CHAPTER 2

[3]

Quality is never an accident; it is always the result of high intention, sincere effort, intelligent direction and skilful execution; it represents the wise choice of many alternatives." – William A. Foster

[3] Photo taken by HVACI personnel at a South African mine.

2 COMPRESSED AIR NETWORK APPLICATIONS IN THE MINING ENVIRONMENT

2.1 Introduction

Due to their age, configuration and inefficient operation, many South African mining compressed air networks can be reconfigured to operate in a more efficient manner. Chapter 2 aims to gather sufficient knowledge to be able to successfully reconfigure a mine's compressed air network. This chapter therefore focuses on basic compressed air network components, operations, technologies, fundamentals and calculations. Finally, previously implemented DSM projects, which are similar to reconfiguring mining compressed air networks, will be evaluated.

2.2 Mining operations and compressed air requirements

Mining operations can be divided into three categories, namely: surface, underground and unregulated operations. Each operating category includes a variety of components. These components have specific compressed air requirements and operating schedules. The productivity of a mine may be negatively influenced if the supply does not comply with these requirements and schedules. Table 2 briefly describes the basic surface operations and compressed air requirements at a typical South African gold mine [22], [26], [28], [31].

Surface Operations and Requirements			
Component	**Application**	**Operating Hours**	**Requirement**
Processing plants	Used to extract minerals from ore. Compressed air is required for agitation and instrumentation.	Working weekdays (00:00 – 24:00)	0.08 – 0.7 m³/s @ 420 – 500 kPa
Maintenance workshops	Used for maintenance on mining equipment, building new equipment and so forth. Compressed air is required for equipment such as grinders, drills, plasma cutters and saws.	Working weekdays (06:00 – 15:00)	0.028 m³/s @ 200 – 250 kPa
Pneumatic cylinders	Used to actuate doors and chutes found in ore handling systems, security gates and demonstration equipment for training centres.	Working weekdays (00:00 – 24:00)	0.0006 – 0.14 m³/s @ 350 – 600 kPa
Other	Actuators for control valves, guide vane control on compressors and ventilation fans.	Working weekdays (00:00 – 24:00)	Very low flow rates @ 350 – 600 kPa

Table 2: Surface operations and compressed air requirements

Table 3 gives a brief description of the basic underground operations and the compressed air requirements of underground end-users at a typical South African gold mine [22], [26], [28], [30], [31], [32].

Underground Operations and Requirements			
Component	**Application**	**Operating Hours**	**Requirement**
Rock drills (stope drills)	Drill 1.8 m deep holes on the rock face wherein the charges, used for blasting, are placed.	Working weekdays (09:00 – 15:00)	0.06 – 0.42 m³/s @ 400 – 620 kPa
Diamond drills	Development on mining levels.	Working weekdays (00:00 – 24:00)	0.14 m³/s @ 500 kPa
Rock breakers	Reduce large rocks into smaller rocks. Eases the process of ore hoisting.	Working weekdays – tramming & loading (15:00 – 09:00)	0.28 m³/s @ 450 kPa
Mechanical ore loaders	Load mined ore into loading boxes. The ore is then transported to the tipping points.	Working weekdays – tramming, loading & hoisting (00:00 – 24:00)	0.12 – 0.3 m³/s @ 450 – 860 kPa Most commonly used is the LM 250 and requires 0.28 m³/s @ 550 kPa
Loading boxes	Load mined ore into skips. Skips are then hoisted from shaft bottom to surface.	Working weekdays – tramming, loading & hoisting (00:00 – 24:00)	0.0006 – 0.14 m³/s @ 350 – 600 kPa
Pneumatic cylinders	Actuate a variety of doors and chutes found on ore handling systems.	Working weekdays (00:00 – 24:00)	0.0006 – 0.14 m³/s @ 350 – 600 kPa
Agitators	Agitation of water dams and agitated tank leaching.	Working weekdays (00:00 – 24:00)	0.47 m³/s @ 400 kPa
Refuge bays	Air used to provide a positive atmospheric charge (relative to the outside pressure) in the refuge bay. Prevents toxic gases to enter from the outside.	Working weekdays (00:00 – 24:00)	0.0014 m³/s @ 200 – 300 kPa per person occupying a refuge chamber
Venturi blowers	Circulates fresh air through mining levels and cool workers down in elevated temperature conditions.	Working weekdays (00:00 – 24:00)	0.019 – 0.091 m³/s @ 350 – 620 kPa
Open-ended pipes	Used to clean mining and developed areas (sweeping).	Working weekdays (09:00 – 15:00)	0.2 – 1.6 m³/s @ 100 – 650 kPa (50 mm hose)
Other	Actuators for underground control valves.	Working weekdays (00:00 – 24:00)	Very low flow rates @ 350 – 600 kPa

Table 3: Underground operations and compressed air requirements

Some mines even make use of pneumatic saws, pneumatic winches and pneumatic starters for ore locomotives [26]. These components all contribute to the total compressed air consumption. By adding all of the compressed air requirements of all the components, the number of required compressors can be calculated.

Unregulated operations occur at most South African mines, especially older mines [33]. These operations are usually uncontrolled and are increasing rapidly in the mining environment [34]. Table 4 gives a brief description of the unregulated compressed air operations on a typical South African mine [34], [33], [35].

Unregulated Operations and Requirements			
Component	**Application**	**Operating Hours**	**Requirement**
Leaks	Corrosion of steel pipes, perished flange gaskets and corroded equipment are all causes of leaks.	Continuously	3 – 200 mm diameter leaks can waste 0.008 – 23.67 m^3/s @ 500 kPa
Open-ended pipes	Ventilation and cooling in poorly ventilated areas.	Continuously during summer	0.2 – 1.6 m^3/s @ 100 – 650 kPa (50 mm hose)
Illegal mining	Additional pneumatic mining equipment is used on the shaft. Open-ended pipes for cooling and ventilation to ensure cool working conditions for the illegal miners (zama zamas).	Continuously	Up to 5.8 m^3/s @ 560 kPa

Table 4: Unregulated operations and compressed air requirements

It becomes evident from Table 2 to Table 4 that these operations and requirements may substantially contribute to the demand required from the supply side, especially combined with inefficient equipment and unregulated mining operations. The following section discusses the improvement of inefficient mining operations through surface network components, as this study focuses on the reconfiguration of a mine's surface compressed network.

2.3 Improving compressed air network efficiencies

2.3.1 Supply-side technologies

The first step to facilitate optimised control on the supply side is to automate the compressors used in the compressed air network [30]. The compressors' efficiencies are improved through automation procedures [32], [36], [37]. Automating compressors includes upgrading of IGV control, controlling blow-off, installing system monitoring equipment and, if necessary, refurbishing switch gear. Figure 9 is a photo taken of a typical centrifugal compressor installed at a South African gold mine that is used for compressed air generation.

