulation results and the baseline power profile can be seen in Figure 48.

The two months that were compared with the baseline were chosen because May 2013 formed part of the Eskom performance assessment period, while August 2013 was after the performance assessment period. These two months were chosen to show that during performance assessment, as well as after performance assessment, DCS continued to show results as expected.

Figure 48 shows that the simulation was valid when compared with the actual power profiles for May 2013 and August 2013. There were time periods where the actual savings were more than the simulation suggested, for example, between 02:00 and 08:00. Only these specific months were chosen to simplify the graph and to show that DCS could keep on performing as predicted.

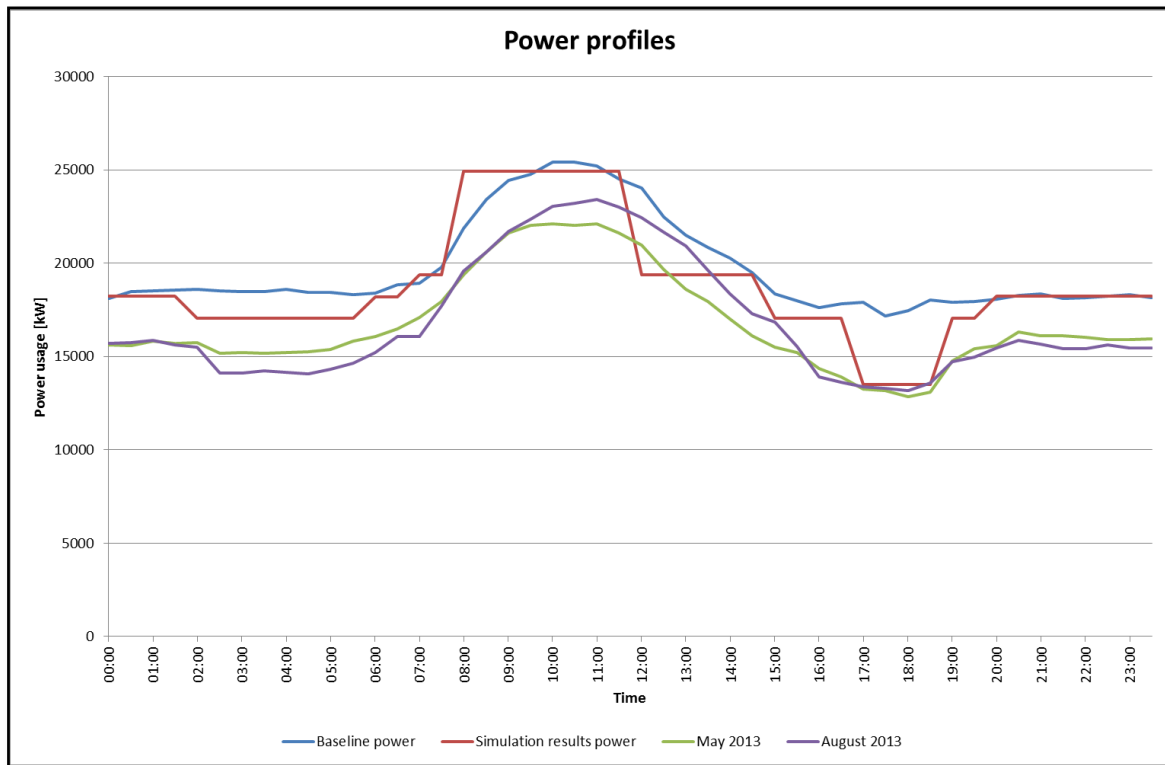


Figure 48: Electrical energy efficiency achieved by DCS

It is also clear from Figure 48 that electrical energy efficiency was achieved by DCS, because DCS not only focused on peak clipping, but attempted to optimise the whole day's power usage. There was also a clear peak clip for May 2013 and August 2013 when compared with the baseline.

Due to the production schedule of the mine, there would be more power savings for some periods during weekdays, and less for other periods. Each month's savings would furthermore vary due to the production changes for the various different months. Table 5 shows a summary of the power savings achieved by DCS.

Table 5: Summary of power savings achieved by DCS

	May 2013	August 2013
Average evening peak-time reduction [kW]	3 793	3 539
Evening peak clip (18:00–20:00) [kWh]	7 585	7 079
Average hourly power reduction [kW]	2 933	2 974
24-hour electrical energy efficiency [kWh]	70 402	71 379

The peak-time power reduction was done successfully in both May 2013 and August 2013, as shown in Table 5. The electrical energy efficiency was also successful, amounting to 70.402 MWh for May 2013 and 71.379 MWh for August 2013.

