The cost-effectiveness of comprehensive system control on a mine compressed air network

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Abstract

Title: The cost-effectiveness of comprehensive system control on a mine compressed air network

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Compressed air leakage accounts for up to 42% of electrical energy loss on a typical mine compressed air system. By using underground control valves it is possible to reduce the amount of air leakage. Underground valve control was successfully implemented in a South African mine. The project implementation and achieved results are documented in this study.

The implementation of underground control valves initially requires a large capital investment. In this study the electrical and financial savings realised by underground valve control and surface valve control were calculated. The payback periods for each control strategy were determined and compared.

It was determined that underground valve control can realise up to 40% higher electrical savings than surface control. Depending on the size of the mine and due to the large initial investment, the payback period for an underground valve control system can be up to six times longer than that of a surface control system.

Key words: underground valve control, compressed air, demand side management

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Table of contents

List of figures

List of tables

List of abbreviations

BRPM	Bafokeng Rasimone Platinum Mine
3CPFS	Three-chamber pipe feeder system
C_v	Flow coefficient
DSM	Demand Side Management
EE	Energy efficiency
EES	Engineering equation solver
ESCO	Energy servicing company
GPM	Gallons per minute
I/O	Input/output
IGV	Inlet guide vane
ISA	Instrument society of America
M&V	Measurement and verification
OPC	Object linking and embedding for process control
PCP	Power conservation programme
PI	Proportional and integral control
PID	Proportional, integral and derivative control
PLC	Programmable logic controller
PSI	Pounds per square inch
PV	Process variable
REMS-OAN	Real-time management system for the optimisation of air networks
SCADA	Supervisory control and data aquisition
UPS	Uninterruptable power supply
USEPA	United States environmental protection agency

1 Introduction

1.1 Preamble

In 2008 South Africa experienced frequent and irregular load shedding due to the excessive demand for electrical energy [1]. In February 2008 the state energy provider, Eskom, implemented a load shedding strategy in order to prevent a total collapse of the national electricity grid [2]. During these periods of load shedding electricity supply to the industrial and mining sector was decreased by 10%. Long-term load shedding, however, may have adverse effects such as decreased production and a potential loss of jobs [3].

From 2006 to 2007 the energy demand in South Africa increased by 4.3% and from 2007 to 2008 the peak demand grew by 4.9% or 1 706 MW [2]. The total energy generated by Eskom in 2008 was 239 109 GWh while the total electricity sales amounted to 224 366 GWh. In 2009/10 the forecasted energy margin was between 6 and 7% with an increase to above 10% predicted by 2014, as shown in Figure 1 [3]. Eskom intends to achieve a minimum target reserve margin of 15% by 2014 [4].

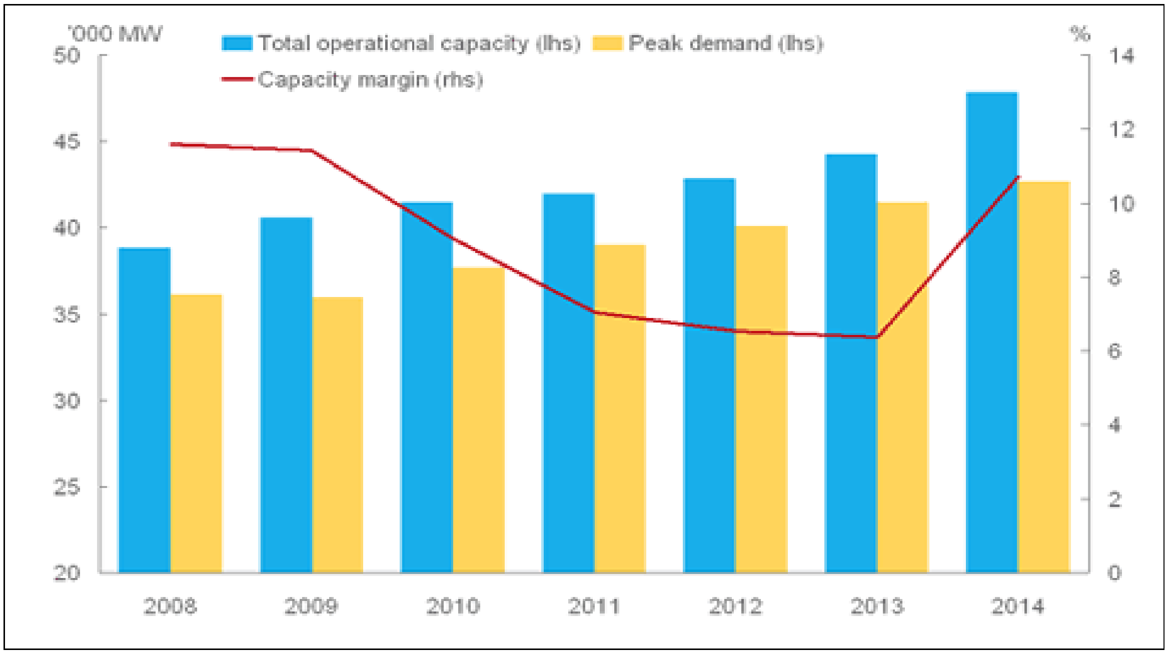

Figure 1: Reserve supply margin in South Africa [3]

Prominent electricity users are the mining and industrial sectors. Figure 2 provides a breakdown of electricity sales in 2010. In response to the low reserve margin during 2008, Eskom initiated supply and demand side management (DSM) initiatives in these sectors with immediate effect.

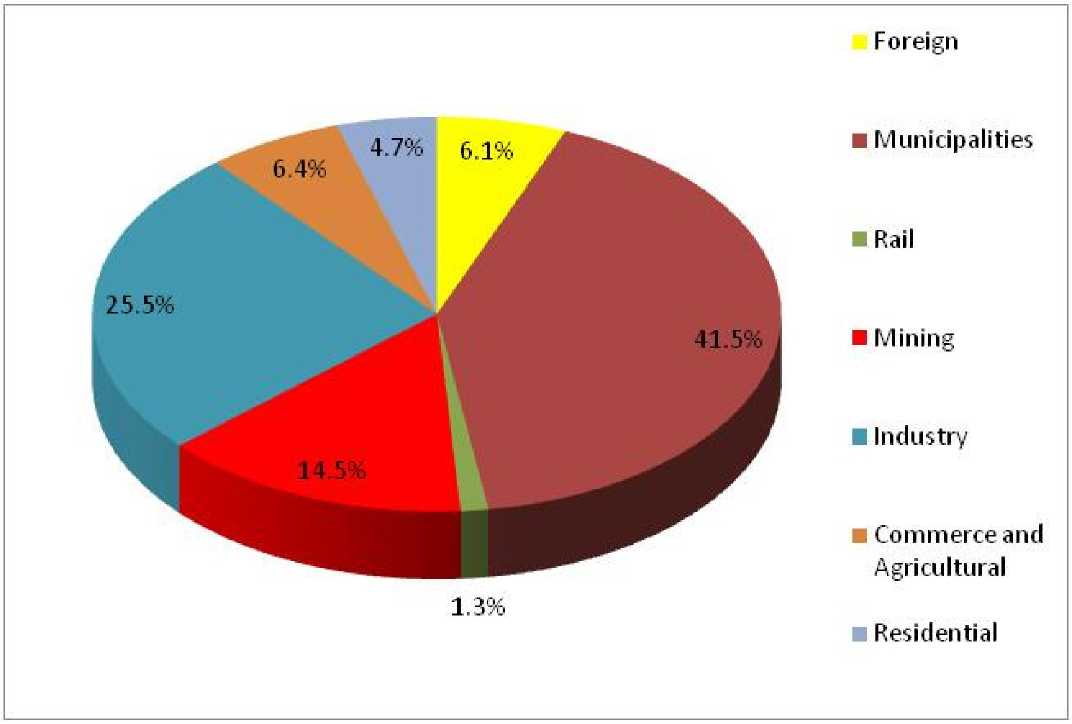

Figure 2: Electricity sales in South Africa in 2010 [5]

Increases on the supply side would require expansion of the existing energy capacity by building new power stations or recommissioning mothballed power stations. This process will take several years to complete, whereas DSM can provide an almost immediate effect in reducing the demand on the power grid. DSM also holds other advantages such as [6]:

- Reduced energy costs for customers
- Stimulation of economic development
- Long-term job creation due to innovation and new technologies
- Reduced air pollution through reduced emissions
- Preservation of natural resources such as oil, coal and gas for use in the petroleum industry

In 2010 DSM interventions resulted in an average load reduction of 372 MW in South Africa [5].

1.2 South African DSM initiatives

Although DSM in South Africa was only initiated in 1995, demand side management had already been successfully implemented throughout the world in order to optimise energy usage. Studies conducted in Nepal over a period of 20 years concluded that through the use of power factor correction and energy efficient lighting, DSM opportunities were possible and financially viable [7].

Another study conducted on the central grid of Oman determined that DSM is beneficial for the consumer and the utility. The payback period for the implemented projects was between 4 and 12 years, with a peak average electrical load reduction of between 372 MW and 596 MW [8].

In South Africa Eskom implemented DSM projects to achieve two key objectives [2]:

- To increase the reserve margin so that both scheduled and unplanned maintenance can be carried out
- To reduce energy consumption

According to the 2010 annual Eskom report, the mining industry uses 14.5% of the total power supplied in South Africa [5]. Many oppurtunities have since been created for independent energy servicing companies (ESCOs) to obtain contracts from Eskom to implement DSM projects. Significant peak electrical power reductions and energy savings were realised through the implementation of load shifting, peak clipping and energy efficiency projects on South African mines.

Eskom also proposed a power conservation programme (PCP) which consisted of [2]:

- Quota allocations for various sectors
- Penalties and cut-offs for offenders
- Incentive schemes for smaller consumers

Solar water heating and an efficient lighting programme was also introduced [2]. These initiatives were mainly aimed at use in the residential and industrial sectors.

As the name implies, load shifting projects shift power usage by mines out of, in particular, the peak periods, while peak clipping consists of reducing the energy usage of mines during peak periods. Energy efficiency projects will reduce the overall energy consumption at all times.

Load shifting strategies, which rely heavily on storage facilities, are mainly implemented on mine pumping systems. A mine water system consists of large storage dams where water can be stored during peak periods and pumped during off-peak periods. However, load shifting projects do not reduce total energy consumption. The same amount of water must still be pumped from the mine, but if sufficient storage capacity is available, pumping can be done during off-peak periods.

Peak clipping projects are mainly implemented on the compressed air systems of the mining sector by reducing the compressed air during the peak energy periods. Therefore, some energy efficiency is achieved with peak clipping during peak periods.

Energy efficiency projects have been successfully implemented on compressed air and water pumping systems. The goal of an energy efficiency project is to reduce energy usage throughout the day. However, these projects often require complete system control to realise any electricity savings.

Compressed air cannot be stored easily as in the case with water storage dams. However, experiments have been conducted by using large compressed air pressure containers built into underground caverns to store compressed air [9]. However, these projects have been abandoned due to high volumes of compressed air required and safety concerns [10]. Peak clipping and energy efficiency projects are much more feasible on compressed air systems where selective initiatives can be implemented that will result in a decrease in supply pressure.

1.3 Achieving electrical savings through system control

1.3.1 Compressor control as a means to reduce energy consumption

The implementation of energy efficiency projects requires an investigation into complete system control at the mine. Previous energy effiency projects on compressed air systems reduced the energy usage of the operating compressors. This was done by decreasing the demand for compressed air and/or air pressure required by end-users.

Large capacity centrifugal compressors are widely used in the mining industry and are managed and controlled in different ways including [11]:

- Start/stop control
- On/off-load control
- Inlet valve modulation control
- Variable speed drives

Compressed air usage accounts for about 15% to 20% of the total energy usage of a mine. Electricity costs make up the largest portion of compressor life cycle costs, at 78% of the total cost [12]. For an energy efficiency project to be successfull, these control functions must be implemented on the operating compressors. When reduced supply pressure or airflow is required, the compressors are managed in order to adapt to the new pressure requirement. This consequently leads to lower energy consumption and electricity savings. Figure 3 gives a breakdown of typical compressor life cycle costs.

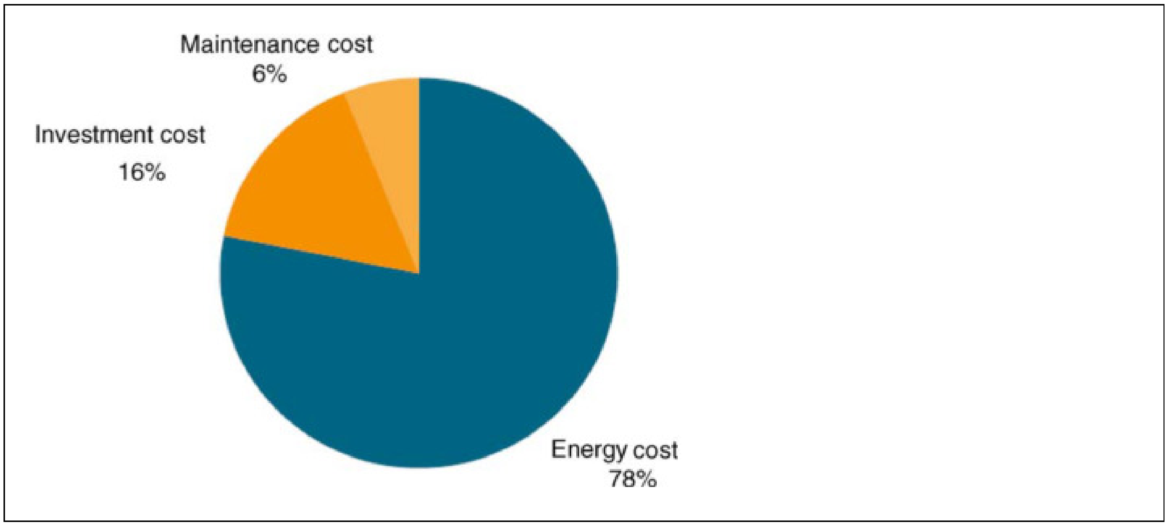

Figure 3: Total life cycle cost of a typical compressor [12]

Therefore, by implementing the appropriate control measures, these electricity costs can be reduced. It has been shown that on/off-load control can reduce the compressors power usage to between 20% and 60% of the rated power [11]. Inlet mass airflow control causes compressors to operate at between 65% rated power at no load and 115% rated power at full load [11]. Therefore, if a compressor is not required, but cannot be switched off, it can still operate below 100% power with the use of inlet flow control.

Energy reduction due to a reduction in pressure, however, does not necessarily have a large impact on the efficiency of compressed air usage. If, for example, large air leakages are present in the system, the pressure within the compressed air system may already be so low that the pressure cannot be reduced any further. It has been determined that about 42% of energy savings potential within a compressed air system can be realised by reducing leakages [12]. Figure 4 illustrates the potential savings that can be realised through different means.

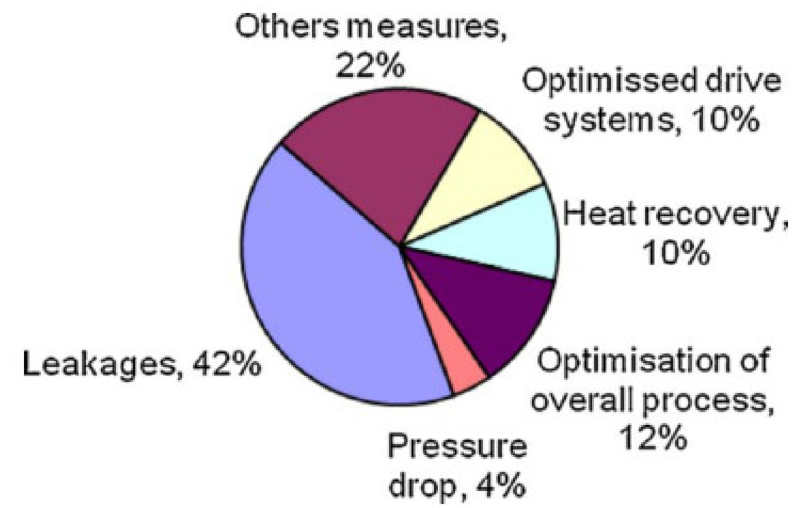

Figure 4: Potential energy savings in compressed air systems [12]

Furthermore, at many South African mines it is not possible to realise sufficient energy savings simply by decreasing supply pressure. This is mainly as a result of the following:

1. Difficulty in reducing compressed air usage at the mine throughout the day because of different consumption schedules. This can be due to the fact that the specific mine has more than one shaft with different working schedules.

2. Difficulty in predicting production periods at the mine. It is important not to reduce mining production schedules when implementing energy efficiency initiatives.

It is therefore clear that electrical energy savings on a compressed air system cannot always be realised without the implementation of some means of demand side control.

1.3.2 Using control valves on an underground mine network

It is often necessary to implement a demand side control system in order to reduce unnecessary wastage of air. This is done by installing control valves at each shaft or underground mining levels and controlling the airflow to the respective area. By installing variable opening control valves, the flow of air can be accurately matched to the required demand.

A decrease in airflow demand will cause the system pressure, upstream of the valve, to increase. This will require the compressors to reduce the airflow output. This is normally accomplished by appropriate inlet vane control [13]. Airflow through leaks in the supply lines will also be reduced if the system pressure is reduced [13].

The United States Enviromental Protection Agency (USEPA) conducted a study on industrial plants within the United States. This study concluded that the reduction of compressor pressure, reduction of compressed air use and the repair of leaks can provide a total energy savings of about 2% of total facility energy use [14]. Figure 5 shows the different energy efficiency oppurtunities investigated by the USEPA and the average payback period for each.

In terms of compressed air energy usage, a reduction in compressor supply pressure of 15 kPa at a pressure of 680 kPa would yield a 1% saving in compressor energy use [14].

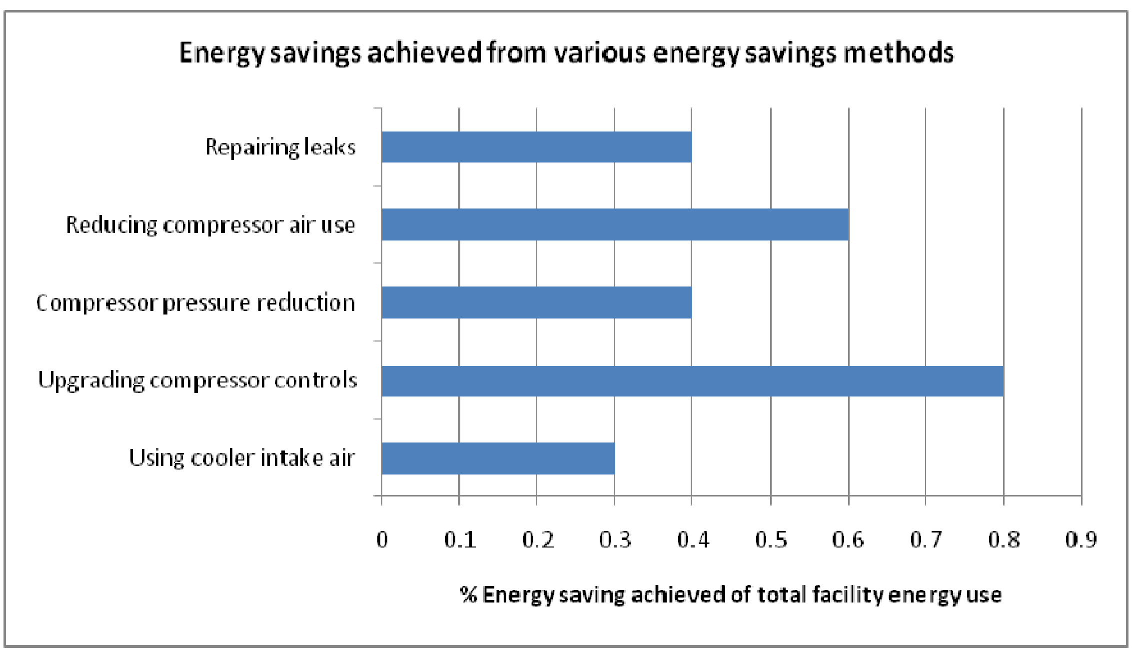

Figure 5: Energy savings rate from various energy saving methods [14]

1.4 Objectives of this study

The objectives of this study are as follows:

- Simulate, validate and verify the energy savings through the use of pressure control valves in the underground mining sections of a typical mine.
- Determine the payback period of each control system.
- Compare the different simulations and determine which implementation is the most effective in terms of energy savings, capital cost for infrastructure and payback periods.

1.5 Overview of the document

In Chapter 2 the fundamental control principles and control strategies implemented on compressed air systems at South African mines are discussed. Two DSM strategies with examples of implementation are discussed. Compressor control concepts and principles are also discussed to determine what limitations must be considered when attempting control of a typical compressed air system. Equipment considerations and limitations as well as other contributing factors that may influence system control are also discussed.

In Chapter 3 the simulation model for predicting electricity savings after implementing control on a system had been developed and validated, is discussed. Three different physical control layouts are simulated and electrical energy savings results obtained.

In Chapter 4 the simulations are verified using historical system data obtained from the mine. The cost required for the control infrastructure is calculated and a payback period analysis is done for each project. Different circumstances and procedures are compared to determine which option would provide the most cost savings and shortest payback period. A summary of the results and a discussion of the control system and recommendations to improve the system are provided in Chapter 5.

2 Control strategies and principles

2.1 Introduction

In this chapter, two DSM programmes frequently implemented on compressed air systems with case studies of such projects are discussed. These case studies are critically evaluated in terms of supply side and demand side management.

Fundamental control theory is discussed with reference to the compressed air system. Control philosophies and how they can be implemented on mine compressed air systems are discussed. The limitations of a typical compressed air system are presented and discussed.

Equipment considerations and limitations are discussed and it is determined which equipment will provide the necessary control in the most efficient manner. Other factors, besides the equipment itself, that influence the control of the system, are also discussed.

2.2 Peak clipping and energy efficiency

Peak clipping and energy efficiency projects are the preferred methods applied to compressor systems instead of load shifting projects. Load shifting is usually not possible on compressed air systems because of the difficulty and dangers involved in storing compressed air at high pressure in accumulators. Although experiments have been conducted in compressed air storage in underground cavern systems, it has been found to be largely impractical. Peak clipping and energy efficiency are therefore more applicable to compressed air systems. Both these strategies have advantages to the client as well as the utility.

2.2.1 Peak clipping

Peak clipping strategies are aimed at reducing energy consumption, primarily during peak electricity usage periods [15]. Energy consumption during off-peak periods remains unchanged. On a compressor system this is done by reducing air supply during peak periods.