Figure 9: Typical centrifugal compressor at a South African gold mine[4]

Figure 10 is a simplified illustration of an automated compressor system. The guide vane controller automatically adjusts the IGVs using information received from the compressor's programmable logic controller (PLC). IGVs regulate the pressure output of a compressor. For example, if the system demand decreases, the PLC will send a command to the IGV controller to automatically close the IGVs and vice versa. The primary objective of automation procedures is to suppress compressor surge. [30]. The secondary objective is to efficiently match supply with demand through regulating the compressor's output [30].

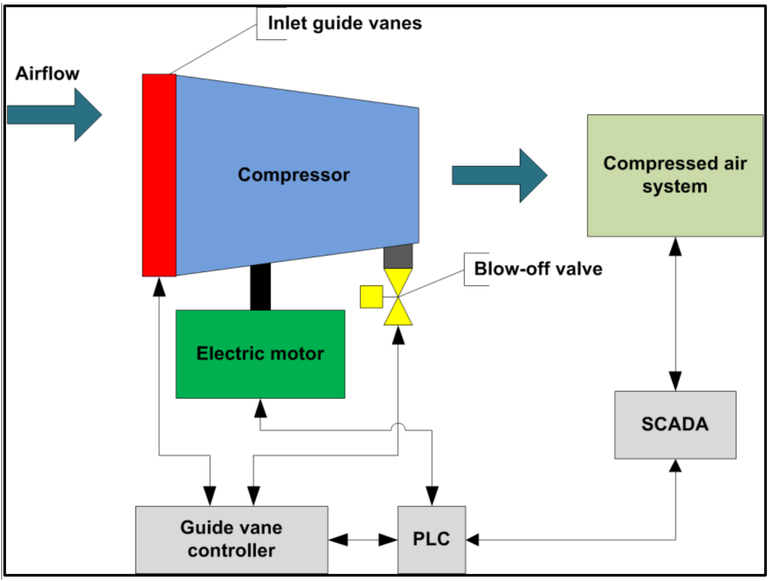

Figure 10: Basic layout of an automated compressor system [30], [38]

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

Figure 11 shows the automated equipment used as part of automation procedures, installed on the compressors of two South African gold mines. In this figure, the IGV actuator and blow-off valve were replaced with newer equipment for optimal operation. Monitoring equipment such as pressure transmitters, flow meters, temperature and vibration sensors were installed. A PLC was incorporated as a communication medium between the supervisory control and data acquisition (SCADA) system and the compressor.

Figure 11: Installed equipment during automation procedures of mining compressors[5]

The automation of compressors eliminates numerous supply-side inefficiencies. Table 5 summarises these inefficiencies that exist in mining operations [24], [26], [28], [29], [30], [32], [36], [39], [40]. All mentioned inefficiencies contribute to increased compressor power consumption. The strategies to eliminate the inefficiencies through automation and regular maintenance of compressors are briefly discussed.

[5] Photos taken by Johan Bredenkamp at a South African gold mine.

Supply-side Inefficiencies		
Inefficiency	**Strategy**	**Strategy Description**
Compressors are running unnecessarily 24 hours a day. Major energy losses occur when compressors blow off excess compressed air into the atmosphere.	Stop/start compressors	The most basic output control of a compressor is to start or stop the electric motor driving the compressor. Compressors should be stopped when the demand for compressed air is low.
Compressors blow off excess compressed air into the atmosphere.	Load/unload compressors	A compressor is unloaded by closing the delivery valve and opening the blow-off valve, allowing the compressor to run freely. The compressor motor will only need sufficient power to overcome friction within itself and the compressor.
Compressors often experience large fluxes in airflow rates. If the demand airflow drops too low, flow through the machines will decrease, increasing the probability of compressors surging.	Compressor IGV control	Automatically adjusting the IGVs will enable the compressor to actively adjust to the changing system parameters, while maintaining good efficiency.
At some mines inefficient compressor combinations are used.	Compressor selection	Run the minimal number of compressors in the most efficient way.
In some circumstances compressor intakes are located inside compressor houses. Suction of hot intake air impairs compressor performance.	Cooler inlet temperatures	Mass flow and pressure capability increase with decreasing intake air temperatures, particularly in centrifugal compressors.
1. Blocked air intake filters cause pressure drops. 2. Moisture in air may cause corrosion in instrumentation and compressors. 3. Poor motor cooling can increase motor temperature and motor winding resistance.	Regular maintenance	1. Replace air inlet filters regularly. 2. Periodically inspect air moisture traps. 3.1 Properly clean and lubricate motors and compressors. 3.2 Inspect fans and water pumps regularly. 3.3 Maintain the coolers on the compressor and aftercooler.

Table 5: Implementing energy savings initiatives to improve supply-side efficiencies

Another method to improve the supply efficiency is to make use of compressor drive speed control. Many compressed air systems are designed to operate at maximum load conditions [29], [40]. However, these systems only operate at maximum loads during peak demand periods. This results in compressors operating inefficiently for the majority of the day. Variable speed drives (VSDs) provide continuous control, matching motor speed with the compressed air demand [29], [40]. Figure 12 illustrates the effect of VSDs on a compressor's power consumption.

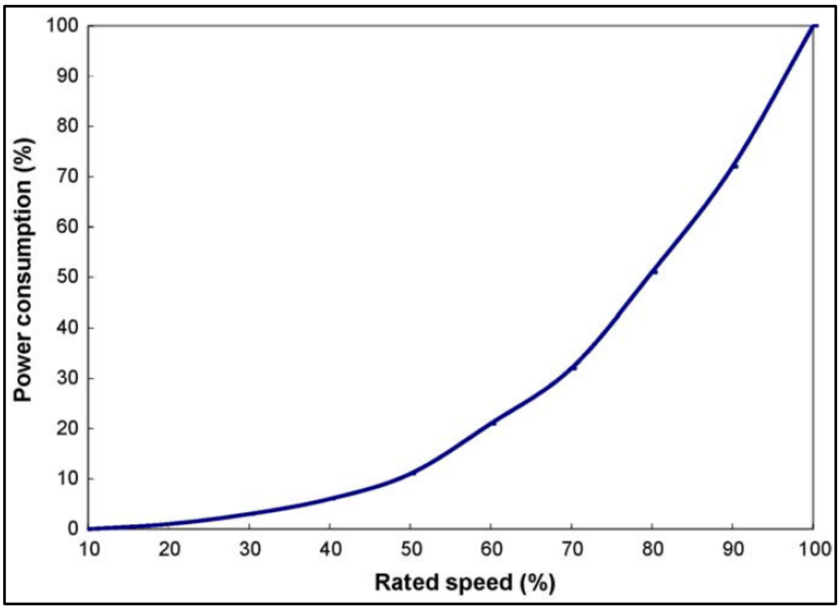

Figure 12: Compressor motor power reduction by using VSDs [29], [40]

It is evident from Figure 12 that VSDs are capable of reducing a compressor's power consumption by reducing the motor's rotational speed. VSDs are even more beneficial with an increase in compressor motor capacity, however, the installation costs of VSDs on larger motors are higher [22].

The section that follows gives an overview of demand-side technologies to improve efficient distribution of compressed air throughout a compressed air network.