3.7. Validation of study

The purpose of the study was to determine if DCS could successfully be implemented on a mine's compressed air network. The simulation that was done to determine feasibility showed that an average evening peak clip of 2.197 MW would be possible. Chapter 2 listed several problems and solutions to the problems as was experienced during the implementation of DCS.

DCS successfully calculated compressor pressure set points according to the demand from the end-users and did this even more successfully than was predicted in the simulation. This was because during the simulation, average results were used and DCS could not actually influence the system. After DCS was installed, it could influence the system.

Furthermore, DCS successfully matched the production with the consumption of compressed air at the mine. By matching the production with the consumption flow, the overall usage of compressed air was lowered.

DCS successfully prioritised and scheduled the compressors, which led to improved overall compressor control. The reduction of compressed air usage, together with improved compressor control, resulted in electrical energy efficiency.

After the implementation of DCS, the power savings for the evening peak time were 3.793 MW for May 2013 and 3.539 MW for August 2013. This was much better than the simulated power saving of 2.197 MW. DCS proved more successful than expected after off-site tests were done.

The solution to the encountered problems, and their results together with the provided results, proved that DCS was implemented successfully and could be implemented successfully in the future as well.

3.8. Summary

Chapter 3 described the results after DCS was successfully implemented. Firstly, results were provided to show that DCS could calculate pressure set points for the compressors. DCS furthermore improved the matching of the production of compressed air with the consumption of compressed air in the compressed air system. In addition, the improved matching resulted in a reduced overall compressed air usage.

The chapter then showed how DCS improved the overall compressor scheduling. DCS calculated priorities for each of the compressors. Lower overall compressed air usage

combined with improved compressor scheduling, resulted in lower overall power usage. Instead of only performing an evening peak clip, total electrical energy efficiency was achieved.

Validation of the study was done at the end of Chapter 3 to show that the purpose of the study was fulfilled. The validation showed that DCS could be implemented on an actual mine.

Chapter 4:

Conclusion and recommendations

4.1. Conclusion

Chapter 1 firstly gave a short introduction and some background information to provide the reader with the required context to understand why there was a need for this study. The chapter then discussed compressed air networks, compressors and the control of both. Shortcomings of existing control methods were listed after retrieving all the required data from work done by other authors.

The shortcomings of the existing control methods showed that there was a need to develop a new dynamic air compressor selector system. The system was developed and tested off-site, but no actual implementation of the control system was done. As shown in this chapter, the implementation of DCS was the main purpose of the study.

In Chapter 2 the problems encountered during the implementation of DCS were provided. Solutions to the problems were provided, which would be helpful in future studies. In Chapter 3, several results were shown that were satisfactory. This meant that the purpose of the study was fulfilled.

DCS was able to accurately match the compressor pressure set point with the pressure set points of the shafts. This meant that all the shafts would receive their required pressures. This would ensure that power savings were achievable, while not influencing the production at any of the shafts.

By accurately matching the pressure set point of the compressors with the pressure set points of the shafts, the production flow and consumption flow of compressed air could also be matched. This was an important aspect of DCS because this meant that as little as possible compressed air would be wasted.

Together with accurately matching the production and consumption of compressed air, the overall usage of compressed air was also reduced by implementing DCS. By reducing the overall usage of compressed air, especially during the Eskom peak periods, less compressed air had to be generated, which resulted in fewer compressors being operated.

The compressor scheduling also proved successful. Less compressor cycling occurred meaning that compressors were started and stopped less frequently. In turn, this resulted in

less compressor maintenance. Apart from saving on power usage of the compressors, savings could also be achieved in terms of maintenance of the compressors.

The main purpose of DCS was to reduce the power usage of compressors. All of the above-mentioned results contributed to the reduction of power usage to generate compressed air. In Chapter 3 it was shown that besides peak clipping, as was initially the purpose of the project, DCS also achieved electrical energy efficiency. This meant that DCS actually performed better than expected.

After the implementation of DCS, the power savings were 3.793 MW for May 2013 and 3.539 MW for August 2013. This was much better than the simulated power saving of 2.197 MW. DCS proved more successful than expected after off-site tests were done.