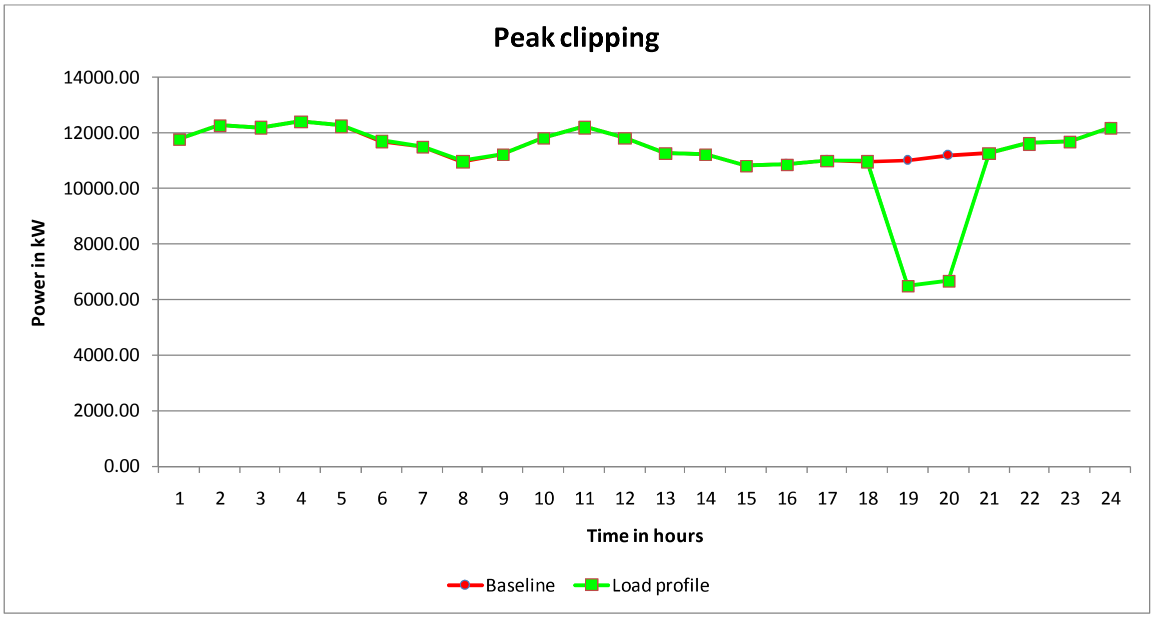

Figure 6: Peak clipping [16]

The final result of peak clipping is increased financial savings due to the fact that less electricity is consumed in the expensive tariff periods. However, overall production may be reduced.

2.2.2 Energy efficiency

The goal of an energy efficiency DSM strategy is to reduce the overall power consumption throughout the day. On a compressor system this can be accomplished if the supply pressure of the compressors can be permanently reduced throughout the entire day.

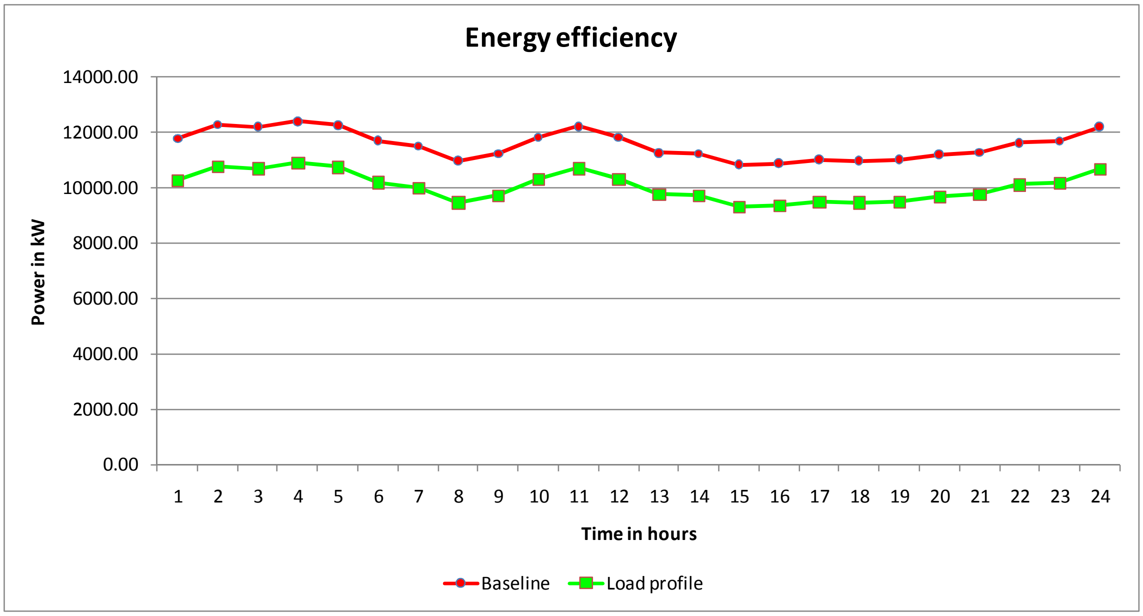

Figure 7: Energy efficiency [16]

Due to the fact that mine production schedules need to be taken into account, accurate and detailed planning must be done to ensure that mining activities are not interrupted. Typically, a mine shaft operates a morning, afternoon and night shift. During each of these shifts different activities take place. Figure 8 shows the working schedule of a typical shaft.

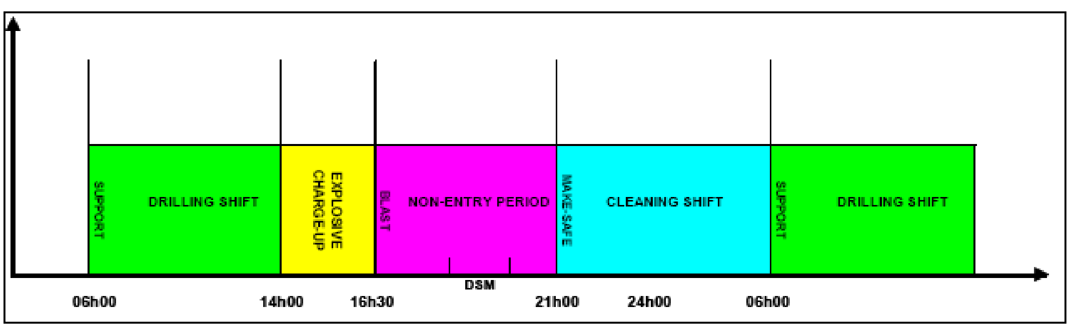

Figure 8: Typical mine shift schedule [17]

Mining activities that require high air pressure occur during the drilling and cleaning shifts. However, during non-entry shifts, pressures can be significantly reduced because no mining activities taking place during this time.

2.2.3 Case studies in peak clipping and energy efficiency

Peak clipping and energy efficiency (EE) projects have been successfully implemented at various mines in South Africa.

Anglo Gold Ashanti started installing compact fluorescent light bulbs instead of incandescent light bulbs, as part of its EE program. Numerous other projects, including solar heating, high-tech lighting systems and energy efficient air conditioning, among others, were also implemented. A total of R4 million has already been invested in these projects [18]. A three-chamber pipe feeder system (3CPFS) will also be installed at Moab mine. This project is expected to realise a power saving of 9 MW, with an annual financial saving of R12 million [18].

At Mponeng mine, several energy efficiency projects have been commissioned. Three underground turbines have been commissioned to generate electricity by converting the total pressure energy of the water sent down the mine to kinetic energy. Use of these underground turbines resulted in a 2.3% reduction in the mines total energy consumption [19].

Another project implemented at Mponeng is the use of ice plants and ice storage dams. It is expected that this system will realise an average load reduction of 10 MW during peak times. This will result in an annual saving of R2 million, which is about 2% of the mines' annual consumption [19].

Anglo Platinum also commenced various energy efficiency programmes. As of January 2009, efforts to reduce primary and secondary air leakages have been undertaken [20]. Investigations were also done on the main and auxiliary ventilation fans. Installations of electronic guide vane control on the main fans are being completed in order to clip peak energy usage. An improved aerodynamic fan design, which is expected to reduce energy consumption, is also being investigated [20].

2.3 Control theory and philosophy

2.3.1 Introduction

In order to achieve electricity savings through complete system control, a solid control philosophy needs to be in place. The control capabilities of the compressors and valves must be correctly identified and understood. In this way, control functions implemented on the equipment can be fully utilised. Equipment limitations and restrictions must be taken into account to ensure that equipment is not damaged during the control process.

Appropriate fail-safe procedures and controls must be put in place to reduce the risk of financial loss and human injury. External factors that may influence the control system, such as environmental hazards, need to be taken into account. A full risk assessment of the control system must be determined and suitable procedures implemented.

2.3.2 Fundamentals of control theory and Proportional, Integral and Derivative (PID) control

A control system consists of at least three basic components, namely:

- A control device (such as a control valve)
- A sensor
- A controller

These components are used to control a process by manipulating an input variable to achieve a desired output. Figure 9 illustrates an elementary control system used to control the temperature in the living room of a house.

The controller communicates an output variable to the control device, which then adjusts accordingly. A sensor measures the output variable and provides feedback to the controller which is then compared to a predetermined set point. If the difference between the set point and the output is not zero, the controller will signal the control device to change the output. This iteration is continued until the output is equal to the set-point, within the accuracy limits of the system.

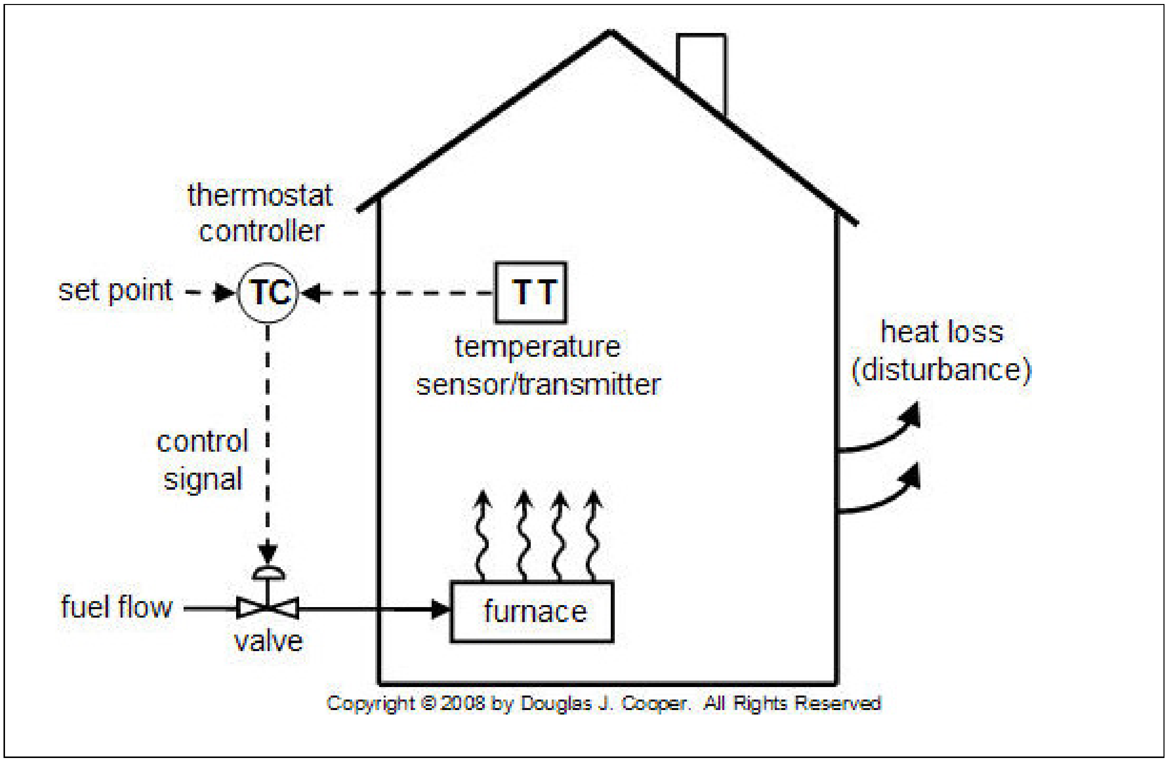

Figure 9: Example of a temperature control system [21]

The same principles are applied when control valves are used to facilitate control on a compressed air system where the process variable (PV) may be flow or pressure. The control device used to regulate the PV is usually an inlet throttle valve that can be adjusted to control the inlet mass airflow. In some cases, the electrically driven compressor can be unloaded and shut down.

Several control software programs are available, such as the ASC control system developed by Ingersoll Rand, which has the ability to manage compressors to meet the set point value as well as other features such compressor load sharing [22].

Controllers use different methods to respond to differences between the process variable and set point. These include but are not limited to:

- On/off control
- Proportional control
- Integral control
- Derivative control

On/off controllers, or two position controllers, are commonly used in applications where the output can be either fully open or fully closed. This is, for example, the case where quick opening valves are used to regulate the flow of a liquid or gas to a location. The two position controller can also be used in applications where finer control is required. However, a major disadvantage is that a large amount of overshoot may occur. The cyclic nature of the two position controller can also cause damage to the final control element if the controller output changes at a high frequency [23].

The PID controller commonly used today is a combination of proportional, integral and derivative control. PID algorithms are frequently used in temperature, flow or pressure applications where the PV fluctuates constantly. The PID controller is capable of managing the output in order to control the PV within acceptable tolerances.

A wide range of PID algorithms are available on the market. Suppliers usually have their own in-house designed PID algorithm. However, most PID control algorithms commonly found today are either in the parallel (non-interacting) or series (interacting) form. The parallel form is more commonly found in the control industry due to a preference for digital control devices over pneumatic control [24].

2.3.3 Compressor control

To achieve significant electricity savings on compressed air systems, experience has shown that compressor control must be automated. Compressor power consumption is proportional to the mass airflow delivered for a given delivery pressure.
Effective compressor control can be done utilising the following control mechanisms:

- Compressor guide vane or inlet guide valve control
- Compressor selection and load sharing

Inlet guide valves are installed near or on the inlet of the compressor. The butterfly valve controls the flow of air into the compressor. As the valve closes the mass airflow into the compressor is reduced. Although the pressure ration remains the same the power consumption will be reduced. However, the decrease in power consumption is not proportional to the decrease in flow. Turbulence in airflow caused by the valve at small openings will also adversely affect operating efficiency.

Control of the inlet guide vanes is accomplished using the PID control algorithms. A desired pressure set point is specified and the IGV or valves are suitably controlled to achieve this set point.

Many software packages exist that facilitate compressor control. Ingersoll Rand designed the ASC compressor controller that has the capability to fully integrate the compressed air system and facilitate control.

2.3.4 Valve control

In a study conducted by Booysen, electricity savings of between 13% and 49% were achieved through optimal compressor control [10]. These savings can be improved even further through efficient valve control. Installing control valves at points of demand throughout the system will make it to possible to regulate the air supply at that point. When valve openings are adjusted to reduce the pressure, losses due to leaks downstream of the valve and wastage of air will be realised.

A wide range of control valves are commercially available. Each valve type has different operational characteristics, specifications and price ranges. Another aspect that must be considered is the positioning of the valves in the delivery lines. Sufficient space must be available for the control actuator installed with the valve.

a. Valve equations and theory

In order to quantify the flow of a valve, the International Standards Association has defined a parameter, $C_{v,}$ called the flow coefficient of the valve. By definition a valve with a C_v value of 1 will provide a flow of 1 GPM [1] (gallon per minute) with a pressure drop of 1 PSI [2] across the valve.

The continuity equation implies that, for an incompressible fluid, the speed of airflow through the valve will increase as the cross sectional area is reduced. However, in practice a critical pressure drop across the valve will result in choked flow as the speed of the air approaches the speed of sound. Figure 10 shows the typical compressible flow conditions as the airflow approaches the speed of sound.

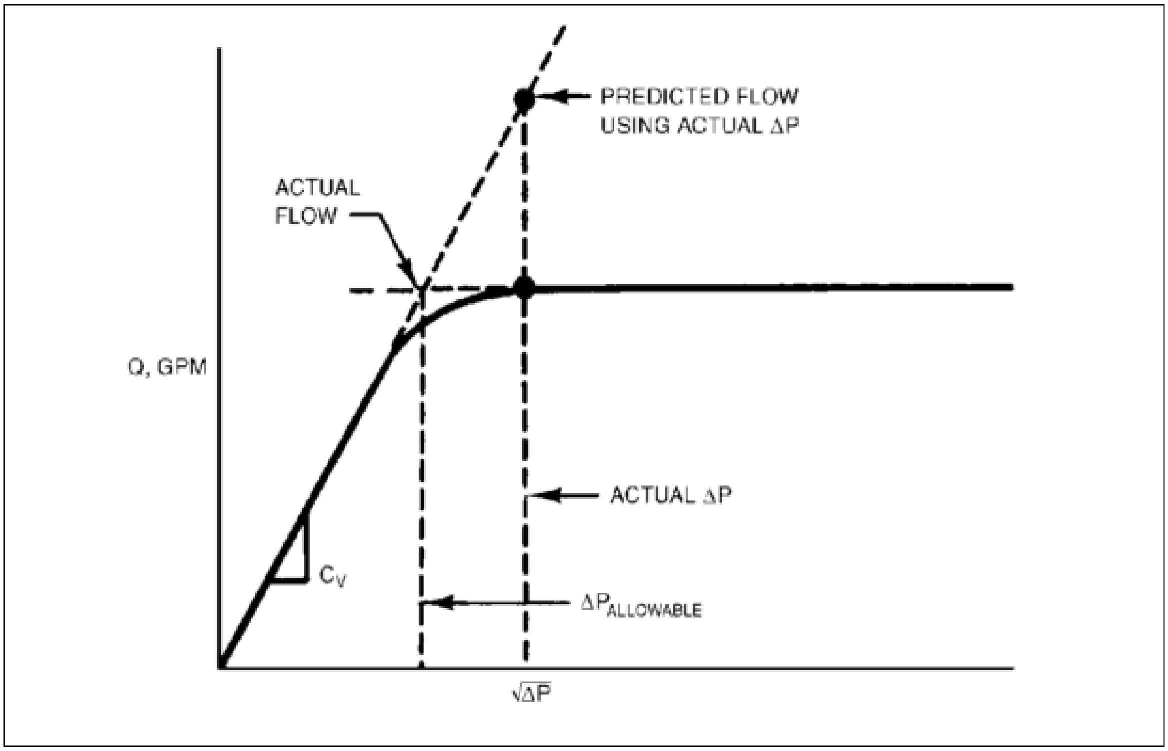

Figure 10: Critical pressure drop where flow becomes choked [23]

The Instrument Society of America (ISA) developed a set of sizing equations that is internationally accepted as the standard valve sizing equations. Equations are provided for:

- Liquid and gas flow
- Laminar and turbulent flow
- Choked and unchoked flow
- Flow for valves with and without attached fittings (reducers, tees, bends, etc.)

In the case of turbulent airflow without attached fittings, the equation for choked flow is given as [25]:

$$C_v = \frac{Q}{0.667NP_1}\sqrt{\frac{G_g T_1 Z}{F_\gamma x_T}} \tag{2.1}$$

where

N	= numerical constant	[dimensionless]
P_1	= upstream pressure	[kPa]
G_g	= gas specific gravity	[dimensionless]
T_1	= upstream temperature	[K]
Z	= compressibility factor	[dimensionless]
F_γ	= specific heat ratio factor	[dimensionless]
x_T	= pressure differential factor of valve at choked flow without attached fittings	[dimensionless]

For non-choked flow without attached fittings:

$$C_v = \frac{Q}{NP_1 Y}\sqrt{\frac{G_g T_1 Z}{x}} \tag{2.2}$$

where

Y	= expansion factor	[dimensionless]
x	= pressure differential ratio	[dimensionless]

These equations are used when sizing control valves to ensure that the required flow conditions are met.

Other factors that should also be taken into consideration include [25]:

- The piping geometry factor, which includes outlet or inlet reducers attached to the valve ports.
- The Reynolds number factor, which has to establish whether fully developed turbulent flow is present.
- The expansion factor, which accounts for density changes as the fluid passes through the control valve.

Control valve flow characteristics

Control valves have three types of flow characteristics, namely:

- Quick opening
- Linear
- Equal percentage

Linear control valves have equal changes in the valve C_v with equal changes in the valve travel throughout the entire range of the valve position. Valves with equal percentage flow characteristics have equal change in percentage for the C_v value of the valve with a change in valve travel. Quick opening valves have the maximum change in C_v with minimal change in valve travel.

The actual flow characteristics are more complex, but can be estimated as either linear, equal percentage or quick opening. Valve flow characteristics can differ largely from the theoretical due to other factors such as valve body and trim types, which influence flow through the valve. A table of the best valve characteristics for applications is provided in Table A1 in Appendix A.

Control valve characteristics have a large impact on the performance of the control valves in the system. Therefore, flow will be affected differently with each valve. Butterfly valves generally have a very narrow control range, between 10% and 40%, where control gain (the change in flow through the valve with a change in valve travel under process conditions [26]) and flow changes are noticeable. However, the control gain for the butterfly valve is much higher than that of the globe valve.

Butterfly valves have an equal percentage flow characteristic. They are generally suited for fixed load applications and a suitable choice for a control valve in a mine compressed air system.

b. Selecting a control valve

Many factors need to be considered in choosing a control valve.

- In what environment is the valve required to operate?
- What are the required system performance specifications (allowable pressure drop, required flow rate, etc.?)
- What is the nature of the process that needs to be controlled?
- Which control valve is financially most cost-effective?

Control valve description

Figure 11 illustrates the parts of the control valve assembly:

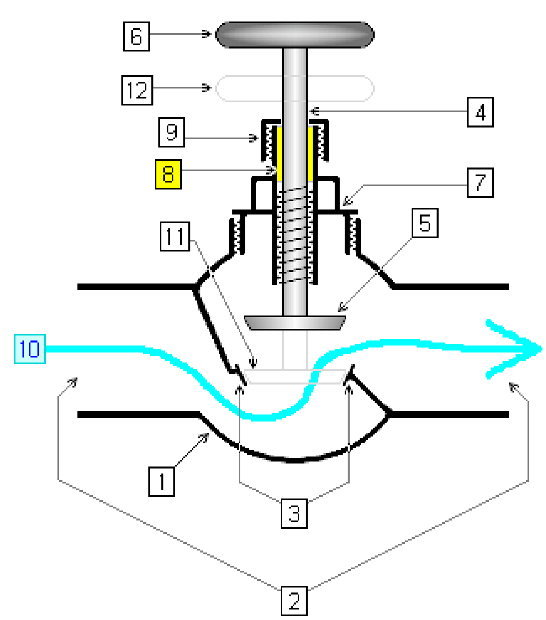

Figure 11: Control valve assembly

The valve body (1) is the outer part of the control valve which houses the valve trim. The trim is the collective name for the internal parts of the valve such the stem (4), the valve seat (3) and the disc/plug (5). The opening through which the stem passes is called the bonnet (7). The stem is used to move the disc or plug using a hand wheel or an actuator (6). The opening between the bonnet and the stem is sealed by valve packing (8) held in place by a gland nut (9). The valve ports (2) are attached to adjacent pipe sections to allow the fluid (10) to pass through the valve.