2.3.2 Demand-side technologies

Surface valve control

As mentioned in Chapter 1, compressed air networks comprise several interconnected shafts and processing plants. These components have specific compressed air requirements and operating schedules. The shafts' requirements vary according to the mining shifts, while processing plants continuously require constant air pressure [26]. The minimum network pressure is determined by the highest pressure requirement (usually processing plants) of the components within the network [26]. This results in inefficient distribution of compressed air to the shafts during low demand periods.

Surface control valves can be installed to separate low-pressure sections from high-pressure sections [26], [41]. These valves can be altered during low demand periods to comply with the requirements of the end-users. It is therefore essential to determine the network requirement constraints (discussed in Section 2.2) as it is crucial for valve control [25], [28]. Figure 13 is an example of a typical surface control valve installed on a surface compressed air pipe section and used to create different pressure sections at a South African gold mine.

Figure 13: Surface control valve at a South African gold mine[6]

In some cases, sections of the network may be entirely isolated from the rest of the system during certain periods [28]. This is usually accomplished by using manually operated butterfly valves [28]. Globe valves and high-performance butterfly control valves are used for high accuracy control [25], [28]. These valves would typically be used to maintain certain pressure set points for shafts or processing plants.

Due to financial constraints, standard butterfly and high-performance butterfly control valves are most commonly used in the mining industry [25]. It is argued that globe valves, on average, can be up to five times more expensive than butterfly valves. It is therefore also important to meticulously choose the location for the installation of the valves. This ensures efficient reticulation of compressed air at the lowest possible implementation costs.

[6] Photo taken by HVACI personnel at a South African gold mine.

Site selection for valve installation

For practical and financial reasons the location of infrastructure, such as control valves, should be meticulously chosen. The strategic placement of infrastructure will ensure optimised control with the lowest implementation costs. The first step is to identify the high- and low-pressure consumers and their location in the network [25], [28]. This is not the only criterion and the following criteria must also be identified and evaluated:

- Human activity in the area of the valve. The valve needs to comply with stringent noise regulations if installed near human workplaces.
- Availability of existing infrastructure (electrical and communication networks) to ensure a reduction in installation costs.
- Accessibility of the infrastructure location.
- Illegal mining activities and potential vandalism of infrastructure.

Supply- and demand-side technologies play a crucial role in improving compressed air network efficiencies. From this chapter it is evident that improving the efficiencies results in electrical energy savings on the mine's compressors. Cost savings resulting from strategic design optimisation and implementation are also viable. The strategic design is discussed in the following section using basic compressed air network fundamentals and calculations.

2.4 Compressed air network fundamentals and calculations

2.4.1 Supply side

It is possible to calculate the power required by a centrifugal compressor's motor if the compressed air conditions and requirements of the system are known. The compression produced by a centrifugal compressor may be considered as a polytrophic process [42]. Hence, the power required by a compressor for polytrophic compression may be calculated by using Equation 1 [22], [35], [42]:

Equation 1: Power required by the electrical motor of a centrifugal compressor

$$P_{motor} = \frac{P_{comp}}{\eta_{motor}}$$

Where:

P_{motor}	=	Power required by the electrical motor in kW
P_{comp}	=	Power required by the compressor to compress air in kW
η_{motor}	=	Dimensionless compressor motor efficiency

The power required by the compressor to compress air is calculated by using the following equation [22], [35], [42]:

Equation 2: Power required by the compressor to compress air

$$P_{comp} = \dot{m}_{air} W_{comp}$$

Where:

P_{comp}	=	Power required by the compressor to compress air in kW
$\dot{m}_{air}$	=	Mass flow rate requirement in kg/s
W_{comp}	=	Mechanical energy required to compress a unit mass of air in kJ/kg

The mass flow rate of the compressed air is determined by converting the volume flow rate using the density of the air. The conversion is done using the following equation [43]:

Equation 3: Volume flow rate to mass flow rate conversion

$$\dot{m} = Q\rho$$

Where:

$\dot{m}$	=	Mass flow rate in kg/s
Q	=	Volume flow rate in m^3/s
ρ	=	Density of air in kg/m^3

In most cases the volume flow rate on a compressor's discharge is measured. The density of air can be calculated by using the perfect gas equation of state [43]. Equation 4 represents the calculation.

Equation 4: Density of compressed air

$$\rho = \frac{p_{abs}}{RT}$$

Where:

ρ	=	Density of air in kg/m^3
p_{abs}	=	Absolute air pressure in kPa
R	=	Gas constant for air taken as 0.278 kJ/kg.K
T	=	Air temperature in K

The density of air varies with different temperatures and pressures. If the air temperature increases at a constant pressure, the density of the air will decrease and vice versa [22], [43]. If the air pressure increases at a constant temperature, the density will increase and vice versa [43]. Table 6 represents varying air properties at different air temperatures. The temperatures vary in increments of 10°C from 10 to 100°C [43].

Temperature °C	Density kg/m^3	Absolute Viscosity kg/m.s
0	1.29	1.72×10^{-5}
10	1.25	1.77×10^{-5}
20	1.20	1.81×10^{-5}
30	1.16	1.86×10^{-5}
40	1.13	1.91×10^{-5}
50	1.09	1.95×10^{-5}
60	1.06	1.99×10^{-5}
70	1.03	2.04×10^{-5}
80	1.00	2.09×10^{-5}
90	0.97	2.19×10^{-5}
100	0.95	2.30×10^{-5}

Table 6: Properties of air at different operating temperatures

The next step is to determine the mechanical energy required by the compressor to compress air at a specific airflow requirement. The calculation is expressed by the following equation [35], [42]:

Equation 5: Mechanical energy required by a centrifugal compressor to compress air

$$W_{comp} = \frac{nRT_{in}}{\eta_{comp}(n-1)}\left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1\right]$$

Where:

W_{comp}	=	Compressor mechanical energy in kJ/kg
n	=	Polytrophic constant for isentropic compression taken as 1.4
R	=	Gas constant for air taken as 0.278 kJ/kg.K
T_{in}	=	Compressor inlet (ambient) temperature in K
η_{comp}	=	Dimensionless compressor efficiency
p_2	=	Compressor discharge pressure in kPa
p_1	=	Compressor inlet (ambient) pressure in kPa

The efficiencies of the compressor and the motor driving the compressor are usually obtained from the compressor specifications [26]. A compressor efficiency of 0.8 and motor efficiency of 0.9 are reasonable assumptions if the specifications are unavailable [26]. With all the information available, one can determine the power required by a centrifugal compressor’s motor to produce compressed air at a required rate. The next section gives an overview on the fundamentals and calculations within the air reticulation network.

2.4.2 Air reticulation network

Pipe losses

As discussed in Chapter 1, numerous mining compressed air networks comprise long intricate pipe networks. Air flowing through long pipe sections experiences pressure losses as a result of pipe friction [44]. Therefore, the longer the pipe sections the higher the pressure losses will be and vice versa. The following factors also contribute to pressure losses:

- pipe diameters;
- pipe materials;
- bends in pipe sections;
- compressed airflows;
- compressed air velocities; and
- compressed air pressures.