In conclusion, when all of the above-mentioned results are taken into account, it can be seen that DCS could be implemented successfully. Through this study it was shown that the overall usage of compressed air could be reduced by implementing DCS, which would in turn reduce power usage. After DCS was implemented on an actual site, it was seen that it could achieve its intended purpose.

4.2. Recommendations for further study

DCS has only been implemented on a few sites so far, which meant that continuous development of DCS was necessary to accommodate the specific implementation sites. At the mine used for this case study, there are three compressed air rings, but only one compressed air ring was used as a case study for this dissertation.

Only one of the compressed air rings was used because there were no flow meters installed on the compressors on one of the compressed air rings. The amount of flow delivered by the compressors is crucial for the DCS compressor scheduling calculations. This meant that DCS could not be implemented before flow meters were installed.

The other compressed air ring was not used because a surface control valve still had to be installed. The surface control valves were also critical to the DCS calculations because the valves would be controlled at certain pressure set points. The pressure set points of the valves were used to calculate the compressor pressure set points. Thus, the implementation of DCS could not proceed before the control valve was not installed.

DCS must still be implemented on the other two compressed air rings at the mine that was used for this case study.

DCS will also have to be tested at other sites. Several improvements to DCS can still be made because DCS is still being enhanced continuously. Therefore, if DCS is implemented on another site and it requires more functionality, it can be added.

DCS can be enhanced not to limit DCS only to compressors. DCS could, for example, be used on large water distribution networks. Apart from the enhancements, DCS still needs other improvements. The characterisation of the compressors currently has to be done manually if no power data is available for the compressors. If the characterisation could be done automatically, a lot of time could be saved when setting up the system.

Furthermore, DCS currently does not take into account where the compressors are in the compressed air network relative to the shafts. This needs to be done in order to supply compressed air to the shafts by the compressor that will be the most efficient.

Reference list

- [1] The World Bank, "The World Bank – Data: South Africa," 2012. [Online]. Available: <http://data.worldbank.org/country/south-africa>. [Accessed 10 February 2014].
- [2] Republic of South Africa - Department of Energy, "Eskom - Tariffs and charges," Republic of South Africa - Department of Energy, 2004. [Online]. Available: http://www.energy.gov.za/files/electricity_frame.html. [Accessed 10 February 2014].
- [3] Eskom, "Eskom Tariffs and Charges," 2013. [Online]. Available: http://www.eskom.co.za/CustomerCare/TariffsAndCharges/Pages/Tariffs_And_Charges.aspx. [Accessed 10 February 2014].
- [4] Inflation.eu - Worldwide inflation data, "Historic inflation South Africa - CPI inflation," Inflation.eu, 2013. [Online]. Available: <http://www.inflation.eu/inflation-rates/south-africa/historic-inflation/cpi-inflation-south-africa.aspx>. [Accessed 28 07 2014].
- [5] E. Bonneville and A. Rialhe, "Demand side management for residential and commercial end-users," Efficiency & eco-design, p. 2, May 2006.
- [6] L. Padachi, G. D. Bolt, M. Kleingeld, J. H. Marais and E. H. Mathews, "Energy efficiency through the integration of compressed air supply control with air network demand control," in Industrial and Commercial Use of Energy, Cape Town, South Africa, 2009.
- [7] Eskom, Don't blow your profits: Improving the energy efficiency of industrial compressed air systems, Megawatt Park, Maxwell Drive, Sunninghill, Sandton, South Africa, 2009.
- [8] NCPI, "Electrical energy equipment: Compressors and compressed air systems," Energy Efficiency Guide for Industry in Asia, National Productivity Council of India, 2006.
- [9] S. Mousavi, S. Kara and B. Kornfeld, "Energy efficiency of compressed air systems," in CIRP Conference on Life Cycle Engineering, Trondheim, Norway, 2014.
- [10] Sustainability Victoria, Energy efficiency best practice guide - compressed air systems, Melbourne, Australia: Sustainability Victoria, 2009.
- [11] P. Radgen and E. Blaustein, Compressed air systems in the European Union: Energy, emissions, savings potential and policy actions, Stuttgart, Germany, 2001.