The underground environment

When air is compressed, the dew point is increased and vapour may condensate. To remove condensate from the compressed air, equipment such as the following is installed in the system:

- Compressed air dryers
- Filters
- Water traps
- Condensate drains on compression stages of the compressor

This equipment will remove the majority of moisture in the compressed air lines. The remaining water will expose the metal surfaces to corrosion. Valve trim material should exhibit corrosion and abrasion resistance. A good selection for valve trim material would be stainless steel. The stainless steel CF8M has excellent corrosion resistance at low cost [23].

Most valve bodies are manufactured from carbon steel due to its high availability and low cost. It is also very workable, making manufacturing easier, and offers very good weldability [23], [26], for attaching end connectors. This is a useful advantage due to difficult logistical conditions in a typical mine. Carbon steel is sufficient for typical mine temperatures. Shaft time is usually limited during production and cleaning periods, so the ability to easily attach valves on underground piping systems becomes crucial. Valves with end connectors can be prepared on the surface and taken underground to be attached to pipes using flanges.

Operational requirements

The service conditions for the control valve must be specified beforehand. This information will be used to correctly determine the required size for the control valve. The procedure for sizing control valves is as follows [26]:

1. Specify the variables that will determine the size of the valve: These variables may differ depending on the working fluid (water or air) and the required service conditions. These can be the required flow needed, a minimum/maximum allowable pressure drop or required temperature. Other conditions may also exist. These service conditions will largely influence the sizing process.

2. Determine the numerical constant in the sizing equations, which is required when the standard ISA valve sizing equations are used. These numerical constants are chosen from a table. The numerical constant will determine what units are used with the sizing equations, metric or imperial, as long as a consistent set of units is used.

3. Determine the piping geometry factor. The piping geometry factor accounts for losses due to attached fittings such as tees, bends and reducers. If the valve size is the same as the piping diameter, this step is not necessary.

4. Determine the maximum flow rate (choked flow rate, for air) through the valve, or the maximum allowable pressure drop across the valve, depending on the chosen service conditions.

5. Calculate the valve C_v value using the appropriate equation [25].

6. Select the valve size using an appropriate flow coefficient table. Such a table is shown in Table A2 in Appendix A [27].

Characteristics of an underground compressed air system

The operational compressed air requirements of a typical South African mine varies between 400 kPa and 600 kPa. Uses for compressed air include [28]:

- Pneumatic underground drilling equipment
- Mechanical ore loaders
- Loading boxes
- Refuge bays
- Pneumatic control systems
- Agitation
- Instrumentation air

Air usage for some equipment is indicated in Table 1 [10]:

Table 1: Air usage of common mining equipment

Appliance	Pressure requirements (kPa)	Flow requirements (m^3/h)
Rock drills	400–600	310–430
Mechanical loaders	400–500	Up to 1010
Fans	400–500	70–680
Diamond drills	400–500	Up to 510
Agitation	300	Up to 1700

Due to the enormity of the compressed air pipe system, a change in downstream pressure does not rapidly decrease when the valve is closed.

Also, if the pressure in the system is low, it requires a lot of energy and a large volume of air to increase system pressure. However, should a high number of air leaks be present on a mining level, a very fast rate of pressure decrease may be observed. This variation in rate of pressure change within the system makes it difficult to select control valves suited for the application. It is therefore necessary to review the change of pressure within the entire system and select a control valve that is best suited for the application.

Financial cost of control valves

The process of selecting a control valve involves a trade-off between cost and system requirement. A larger control valve would be more expensive and the smallest size should be chosen for installation. However, a control valve that is too small can lead to insufficient flow provision and an undesirable drop in pressure.

When choosing a control valve, the type of valve must be specified correctly. Different valve types have inherent control characteristics and the valve type that best suits the required service conditions should be selected. The two main control valve types that are commercially available are:

- Globe/Gate valves
- Rotary valves, which includes ball valves

Table 2 provides a comparison of valve types in terms of recommended pressure drop, cost and other factors.

Table 2: Comparison between different valve types [29]

Application	Globe	Pinch/diaphragm	Butterfly	Disk	Ball
Controllability	1	3	1	1	1
High pressure: >30 bar	1	x	x	2	1
High pressure drop: P>0.5P1; P1>10 bar	1	x	x	3	3
Slurry	3	1	2	3	3
Cost (<100 mm)	2	1	3	3	3
Cost (>100 mm)	3	2	1	1	2
Anti-corrosion	2	1	1	2	2
Size and weight (<100 mm)	2	2	2	2	2
Size and weight (>100 mm)	3	3	1	1	3
Temperature > 100^{o}C	1	x	3	1	2
Performance ratings					
1: Good	2: Average		3: Poor	x: Not applicable	

From Table 2 it is clear that butterfly valves are financially more economical for sizes above 100 mm and are not suitable for pressure drops greater than 500 kPa across the valve.

For use in underground compressed air control, butterfly valves are an ideal choice in terms of controllability and capital cost. Typical pressure drops that can be expected can range from 200 kPa during off-peak and blasting periods and up to 400 kPa during high demand periods. Butterfly valves also display resistance to corrosion, especially when trim materials are selected from a high chromium stainless steel, which will protect against moisture that may be present in the compressed air.

2.4 Equipment considerations and limitations

It is necessary to ensure that the installed control equipment operates at an optimum efficiency. Pressure set point control must be implemented on compressors in such a way that compressor surge does not occur. Compressors should not be turned on and off frequently within a short period, as this causes undesirable cyclic stresses on the motor and drive-end bearings. Actuator type selection and sizing should be accurately done to prevent unnecessary costs.

2.4.1 Compressor system

Compressor surge

Compressor surge occurs when a momentary and cyclic flow reversal at high frequency takes place through the compressor [30]. This may result in large vibrations and may also lead to catastrophic equipment failure.

Anti-surge systems, such as compressor blow-off, are used to prevent compressor surge. An example of an anti-surge valve system is shown in Figure 12.

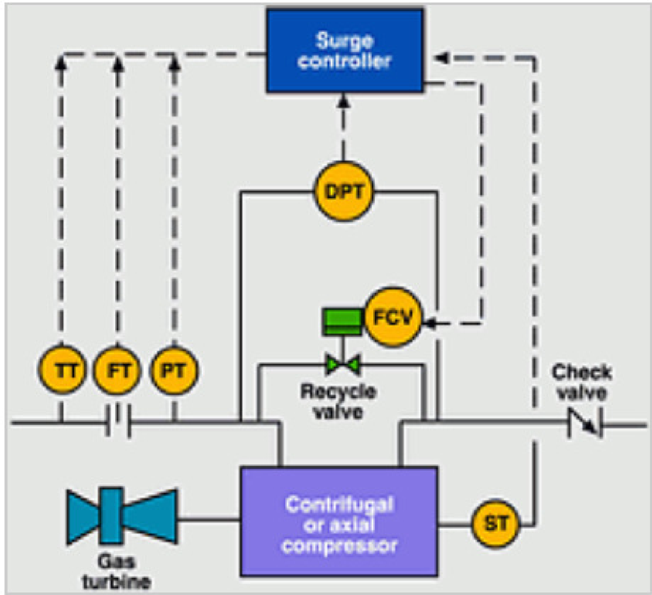

Figure 12: Compressor anti-surge valve system [32]

Quick opening valves are used since fast response is required when surging occurs so that the supply pressure can be rapidly reduced. Actuators capable of high torque are therefore a requirement.

If pneumatic actuators are used, a minimum air pressure in the supply line must be maintained in order for the actuators to function. If the delivery pressure set-point is set too low, it is possible that the recycle valve may not be able to operate effectively, if at all. When implementing set point control, it is important to ensure that adequate air pressure is still maintained within the supply line in order for the pneumatic actuators to operate.

Compressor cycling

The frequent stopping and starting of compressors within a short period of time is not desirable. This will cause the motor armature to overheat due to the excessive torque required during start-up, especially on large machines. When a compressor is shut down, there should be a delay before it is started up again to allow for the starter components to cool down.

Some control systems, such as the ASC control software package, introduces start-up and shutdown delays. Shutdown delays are used to determine whether a compressor really needs to be shut down. When the set point is reached and a compressor needs to be stopped, the compressor is firstly unloaded. If the shutdown delay time has expired without the pressure changing, the compressor then proceeds to shut down.

2.4.2 Valve system

Actuator type and size

Incorrect selection and sizing of actuators have undesirable cost implications. The advantages and disadvantages of different actuators must be investigated and a selection must be made that best suits the application at the lowest cost.

Pneumatic actuators

Pneumatic actuators use compressed air from the main supply line to move a positioner, which adjusts the valve travel. The positioner is fitted with a spring in either a normal open or normal closed configuration. These actuators can provide high speed and torque for applications and is very suitable for quick opening valves.

However, due to changes in air pressure of the mainline, it can be difficult for these actuators to accurately achieve mid-stroke positioning. It can also be difficult to control the velocity of movement, limiting modulation capabilities. The initial cost for pneumatic actuators is generally lower than that of electric actuators and is a good choice for mine applications where compressed air is already available [33]. These actuators are also easy to maintain.

Electric actuators

The electric actuator drives the valve stem using a motor. These actuators have high accuracy and modulating capabilities. They are, therefore, well suited for applications which require high accuracy. Electric actuators require an increased capital investment, being up to 40% more expensive than pneumatic actuators [34]. It also requires more specialist knowledge to maintain.

Sizing of actuators

Actuators need to be sized correctly to deliver the required torque to open and close the control valve. Larger control valves would require larger actuators. Pneumatic actuators are sized with a safety factor of two due to pressure spikes and other factors [35]. More expensive electric actuators, due to increased cost, need to be sized more accurately, as over sizing can lead to unnecessary costs.

2.5 Other factors that influence control

2.5.1 Safety

Safety must always be considered when designing a compressed air control system. This can be effectively accomplished by means of risk assessments to identify potential hazards and events in order to implement safety controls.

Risk assessments

When designing the control system, safety must be taken into account and a fail-safe system should be a standard feature. In most cases, mine safety standards require that compressed air is available at all times at underground refuge bays. Therefore, the system must be designed to automatically revert to a fail open position in case of an emergency. In order to effectively implement controls, a risk assessment on the control system should be done beforehand. Many techniques for assessing risk exist. The risk assessment process includes:

- Identifying potential hazards within a specific operating environment
- Determining potential unwanted events that can take place as a result of these hazards
- Ranking the risk between low or high
- Designing controls to minimise the likelihood or consequence of the event
- Appointing accountable persons

An example of a risk assessment is shown in Table A3 in Appendix A.

Safety controls

Safety controls are installed to minimise the risk of unwanted events. Typical safety devices installed on air control valve assemblies are:

- Watchdog timers: The timers are implemented between the PLC and other control software. A continuous sequence of numbers is sent to the PLC. Whenever a communication failure occurs and the sequence is interrupted, the PLC reverts to a fail safe mode.

- Uninterruptable power supplies (UPS): The units are installed to ensure backup power is available for long enough periods for the system to implement fail safe procedure should a main power failure occur.

- PLC alarms: These are alarm signals set up within the PLC. Alarms can be set up for actuator over-torque, high flow, high pressure, etc. These alarms will then alert the operator. This can also be used to trip the equipment should the alarm condition be exceeded.

2.5.2 Sustainability

When designing a compressed air control system, changes in system operation should be accounted for at all times. A typical mine continues to expand and develop new mining levels after the control system is implemented, which leads to increased compressed air usage. Control equipment needs to be regularly monitored, maintained and calibrated to perform at optimum efficiency.

It is necessary for the system control parameters to be adjustable should control requirements change. If an increase in air usage is required by the mine, control set-points must be changed in the control software accordingly, as well as control schedules. Mine personnel should receive training to allow them to modify the control system. Training should also be provided for maintenance of control instrumentation such as pressure and flow meters.

3 Developing a compressed air control simulation

3.1 Introduction

In this chapter, the compressed air system of a typical mine is modeled and the different control valve configurations are simulated. The modeling of the system consists of three different models: the compressor, the surface pipe network and the control valve. Each of these systems can be modeled independently; however a change in one system will indeed effect a change in the other. Each of these models is then used to generate results regarding energy usage of the entire system.

The following sections explain how each of these models is individually developed and the assumptions made in the process.

3.2 Developing a compressed air control simulation model

3.2.1 Modeling the compressor system

The energy usage of the compressor must be modeled in order to determine the energy saving with a corresponding decrease in air demand.

The energy required to compress a unit of air is calculated using the following equation [36]:

$$w_{comp,in} = \frac{w_{reversible\ comp,in}}{\eta_{comp}} = \frac{nRT_1}{\eta_{comp}(n-1)}\left[\left(\frac{P_2}{P_1}\right)^{(n-1)/n} - 1\right] \qquad (3.1)$$

where:

$w_{comp,in}$	= actual energy required
$w_{reversible\ comp,in}$	= energy required for a reversible process
η_{comp}	= total efficiency of compressor
n	= polytropic compression exponent
R	= specific gas constant of air
T_1	= atmospheric temperature
P_1	= atmospheric pressure
P_2	= compressor delivery pressure

Using this equation, the power required to compress one unit/kg of air from pressure P_1 to pressure P_2 is calculated.

3.2.2 Modeling the surface pipe network

It is necessary to determine the pressure losses between the supply and demand points within the system. In the case of the mine, this includes the pressure difference between the compressors and the respective mining shafts.

Since North shaft is relative close to the supply point, at a distance of 800 m, the pressure drop is expected to be small. However, South shaft is more than 3 km away from the compressor house.

Empirical data from measurement instruments were collected and using this data, the pressure drop throughout the day was calculated. The results are shown in Figure 13:

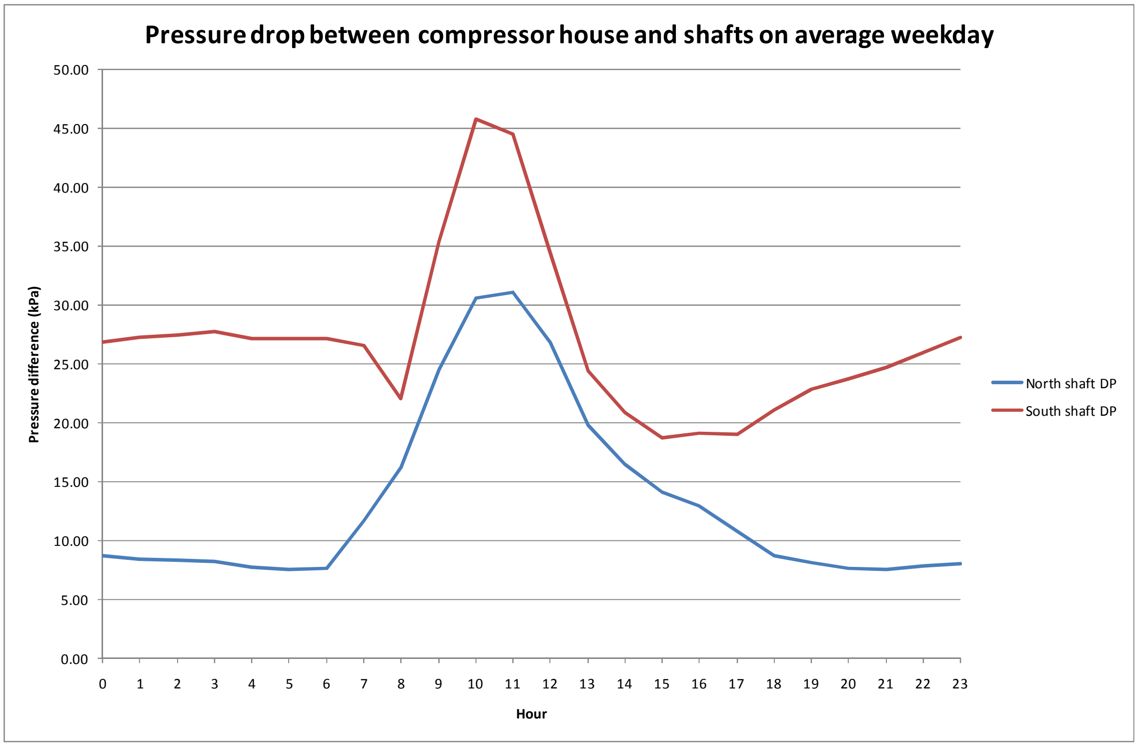

Figure 13: Pressure drop between compressors and shafts

The drop in pressure at South shaft reaches a maximum of 45 kPa during peak production periods while that at North shaft reaches a maximum of 30 kPa. The pressure drop is expected to be highest during the peak production periods, since the highest airflow is expected at this time.

3.2.3 Modeling the control valve

The control valve model is divided into two separate systems:

a) The underground compressed air system
b) The control valve itself

The steps taken to build these models are discussed below.

a. The underground compressed air system

In order to predict the effect of the control valves on the system, it is firstly necessary to simulate the underground compressed air system. A simulation has been built using the EES programming package with the following assumptions:

- Changes in density are negligible throughout the underground system.
- Flow is assumed as being steady.
- The relative pipe roughness for galvanised steel pipes is 0.15 mm [37], [38]. From the Moody chart, the friction factor obtained is 0.015. This friction factor is assumed to be constant throughout the system.
- Leaks and other flows that are not measured are assumed to be small in comparison to the total flow and are not taken into account.
- With low Mach numbers (<0.3) and relatively short pipe lengths (<300 m), the flow can be modeled as being incompressible with reasonable accuracy [38].

The pressure on each mining level was calculated using actual flow measurements underground and a measured surface pressure. The flows and surface pressures for each shaft are provided in Appendix B2 and B3.

One of the assumptions made is that flow velocity in the system is very low compared to the speed of sound. It is, therefore, reasonable to estimate the flow as incompressible in order to simplify the model. The energy equation states that, for adiabatic flow and no work being done on or by the fluid:

$$\frac{p_1}{\gamma_1}+\frac{V_1^2}{2g}+z_1=\frac{p_2}{\gamma_2}+\frac{V_2^2}{2g}+z_2+h_{loss} \tag{3.2}$$

where:

p	= pressure	[kPa]
γ	= specific gravity	[dimensionless]
V	= air velocity	[m/s]
g	= gravity constant	[m/s^2]
z	= elevation	[m]

The term h_{loss} is calculated using the Darcy-Weisbach equation:

$$h_{loss}=f\frac{L}{D}\frac{V^2}{2g} \tag{3.3}$$

where:

f	= friction factor	[dimensionless]
L	= pipe length	[m]
D	= pipe diameter	[m]

Substituting for h_{loss} from equation 3.3 into 3.2 results in:

$$p_1+\frac{1}{2}\rho V_1^2+\rho g z_1=p_2+\frac{1}{2}\rho V_2^2+\rho g z_2+\rho g f\frac{L}{D}\frac{V^2}{2g} \tag{3.4}$$

Therefore, given the depth of the mining level, velocity at each mining level and at least one pressure (the surface pressure), the conditions throughout the entire system can be calculated.

The code for the simulation is provided in Appendix B1.

b. Control valve

The control valve must be simulated in order to determine the reduction in air usage.

When the line pressure is more than twice the atmospheric pressure, the velocity of air through leaks must be equal to the speed of sound [36].

The mass flow of air through a leak can then be calculated as follow [36]:

$$\dot{m}_{air} = C_{discharge}\left(\frac{2}{k+1}\right)^{1/(k-1)}\frac{P_{line}}{RT_{line}}A\sqrt{kR\left(\frac{2}{k+1}\right)T_{line}} \quad (3.5)$$

where:

$\dot{m}_{air}$	= mass flow of air	[kg/s]
$C_{discharge}$	= leak discharge coefficient	[dimensionless]
k	= specific heat ratio of air	[dimensionless]
P_{line}	= line pressure	[kPa]
R	= specific gas constant for air	[$J.kg^{-1}.K^{-1}$]
T_{line}	= line temperature	[K]
A	= leak cross sectional area	[m^2]

The amount of air lost through leakage can be determined by comparing flow readings underground with flow readings on the surface. However, the amount of air lost through leaks in the working sections are not measured and need to be estimated. These leaks underground are estimated at 15% and 25% and are both simulated separately.

Estimating the percentage of air lost through leakage, equation (3.5) is first used to determine the cross sectional area of the leak by using the actual flow.

$$A_{calculated} = \frac{\dot{m}_{air\ flow\ with\ estimated\ leaks}}{C_{discharge}\left(\frac{2}{k+1}\right)^{1/(k-1)}\frac{P_{line}}{RT_{line}}\sqrt{kR\left(\frac{2}{k+1}\right)T_{line}}} \quad (3.6)$$

Where:

$\dot{m}_{air\ flow\ with\ estimated\ leaks}$ = Calculated leak air estimating leakage of 15% 25% of total flow respectively

$A_{calculated}$ = calculated minimum cross sectional leak area

The mass flow of air through the leak at the lower set-point pressure is then determined using the same equation and the mass flow saving is obtained.

$$\dot{m}_{reduced\ airflow} = C_{discharge}\left(\frac{2}{k+1}\right)^{1/(k-1)} \frac{P_{setpoint}}{RT_{line}} A_{calculated}\sqrt{kR\left(\frac{2}{k+1}\right)T_{line}} \quad (3.7)$$

Where:

$P_{setpoint}$ = set-point pressure

$\dot{m}_{reduced\ airflow}$ = calculated airflow at set-point pressure

Finally, using equation (3.1), the power saving as a result of reduced airflow can be calculated:

$$Energy\ saved\ [kW] = \dot{m}_{reduced\ airflow} \times w_{comp,in} \quad (3.8)$$

Simulation of different control scenarios can be done using the derived models.

3.3 Validation of simulation models

3.3.1 Underground pipe network model validation

The simulation was validated using the actual measurements on the mine system on a day when no control was done on the system. The surface pressure at each shaft was calculated using measured pressure data between the compressors and the shafts. Trend estimation was conducted and a least squares value obtained.

Results

The actual and simulated measurements for North shaft level 8 and South shaft level 8 are provided in Tables 3 and 4.