The age of the pipe network also influences pressure losses. Due to the moisture content in compressed air, older pipes will have evidence of corrosion that developed over the years.

Pipe friction coefficients increase with amplified corrosion, which directly results in larger pressure losses over pipe sections [22], [29], [43]. Figure 14 shows corrosion that developed on the inside surface of a compressed air pipeline at a South African gold mine.

Figure 14: Corrosion on the inside of an old compressed air pipeline[7]

The increased friction losses of older pipelines are caused by increased pipe wall roughness due to corrosion. Figure 15 illustrates the effect of increased pipe wall roughness on the amount of pressure lost. The effect was determined in a constant diameter pipe over a distance of 100 m. The flow through the pipeline was varied to verify the effect of pipe wall roughness at different flow rates.

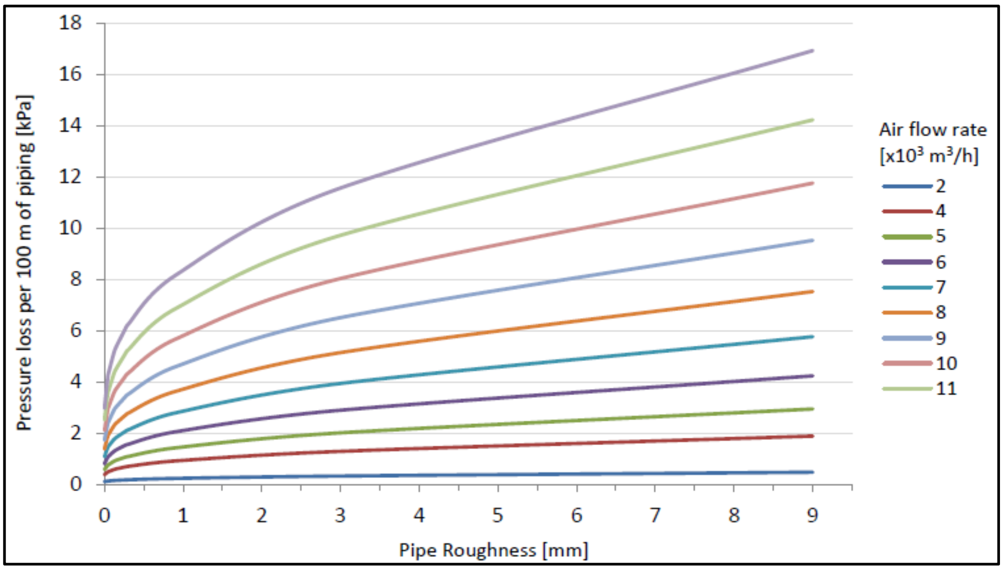

Figure 15: Increasing pressure losses with increased pipe wall roughness [22]

[7] Photo taken by HVACI personnel at a South African gold mine.

The compressed airflow through long pipe networks can be considered as isothermal [43]. Isothermal flow is the state where compressed airflow occurs at constant temperatures. The pressure drops in large compressed air networks can therefore be calculated by using the Darcy-Weisbach equation [43]. The assumption is also made that pipes in mining compressed air reticulation networks are round. The Darcy-Weisbach equation is expressed by the following:

<u>Equation 6:</u> Darcy-Weisbach equation for pressure drops in large compressed air networks

$$\Delta p = \frac{f \rho L Q^2}{82.76 D^5}$$

Where:

Δp	=	Pressure loss between two points in kPa
f	=	Dimensionless Darcy friction factor
ρ	=	Density of air in kg/m^3
L	=	Length of the pipe in m
Q	=	Volume flow rate in m^3/s
D	=	Inside diameter of the pipe in m

The Darcy friction factor is dimensionless and needs to be calculated with the help of another dimensionless parameter, namely the Reynolds number. The Reynolds number is a function of flow velocity, pipe size and the properties of compressed air at the required conditions. The Reynolds number can be calculated using the following equation:

<u>Equation 7:</u> Reynolds number calculation for compressed airflow

$$Re = \frac{\rho v D}{\mu}$$

Where:

Re	=	Dimensionless Reynolds number
ρ	=	Density of air in kg/m^3
v	=	Flow velocity in m/s
D	=	Inside diameter of the pipe in m
μ	=	Dynamic viscosity of air in kg/m.s

The outstanding variables in this equation are velocity, density and viscosity of air flowing through the pipes. The velocity of the air can be calculated by multiplying the volume flow with the cross-sectional area of the specific pipe. Equation 8 represents this calculation. The density and absolute viscosity can be determined by referring to Table 6 where the properties of air at different temperatures were discussed.

Equation 8: Calculation to determine the velocity of air

$$v = QA$$

Where:

v	=	Flow velocity in m/s
Q	=	Volume flow rate in m^3/s
A	=	Cross-sectional area of the pipe in m^2

If the Reynolds number is higher than 4 000, the flow is said to be turbulent. It is stated that compressed airflow in large mining compressed air networks follow the trend of turbulent conditions [44]. Therefore, the friction factor can be calculated by using the Colebrook-White equation for turbulent flow [43]. Equation 9 states the Colebrook-White equation in determining the dimensionless friction factor.

Equation 9: Colebrook-White equation to determine the friction factor for turbulent flow

$$\frac{1}{\sqrt{f}} = -2log_{10}\left[\frac{e}{3.7D} + \frac{2.51}{Re\sqrt{f}}\right]$$

Where:

f	=	Dimensionless Darcy friction factor
e	=	Absolute pipe roughness in m
D	=	Inside pipe diameter in m
Re	=	Dimensionless Reynolds number

The absolute pipe roughness depends on the type of material used for the pipe network. Table 7 represents the absolute pipe roughness of general pipe materials used in the mining industry [43].

Pipe Roughness of Different Materials	
Pipe Material	**Roughness (mm)**
Wrought iron	0.045
Commercial steel/welded steel	0.045
Galvanised iron	0.15
Cast iron	0.26
Riveted steel	0.9 – 9.0

Table 7: Absolute roughness of general pipe materials used in the mining industry

With all the information in hand one is able to determine the pressure loss in compressed air network pipe sections by using Equation 6. These calculations are very useful, especially in determining the effectiveness of certain pipe sections in a network. The calculations are also convenient for investigating new possibilities such as adding or eliminating pipe sections in an air reticulation network. The following section discusses additional losses in networks due to compressed air leaks.

Compressed air leaks

Poorly maintained and older compressed air networks lose between 40% and 50% of the generated compressed air through air leaks [25], [31], [45]. It is estimated that highly efficient and well maintained systems should not lose more than 5% of the generated compressed air [45]. The energy wastage is significantly high if these leaks remain unrepaired. Figure 16 is an example of existing compressed air leaks in surface mining reticulation networks.

Figure 16: Existing compressed air leaks in mining compressed air reticulation networks[8]

[8] Photos taken by HVACI personnel at South African gold and platinum mines.