- [12] U.S. Department of Energy – Industrial Technologies Program, Tip Sheet #1, “Determine the cost of compressed air for your plant,” Energy Tips – Compressed Air, p. 1–2, 2000.
- [13] J. H. Marais, “An integrated approach to optimise energy consumption of mine compressed air systems,” PhD Thesis, Faculty of Engineering, North-West University, Potchefstroom, South Africa, 2012.
- [14] P. A. de Villiers, R. P. Coetzee and L. J. Grobler, “Measurement and verification methodology for industrial compressed air load management on a mine,” in *Industrial & Commercial Use of Energy*, Cape Town, South Africa, 2009.
- [15] H. Naser, “Energy savings through the automatic control of underground compressed air demand,” M.Eng. Dissertation, Faculty of Engineering, North-West University, Potchefstroom, South Africa, 2008.
- [16] J. W. Lodewyckx, “Investigating the effects of different DSM strategies on a compressed air ring,” M.Eng. Dissertation, Faculty of Engineering, North-West University, Potchefstroom, South Africa, 2007.
- [17] A. J. M. van Tonder, “Sustaining compressed air DSM project savings using an air leakage management system,” M.Eng. Dissertation, Faculty of Engineering, North-West University, Potchefstroom, South Africa, 2010.
- [18] B. L. Capehart, “Compressed air systems,” in *Encyclopedia of Energy Engineering and Technology: Volumes 2–3*, Boca Raton, FL, CRC Press, 2007, p. 236–245.
- [19] R. Joubert, “Cost and time effective DSM on mine compressed air systems,” M.Eng. Dissertation, Faculty of Engineering, North-West University, Potchefstroom, South Africa, 2010.
- [20] R. Joubert and L. Liebenberg, “Cost and efficient DSM on mine compressed air systems,” in *Industrial & Commercial Use of Energy*, Cape Town, South Africa, 2010.
- [21] J. Venter, “Development of a dynamic centrifugal compressor selector for large compressed air networks in the mining industry,” M.Eng. Dissertation, Faculty of Engineering, North West-University, Potchefstroom, South Africa, 2012.
- [22] G. D. Bolt, J. Venter and J. F. van Rensburg, “Dynamic compressor selection,” in *Industrial & Commercial Use of Energy*, Cape Town, South Africa, 2012.

- [23] WIKA Instruments (Pty.) Ltd., "Differential pressure transmitter with diaphragm, pressure rating PN 40/100/250 bar," April 2006. [Online]. Available: http://www.wika.co.za/upload/DS_PE8172_GB_1654.pdf. [Accessed 8 April 2014].
- [24] H. van Ormer, D. van Ormer and S. van Ormer, "The secret is in the pipe," Plant Services, p. 57–59, 2005.
- [25] F. W. Schroeder, "Energy efficiency opportunities in mine compressed air systems," M.Eng. Dissertation, Faculty of Engineering, North-West University, Potchefstroom, South Africa, 2009.
- [26] R. Marshall, "Finding and fixing leaks," Compressed Air Best Practices, p. 30–34, May/June 2010.
- [27] U.S. Department of Energy – Industrial Technologies Program, Tip Sheet #3, "Minimize compressed air leaks," Energy Tips – Compressed Air, p. 1–2, 2004.
- [28] R. Saidur, N. A. Rahim and M. Hasanuzzaman, "A review on compressed air energy use and energy savings," Renewable and Sustainable Energy Reviews, vol. 14, no. 4, p. 1135–1153, 2009.
- [29] D. Kaya, P. Phelan, D. Chau and H. Ibrahim Sarac, "Energy conservation in compressed air systems," International Journal of Energy Research, vol. 26, no. 9, p. 837–849, 2002.
- [30] Y. A. Cengel and M. A. Boles, Thermodynamics: An engineering approach, 5th ed., Boston, MA: McGraw-Hill Higher Education, 2006, pp. 392–395.
- [31] A. Pregelj and M. Mozetic, "Leak detection methods and defining the sizes of leaks," Application of Contemporary Nondestructive Testing in Engineering, vol. 4, no. 2, p. 3–8, 1999.
- [32] H. G. Brand, "An integrated sustainability framework for environmental impact reduction in the gold mining industry," PhD Thesis, Faculty of Engineering, North-West University, Potchefstroom, South Africa, 2014.
- [33] H. P. R. Joubert, G. Bolt and J. F. van Rensburg, "Energy savings on mining compressed air networks through dedicated process plant compressors," in Industrial & Commercial Use of Energy, Cape Town, South Africa, 2012.
- [34] R. Marshall and B. Scales, "Compressed air controls," Compressed Air Best Practices, p. 38–43, November/December 2010.