Table 3: Simulated and actual results for South shaft level 8

Hour of the day	Calculated surface pressure (kPa)	Actual pressure measurements at level 8 (kPa)	Simulated results (kPa)	Percentage error (%)	Pressure drop between shaft and compressor house (kPa)
0	476.82	525.01	477.89	8.98%	26.83
1	482.89	519.56	484.36	6.78%	27.20
2	497.93	547.90	499.43	8.85%	27.39
3	513.00	562.29	514.53	8.49%	27.73
4	525.80	561.76	527.43	6.11%	27.15
5	534.55	560.22	536.29	4.27%	27.13
6	535.33	565.89	536.71	5.16%	27.10
7	523.79	552.30	524.22	5.08%	26.54
8	551.45	573.57	546.53	4.71%	22.05
9	549.39	566.69	536.61	5.31%	35.33
10	550.45	581.93	536.98	7.73%	45.80
11	545.20	572.96	534.82	6.66%	44.48
12	556.83	578.32	551.03	4.72%	34.48
13	463.41	483.20	463.48	4.08%	24.38
14	441.35	458.95	443.07	3.46%	20.83
15	420.79	437.72	423.23	3.31%	18.66
16	426.05	444.65	428.45	3.64%	19.07
17	435.54	454.13	437.93	3.57%	18.95
18	433.55	456.84	435.92	4.58%	21.10
19	432.08	447.73	434.51	2.95%	22.82
20	431.03	448.66	433.46	3.39%	23.75
21	430.06	447.00	432.50	3.24%	24.70
22	429.10	447.61	431.53	3.59%	25.92
23	427.77	454.89	430.16	5.44%	27.27

Table 4: Simulated and actual results for North shaft level 8

Hour of the day	Calculated surface pressure (kPa)	Actual pressure measurements at level 8 (kPa)	Simulated results (kPa)	Percentage error (%)	Pressure drop between shaft and compressor house (kPa)
0	494.94	520.94	496.87	4.62%	8.70
1	501.67	527.52	503.57	4.54%	8.42
2	517.00	543.38	518.83	4.52%	8.32
3	532.50	559.49	534.28	4.51%	8.23
4	545.20	572.27	547.02	4.41%	7.75
5	554.15	581.46	555.96	4.39%	7.52
6	554.76	582.34	556.79	4.39%	7.67
7	538.71	568.62	540.23	4.99%	11.62
8	557.32	589.84	557.50	5.48%	16.19
9	560.28	596.16	558.21	6.37%	24.45
10	565.73	608.02	563.13	7.38%	30.51
11	558.61	604.85	557.06	7.90%	31.08
12	564.50	611.24	564.56	7.64%	26.81
13	467.98	506.57	469.84	7.25%	19.81
14	445.69	479.87	447.81	6.68%	16.49
15	425.39	457.30	427.65	6.48%	14.07
16	432.16	462.67	434.36	6.12%	12.96
17	443.68	472.52	445.89	5.64%	10.81
18	445.95	471.97	448.16	5.04%	8.69
19	446.80	471.69	449.00	4.81%	8.11
20	447.18	470.95	449.39	4.58%	7.60
21	447.20	470.74	449.43	4.53%	7.55
22	447.22	470.93	449.45	4.56%	7.80
23	446.99	470.62	449.21	4.55%	8.06

The correlation between the simulated and actual measurements for mining level 8 at both shafts is shown in Figures 14 and 15.

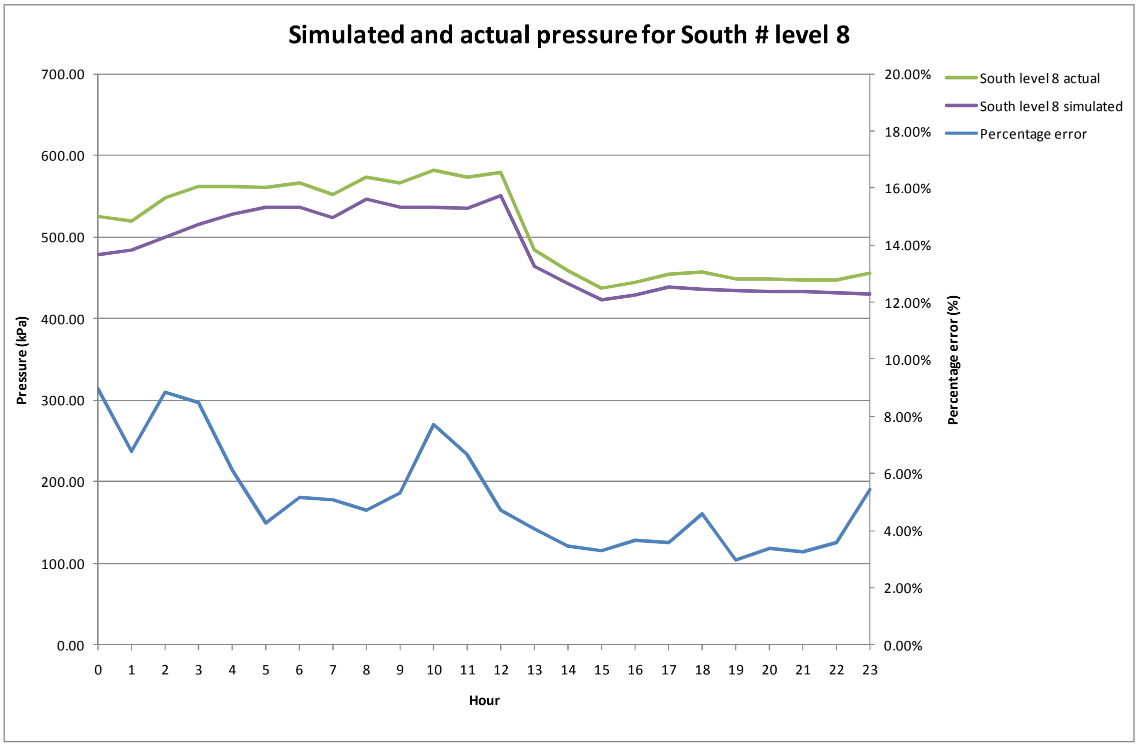

Figure 14: South shaft level 8 results

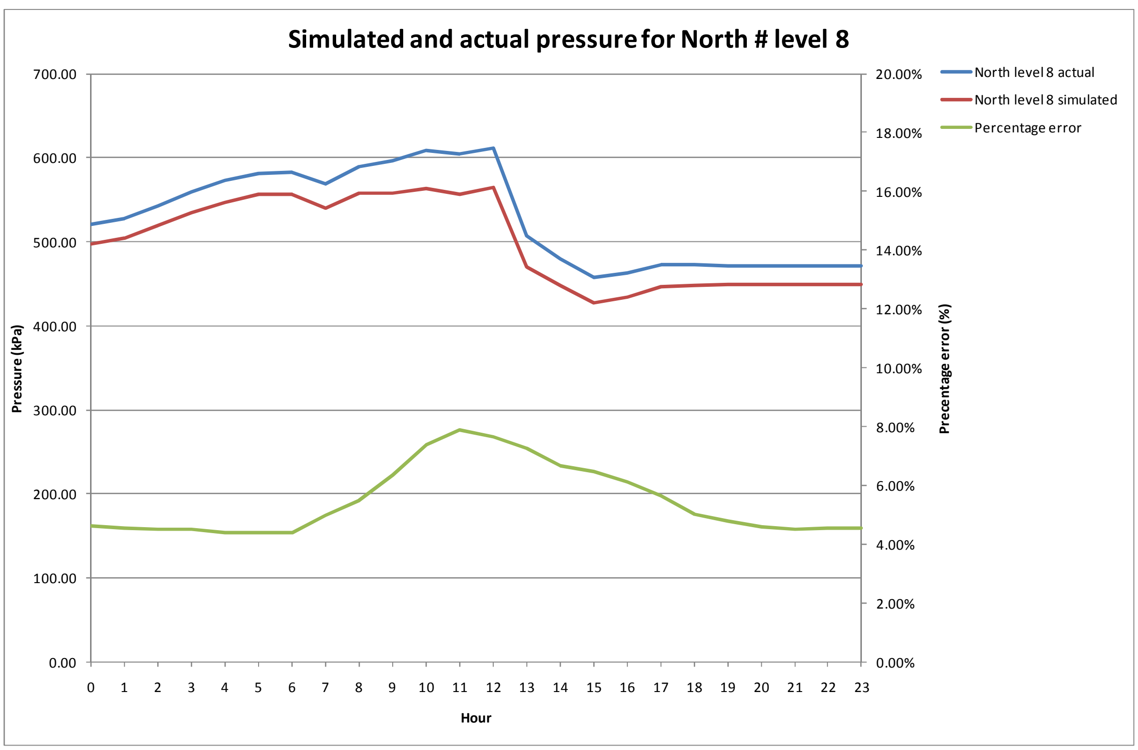

Figure 15: North shaft level 8 results

The trend estimation results are shown in Figures 16 and 17.

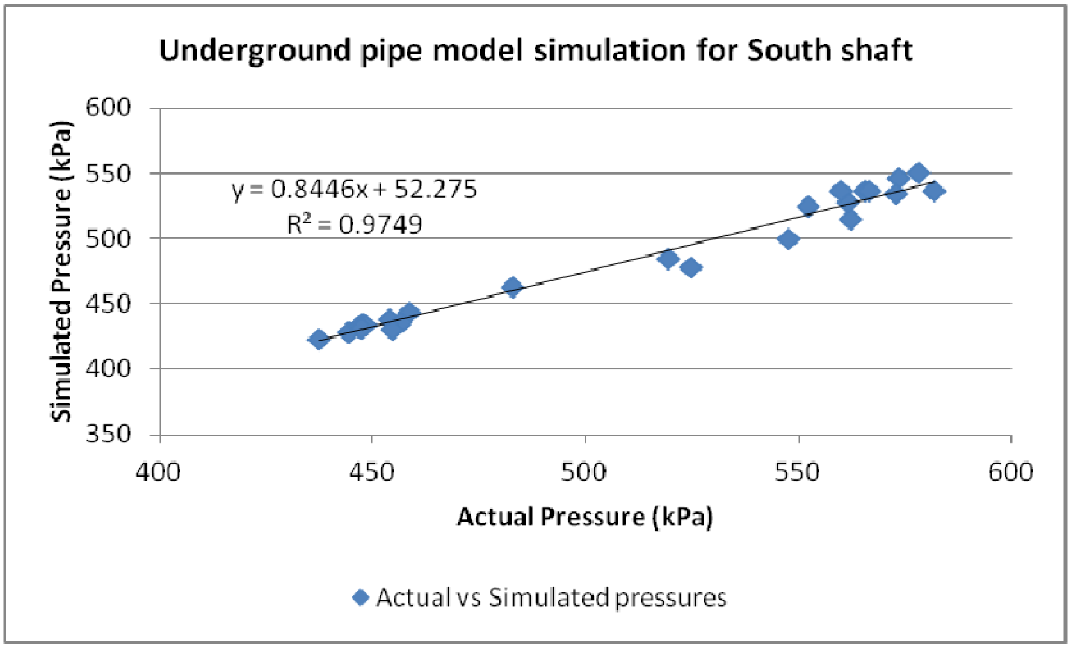

Figure 16: Trend estimation and least squares value of trend fit for South shaft

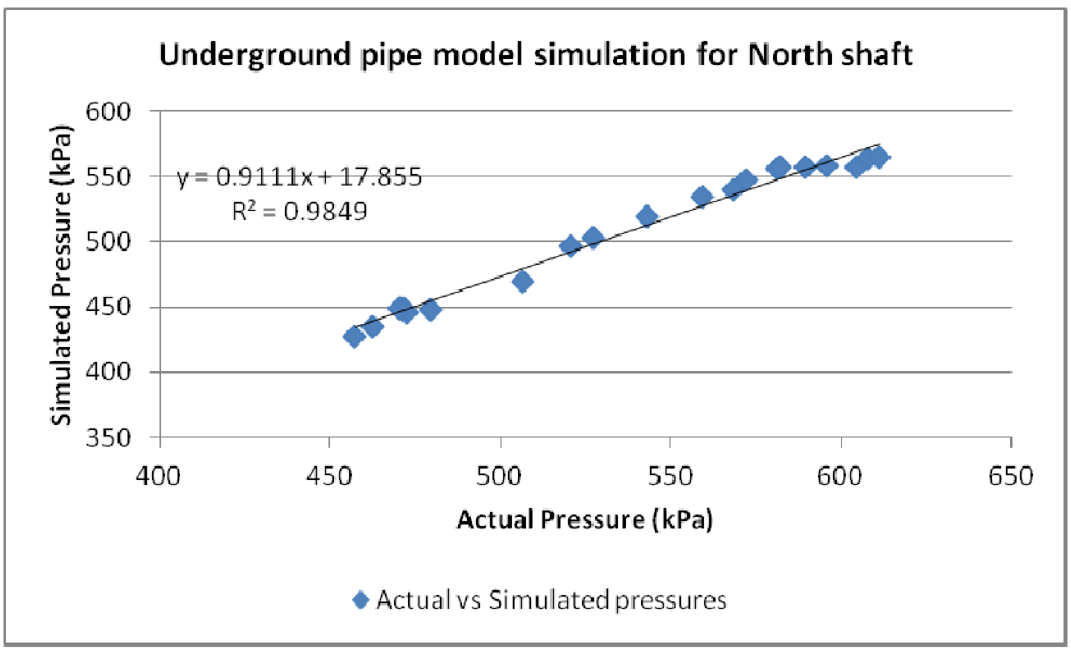

Figure 17: Trend estimation and least squares value of trend fit for North shaft

The simulation values plotted against actual pressure values indicate a good fit on both shafts.

3.4 Simulation of control scenarios

3.4.1 Preamble

In this section, simulations are done to determine the average power saving per day for two control scenarios. Data collected from site measurements were used as input in the simulation.

3.4.2 Control valve installed on shaft compressed air supply line

In this control scenario, control valves are installed at the surface. System parameters are shown in Table 5.

Table 5: System parameters for simulation of control at the surface

Parameter	Value
Minimum required downstream pressure	400 kPa
Pipe diameter	450 mm
Line temperature	298.15 K
Atmospheric pressure	101.3 kPa
Specific gas constant (R)	0.287 kJ/kgK
Specific heat ratio (k)	1.4
Leak discharge coefficient (C_d)	0.65
Compressor efficiency (η_{comp})	0.95
Polytropic compression exponent (n)	1.4

Due to engineering activities taking place at the various mining levels, a minimum pressure of 400 kPa is required. Leak flows within the working sections are estimated as 15% and 25% and simulated separately and these values are provided in Appendix C1 and C2 for both shafts respectively. The simulation was done in Microsoft Excel and the results are shown in Table 6.

Table 6: Results of simulation for leak flows of 25% and 15% respectively

		Estimated 15% leaks underground		Estimated 25% leaks underground	
		North shaft power saving (kW)	South shaft power saving (kW)	North shaft power saving (kW)	South shaft power saving (kW)
Hour	0	0.0	0.0	0.0	0.0
	1	0.0	0.0	0.0	0.0
	2	0.0	0.0	0.0	0.0
	3	0.0	0.0	0.0	0.0
	4	0.0	0.0	0.0	0.0
	5	0.0	0.0	0.0	0.0
	6	0.0	0.0	0.0	0.0
	7	0.0	0.0	0.0	0.0
	8	0.0	0.0	0.0	0.0
	9	0.0	0.0	0.0	0.0
	10	0.0	0.0	0.0	0.0
	11	0.0	0.0	0.0	0.0
	12	0.0	0.0	0.0	0.0
	13	0.0	0.0	0.0	0.0
	14	0.0	0.0	0.0	0.0
	15	0.0	0.0	0.0	0.0
	16	73.0	84.4	90.5	103.0
	17	109.6	113.0	135.8	138.0
	18	106.7	99.3	132.3	121.3
	19	109.3	96.7	135.5	118.0
	20	101.8	77.5	126.2	94.6
	21	91.0	63.8	112.8	77.9
	22	0.0	0.0	0.0	0.0
	23	0.0	0.0	0.0	0.0
Average power saving (kW)		24.6	22.3	30.5	27.2
Total energy saving (kWh)		591.4	534.7	733.1	652.7

A simulation of the energy saved with control valves installed in the working sections on each level is provided in the following sections.

3.4.3 Control valves installed in underground working sections

In this scenario, the control valves are installed at the working sections at each mining level, thereby controlling the flow to each section, as illustrated.

Engineering related activities are located closer to the main shaft upstream from the control valves and remain unaffected. This makes it possible to lower the pressure even more during blasting times. The system parameters used in the simulation are shown in Table 7.

Table 7: System parameters for simulation of control on working sections

Parameter	Value
Minimum downstream pressure	200 kPa
Pipe diameter	200 mm
Line temperature	298.15 K
Atmospheric pressure	101.3 kPa
Specific gas constant (R)	0.287 kJ/kgK
Specific heat ratio (k)	1.4
Leak discharge coefficient (C_d)	0.65
Compressor efficiency (η_{comp})	0.95
Polytropic compression exponent (n)	1.4

The leak flow assumptions for each shaft were the same as for the previous example. Using this information, the leak area was calculated for each working section. The leak flow at set-point pressure was then calculated and the power saving as a result of flow reduction calculated. All the values for the calculations are provided in Appendix D1 to D4. A summary of the results of the simulation is shown in Table 8.

Table 8: Simulation results for 15% and 25% leak flow on both shafts

		Leak flow at 15% of main flow		Leak flow at 25% of main flow	
		North shaft power saving (kW)	South shaft power saving (kW)	North shaft power saving (kW)	South shaft power saving (kW)
Hour	0	0.0	8.3	0.0	13.8
	1	0.0	6.0	0.0	9.9
	2	0.0	5.3	0.0	8.8
	3	0.0	4.6	0.0	7.6
	4	0.8	10.4	1.3	17.3
	5	5.7	14.6	9.5	24.3
	6	0.0	0.0	0.0	0.0
	7	0.0	0.0	0.0	0.0
	8	0.0	21.5	0.0	35.8
	9	0.0	0.0	0.0	0.0
	10	0.0	0.0	0.0	0.0
	11	0.0	0.0	0.0	0.0
	12	0.0	0.0	0.0	0.0
	13	0.0	0.0	0.0	0.0
	14	0.0	0.0	0.0	0.0
	15	0.0	0.0	0.0	0.0
	16	46.8	44.3	78.0	73.8
	17	278.9	237.5	464.8	395.9
	18	275.7	235.3	459.6	392.2
	19	275.3	241.1	458.8	401.8
	20	266.6	234.8	444.4	391.3
	21	39.7	38.1	66.2	63.5
	22	0.0	7.3	0.0	12.1
	23	0.0	7.8	0.0	13.0
Average power saving (kW)		49.6	46.5	82.6	77.5
Total energy saved (kWh)		1189.6	1116.7	1982.7	1861.1

The greater power saving between 16:00 and 21:00 resulted from the lower pressure set-point control done by the control valves. From 09:00 to 11:00 and 14:00 to 15:00, the set-point pressure was higher than the actual pressure in order to provide sufficient air for production activities. Therefore, during these times, no saving was achieved and the valves were fully open. Figure 18 illustrates the power saving achieved for both simulation scenarios.

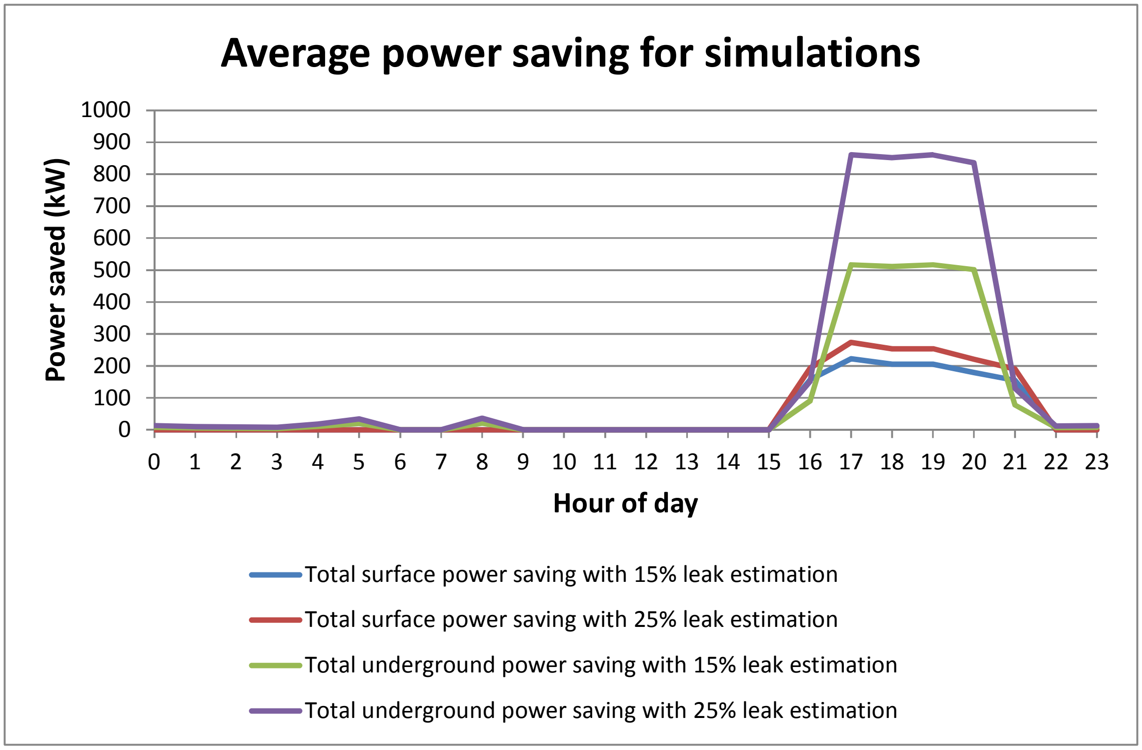

Figure 18: Total power saving for the control simulations

3.5 Comparison of financial cost between scenarios

In order to calculate the payback period for each scenario, the initial capital cost and revenue must be determined. Costs included are:

- Equipment costs
- Labour and overhead costs

The labour and overhead costs are estimated at 15% of the total costs. Operating costs that may be incurred are not included in the analysis. The revenue generated by the system will be the capital generated by the power saved. Electricity tariffs for 2010/11 are provided in Figure 19 [39].

		Active energy charge (c/kWh)												Transmission network charges (R/kVA/mth)	
Transmission zone	Voltage	High demand season (Jun-Aug)						Low demand season (Sep-May)							
		Peak		Standard		Off Peak		Peak		Standard		Off Peak			
		VAT excl.	VAT incl.	VAT excl.	VAT incl.	VAT excl.	VAT incl.	VAT excl.	VAT incl.	VAT excl.	VAT incl.	VAT excl.	VAT incl.	VAT excl.	VAT incl.
≤ 300km	< 500V	147.08	167.67	38.20	43.55	20.38	23.23	41.03	46.77	25.12	28.64	17.55	20.01	R3.67	R4.18
	≥ 500V & < 66kV	142.38	162.31	37.01	42.19	19.77	22.54	39.75	45.32	24.35	27.76	17.03	19.41	R3.35	R3.82
	≥ 66kV & ≤ 132kV	137.22	156.43	35.70	40.70	19.11	21.79	38.35	43.72	23.51	26.80	16.47	18.78	R3.26	R3.72
	>132kV	132.45	150.99	34.51	39.34	18.48	21.07	37.04	42.23	22.74	25.92	15.94	18.17	R4.12	R4.70
> 300km and ≤ 600km	< 500V	148.53	169.32	38.56	43.96	20.59	23.47	41.43	47.23	25.34	28.89	17.72	20.20	R3.69	R4.21
	≥ 500V & < 66kV	143.77	163.90	37.36	42.59	19.96	22.75	40.13	45.75	24.58	28.02	17.19	19.60	R3.38	R3.85
	≥ 66kV & ≤ 132kV	138.58	157.98	36.05	41.10	19.29	21.99	38.73	44.15	23.74	27.06	16.61	18.94	R3.29	R3.75
	>132kV	133.75	152.48	34.83	39.71	18.65	21.26	37.42	42.66	22.96	26.17	16.07	18.32	R4.17	R4.75
> 600km and ≤ 900km	< 500V	150.00	171.00	38.94	44.39	20.77	23.68	41.83	47.69	25.59	29.17	17.87	20.37	R3.74	R4.26
	≥ 500V & < 66kV	145.20	165.53	37.73	43.01	20.13	22.95	40.52	46.19	24.81	28.28	17.33	19.76	R3.41	R3.89
	≥ 66kV & ≤ 132kV	139.95	159.54	36.38	41.47	19.45	22.17	39.09	44.56	23.95	27.30	16.75	19.10	R3.32	R3.78
	>132kV	135.07	153.98	35.16	40.08	18.82	21.45	37.78	43.07	23.16	26.40	16.23	18.50	R4.22	R4.81
> 900km	< 500V	151.49	172.70	39.30	44.80	20.96	23.89	42.21	48.12	25.82	29.43	18.04	20.57	R3.75	R4.28
	≥ 500V & < 66kV	146.64	167.17	38.09	43.42	20.32	23.16	40.90	46.63	25.02	28.52	17.50	19.95	R3.45	R3.93
	≥ 66kV & ≤ 132kV	141.35	161.14	36.73	41.87	19.64	22.39	39.46	44.98	24.18	27.57	16.91	19.28	R3.33	R3.80
	>132kV	136.42	155.52	35.48	40.45	18.99	21.65	38.11	43.45	23.38	26.65	16.36	18.65	R4.25	R4.85

Figure 19: Electricity tariffs for 2010/11 [39]

The costs shown in Figure 19 were used to determine the revenue generated by the system. Equipment costs were estimated using quotations supplied by contractors.