There is definitely a need among mining industries to continuously identify, repair and monitor compressed air leaks. It is therefore crucial to have a thorough understanding of the effect leaks have on mining compressed air networks. These effects include the amount of air (energy) lost through leaks and the financial impact thereof. The amount of compressor power lost through a leak is calculated by using Equation 10 [35].

Equation 10: Compressor power wastage through compressed air leaks

$$P_{lost} = \dot{m}_{air\_leak} W_{comp\_wasted}$$

Where:

P_{lost}	=	Compressor power wasted through leak in kW
$\dot{m}_{air\_leak}$	=	Mass flow rate through leak in kg/s
W_{comp_wasted}	=	Compressor mechanical energy wasted in kJ/kg

The mechanical energy wasted by a compressor through a leak is calculated with the help of Equation 5, discussed earlier in this chapter. The mass flow rate through the leak is calculated by using the following equation [35]:

Equation 11: Calculation for the mass flow rate through a compressed air leak

$$\dot{m}_{air\_leak} = C_{discharge} \left(\frac{2}{k+1}\right)^{\frac{1}{k-1}} \left(\frac{p_{leak}}{RT_{leak}}\right) A_{leak} \sqrt{kR\left(\frac{2}{k+1}\right) T_{leak}}$$

Where:

$\dot{m}_{air\_leak}$	=	Mass flow rate through leak in kg/s
$C_{discharge}$	=	Dimensionless leak discharge coefficient
k	=	Specific heat ratio for compressed air taken as 1.4
p_{leak}	=	Absolute air pressure at the leak in kPa
R	=	Gas constant for air taken as 0.278 kJ/kg.K
T_{leak}	=	Temperature of the air at the leak in K
A_{leak}	=	Cross-sectional area of the leak in m^2

In 2010, Van Tonder completed a study regarding the impact of air leaks on compressed air networks. The aforementioned equations and the Eskom energy tariffs at the time

(2010/2011) were used to determine the negative impact of the leaks. Table 8 represents the results obtained from the calculations by using the actual conditions that occurred in a compressed air network [34], [35]. The conditions included the following:

- absolute system pressure of 587 kPa;
- ambient pressure of 87 kPa;
- ambient air temperature of 25°C;
- system compressed air temperature of 28°C;
- compressor efficiency of 80%;
- dimensionless leak discharge coefficient of 0.65; and
- 24-hour, 7 days per week operation.

Financial Impact of Compressed Air Leaks				
Leak Diameter mm	**Leak Area m^2**	**Mass Flow Through Leak kg/s**	**Annual Electrical Energy Wasted kW/h**	**Annual Cost R**
3	0.000007	0.01	15 245	7 096
6	0.000028	0.03	60 978	28 385
10	0.000079	0.07	169 384	78 849
25	0.000491	0.44	1 058 650	492 804
50	0.001963	1.75	4 234 599	1 971 215
100	0.007854	6.98	16 938 398	7 884 859
150	0.017671	15.71	38 111 395	17 740 934
200	0.031416	27.93	67 753 591	31 539 438

Table 8: Compressor power wastage and cost implications of compressed air leaks

It is evident from Table 8 that compressed air leaks contribute to major compressor power and financial losses. Leaks may have a significant impact on the reconfiguration of mining compressed air networks. Major leaks occurring in these networks may damper the cost saving effect of reconfiguration initiatives. Maintaining the leaks would ensure a more efficient and electricity cost effective system. Auto compression is another factor that plays a crucial part in the effective utilisation of compressed air. The term auto compression is discussed in the following section.

Auto compression

Auto compression is a term used when referring to air being compressed by its own weight [37]. The compressed air in a mine's shaft column will gain pressure with depth [31]. Due to their depth, gold and platinum mines experience auto compression. The highest pressures at these mines are more likely to be measured at the shaft bottom. Equation 12 can be used to calculate the pressure gain at constant airflow rates due to auto compression [31].

Equation 12: Pressure gain due to auto compression (constant airflow)

$$p_2 = p_1[1 - \frac{g(Z_1 - Z_2)}{T_1 C_p}]^{\frac{1}{k}}$$

Where:

p2	=	Final pressure in kPa
p1	=	Initial pressure in kPa
g	=	Gravitational acceleration taken as 9.81 m/s^2
Z1	=	Initial altitude in m
Z2	=	Final altitude in m
T1	=	Temperature of the compressed air in K
Cp	=	Specific heat capacity of compressed air in kJ/kg.K
k	=	Specific heat ratio of compressed air taken as 1.4

Lower surface pressures are normally required due to the effect of auto compression. Figure 17 is a simplified illustration of the effect a shaft's depth has on auto compression. The illustration is based on different surface discharge pressures that increase when shaft depth increases. The airflow in this illustration is neglected.

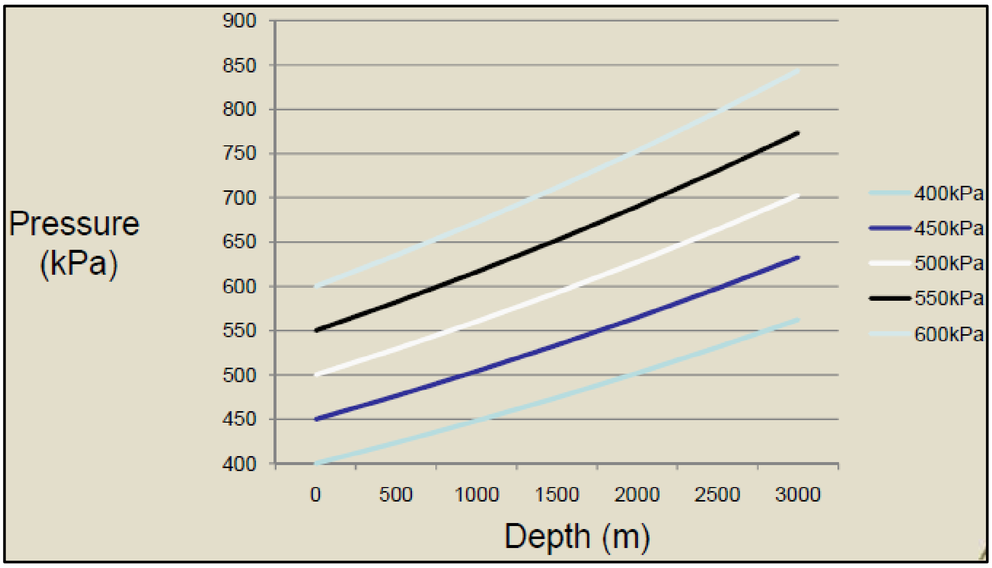

Figure 17: Increasing shaft column pressure with increasing shaft depth [37]

The gain in pressure is reduced by pipe friction losses caused by moving air [31]. The measurable effect of auto compression therefore decreases as the underground demand for compressed air increases. If the underground air demand increases, the air velocity increases [37]. The increased velocity of the air causes an increase in pipe friction losses, which will damper the effect of auto compression [31], [37]. Figure 18 illustrates the effect of an increased airflow (demand) on auto compression.