- [35] M. R. Muller and S. C. Schultz, "Wise rules for industrial efficiency: A tool kit for estimating energy savings and greenhouse gas emissions reductions," *Climate Wise*, p. 22–26, July 1998.
- [36] U.S. Department of Energy – Industrial Technologies Program, Tip Sheet #4, "Analyzing your compressed air system," *Energy Tips – Compressed Air*, p. 1–2, 2004.
- [37] U.S. Department of Energy – Industrial Technologies Program, Tip Sheet #14, "Effect of intake on compressor performance," *Energy Tips – Compressed Air*, p. 1–2, 2004.
- [38] J. T. Gravdahl, O. Egeland and S. O. Vatland, "Drive torque actuation in active surge control of centrifugal compressors," *Automatica*, vol. 38, no. 11, p. 1881–1893, 2002.
- [39] Emerson Process Management, "Compressor anti-surge control application: DeltaV," Emerson Process Management, 2007.
- [40] R. Kurz and R. C. White, "Surge prevention in centrifugal compressor systems," *GM Journal*, vol. Third Quarter, p. 1–10, 2007.
- [41] S. Marelli, C. Carraro, G. Marmorato, G. Zamboni and M. Capobianco, "Experimental analysis on the performance of a turbocharger compressor in the unstable operating region and close to the surge limit," *Experimental Thermal and Fluid Science*, vol. 53 (2014), p. 154–160, 2014.
- [42] J. Ghislain, "Squeezing money out of thin air," *Plant Services*, p. 38–40, 2005.
- [43] U.S. Department of Energy – Industrial Technologies Program, Tip Sheet #7, "Compressed air system control strategies," *Energy Tips – Compressed Air*, p. 1–2, 2004.
- [44] Oregon State University, "AIRMaster compressed air system audit and analysis software version 1.4," *Analysis methodology manual for AIRMaster*, p. 32, 1997.
- [45] W. Booyesen, "Reducing energy consumption on RSA mines through optimised compressor control," M.Eng. Dissertation, Faculty of Engineering, North-West University, Potchefstroom, South Africa, 2010.
- [46] J. de la Vergne, in *Hard Rock Miner's Handbook*, Ontario, Canada, McIntosh Engineering Limited, 2003, p. 180.
- [47] A. Garbers, M. Kleingeld and J. F. van Rensburg, "Energy savings through auto compression and the air distribution control of a deep level gold mine," in *Industrial & Commercial Use of Energy*, Cape Town, South Africa, 2010.

- [48] C. Galitsky and E. Worrell, "Energy efficiency improvement and cost saving opportunities for the vehicle assembly industry," An ENERGY STAR® Guide for Energy and Plant Managers, LBNL-50939, p. 22–30, 2008.
- [49] L. Liebenberg, D. Velleman and W. Booysen, "A simple demand-side management solution for a typical compressed air system at a South African gold mine," *Journal of Energy in Southern Africa*, vol. 23, no. 2, p. 20–29, 2012.
- [50] W. Booysen, M. Kleingeld and J. F. van Rensburg, "Optimising compressor control strategies for maximum energy savings," *Energize*, p. 65–68, 2009.
- [51] D. E. Smith, "Eliminating pressure problems in compressed air systems," *Compressed Air Best Practices*, p. 32–36, April 2012.
- [52] L. Berkeley, *Improving compressed air system performance: A sourcebook for industry*, 2nd ed., Washington, DC: US Department of Energy, 2004.
- [53] S. W. van Heerden, "Developing a dynamic control system for mine compressed air networks," M.Eng. Dissertation, Faculty of Engineering, North-West University, Potchefstroom, South Africa, 2013.
- [54] G. D. Bolt, K. van Tonder and S. W. van Heerden, "Practical challenges faced with implementing a dynamic compressor selection program," in *Industrial & Commercial Use of Energy*, Cape Town, South Africa, 2013.
- [55] J. N. du Plessis and R. Pelzer, "Development of an intelligent control system for mine compressor systems," in *Industrial & Commercial Use of Energy*, Cape Town, South Africa, 2011.
- [56] Veris, Inc., "Models: Regular Models – V150," June 2008. [Online]. Available: http://www.veris-inc.com/vera_models_regular.asp. [Accessed 7 January 2014].