3.5.1 Valves installed on surface pipeline

A list of equipment quantities and costs for the system is shown in Table 9.

Table 9: List of equipment quantities and costs for the surface control system

Cost of equipment for surface implementation			
Equipment	**Quantity**	**Unit cost**	**Total cost**
Control & actuator assembly	2	R 50 000.00	R 100 000.00
Pressure transducer	2	R 5 000.00	R 10 000.00
Flow meter	2	R 70 000.00	R 140 000.00
PLC	2	R 15 000.00	R 30 000.00
Instrumentation cabling	50	R 35.00	R 1 750.00
PLC enclosures	2	R 5 000.00	R 10 000.00
Network switches	2	R 5 500.00	R 11 000.00
Network cabling	200	R 55.00	R 11 000.00
Total			R 313 750.00
Labour & overhead at 15%			R 47 062.50
Grand total			R 360 812.50

The revenue generated as a result of power saved is shown in Table 10. The following tariffs were used:

- The transmission zone was less than 300 km
- The supply voltage was between 500 V and 66 kV
- Vat was not included

Table 10: Revenue generated through the surface control system

Revenue generated through surface implementation				
	Low demand season		High demand season	
Per day	**15% leaks**	**25% leaks**	**15% leaks**	**25% leaks**
	R 337.67	R 415.55	R 850.97	R 1 047.25
	Low demand season		High demand season	
Per month	**15% leaks**	**25% leaks**	**15% leaks**	**25% leaks**
	R 6 753.34	R 8 311.09	R 17 019.36	R 20 945.03
	Low demand season		High demand season	
Per year	**15% leaks**	**25% leaks**	**15% leaks**	**25% leaks**
	R 60 780.02	R 74 799.81	R 51 058.07	R 62 835.10
Total revenue generated				
Per year	**15% leaks**		**25% leaks**	
	R 111 838.09		R 137 634.90	

The revenue generated is estimated to be uniform. For this calculation, the following was not considered:

- Changes in electricity tariffs, which would increase/decrease the revenue generated
- The rate of inflation

The payback period was calculated with equation (4.1) [40]:

$$Payback\ period = \frac{Initial\ cost}{Net\ annual\ profit} \tag{4.1}$$

Therefore, the payback period for the system with 15% estimated air leaks are:

$$Payback\ period = \frac{\text{R}\quad 360\ 812.50}{\text{R}\quad 111\ 838.09} = 3.2 \text{ years}$$

For 25% estimated air leakage the payback period is:

$$Payback\ period = \frac{\text{R} \quad 360\ 812.50}{\text{R} \quad 137\ 634.90} = 2.6 \text{ years}$$

3.5.2 Valves installed underground at working sections

A list of equipment quantities and costs are shown in Table 11.

Table 11: List of equipment and costs for the underground control system

Cost of equipment for underground implementation			
Equipment	**Quantity**	**Unit cost**	**Total cost**
Control & actuator assembly	33	R 50 000.00	R 1 650 000.00
Pressure transducer	33	R 5 000.00	R 165 000.00
Flow meter	33	R 70 000.00	R 2 310 000.00
PLC	17	R 15 000.00	R 255 000.00
Instrumentation cabling	1700	R 35.00	R 59 500.00
PLC enclosures	16	R 5 000.00	R 80 000.00
Network switches	16	R 5 500.00	R 88 000.00
Network cabling	7850	R 55.00	R 431 750.00
Total			R 5 039 250.00
Labour & overhead at 15%			R 755 887.50
Grand total			R 5 795 137.50

The revenue generated by the system is shown in Table 12. The same tariffs were used as indicated above.

Table 12: Revenue generated by the underground control system

Revenue generated underground implementation				
	Low demand		High demand	
Per day	**15% leaks**	**25% leaks**	**15% leaks**	**25% leaks**
	R 718.48	R 1 197.47	R 1 730.79	R 2 884.66
	Low demand		**High demand**	
Per month	**15% leaks**	**25% leaks**	**15% leaks**	**25% leaks**
	R 14 369.61	R 23 949.35	R 34 615.87	R 57 693.11
	Low demand		**High demand**	
Per year	**15% leaks**	**25% leaks**	**15% leaks**	**25% leaks**
	R 129 326.47	R 215 544.11	R 103 847.60	R 173 079.33
Total revenue generated				
Per year	**15% leaks**		**25% leaks**	
	R 233 174.06		R 388 623.44	

The payback was again calculated with equation (4.1) with the same assumptions. The payback period calculated for 15% estimated air leaks is:

$$Payback\ period = \frac{\text{R} \quad 5\,795\,137.50}{\text{R} \quad 233\,174.06} = 24.8 \text{ years}$$

For an estimated 25% air leaks, the payback period is:

$$Payback\ period = \frac{\text{R} \quad 5\,795\,137.50}{\text{R} \quad 388\,623.44} = 14.9 \text{ years}$$

3.5.3 Summary

A summary of the results obtained in chapter 3 are shown in Table 13.

Table 13: Summary of simulation results

Control scenario	Power saving achieved (kW)		Cost of implementation (R)	Calculated payback period (years)	
	15% leaks estimation	25% leaks estimation		15% leaks estimation	25% leaks estimation
Surface implementation	46.9	57.7	R 360 812.50	3.2	2.6
Underground implementation	96 .1	160.1	R 5 795 137.50	24.8	14.9

From Table 13 it is clear that the underground control system provides a much higher power saving than the surface system. This is due to the fact that the set point can be reduced more than in the surface simulation (200 kPa instead of 400 kPa). This lower set point has an even larger effect with an increase in air leakage, resulting in a 40% increase in power saving with a 10% increase in air leaks, compared to the 20% increase in power saving with the surface implementation. Although more of the system is controlled through the surface control system implementation (more leak control), the number of leaks controlled does not justify the higher set point requirement.

The underground control system is unfortunately more capital intensive, due to the greater quantity of equipment required, than the surface system. Even with the large revenue advantage with higher estimated leaks, the payback period for the underground control system is almost six times longer than that of the surface implementation.

4 Verification of cost-effective solutions

4.1 Introduction

In this section, the underground control simulation is verified with actual data. A case study of the simulated implemented control system is presented here.

4.2 Application to mining industry: BRPM platinum mine

The proposed underground control system was implemented on a Bafokeng Rustenburg platinum mine (BRPM) and has proven to be successful in delivering sustainable power savings.

BRPM has two shafts. North shaft has eight mining levels with a split on each level to the northern and southern crosscuts. The only exception is the fourth mining level, which splits into three sections. South shaft has eight mining levels with one split each. Each section of each level is supplied with compressed air from the surface. The pipeline enters the shaft on the surface and splits to each level underground. The location where this split occurs is called the apex. It is at this location where the control equipment is installed on each split of the pipeline.

The control valves therefore regulate the flow to each working section of the level. Valve outputs are PI (proportional-integral) controlled using the measured downstream pressure and predefined pressure set-points from the Real Time Energy Management for the Optimisation of Air Networks (REMS-OAN) software package.

4.2.1 Mine layout

The compressed air to the mine is supplied by seven 2.6 MW compressors. These compressors supply compressed air to the surface pipe network. All shafts as well as the concentrator plant of BRPM receive compressed air via this surface network. Semi-automated compressor control was implemented using an Ingersoll Rand ASC control system. This system uses predetermined pressure set-points and measured system pressure to perform the following actions:

- Throttling of compressor inlet guide valves
- Throttling of compressor bypass valves
- Loading and off-loading of compressors
- Shutting down and starting up of compressors

These actions facilitate the optimal usage of compressors to provide the required pressure. The ASC also starts and stops compressors according to a compressor schedule in order to share the compressor load equally between compressors. Both shafts are approximately 400 m deep. A third shaft, D-shaft, has a very low production output and subsequently the compressed air supply line has been completely shut down on the surface. The diameter of the compressed air pipelines is smaller from the apex on each level. The distance to the apex is also different for each level. The depth, distance to the split and the pipe diameters are shown in Table 14.

Table 14: Underground piping specifications

Level	Pipe diameter	Main column diameter	Depth (m)	Distance to apex (m)	Valve type
N# Level 2	200 mm	450 mm	90	218	Butterfly
N# Level 3	200 mm	450 mm	124	241	Butterfly
N# Level 4	200 mm	450 mm	157	171	Butterfly
N# Level 5	250 mm	450 mm	191	239	Butterfly
N# Level 6	200 mm	450 mm	225	288	Butterfly
N# Level 7	250 mm	450 mm	283	154	Butterfly
N# Level 8	200 mm	450 mm	322	270	Butterfly
S# Level 2	200 mm	450 mm	90	218	Butterfly
S# Level 3	200 mm	450 mm	124	241	Butterfly
S# Level	200 mm	450 mm	157	171	Butterfly
S# Level 5	200 mm	450 mm	191	239	Butterfly
S# Level 6	200 mm	450 mm	225	288	Butterfly
S# Level 7	200 mm	450 mm	283	154	Butterfly
S# Level 8	200 mm	450 mm	322	270	Butterfly

On each section split, one control valve is installed. The control valve unit consists of a 200 mm diameter butterfly valve outfitted with an actuator with modulation capabilities for more sensitive valve movement. An exception is North shaft level 5, where a 250 mm butterfly valve is installed.

A flow meter is installed at a position, five times the pipe diameter, upstream from the control valve to ensure an accurate reading.

A pressure transmitter is installed after the control valve to measure downstream pressure. The rated pressure is 10 bar gauge. On the main compressed air line on the level an isolation valve is installed for maintenance purposes.

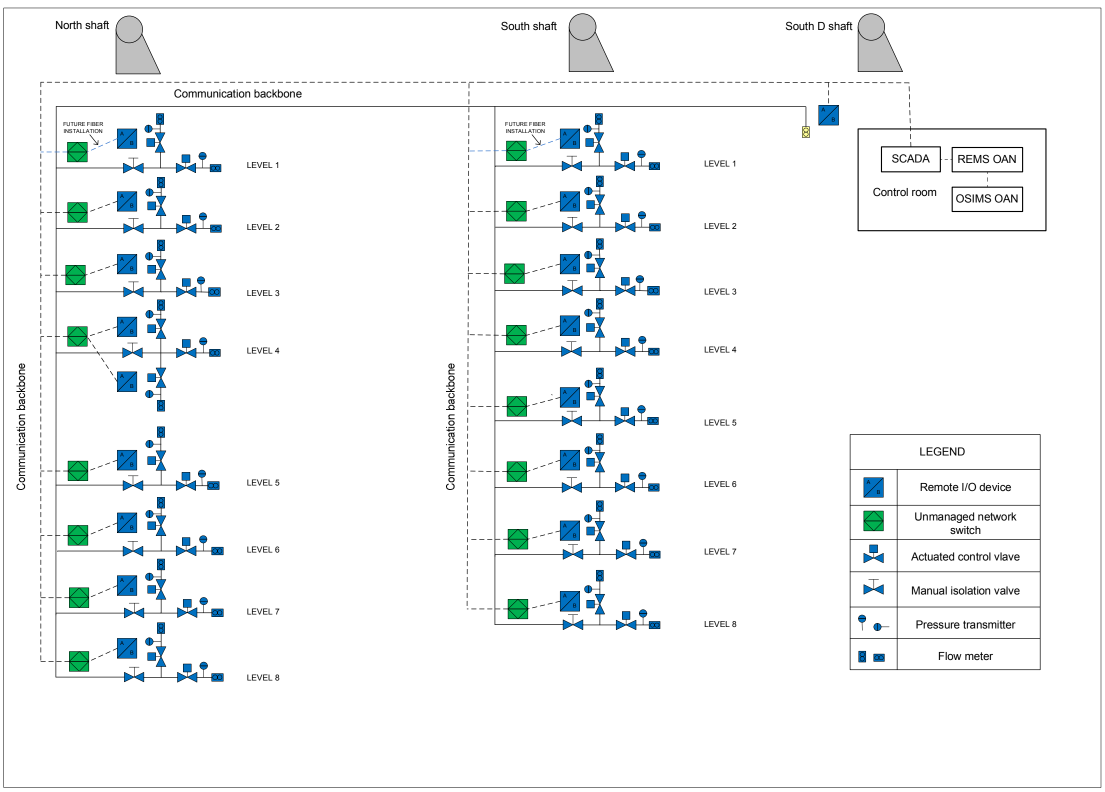

Figure 20: BRPM compressed air system

The fibre network on each mining level runs from the surface down to the lowest level in a ring configuration. Two fibre ring networks run down each shaft in order to establish network redundancy in case one network ring malfunctions.

At the apex on each mining level an I/O (Input/Output) control unit is installed to establish communication between the valve and measurement equipment and the mining network. The output of the equipment is a digital signal varying between 4 mA and 20 mA. The unit scales this signal to a pressure between 0 kPa and 1000 kPa respectively. Unit scaling is programmable.

A fibre-to-ethernet network switch is installed to connect the I/O controller to the mining network. The I/O controller communicates with the switch using a TCP/IP protocol. The fibre network utilises the Modbus industrial ethernet network communication protocol.

4.2.2 Control philosophy

The I/O controller samples the outputs of the pressure transmitters, flow meters and control valves. This information is communicated to the SCADA system situated in the shaft control room. The REMS-OAN system uses the OPC network communication protocol to retrieve information for feedback from the shaft SCADA system and the compressor SCADA system. REMS-OAN will also signal pressure set point values to the SCADA. The SCADA uses these set-points along with the pressure feedback to determine the correct valve position. This valve position is then communicated to the I/O devices that send output signals to the control valve actuators. Furthermore, the SCADA system at the shaft interfaces with all I/O controllers and displays pressure, flow and control valve data.

4.2.2.1 SCADA and I/O interface

The SCADA system at each shaft retrieves instrumentation signals from the I/O device. These values include compressed airflow, pressure and valve position. This signal is converted to the required values of pressure, in kPa, and flow in cubic meters per minute (m^3/min).

The SCADA uses the scaled pressure to perform PID control according to the pressure set point supplied by REMS-OAN. In instances where there is a deviation between the actual pressure and the set point pressure, the SCADA will signal a new valve position to the I/O device. The I/O device will then signal a new valve position to the control valve.

A simplified layout of the PID control loop is illustrated in Figure 22:

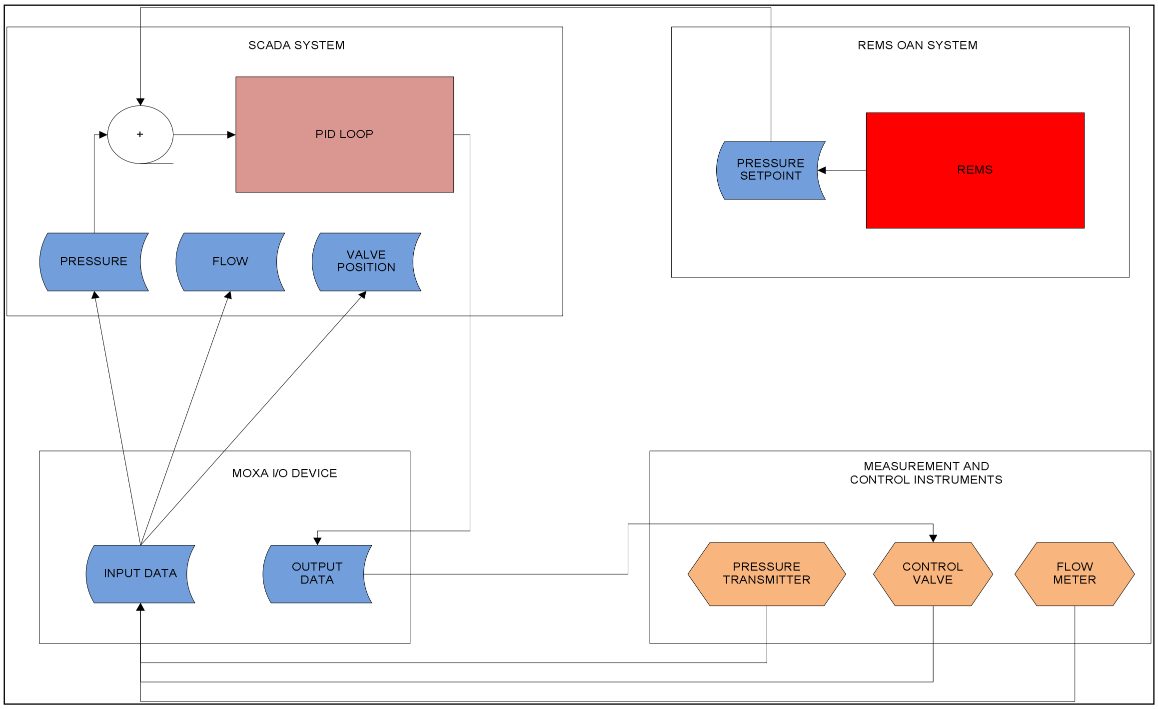

Figure 21: PID control process

4.2.2.2 The REMS-OAN system and the SCADA interface

The REMS-OAN system communicates the set point to the SCADA according to a specified pressure schedule. Individual pressure schedules are programmed into the REMS-OAN system for each valve. The SCADA will control the valves according to these pressure set points.

The REMS-OAN communicates with the SCADA systems of both North and South shaft through the OPC server. The OPC server is installed on the North and South shaft SCADA servers and runs as a background service. The OPC Data Manager runs from the REMS-OAN server. The Data Manager establishes a remote OPC connection between the SCADA systems and the REMS-OAN system.

A simplified flow diagram of the system is shown in Figure 23.

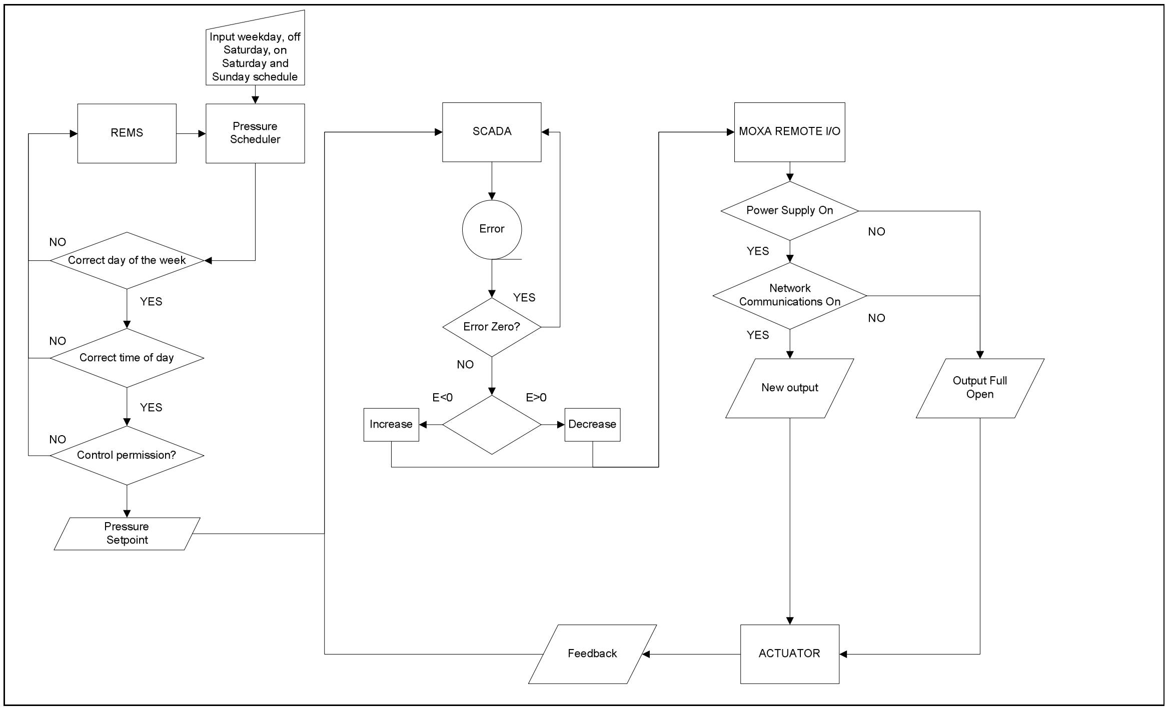

Figure 22: REMS & SCADA control flow diagram

The equipment installed underground allows control of the flow to each of the levels. On the surface, the compressors are controlled to start, stop, load and off-load as necessary to control the ring pressure according to a pressure set point. The compressor control system is configured to maintain a low pressure set-point during periods of little underground operational activity. The method adopted is to reduce the demand of air underground. This will increase the surface ring pressure and cause the compressors to start closing the IGV or even unload or switch off. The constraints for the compressed air system are shown in Table 15:

Table 15: System constraints

Constraint	Value
Minimum pressure of compressed air ring	400 kPa
Maximum pressure compressed air ring	600 kPa

The configuration of the compressor control system and underground pressure set-points is show Table 16. The REMS-OAN control system maintains the underground pressure set-points throughout the day.