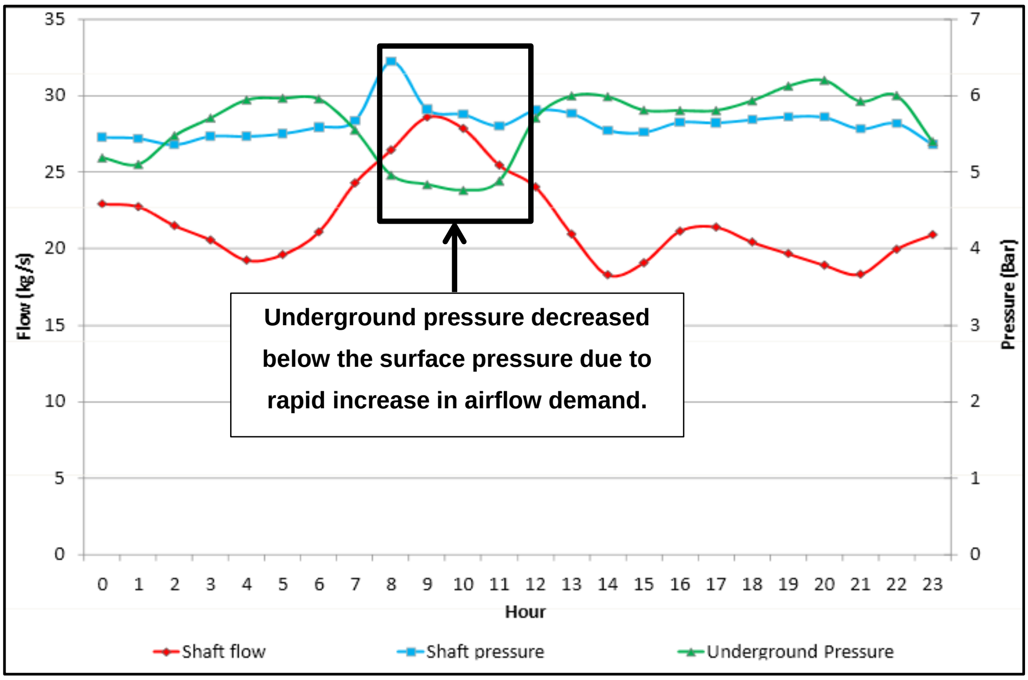

Figure 18: Effect of airflow demand on auto compression [37]

The pipe diameter in a shaft's main column also affects the phenomenon of auto compression [31]. Assuming constant flow, a decrease in pipe diameter will result in an increase in air velocity. In turn, the increased velocity decreases the amount of auto compression gained by the depth of a shaft. The correct relation between compressed air demand and the effect of auto compression must be maintained for optimal air distribution. The following section discusses the value of simulation models in analysing compressed air networks.

2.4.3 Value of simulation software

It will be a very time-consuming process to manually solve all the aforementioned calculations in this chapter. In most cases, one does not have the time to solve the equations and to obtain suitable answers through trial and error. Simulation software is the modern day answer to this dilemma. It enables one to analyse a compressed air network with great simplicity.

A study by Venter proved the convenience of simulation software during the development of dynamic compressor selection (DCS) software. DCS is used to dynamically prioritise the selection of compressors in large mining compressed air networks. Additional simulation software was required to successfully develop and analyse the DCS software. Software packages such as KYPipe and Flownex were used to compare the results obtained from the DCS software. The author concluded that it was possible to accurately simulate mining compressed air networks using simulation software [46].

Van Niekerk investigated the value of simulation models during the implementation of mining DSM projects. The study demonstrated the simulations' potential to increase the effectiveness of already implemented DSM solutions [38]. Through two case studies the value of developing simulation models, prior to the implementation of projects, was proven. Benefits such as effortless project implementation, reduced implementation costs and implementation periods were realised by using simulation models. The author concluded by iterating the significant value of simulation models for mine DSM projects [38].

Due to their value, simulation software packages (specifically KYPipe) will be used in this study to simplify the calculation of equations discussed earlier in this chapter. The software will also be used to analyse compressed air networks to identify reconfiguration potential. The following section focuses on previously implemented DSM projects on the compressed air networks of two South African gold mines. The projects focused on optimising the distribution of compressed air throughout the reticulation networks of the mines.

2.5 Previously implemented DSM projects relevant to the study

2.5.1 Introduction

As discussed in Chapter 1, many methods are available to reduce the electricity demand of compressed air systems in the mining industry. For reference purposes, the methods include the following:

- replacing pneumatic mining equipment with non-pneumatic equipment;
- controlling the supply side;
- controlling the demand side;
- optimising surface compressed air distribution and
- reducing leaks on pipe networks.

One method not implemented in many mining applications is the reconfiguration of the physical compressed air reticulation network. There have, however, been case studies regarding the optimisation of mining compressed air networks for optimal air distribution. These case studies investigated DSM projects implemented on two separate South African mining compressed air networks. The case studies are examined in the following sections. The mines' names will be kept anonymous to ensure confidentiality.

2.5.2 Case study 1

Background compressed air network layout

In 2005, an energy efficiency (EE) project was identified on Mine A's compressed air network and submitted to Eskom for approval. Subsequently, the project was approved and implemented. The following sections briefly discuss the inner details and outcome of the study.

Mine A's surface compressed air network was approximately forty kilometres long [27], [41]. Ten shafts and six processing plants were connected via a surface pipe reticulation network, which was also connected to multiple compressor houses. Figure 19 is a simplified schematic layout (prior to project implementation) of Mine A's surface compressed air network [41].

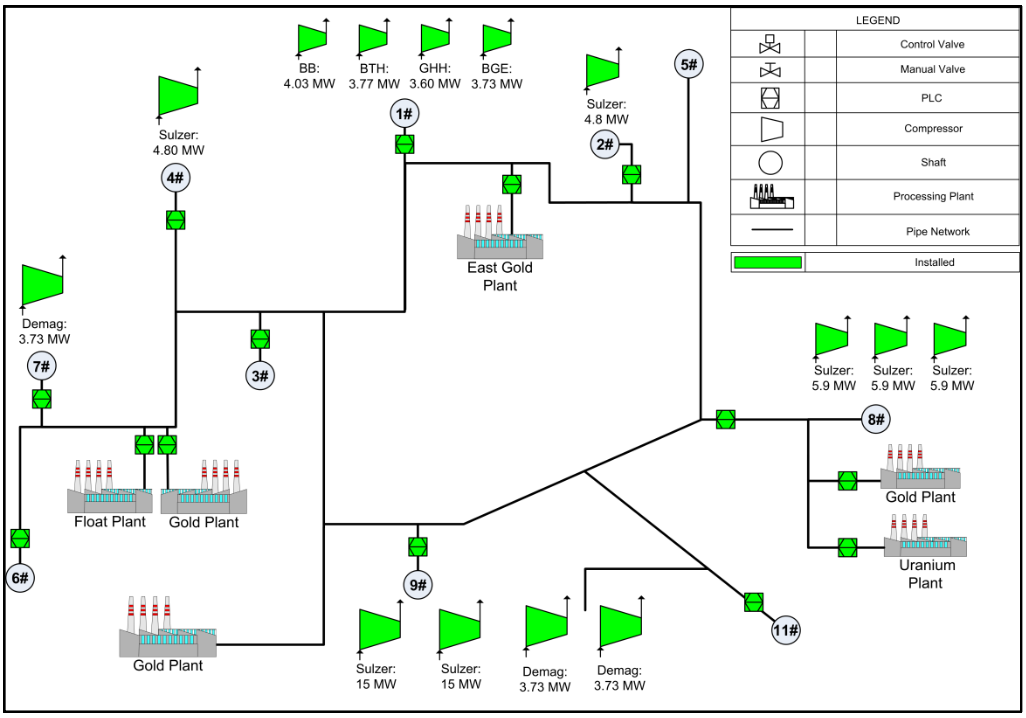

Figure 19: Surface compressed air network layout of Mine A

Figure 19 indicates that Mine A used fourteen compressors to supply compressed air to the network. These compressors were located at different shafts in the network. The compressors had a total installed capacity of 83 620 kW delivering 533 000 CFM of air, which made it one of the largest compressed air networks in South Africa [27]. Table 9 gives a brief summary of the compressors used at Mine A.

Mine A Compressor Summary			
Shaft	Compressor	Installed Capacity	
		Power (kW)	Airflow (CFM)
1#	BB	4 030	25 000
	BTH	3 767	25 000
	GHH	3 600	25 000
	BGE	3 730	20 000
2#	Sulzer	4 800	30 000
4#	Sulzer	4 800	30 000
7#	Demag	3 730	18 000
8#	Sulzer	5 900	40 000
	Sulzer	5 900	40 000
	Sulzer	5 900	40 000
9#	Sulzer	15 000	100 000
	Sulzer	15 000	100 000
11#	Demag	3 730	20 000
	Demag	3 730	20 000
Total	**14**	**83 617**	**53 300**

Table 9: Mine A compressor summary

Investigations and purpose of study

During investigations on Mine A’s compressed air network it was discovered that only 8#, 9# and 11# were fully productive (main) shafts (shafts are indicated using the # symbol). The remaining shafts had experienced vast downscaling in production at the time of the investigation. There were, however, still operational processing plants, which required certain compressed air requirements. Table 10 summarises Mine A’s compressed air requirements [41]:

Mine A Compressed Air Requirement Schedule		
Shaft	Time Period	Pressure Requirement (kPa)
Main shafts	07:00 – 14:00	590
	14:00 – 07:00	520
Remaining shafts	00:00 – 24:00	440
Processing plants	00:00 – 24:00	440

Table 10: Mine A compressed air requirement- and operating schedule

The compressors located at the main shafts supplied sufficient compressed air to these shafts [41]. The compressors at the other shafts were used as standby machines when the air pressure dropped below the requirements of the processing plants and remaining shafts [41].

The basis of the proposed EE intervention was to identify high- and low-pressure consumers and, if possible, to divide the single network into two separate systems. The new setup would ensure that the various points received compressed air at different, but correct operating pressures [41]. The reduction in pressure would result in savings due to increased compressor efficiency and reduced pipe friction losses [41].

Proposed solution and control philosophy

Creating different pressure sections requires sufficient knowledge of the system's compressed air requirements [47]. The pressure and flow requirements of every shaft and processing plant in the compressed air network were thoroughly determined and documented [41]. Identifying these requirements enabled the engineers to determine the exact locations to split the network into high- and low-pressure sections. Figure 20 is a simplified schematic layout of the proposed solution. The proposed infrastructure is marked in blue.

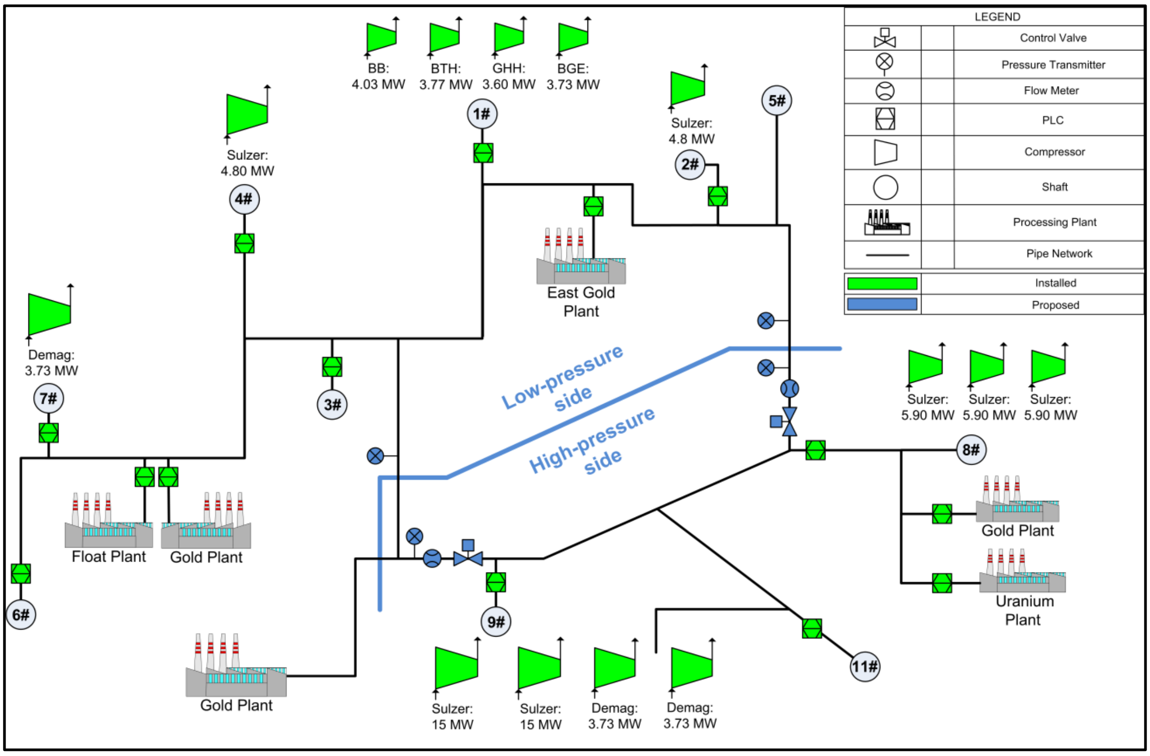

Figure 20: Proposed compressed air network layout for Mine A

According to Figure 20, two control valves were required to divide the network into high- and low-pressure sections. Flow meters and pressure transmitters were installed to measure the pressure and flow to the low-pressure section. The control valves were controlled according to the pressure measured on the low-pressure side.

The ESCO proposed that the high-pressure section of the network be isolated from the low-pressure section [41]. A low-pressure set point of 440 kPa must be maintained in the low-pressure section by using the control valves [41]. One of the backup compressors in the low-pressure section could be started if the pressure dropped below 440 kPa [41].