Table 16: Compressor control system configuration

Time of day	Surface pressure set point (kPa)	Proposed underground control pressure (kPa)
00:00	480	450
01:00	480	450
02:00	480	450
03:00	480	450
04:00	480	450
05:00	480	450
06:00	550	600
07:00	600	600
08:00	600	600
09:00	600	600
10:00	600	600
11:00	600	600
12:00	550	600
13:00	550	600
14:00	500	600
15:00	480	600
16:00	480	400
17:00	480	200
18:00	480	200
19:00	480	200
20:00	480	200
21:00	480	400
22:00	480	450
23:00	480	450

Pressure schedules for valve controllers for working weekdays as well as working and non-working weekends can be set on the REMS-OAN platform. The REMS-OAN system is divided into several display platforms. These platforms are summarised as follows:

- The system display at North, South and D-shaft as well as the surface flow and pressures measured at the shafts, are shown in Figure 24
- A display of the pressure and flow values of each shaft is shown in Figure 25
- Displays of the pressure and flow values for each level can also be selected. An example of such a view is shown in Figure 26

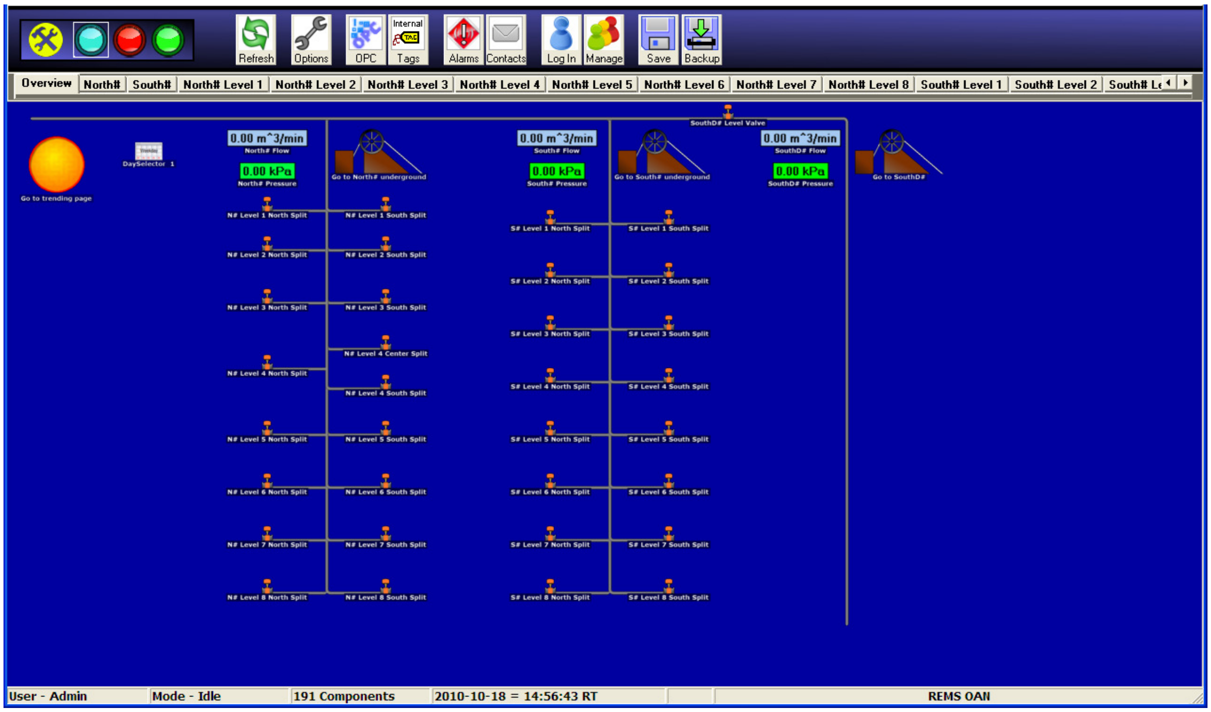

Figure 23: Overview of BRPM on the REMS-OAN system

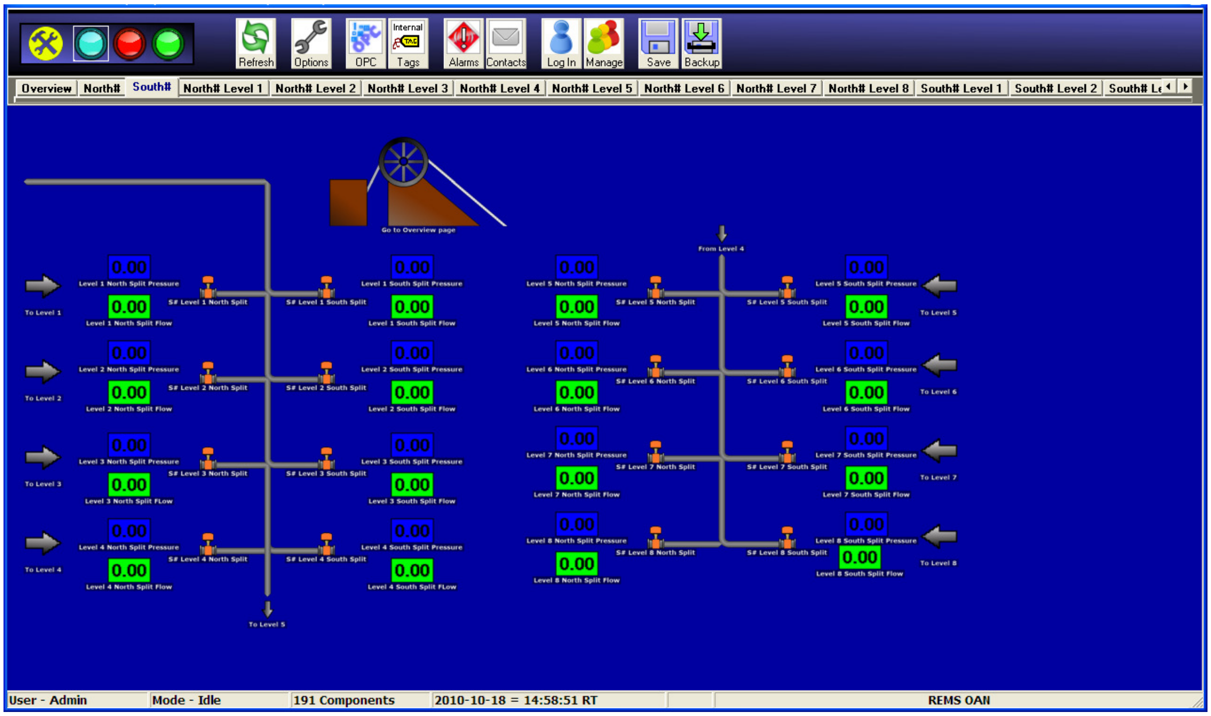

Figure 24: Layout of South shaft showing pressures and flows for each level

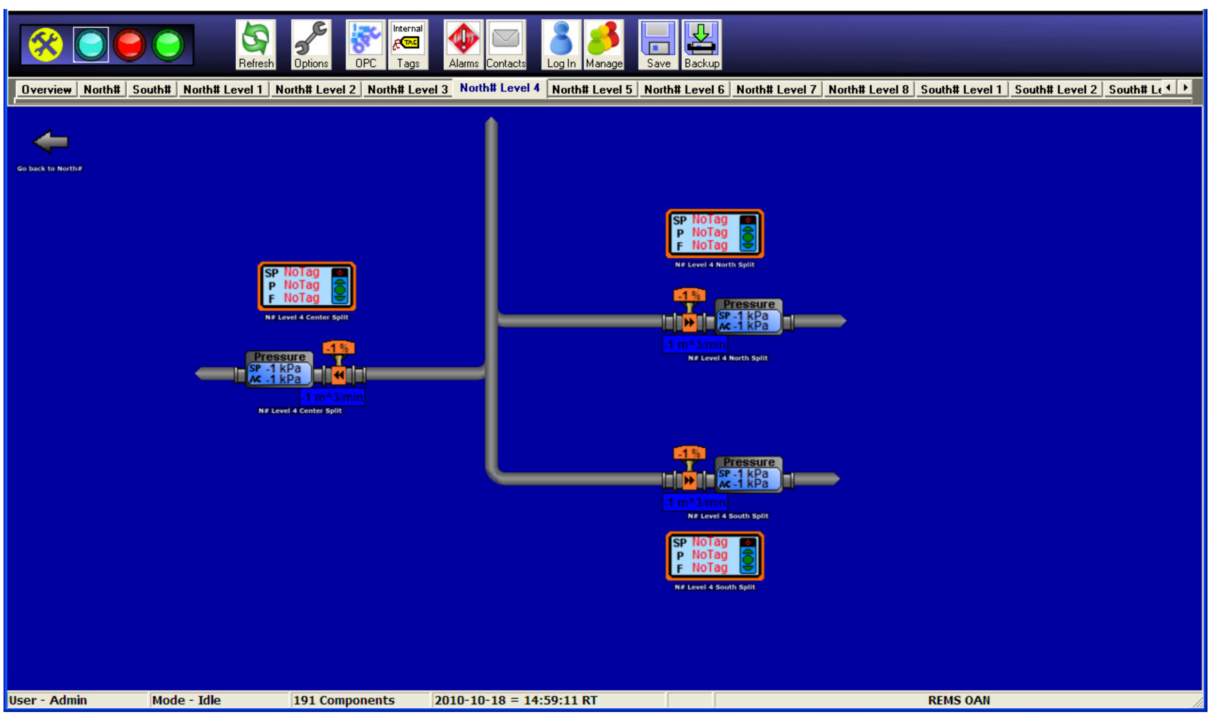

Figure 25: Valve layout on North shaft level 4.

4.3 Verification of underground control system simulation

In order to determine the success of the project a standard of measure was defined. This was done by calculating the average daily power consumption of the mine before any interventions were implemented. The power profile was obtained from actual power usage taken at two-minute intervals over an extended period of time. This profile is referred to as the baseline power profile. These results were then used as standard against which the effectiveness of the implemented control system could be measured.

It was assumed that the system and production remained unchanged. In order to ensure a valid and accurate baseline, an independent Measure and Verification team (M&V team) was deployed to evaluate the original baseline according to a set of criteria. In the event of any change, a new baseline had to be set up for the system.

The actual average power consumption profile of the system, before and after the implementing of DSM interventions is shown in Figure 20.

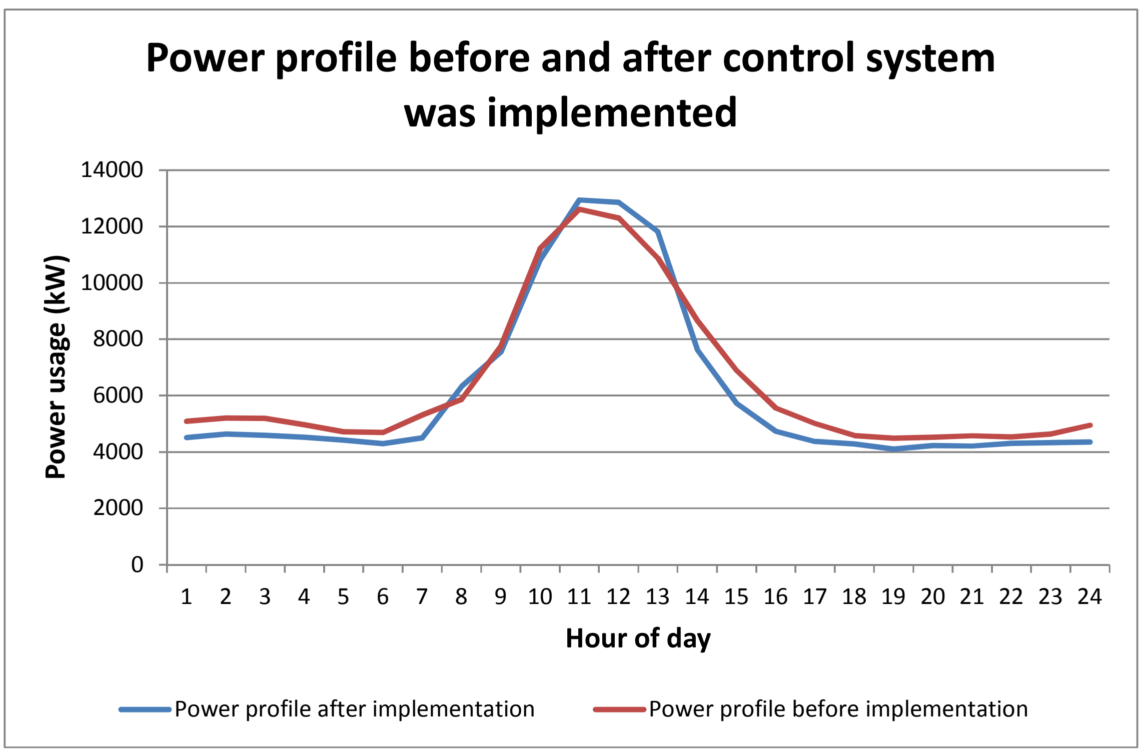

Figure 26: Resulting energy usage after DSM intervention

During the morning and afternoon shifts, between 00:00–08:00 and 14:00–23:00, the actual energy consumption was slightly more than originally expected. During project implementation new working schedules were introduced. The underground pressure control set point was increased to allow cleaning activities to take place, which was not taken into account in the original simulations. The average daily power usage after implementation is shown in Table 17.

Table 17: Power usage before and after implementation

		After implementation			Before implementation
		Month 1 (kW)	Month 2 (kW)	Month 3 (kW)	Baseline power usage (kW)
Hour of day	0	4768.1	4260.7	4250.7	6086.0
	1	4982.4	4408.6	4263.3	6256.0
	2	4936.0	4392.2	4218.1	6178.0
	3	4876.9	4293.9	4140.5	6124.0
	4	4738.2	4179.0	4134.2	5819.0
	5	4412.3	4152.6	4098.8	5623.0
	6	4792.3	4209.1	4161.6	6538.0
	7	6174.4	6170.5	6470.3	8151.0
	8	7082.3	7385.0	7920.4	10081.0
	9	10525.3	10784.4	11099.8	12074.0
	10	12965.2	13061.4	12998.7	12411.0
	11	12749.5	13049.3	12928.7	12609.0
	12	11776.7	12093.3	11701.1	12083.0
	13	8615.7	7283.0	6747.4	9452.0
	14	6566.5	5527.5	4902.2	6850.0
	15	5330.8	4492.9	4299.8	5031.0
	16	4705.2	4234.5	4120.8	4623.0
	17	4731.9	3973.6	4039.7	4846.0
	18	4187.0	4065.2	3954.9	4944.0
	19	4363.4	4129.5	4093.2	4999.0
	20	4349.3	4133.0	4060.7	4942.0
	21	4370.9	4282.3	4179.4	4900.0
	22	4545.7	4211.1	4110.6	5088.0
	23	4513.8	4224.3	4175.1	5602.0
Average daily power saving (kW)		843.8	1179.7	1260.0	
Average energy saving (kWh)		20250.2	28313.2	30240.0	

The financial savings for this period is shown in Table 18.

Table 18: Financial savings achieved after implementation

		After implementation		
		Month 1 (R/c)	Month 2 (R/c)	Month 3 (R/c)
Hour of day	0	R 224.43	R 310.84	R 312.55
	1	R 216.89	R 314.61	R 339.35
	2	R 211.52	R 304.12	R 333.77
	3	R 212.37	R 311.67	R 337.79
	4	R 184.07	R 279.30	R 286.92
	5	R 206.18	R 250.42	R 259.57
	6	R 425.08	R 567.10	R 578.66
	7	R 785.71	R 787.26	R 668.08
	8	R 1 191.97	R 1 071.67	R 858.85
	9	R 615.62	R 512.63	R 387.23
	10	R -	R -	R -
	11	R -	R -	R -
	12	R 74.59	R -	R 92.99
	13	R 203.64	R 528.15	R 658.56
	14	R 69.03	R 322.04	R 474.29
	15	R -	R 131.02	R 178.04
	16	R -	R 94.59	R 122.30
	17	R 27.78	R 212.43	R 196.33
	18	R 300.92	R 349.31	R 393.19
	19	R 252.67	R 345.64	R 360.04
	20	R 144.32	R 196.99	R 214.60
	21	R 128.84	R 150.41	R 175.46
	22	R 92.35	R 149.33	R 166.45
	23	R 185.31	R 234.63	R 243.01
Total financial saving achieved (R/c)		R 5 753.30	R 7 424.15	R 7 638.01

The system has shown sustainable financial savings when implemented on an underground compressed air system.

5 Conclusion

5.1 Summary

It has been shown that comprehensive control on a mine compressed air network can yield significant savings if the high initial cost can be justified. The implementation of an underground control system requires a very large initial capital investment, resulting in longer payback periods. Although this is the case, it has also been shown and verified that sustainable savings can be achieved if the system is utilised properly and serviced and maintained throughout operation. The underground system of valves also provides the opportunity to seal off compressed air supply to certain mining levels should it be required by the mine.

The mine at which the system was implemented consisted of a total of 33 mining levels. When only surface valves were installed, the payback period of the system was significantly shorter. Improved savings can be expected with the implementation of underground compressed air control on smaller mines while surface air control would be more beneficial to larger mines.

The use of butterfly valves proved adequate for compressed air control. Although linear valves such as ball or globe valves should provide more stable control, the initial cost increase could negatively affect the viability of the project.

Effective valve control on compressed air system has a beneficial effect on reducing compressed air leaks. The best course of action for higher energy savings would be to detect and repair any leaks in the pipeline. For this purpose it is necessary to implement a leakage detection programme.

It is possible to accurately identify air loss with the implementation of control valve systems as a result of flow measurement that is commissioned with the system. As was done in the simulation, calculations can be done to determine air leakage between points of measurement. Due to the size of mining operations, implementation of flow measurement will require a large capital investment which outweighs the need to have accurate leakage data. Other methods such ultrasonic leakage detection might need to be implemented to detect leaks that occur in areas where flow measurement is present.

5.2 Limitations

It is obvious that the maximum electrical cost saving will be achieved by completely shutting off the compressed air to the working section. However, this cannot be done because mining safety rules and regulations stipulate that underground refuge bays must always have a constant air supply. Other mining related activities such as underground engineering workshops also require a constant supply of compressed air.

The underground compressed air control system presented in this study was implemented at a mine where a central blasting system is used. This means that all mining levels on the respective mining shaft were scheduled for blasting at the same time. On mines that do not have a centralised blasting system, blasting schedules may differ from section to section.

If that is the case, the underground control system provides the advantage of flexible control by changing the pressure schedule of each valve to accommodate the varying pressure requirements. The surface control implementation would fail in this case, as the system would always be required to provide maximum air pressure to a section of the mine.

5.3 Recommendations

Further study is required to determine whether a combination of both strategies will provide improved results. This study presented two scenarios where automatic valve control is implemented either on the surface or underground. However, it is also possible to implement a combination of underground and surface control. For example, underground control valves can be installed on the upper mining levels with controls installed underground on the main airline to provide collective control for the deeper mining levels. If possible, control valves can be installed only on sections that consume the most air. Savings can be realised by reducing the pressure requirements at these sections alone.

An improved control valve simulation can be developed for further study. The model presented in this paper only took the energy savings realised as a result of the reduction in air leakage into account. The control valve model should be expanded to also take savings as a result of frictional losses into account. The reduction in air pressure would result in reduced frictional loss proportional to the square of the flow velocity.

References

[1] M. Webb. (2008, March) Eskom says load shedding may resume. *Engineering News.* Article. [Online]. http://www.engineeringnews.co.za/article/eskom-says-load-shedding-may-resume-2008-03-05

[2] (2008, January) National response to South Africa's electriciy shortage. Report. [Online]. http://www.info.gov.za/otherdocs/2008/nationalresponse_sa_electricity1.pdf

[3] Sim.Intelligence. (2009, November) Eskom - On the road to excess capacity. Article. [Online]. http://simintelligence.co.za/simblog/economy/eskom-on-the-road-to-excess-capacity/

[4] Mail & Guardian. (2009, October) Eskom to reach reserve margin target in five years. Article. [Online]. http://mg.co.za/article/2009-10-06-eskom-to-reach-reservemargin-target-in-five-years

[5] ESKOM, "ESKOM Annual Report," Eskom, 2010. Report. [Online]. http://financialresults.co.za/2012/eskom_ar2012. Physical address: *Megawatt Park, Maxwell Drive, Sunninghill, Sandton.*

[6] S. Saini, "Conservation v. Generation," *Focus*, no. June, pp. 52-54, 2004.

[7] M. Yang, "Demand side management in Nepal," *Energy*, vol. 31, pp. 2677-2698, 2006.

[8] S. Malik, "Impact on power planning due to demand-side management (DSM) in commercial and government sectors with rebound effect - A case study of central grid of Oman," *Energy*, vol. 32, pp. 2157-2166, 2007.

[9] H. Lund, G. Salgi, B. Elmegaard, and N. Andersen, "Optimal operation strategies of compressed air energy storage (CAES) on electricity spot markets with fluctuating prices," *Applied Thermal Engineering*, vol. 29, no. 5-6, pp. 799–806, May 2009.

[10] W. Booysen, "Reducing energy consumption on RSA mines through optimised compressor control," North-West University, Potchefstroom, M.Eng Dissertation 2010.

[11] C. Scmidt and K. Kissock, "Modeling and Simulation of Air Compressor Energy Use," ACEEE Summer Study on Energy in Industry, West Point, NY,.

[12] R. Saidur, N.A. Rahimb, and M. Hasanuzzamana, "A review on compressed-air energy use and energy savings," *Renewable and Sustainable Energy Reviews*, vol. 14, pp. 1135–1153, 2010.

[13] H. Neser, "Energy Savings through the Automatic Control of Underground Compressed Air Demand," North-West University, Potchefstroom, M.Eng Dissertation November 2008.

[14] United States Enviromental Protection Agency. (1998, July) Wise Rules for Industrial Efficiency: A tool for estimating energy savings and greenhouse gas emissions reductions. Office of Policy Planning and Evaluation EPA 231-R-98-014.

[15] A. Hussein, "Mathematical Formulation of the Demand Side Management (DSM) Problem and its Optimal Solution," in *Proceedings of the 14th International Middle East Power Systems Conference (MEPCON'10)*, Cairo, 2010.

[16] R. Joubert, "Cost and time effective DSM on mine compressed air systems," North-West University, Potchefstroom, M.Eng Dissertation 2010.

[17] J.W. Lodewyckx, "Investigating the effects of different DSM strategies on a compressed air ring," North-West University, Potchefstroom, M.Eng Dissertation 2007.

[18] Anglo Gold Ashanti. (2007) National energy efficiency accord - Anglo Gold Ashanti's role and contribution. Anglo Ashanti report to society 2007 Case studies - Environment. [Online]. http://www.anglogold.co.za/subwebs/informationforinvestors/reports07/ReportToSociety07/energy-accord.htm

[19] Anglo Gold Ashanti. (2007) Energy recovery at Mponeng using ice. AngloGold Ashanti Report to Society 2007 Case Studies – Environment. [Online]. http://www.anglogold.co.za/subwebs/informationforinvestors/reports07/ReportToSociety07/files/energy_mponeng.pdf

[20] M. Biffi and D. Stanton, "Meeting the reduced availability and rising costs of electrical power: Anglo Platinum ventilation and cooling strategies," *The Journal of The South African Institute of Mining and Metallurgy*, vol. 111, pp. 109-116, February 2011.

[21] J. Cooper. (2008) Practical Process Control: Proven Methods and Best Practices for Automatic PID Control. Electronic Book. [Online]. http://www.controlguru.com/

[22] Ingersoll Rand. (2012, February) Ingersoll Rand Company website. [Online]. www.ingersollrand.pl/air/Download/J-Centac-services/Control enhancements/ASC-Flyer_E.pdf

[23] K. McMillan and M. Considine, *Process/Industrial Instruments and Controls Handbook*, 5th ed. New York, United States: McGraw-Hill, 1999.

[24] B.G. Lipták, *Process Control and Optimization Volume II*, 4th ed., Béla G. Lipták, E. United States: CRC Press, 2006.

[25] Instrument Society of America (ISA). (2002, July) Flow equations for sizing control valves. ANSI/ISA-75.01.01-2002 (60534-2-1 Mod).

[26] Emerson Process Management, *Control Valve Handbook*, 4th ed. United States: Fisher Controls International, 2005.

[27] Sure Flow Equipment Inc. (2012, August) Sure Flow Equipment Inc. [Online]. http://www.sureflowequipment.com/butterfly/page7.cfm

[28] F.W. Schroeder, "Energy efficiency oppurtunities in mine compressed air systems," North-West University, Pretoria, Masters Dissertation 2009.

[29] M Sessions. (1997, August) IDC Online. [Online]. http://www.idc-online.com/technical_references/pdfs/instrumentation/valveselect.pdf

[30] R.S., Hussein, A.A., Fayez, F.G.A. Shehata, "Variable structure surge control for constant speed centrifugal compressors," *Control Engineering Practice*, vol. 17, no. 7, pp. 815-833, July 2009.

[31] M. Nored, A. Garcia-Hernandez, K. Brun, and J. Moore, "Compressor Surge Control: Design And Modeling For Performance Verification," *Pipeline and Gas Journal*, vol. 236, no. 9, September 2009.

[32] P. Underhill. (2005, August) Anti-surge control valve solutions. Article from SA Instrumentation and Control. [Online]. http://www.instrumentation.co.za/article.aspx?pklarticleid=3603

[33] B.P. Urbanowicz, "Q&A: Trends in Valve Actuation & Control," *Flow Control*, vol. XV, no. 8, 2009.

[34] SMAC Europe Ltd. (2012, October) Actuator delivers benefits of electronics and pneumatics. Article. [Online]. http://www.machinebuilding.net/p/p0670.htm

[35] Design News. (2007, July) Linear Actuators: Choosing Pneumatic or Electric Control. Article. [Online]. http://www.designnews.com/document.asp?doc_id=221771

[36] A. Cengel and A. Boles, *Thermodynamics: An Engineering Approach*, 5th ed. United States of America: McGraw-Hill, 1989.

[37] Efunda. [Online]. http://www.efunda.com/formulae/fluids/roughness.cfm

[38] B. R. Munson, D. F. Young, and T. H. Okiishi, *Fundamentals of Fluid Mechanics*, 5th ed. Ames, United States of America: John Wiley & Sons Inc., 2006.

[39] Eskom. (2010, April) Tariffs & Charges 2010/11. Document. [Online]. http://www.eskom.co.za/c/53/tariffs-and-charges/

[40] L. Blank and A. Tarquin, *Engineering Economy*, 6th ed., Kenneth E Case and Philip M Wolfe, Eds. New York, United States of America: McGraw-Hill, 2005.

Appendix A

Table A1: Best inherent valve characteristics for various applications

Liquid-Level Systems

Control Valve Pressure Drop	Best Inherent Characteristic
Constant ΔP	Linear
Decreasing ΔP with increasing load, ΔP at maximum load >20% of minimum-load ΔP	Linear
Decreasing ΔP with increasing load, ΔP at maximum load <20% of minimum-load ΔP	Equal percentage
Increasing ΔP with increasing load, ΔP at maximum load <200% of minimum-load ΔP	Linear
Increasing ΔP with increasing load, ΔP at maximum load >200% of minimum-load ΔP	Quick opening

Pressure Control Systems

Application	Best Inherent Characteristic
Liquid process	Equal percentage
Gas process, small volume, less than 10 ft of pipe between control valve and load valve	Equal percentage
Gas process, large volume (process has receiver, distribution system, or transmission line exceeding 100 ft of nominal pipe volume), decreasing ΔP with increasing load, ΔP at maximum load >20% of minimum-load ΔP	Linear
Gas process, large volume, decreasing ΔP with increasing load, ΔP at maximum load <20% of minimum load ΔP	Equal percentage

Flow Control Processes

Flow measurement signal to controller	Location of control valve in relation to measuring element	Best Inherent Characteristic	
		Wide range of flow set point	Small range of flow but large ΔP change at valve with increasing load
Proportional to flow	In series	Linear	Equal percentage
	In bypass[†]	Linear	Equal percentage
Proportional to flow squared	In series	Linear	Equal percentage
	In bypass	Equal percentage	Equal percentage

* Based on a combination of applied control theory and actual experience. (*Fisher Controls International, Inc.*)
† When control valve closes, flow rate increases in measuring element.

Table A2: C_v table for a typical butterfly valve

Size	Flow in GPM @ 1 PSI △ P@Various Disc Angles.								Full 90° Open
	10°	20°	30°	40°	50°	60°	70°	80°	
2"	0.1	5	12	24	45	64	90	125	135
2 1/2"	0.2	8	20	37	65	98	144	204	220
3"	0.3	12	22	39	70	116	183	275	302
4"	0.5	17	36	78	139	230	364	546	600
5"	0.8	29	61	133	237	392	620	930	1,022
6"	2	45	95	205	366	605	958	1,437	1,579
8"	3	89	188	408	727	1,202	1,903	2,854	3,136
10"	4	151	320	694	1,237	2,047	3,240	4,859	5,340
12"	5	234	495	1,072	1,911	3,162	5,005	7,507	8,250
14"	6	338	715	1,549	2,761	4,568	7,230	10,844	11,917
16"	8	464	983	2,130	3,797	6,282	9,942	14,913	16,388
18"	11	615	1,302	2,822	5,028	8,320	13,168	19,752	21,705
20"	14	791	1,674	3,628	6,465	10,698	16,931	25,396	27,903
24"	22	1,222	2,587	5,605	9,989	16,528	26,157	39,236	43,116
28"	36	1,813	3,639	6,636	11,061	18,673	29,732	44,343	49,500
32"	45	2,387	4,791	8,736	13,788	20,613	31,395	48,117	68,250
36"	60	3,021	6,063	11,055	17,449	26,086	39,731	60,895	86,375
40"	84	4,183	8,395	15,307	24,159	36,166	55,084	84,425	119,750

Table A3: Typical risk assessment form

Scope: Mine Name North & South shaft Level 1 to 8 both splits | Page: 1 of 1

Operation Description: Operation of air control system to control compressed air consumption | Relevant Documents: Risk rank table | Date: 2010-06-10

No	Step in operation	Hazard	Unwanted event/Incident	Likelihood	Consequence	Risk Ranking	Existing recommended controls	Agreed action	Accountable person
1	REMS	System Failures	Control system malfunction, does not schedule pressure set-point	4	2	12	1. Manually check server and restart 2. Watchdog timer	1. Instrumentation specialist must resolve problem 2. Operator must inform instrumentation specialist about incident	Instrumentation specialist, Operator
		Network failures	REMS-SCADA communication failure	4	2	12	1. Manually check server and restart OPC 2. Alarms indicating no connection 3. Watchdog timer	1. Instrumentation specialist must resolve problem 2. Operator informs instrumentation specialist about incident when he sees the alarm	Instrumentation specialist, Operator
			Networking equipment malfunction	4	2	12	1. Instrumentation specialist fixes network problems	1. Instrumentation specialist repairs faulty equipment	Instrumentation specialist
		Power failure	REMS system malfunction after extended power failure	4	2	12	1. Manually open control valve using override	1. Operator or instrumentation specialist must phone foreman informing him of power failure and request to manually open control valve 2. Restart REMS server after power is restored	Instrumentation specialist, Operator, Foreman
			REMS system malfunction after abrupt power failure	4	1	7	1. Server connected to UPS	1. Ensure server is connected to UPS	Instrumentation specialist
2	SCADA	System failures	System malfunctions and does not execute commands and/or give correct feedback	4	2	12	1. Manually check server and restart	1. Instrumentation specialist must resolve problem 2. Operator must inform instrumentation specialist of incident	Instrumentation specialist
		Power failure	SCADA server malfunction after extended power failure	4	2	12	1. Manually open control valve using manual override	1. Operator or instrumentation specialist must phone foreman informing him of power failure and to manually open control valve 2. Restart SCADA server after power is restored	Instrumentation specialist, Foreman
			SCADA server malfunction after abrupt power failure	4	1	7	1. SCADA server connected to UPS	1. Ensure server is connected to UPS	Instrumentation specialist
3	Control valve unit	Control valve unit failure	Control valve failure	4	2	12	1. Shaft technician to fix problem	1. Shaft technician must resolve problem	Shaft technician, Mechanical foreman
			I/O failure	4	2	12	1. Shaft technician to fix problem 2. Valve opened using override	1. Shaft technician must resolve problem 2. Foreman must manually open control valve	Instrumentation technician, Foreman
			Pressure and/or flow transmitter failure	4	2	12	1. Mechanical foreman to fix problem	1. Mechanical foreman must replace faulty pressure/flow transmitter	Mechanical foreman
3	Control valve unit	Control valve unit failure	Cabling fault	3	2	8	1. Shaft technician to fix problem 2. Valve opened using override	1. Ensure enclosure is secured and equipment is protected from tampering and environmental damage. 2. Shaft technician resolves cabling problem	Shaft technician, Mechanical foreman
			Valve opened manually without authorisation	3	1	4	1. Disengage and lock manual override	1. Ensure manual override is disengaged and locked out	Technician, Foreman
		Power failure	Abrupt power failure	4	1	7	1. Control valve unit connected to UPS 2. Power failure signal from UPS 3. Valve return to open position when supply to UPS fails	1. Ensure that UPS is connected to valve 2. Import the power failure signal as tag in SCADA and check for alarm	Technician, Instrumentation specialist
			Complete failure of underground power	4	2	12	1. Manual override on valve 2. Valve return to open position when power fails	1. Open valve using manual override	Foreman, Technician

Appendix B1: Code used for underground piping simulation

```
g = 9.81
rho = DENSITY(Air_ha,T=35,P=101)
gg = g*2
f = 0.025
D_1 = 0.45

q_2 = (q_1N + q_1S)/60
q_4 = (q_2N + q_2S)/60
q_6 = (q_3N + q_3S)/60
q_8 = (q_4N + q_4S +q_4C)/60
q_10 = (q_5N + q_5S)/60
q_12 = (q_6N + q_6S)/60
q_14 = (q_7N + q_7S)/60
q_16 = (q_8N + q_8S)/60

q_s_leaks = q_s
q_1 = q_s
q_1 = q_2 + q_3
q_3 = q_4 + q_5
q_5 = q_6 + q_7
q_7 = q_8 + q_9
q_9 = q_10 + q_11
q_11 = q_12 + q_13
q_13 = q_14 + q_15
q_15 = q_16

l_2 = 218
l_3 = 241
l_4 = 171
l_5 = 239
l_6 = 288
l_7 = 154
l_8 = 270
l_1 = 230

h_1 = 45
h_2 = 90 - h_1
h_3 = 124 - h_2 - h_1
h_4 = 157 - h_3 - h_2 - h_1
h_5 = 191 - h_4 - h_3 - h_2 - h_1
h_6 = 224 - h_5 - h_4 - h_3 - h_2 - h_1
h_7 = 283 - h_6 - h_5 - h_4 - h_3 - h_2 - h_1
h_8 = 322 - h_7 - h_6 - h_5 - h_4 - h_3 - h_2 - h_1

A_1 = (pi/4)*(D_1**2)

Power_req = P_s*q_s_leaks

V_1 = (q_1)/A_1
V_2 = (q_2)/A_1
V_3 = (q_3)/A_1
V_4 = (q_4)/A_1
V_5 = (q_5)/A_1
V_6 = (q_6)/A_1
V_7 = (q_7)/A_1
V_8 = (q_8)/A_1
```

V_9 = (q_9)/A_1
V_10 = (q_10)/A_1
V_11 = (q_11)/A_1
V_12 = (q_12)/A_1
V_13 = (q_13)/A_1
V_14 = (q_14)/A_1
V_15 = (q_15)/A_1
V_16 = (q_16)/A_1

P_s + 0.5*rho*V_1**2 = P_1 + 0.5*rho*V_2**2 - rho*g*h_1 + rho*g*f*(h_1/D_1)*(V_1**2/gg) + rho*g*f*(l_1/D_1)*(V_2**2/gg)

P_s + 0.5*rho*V_1**2 = P_2 + 0.5*rho*V_4**2 - rho*g*(h_1 + h_2) + rho*g*f*(h_1/D_1)*(V_1**2/gg) + rho*g*f*(h_2/D_1)*(V_3**2/gg) + rho*g*f*(l_2/D_1)*(V_4**2/gg)

P_s + 0.5*rho*V_1**2 = P_3 + 0.5*rho*V_6**2 - rho*g*(h_1 + h_2 + h_3) + rho*g*f*(h_1/D_1)*(V_1**2/gg) + rho*g*f*(h_2/D_1)*(V_3**2/gg) + rho*g*f*(h_3/D_1)*(V_5**2/gg) + rho*g*f*(l_3/D_1)*(V_6**2/gg)

P_s + 0.5*rho*V_1**2 = P_4 + 0.5*rho*V_8**2 - rho*g*(h_1 + h_2 + h_3 + h_4) + rho*g*f*(h_1/D_1)*(V_1**2/gg) + rho*g*f*(h_2/D_1)*(V_3**2/gg) + rho*g*f*(h_3/D_1)*(V_5**2/gg) + rho*g*f*(h_4/D_1)*(V_7**2/gg) + rho*g*f*(l_4/D_1)*(V_8**2/gg)

P_s + 0.5*rho*V_1**2 = P_5 + 0.5*rho*V_10**2 - rho*g*(h_1 + h_2 + h_3 + h_4 + h_5) + rho*g*f*(h_1/D_1)*(V_1**2/gg) + rho*g*f*(h_2/D_1)*(V_3**2/gg) + rho*g*f*(h_3/D_1)*(V_5**2/gg) + rho*g*f*(h_4/D_1)*(V_7**2/gg) + rho*g*f*(h_5/D_1)*(V_9**2/gg) + rho*g*f*(l_5/D_1)*(V_10**2/gg)

P_s + 0.5*rho*V_1**2 = P_6 + 0.5*rho*V_12**2 - rho*g*(h_1 + h_2 + h_3 + h_4 + h_5 + h_6) + rho*g*f*(h_1/D_1)*(V_1**2/gg) + rho*g*f*(h_2/D_1)*(V_3**2/gg) + rho*g*f*(h_3/D_1)*(V_5**2/gg) + rho*g*f*(h_4/D_1)*(V_7**2/gg) + rho*g*f*(h_5/D_1)*(V_9**2/gg) + rho*g*f*(h_6/D_1)*(V_11**2/gg) + rho*g*f*(l_6/D_1)*(V_12**2/gg)

P_s + 0.5*rho*V_1**2 = P_7 + 0.5*rho*V_14**2 - rho*g*(h_1 + h_2 + h_3 + h_4 + h_5 + h_6 + h_7) + rho*g*f*(h_1/D_1)*(V_1**2/gg) + rho*g*f*(h_2/D_1)*(V_3**2/gg) + rho*g*f*(h_3/D_1)*(V_5**2/gg) + rho*g*f*(h_4/D_1)*(V_7**2/gg) + rho*g*f*(h_5/D_1)*(V_9**2/gg) + rho*g*f*(h_6/D_1)*(V_11**2/gg) + rho*g*f*(h_7/D_1)*(V_13**2/gg) + rho*g*f*(l_7/D_1)*(V_14**2/gg)

P_s + 0.5*rho*V_1**2 = P_8 + 0.5*rho*V_16**2 - rho*g*(h_1 + h_2 + h_3 + h_4 + h_5 + h_6 + h_7 + h_8) + rho*g*f*(h_1/D_1)*(V_1**2/gg) + rho*g*f*(h_2/D_1)*(V_3**2/gg) + rho*g*f*(h_3/D_1)*(V_5**2/gg) + rho*g*f*(h_4/D_1)*(V_7**2/gg) + rho*g*f*(h_5/D_1)*(V_9**2/gg) + rho*g*f*(h_6/D_1)*(V_11**2/gg) + rho*g*f*(h_7/D_1)*(V_13**2/gg) + rho*g*f*(h_7/D_1)*(V_15**2/gg) + rho*g*f*(l_8/D_1)*(V_16**2/gg)

Appendix B2: Input parameters for North shaft simulation

Ps (Pa)	q1N	q1S	q2N	q2S	q3N	q3S	q4N	q4C	q4S
494944	0	0	0	0	2.654	22.51	39.41	0	18.09
501676	0	0	0	0	3.604	22.57	39.55	0	18.16
517009	0	0	0	0	3.34	22.87	39.9	0	18.34
532502	0	0	0	0	0.8032	23.15	40.31	0	18.46
545202	0	0	0	0	0.4086	23.36	40.7	0	18.57
554160	0	0	0	0	0.6857	23.42	40.76	0	18.65
554765	0	0	0	0	0.6743	23.42	40.68	0	18.52
538719	0	0	0	0	1.331	23.33	40.29	0	18.88
557326	0	0	0.6012	0.09064	2.158	23.91	41.33	0	21.81
560284	0	0	12.48	0	2.668	27.6	41.75	0	29.06
565734	0	0	24.34	0.4015	2.423	29.14	42.45	0	29.76
558614	0	0	13.02	1.631	2.583	28.23	42.61	0	23.61
564508	0	0	0	3.32	0.5235	24.85	42.92	0	29.48
467988	0	0	0	1.374	2.444	22.33	39.9	0	18.4
445695	0	0	0	1.896	3.091	21.73	39.19	0	18.25
425390	0	0	0	0	1.741	21.07	38.48	0	17.69
432165	0	0	0	0.6921	2.529	21.38	38.78	0	17.93
443689	0	0	0	0	1.417	21.48	39.17	0	17.97
445956	0	0	0	0	1.474	21.53	39.03	0	17.91
446801	0	0	0	0	1.566	21.52	38.75	0	17.74
447183	0	0	0	0	1.686	21.38	38.44	0	17.58
447208	0	0	0	0	1.573	21.37	38.09	0	17.47
447228	0	0	0	0	1.266	21.33	37.81	0	17.33
446993	0	0	0	0	1.913	21.3	37.61	0	17.2

q5N	q5S	q6N	q6S	q7N	q7S	q8N	q8S
20.28	24.17	0	14.05	26.5	18.76	12.84	0
20.49	24.62	0	14.66	26.79	19.07	12.88	0
20.88	25.61	0	15.35	27.42	19.68	13.59	0
21.24	26.63	0	16.34	28.31	20.27	13.46	0
21.48	23.73	0	14.88	28.85	20.69	13.44	0
21.54	23.26	0	14.74	29.39	20.78	13.54	0
21.51	25.91	0	5.895	25.18	17.02	13.67	0.1544
21.69	34.8	0	16.32	25.81	27.36	14.6	2.564
24.55	56.27	2.235	22.49	31.9	32.99	21.09	18.17
25.02	92.77	3.093	44.32	40.39	32.51	30.09	22.57
25.39	99.76	1.726	57.79	42.93	31.64	24.06	20.72
25.6	79.96	0	60.86	41.86	28.67	20.28	17.42
23.89	56.06	0	42.88	36.83	21.73	16.32	13.24
19.97	30.3	0	16.59	24.61	18.82	12.02	0.634
19.77	27.04	0	3.413	24.03	16.62	12.05	0
18.96	27.1	0	0.7988	22.57	14.26	11.38	0
19.39	27.88	0	1.101	23.26	15.11	11.69	0
19.47	28.28	0	0	23.63	15.35	11.7	0
19.46	28.26	0	0	23.74	15.36	11.69	0
19.49	28.23	0	0	23.75	15.36	11.7	0
19.39	28.09	0	0	23.82	15.29	11.68	0
19.32	28.13	0	0	23.87	15.26	11.67	0
19.26	28.13	0	0	24	15.27	11.73	0
19.34	28.14	0	0	24.04	15.23	11.7	0

Appendix B3: Input parameters for South shaft simulation

Ps (Pa)	q1N	q1S	q2N	q2S	q3N	q3S	q4N	q4S
476820	0	0	18.4	0	17.92	22.01	6.653	3.577
482893	0	0	19.01	0	10.83	22.12	6.393	3.128
497936	0	0	19.12	0	16.08	22.34	6.445	4.093
513009	0	0	18.94	0	7.581	22.64	6.903	3.742
525801	0	0	19.22	0	7.51	22.84	6.654	3.371
534553	0	0	19.41	0	7.363	23.02	6.598	3.229
535338	0	0	19.44	0	11.89	23.04	6.278	3.194
523797	0	0	19.74	0	26.39	22.76	6.97	4.846
551457	0	0	24.51	0	34.84	22.98	8.151	15.3
549399	0	0	31.54	0	28.66	22.87	17.41	28.67
550453	0	0	29.8	0	28.23	23.12	23.27	30.69
545207	0	0	29.72	0	30.75	23.11	21.24	26.57
556839	0	0	22.86	0	29.35	23.35	14.65	25.13
463416	0	0	17.83	0	20.76	21.68	8.476	6.857
441356	0	0	17.15	0	20.32	21.17	7.687	3.797
420799	0	0	16.59	0	18.61	20.86	6.956	3.002
426059	0	0	16.77	0	19.45	20.89	7.485	3.798
435543	0	0	16.79	0	19.64	21.14	7.423	4.11
433553	0	0	16.79	0	19.49	21.09	7.331	4.207
432083	0	0	16.77	0	19.47	21.1	7.185	3.829
431032	0	0	16.77	0	19.48	21.1	6.787	3.578
430062	0	0	16.77	0	19.59	21.11	6.596	3.205
429104	0	0	16.76	0	19.73	21.12	6.629	3.313
427780	0	0	16.78	0	19.51	21.1	6.603	3.263

q5N	q5S	q6N	q6S	q7N	q7S	q8N	q8S
17.77	23	17.77	19.2	37.06	22.16	24.19	22.54
18.07	23.91	18.07	18.74	36.08	22.45	14.08	15
18.86	23.88	18.86	20.19	31.08	21.48	11.46	17.43
19.3	24.61	19.3	20.52	31.2	21.95	11.65	17.51
19.35	25.1	19.35	19.61	31.29	21.8	8.715	14.74
19.56	25.43	19.56	17.91	30.18	22.45	6.242	12.18
19.32	25.21	19.32	18.99	29.79	25.79	7.223	26.64
19.22	25.47	19.22	21.59	30.6	33.49	17.21	42.01
18.73	42.64	18.73	51.51	46.87	65.24	41.38	83.09
18.47	74.33	18.47	80.58	97.98	90.86	56.49	80.57
14.6	87.77	14.6	96.68	116.1	86.7	59.62	50.42
16.28	77.67	16.28	82.85	110.6	81.59	46.33	37.16
14.75	63.41	14.75	68.53	83.62	77.11	32.83	21.7
11.69	38.33	11.69	47.03	43.24	45.24	17.83	8.637
12.12	24.83	12.12	32.37	23.27	26.05	12.74	4.894
11.44	20.89	11.44	13.26	15.74	15.86	7.375	3.071
12.01	21.39	12.01	14.16	15.84	16.25	5.682	4.008
11.71	21.63	11.71	13.93	15.9	16.41	5.84	3.919
11.75	21.51	11.75	14.48	15.98	16.42	6.44	4.661
11.94	21.52	11.94	13.17	15.92	16.4	4.569	2.509
11.91	21.5	11.91	13.45	15.96	16.36	4.742	2.737
11.94	21.59	11.94	13.15	15.92	16.36	4.472	2.445
12.06	21.65	12.06	13.15	15.91	16.4	4.635	2.695
12.18	21.54	12.18	14.64	16	16.39	6.071	4.318

Appendix C1: North shaft simulation results

P1	P2	P3	P4	P5	P6	P7	qs	qs leaks
495075	494957	494810	494671	494931	495397	495887	3.321	3.321
501795	501657	501491	501347	501598	502065	502552	3.373	3.373
517110	516942	516754	516586	516819	517291	517768	3.45	3.45
532595	532415	532227	532027	532241	532717	533186	3.483	3.483
545307	545145	544972	544779	545029	545489	545944	3.435	3.435
554262	554096	553918	553724	553978	554433	554883	3.446	3.446
554920	554843	554732	554597	554865	555388	555882	3.211	3.211
538738	538435	538151	537874	537957	538498	538916	3.783	3.783
556986	556083	555344	554657	554195	554893	555144	4.993	4.993
559250	557179	555672	554291	552759	553787	554045	6.739	6.739
564479	562000	560372	558861	557088	558115	558527	7.209	7.209
557714	555861	554538	553369	552147	552791	553308	6.439	6.439
564096	563073	562268	561428	561055	561603	562095	5.201	5.201
468088	467917	467740	467564	467764	468269	468782	3.456	3.456
445870	445825	445744	445657	445933	446461	446968	3.118	3.118
425610	425639	425614	425560	425852	426384	426916	2.901	2.901
432366	432363	432313	432246	432524	433063	433584	2.996	2.996
443893	443898	443854	443778	444055	444599	445116	2.975	2.975
446161	446166	446122	446048	446324	446867	447384	2.974	2.974
447006	447013	446970	446902	447174	447718	448234	2.968	2.968
447391	447402	447362	447300	447571	448113	448629	2.956	2.956
447419	447433	447397	447339	447607	448148	448664	2.946	2.946
447440	447458	447425	447370	447635	448176	448691	2.935	2.935
447204	447220	447183	447134	447396	447937	448453	2.941	2.941

Appendix C2: South shaft simulation results

P1	P2	P3	P4	P5	P6	P7	qs	qs leaks
477125	477013	476932	477129	477181	477412	477890	4.204	4.204
483234	483231	483259	483473	483562	483834	484358	3.798	3.798
498272	498254	498251	498491	498584	498855	499430	3.855	3.855
513353	513359	513402	513604	513685	513955	514529	3.764	3.764
526154	526186	526248	526467	526559	526847	527428	3.659	3.659
534914	534972	535053	535287	535390	535699	536285	3.552	3.552
535667	535627	535625	535832	535894	536165	536706	3.935	3.935
524039	523734	523481	523646	523611	523796	524223	4.825	4.825
551256	549616	548404	547882	547110	546715	546530	7.9	7.9
548591	545108	542700	540938	539019	537976	536608	10.78	10.78
549584	545926	543367	541441	539385	538280	536976	11.03	11.03
544582	541652	539602	538199	536618	535862	534818	10	10
556584	554784	553471	552735	551831	551468	551026	8.201	8.201
463639	463285	463017	463085	462979	463052	463478	4.988	4.988
441711	441750	441761	442046	442199	442429	443072	3.642	3.642
421218	421451	421601	421973	422229	422587	423228	2.752	2.752
426473	426691	426828	427197	427448	427803	428448	2.829	2.829
435956	436173	436308	436678	436930	437287	437929	2.836	2.836
433964	434176	434307	434674	434923	435275	435918	2.865	2.865
432500	432730	432873	433249	433504	433866	434509	2.772	2.772
431450	431679	431822	432199	432452	432813	433457	2.772	2.772
430481	430714	430859	431239	431493	431855	432499	2.751	2.751
429522	429752	429894	430273	430525	430887	431531	2.769	2.769
428193	428408	428542	428913	429158	429511	430156	2.843	2.843

Appendix D1: Underground valve simulation input data for North shaft (line pressure)

	Hour	N# 2L N	N# 2L S	N# 3L N	N# 3L S	N# 4L N	N# 4L C	N# 4L S
Line pressure	0	436.42176	432.58818	437.38664	437.76354	442.8219	442.20391	442.916
	1	429.50891	425.64075	430.3212	430.67521	435.75087	435.07032	435.89482
	2	428.60253	424.80761	429.33699	429.71542	435.07896	434.21734	435.00369
	3	425.32336	421.68104	426.02681	426.47898	432.70212	430.94428	432.67872
	4	443.18093	439.57612	444.03964	444.45269	450.90883	448.99251	450.82412
	5	449.49569	445.98255	450.39343	450.84001	457.40139	455.42179	457.21726
	6	442.38753	438.91661	443.26289	443.73795	450.20015	448.32939	450.00839
	7	486.13667	482.77104	486.96778	487.6051	494.20818	492.18992	494.15376
	8	579.26045	576.47314	580.65766	581.57779	587.88536	585.81419	588.27649
	9	551.3695	548.13143	552.19822	553.14322	559.3889	557.07689	559.60464
	10	471.83032	468.13255	471.41273	472.3237	477.58246	475.70001	477.80423
	11	446.86961	443.02993	446.11175	446.88233	451.88881	450.07299	452.26622
	12	503.41141	499.49544	503.52382	503.72981	509.24797	507.43623	509.88735
	13	494.27584	490.26271	494.23819	494.65883	500.40893	498.79148	501.25583
	14	465.31777	461.17342	465.24351	466.25823	472.44627	470.44836	472.96813
	15	436.52379	432.29283	436.8016	437.44037	443.15199	441.45245	443.87758
	16	435.02708	430.78203	435.38872	436.01587	441.73037	439.99186	442.50248
	17	441.38908	437.09366	439.85097	442.44348	448.1941	446.3503	448.89804
	18	437.96287	433.7056	435.84239	438.99311	444.57687	442.89995	445.32561
	19	436.81697	432.61514	434.88263	437.91663	443.70235	442.05183	444.29491
	20	432.52409	428.42044	430.68386	433.62326	439.23705	437.68826	439.735
	21	430.37156	426.35742	428.84057	431.48292	437.3017	435.73154	437.65265
	22	433.00831	429.14422	433.56273	434.19547	440.11495	438.46291	440.37792
	23	435.35281	431.43006	436.03594	436.47728	442.48346	440.8261	442.66188

	Hour	N# 5L N	N# 5L S	N# 6L N	N# 6L S	N# 7L N	N# 7L S	N# 8L N	N# 8L S
Line pressure	0	151.7347	441.69324	445.95153	444.46632	446.03037	443.76542	0	0
	1	148.14628	434.55151	438.80217	437.37494	438.79352	436.72084	0	0
	2	148.96773	433.52916	437.76862	436.29969	437.74929	435.56573	0	0
	3	146.76941	430.31408	434.48793	433.02815	434.45894	432.33794	0	0
	4	155.59046	448.59525	452.77201	451.27873	452.70361	450.59944	0	0
	5	159.94202	455.0576	459.30317	457.78846	459.19534	457.14147	0	0
	6	157.95682	447.81516	452.0175	450.53585	451.86084	449.49264	0	0
	7	172.09735	491.91069	496.31749	494.69393	496.15626	494.13392	0	0
	8	225.45103	586.2506	591.05109	588.56692	590.91477	588.90364	0	0
	9	211.12067	556.44601	560.1829	556.63859	559.85404	556.3813	0	0
	10	167.22209	474.19852	477.10892	474.07492	475.9528	471.9173	0	0
	11	150.08825	448.27039	450.99311	448.24903	449.09743	445.76486	0	0
	12	172.67567	505.6606	509.0669	506.23433	507.51049	504.6372	0	0
	13	170.94021	497.24119	501.04065	498.54633	499.95931	497.33729	0	0
	14	162.10575	469.86089	474.35976	472.61768	474.20106	471.93561	0	0
	15	150.87068	440.94206	429.47727	427.99136	429.5141	427.31523	0	0
	16	147.57254	439.4995	444.03754	442.54673	444.01516	441.93484	0	0
	17	150.48803	446.06445	450.66605	449.15185	450.69962	448.63152	0	0
	18	148.05566	442.6416	447.15195	445.61816	447.15301	445.11145	0	0
	19	147.93571	441.6256	446.10818	444.56194	446.13514	444.0767	0	0
	20	146.20889	437.37189	441.73648	440.21007	441.76649	439.69889	0	0
	21	145.69518	435.20053	439.56461	438.04888	439.58139	437.56619	0	0
	22	147.31009	438.01277	442.30869	440.83365	442.31378	440.26805	0	0
	23	150.63472	440.35894	444.57747	443.16777	444.65259	442.56446	0	0

Appendix D2: Underground valve simulation input data for North shaft (line flow)

	Hour	N# 2L N	N# 2L S	N# 3L N	N# 3L S	N# 4L N	N# 4L C	N# 4L S
Line flow	0	4.3115892	0.2034028	5.4457924	28.228275	44.032654	205.37485	0
	1	0	0	1.4619669	28.01236	43.783322	191.46764	0
	2	0	0	0	27.957733	43.52285	192.83517	0
	3	0	0	0	27.744259	43.543908	191.86813	0
	4	0	0	0	28.213984	44.308253	201.24795	0
	5	0	0	0	28.312657	44.440376	203.0696	0
	6	0	0	0.1469444	28.106813	43.952392	196.58608	0
	7	5.534905	1.0647746	6.509041	29.211261	47.450675	230.84737	0
	8	39.008469	0.3256275	21.135882	31.531853	63.043259	243.36752	0
	9	68.705219	0.1100228	29.913892	31.010174	51.357764	237.00897	0
	10	58.238193	0	31.992523	28.956588	50.567178	205.73382	0
	11	49.748989	0	38.834821	28.266117	46.928206	212.93529	0
	12	40.659953	0	19.478447	29.849698	56.907911	212.0464	0
	13	28.632486	0	15.528039	29.583428	54.909742	198.00488	0
	14	12.827192	0	9.7061112	28.776684	47.009384	225.16728	0
	15	0.6719757	0	5.2695717	27.975943	45.749126	196.04143	0
	16	0.1731899	0	0.4982071	27.960479	46.053559	197.42857	0
	17	0	0	0	28.139315	46.336156	200.95971	0
	18	0	0	0	28.021089	46.060726	197.56726	0
	19	0	0	0	28.072633	45.674831	201.29426	0
	20	0	0	0	27.953918	45.069962	199.08181	0
	21	0	0	0	27.905242	44.604562	199.59707	0
	22	7.8129243	0	1.7860685	27.916075	44.509346	196.51038	0
	23	10.101238	0	2.3458986	28.068032	44.261493	202.49084	0

	Hour	N# 5L N	N# 5L S	N# 6L N	N# 6L S	N# 7L N	N# 7L S	N# 8L N	N# 8L S
Line flow	0	13.416241	23.800514	0	19.59472	13.062943	7.7135882	0	0
	1	13.382925	23.730068	0	18.679484	13.056535	4.7631037	0	0
	2	13.409374	23.378093	0	17.500115	12.449836	6.5409323	0	0
	3	13.43328	23.561964	0	18.18555	12.484016	5.369955	0	0
	4	13.56264	24.269737	0	19.657619	13.51781	3.719939	0	0
	5	13.673355	24.668243	0	18.505074	14.715343	0	0	0
	6	13.633682	24.760052	0	13.694972	15.392386	19.437705	0	0
	7	13.724982	25.635411	0.5470359	23.557794	21.94522	12.852369	0	0
	8	14.306859	28.475624	0	60.429389	24.46128	31.326925	0	0
	9	14.109597	55.423924	0	112.46336	27.440352	69.826285	0	0
	10	13.414206	61.538363	0	94.845045	45.521477	77.656978	0	0
	11	13.174131	58.587269	0	84.426185	55.25185	68.989852	0	0
	12	13.367158	57.206074	0	86.47593	55.866636	61.997406	0	0
	13	13.418275	51.301596	0	73.822997	45.908598	50.815747	0	0
	14	13.366903	35.056586	0	37.409323	20.585031	24.271	0	0
	15	13.404261	36.411973	0	26.83641	15.873119	14.844555	0	0
	16	13.387503	38.036927	0	22.472724	17.155566	5.5906005	0	0
	17	13.311462	38.07126	0	22.741588	17.275502	0	0	0
	18	13.151961	37.88894	0	24.132564	17.787547	0	0	0
	19	13.200071	37.823555	0	24.796826	18.141299	0	0	0
	20	13.168282	37.537957	0	24.724651	18.220645	0	0	0
	21	13.141578	37.384604	0	23.631495	17.975128	0	0	0
	22	13.246103	30.971491	0	16.63386	16.791791	2.3363088	0	0
	23	13.112195	22.671972	0	13.460218	16.238886	6.0203884	0	0

Appendix D3: Underground valve simulation input data for South shaft (line pressure)

	Hour	S# 2L N	S# 2L S	S# 3L N	S# 3L S	S# 4L N	S# 4L S
Line pressure	0	439.16076	431.41156	315.56064	315.11864	414.92994	440.62562
	1	431.94052	424.24708	308.0944	307.67071	407.91638	433.45235
	2	431.36785	423.73469	308.1468	307.90569	407.25719	432.92999
	3	428.1036	420.36645	309.04707	308.71901	404.31423	429.55469
	4	446.63174	438.72912	324.72882	324.63621	422.38446	448.25271
	5	453.28324	445.33812	326.81773	326.69464	429.05114	455.052
	6	445.81886	437.95362	320.07375	319.54732	422.00809	447.776
	7	484.96877	477.12613	357.72844	357.70809	459.73907	486.73025
	8	572.9242	564.29338	439.01732	438.62669	544.65146	574.26566
	9	536.89828	528.71037	403.09758	403.26385	508.4927	536.97551
	10	454.46175	447.54142	330.13148	330.67877	427.93265	453.85621
	11	432.8357	426.01032	310.68437	310.76168	406.04766	431.86135
	12	510.01278	502.11137	382.49688	381.91908	481.32092	509.09845
	13	481.14089	472.82806	352.24435	351.72961	454.76463	481.65459
	14	468.51038	460.4236	342.53147	341.9679	428.21139	453.67157
	15	424.66001	417.26269	316.32426	315.73074	400.93501	425.6662
	16	438.72371	431.05589	326.19669	325.48104	414.06272	439.60632
	17	445.2914	437.57385	321.9028	321.45825	420.49439	446.16464
	18	441.95938	434.21424	318.02327	317.3603	417.31951	442.8547
	19	440.1539	432.52224	315.85361	315.21681	415.62982	441.08288
	20	435.7247	428.12319	312.8308	312.39592	410.99311	436.82053
	21	433.29083	425.68932	314.97063	314.36841	409.22764	434.51031
	22	435.681	428.2543	317.79507	317.14656	411.11976	437.07383
	23	438.2818	430.7524	320.50754	320.30565	414.16859	439.82252

	Hour	S# 5L N	S# 5L S	S# 6L N	S# 6L S	S# 7L N	S# 7L S	S# 8L N	S# 8L S
Line pressure	0	435.28191	437.32713	479.14501	478.17593	443.33918	442.75578	482.85577	487.80437
	1	428.04151	430.0852	471.36422	470.39293	436.11506	435.56166	475.20302	479.87402
	2	427.45708	429.56334	470.61533	469.62087	435.41466	434.85008	474.43095	479.11742
	3	424.16571	426.26383	466.96969	465.92059	432.01241	431.4285	470.73564	475.288
	4	442.93889	445.01991	487.48285	486.4678	451.04406	450.41475	491.49284	496.19876
	5	449.75764	451.88322	494.89697	493.94003	457.96902	457.32307	498.97638	503.74176
	6	442.38448	444.48565	486.74368	485.85627	450.41174	449.8675	490.785	495.78658
	7	481.34381	483.54366	529.27559	528.38432	489.43719	488.9545	533.53435	538.3792
	8	568.38026	570.83238	623.33431	622.11578	575.48282	575.56929	626.82212	632.29498
	9	530.27153	532.9908	580.13044	573.51374	535.67533	535.8395	583.66717	588.37878
	10	446.82739	449.21238	489.19342	480.9772	451.65993	451.84965	492.91743	497.05533
	11	425.41594	427.64986	466.03262	458.12712	430.08011	430.17471	469.62473	473.63626
	12	503.62249	505.87014	551.64059	541.23512	509.45703	509.4555	556.19681	560.62721
	13	476.23357	478.34897	523.57148	516.8398	484.27914	483.8997	528.02285	532.65744
	14	448.9133	450.89698	510.83492	508.47127	456.80425	456.23153	512.05234	516.81607
	15	420.99589	422.92957	463.59934	462.19722	428.87849	428.26602	467.34672	471.91561
	16	434.8806	436.82307	478.91929	477.67318	443.03553	442.41245	482.22939	486.95118
	17	441.48369	443.4755	485.94016	484.77903	449.72661	449.11574	489.90478	494.64974
	18	438.04022	440.04494	482.14153	480.96491	446.24642	445.63237	486.08187	490.81005
	19	436.35208	438.32761	480.19797	479.12625	444.47598	443.83764	484.22219	488.90203
	20	431.94781	433.90402	475.41935	474.33051	439.95931	439.32301	479.29512	484.01966
	21	429.51501	431.50479	472.92324	471.78088	437.55092	436.92785	476.67926	481.48327
	22	431.91628	433.91979	475.51372	474.54353	440.04883	439.51527	479.47668	484.1946
	23	434.61216	436.61344	478.30778	477.42012	442.65953	441.99166	482.47735	486.99715

Appendix D4: Underground valve simulation input data for South shaft (line flow)

	Hour	S# 2L N	S# 2L S	S# 3L N	S# 3L S	S# 4L N	S# 4L S
Line flow	0	4.5736582	6.4923322	9.7965972	0.8596933	28.260166	8.9146258
	1	8.9249674	6.6609701	9.9005112	0.6802472	23.11223	9.7405966
	2	0.6999602	6.5551758	9.020676	0.8426032	23.105516	9.5054551
	3	0	6.5488462	0.2885481	1.1633478	18.335698	9.7813383
	4	0	6.6346384	1.332744	1.3687343	18.870096	9.8725345
	5	0	6.7265264	2.6497291	0.9695583	18.892042	9.8684672
	6	10.128943	6.5257885	3.9519341	0.8473335	18.048066	9.4084078
	7	35.10272	7.9137732	30.128023	1.4787518	24.848707	12.242008
	8	50.678168	7.2966399	29.903868	2.6031891	23.144884	11.745937
	9	60.88624	6.965304	48.002778	1.972518	29.032289	13.469191
	10	66.048629	6.3991971	45.359579	1.3916228	42.185855	21.477379
	11	60.463234	6.624801	37.609522	1.0949874	43.744869	23.159686
	12	47.169777	7.695855	15.23003	1.9943541	48.682383	28.813764
	13	20.317112	6.6980433	2.5055314	1.2811475	36.212864	21.08217
	14	9.7151693	6.938567	0.1397726	2.7003891	28.012818	13.728237
	15	1.8187073	6.0451464	0.1659024	2.2310795	24.604226	11.435427
	16	1.5152994	6.5691912	0.3266957	2.2177462	27.690242	12.493629
	17	0	6.495497	0	1.0510414	27.01915	12.448158
	18	0.0296523	6.5729017	0	0.8418244	27.123069	12.651045
	19	0.0641095	6.507704	0	0.8067445	29.329824	12.536049
	20	0.0164569	6.4548069	0	0.8641184	29.490959	12.345922
	21	1.6492152	6.527597	7.7671472	1.4558633	25.064317	12.164034
	22	7.9198315	6.6279658	12.002289	1.5574883	29.178454	13.597314
	23	0	6.229968	12.383753	1.6592426	25.186541	12.162614

	Hour	S# 5L N	S# 5L S	S# 6L N	S# 6L S	S# 7L N	S# 7L S	S# 8L N	S# 8L S
Line flow	0	13.060197	21.780423	16.251621	18.234378	16.962997	15.362173	13.036545	100
	1	13.090867	21.415732	16.043793	18.082094	17.988098	15.291371	12.635538	100
	2	12.856336	21.201953	15.755093	18.183413	18.094453	14.993362	9.5274281	100
	3	13.053636	21.206378	15.663081	18.98024	18.550546	14.986954	10.890516	100
	4	13.373533	21.465182	16.321418	18.960703	19.973323	15.48133	9.9637731	100
	5	13.432822	21.41741	16.391089	18.552224	20.549783	15.537194	10.342413	100
	6	13.139086	21.124895	19.887541	17.731289	21.86862	15.992676	11.129625	100
	7	18.237888	23.881132	21.42565	21.085222	39.293202	26.935531	14.046235	80.304722
	8	25.712367	26.191348	37.647364	31.933318	86.181583	52.713359	49.747006	46.276646
	9	31.936449	36.868849	59.094876	68.61477	106.24604	65.52182	71.872992	64.834953
	10	29.597009	37.143054	66.65507	72.035096	100.52155	62.689861	62.946517	96.919559
	11	26.372015	37.296712	55.972534	67.384604	94.645914	60.460517	42.538491	100
	12	24.982223	37.327688	55.120623	81.710689	91.490502	59.092851	38.247502	79.792376
	13	14.771649	28.773022	29.710994	62.469215	51.563134	30.874037	17.21706	89.273569
	14	13.806821	25.113909	24.968338	34.853895	27.686427	20.444343	7.6972609	94.234737
	15	12.813632	20.59668	20.299603	23.368245	17.527407	16.09569	5.750073	96.551724
	16	13.945525	21.553369	18.975204	21.28481	18.963302	15.867552	6.4226748	100
	17	13.962005	21.508202	16.374914	20.202029	18.960708	15.887236	6.4789807	100
	18	13.911492	21.465971	17.576025	20.458402	18.910506	15.831919	6.4166818	100
	19	13.90692	21.457084	20.353399	20.561837	18.880293	15.854124	6.7444877	100
	20	13.918059	21.397269	20.881514	20.52018	18.742657	15.691005	6.6044098	100
	21	13.580835	21.351797	20.092775	20.444495	18.031128	15.27657	6.0808728	100
	22	13.841764	21.240406	23.165026	19.315786	17.758144	15.142596	6.124361	100
	23	13.496488	20.651795	21.735655	18.585136	17.734387	16.098385	6.0901104	100