Implementation and results

In 2010, the ESCO implemented the proposed EE strategy on Mine A's compressed air network. Figure 21 is an illustration of the effect the project had on the power consumption of the mine's compressors. The power consumption after implementation was compared to the power consumption baseline constructed prior to the project's implementation.

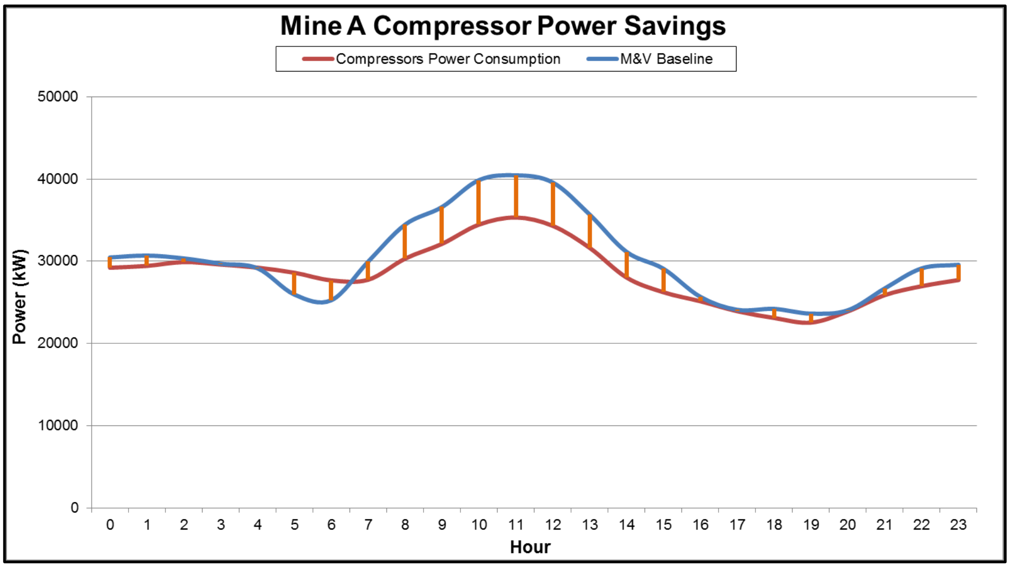

Figure 21: Effect of the DSM strategy on Mine A's compressor power consumption [41]

Mine A achieved an average power saving of 3.62 MW over 24 hours [41], [47]. The bulk of the electricity saving was made possible by reducing the pressure to 440 kPa on the low-pressure section [41], [47]. The reduction in pipe friction losses and air leaks due to lower operating pressures also contributed to the compressor power saving [41]. The network-split strategy gave an average daily financial saving of R64 000 to the client [47]. The average was calculated over an annual basis.

The effect of the reduced pressure and airflow was obtained by comparing the total amount of compressed air used over a period of one month with the corresponding values when the power baseline was originally measured. After implementation, the total amount of compressed air usage reduced from an average of 197 000 tons of air per month to an average of 192 000 tons of air per month [41]. The reduction in air usage was the result of reduced air leaks [41].

The power saving achieved was a direct result of the compressors being able to supply lower pressure compressed air to selected parts of the network [41]. High-pressure compressed air was maintained on the high-pressure section. Each section of the compressed air system still received compressed air at their specific requirements to maintain the operational production as before [41].

2.5.3 Case study 2

Background

The first proposal to optimise Mine B's compressed air network was presented during February 2010. The following optimisation initiatives were identified by an ESCO and proposed to the client [22]:

- optimising the compressed air supply;
- controlling underground air demand via control valves;
- reducing compressed air leaks; and
- dividing the compressed air network for optimised air distribution.

For the purposes of this study, the focus was on the division strategy implemented on Mine B's compressed air network. The following sections briefly discuss the inner details and outcome of the study.

Compressed air network layout

Mine B's surface compressed air network consisted of one shaft, referred to as one shaft (1#), and a gold plant. The shaft and gold plant were connected via a pipe network to a single compressor house. The pipe network allowed compressed air to be supplied from the compressors to the end-users and consisted of several kilometres of piping [22]. Figure 22 is a simplified schematic layout of Mine B's surface compressed air network, prior to the project's implementation.

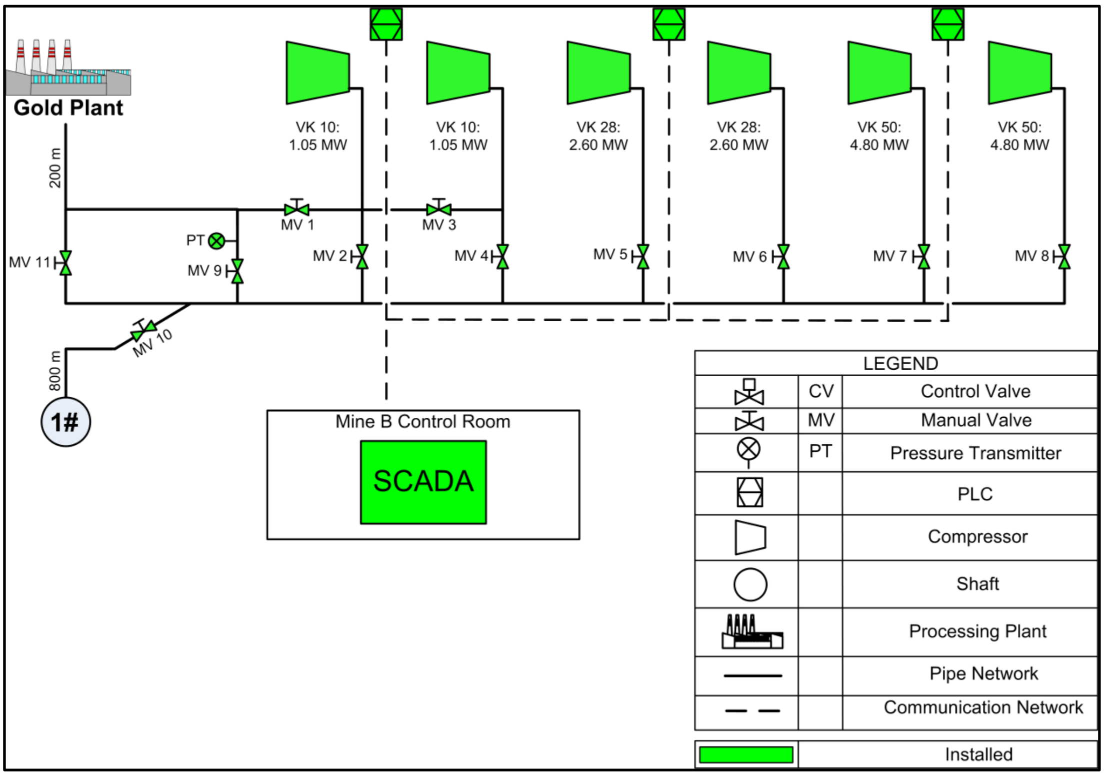

Figure 22: Surface compressed air network layout of Mine B

Figure 22 indicates that Mine B used six compressors to satisfy the compressed air demand at the time of the study. The compressors had a total installed capacity of 17 500 kW delivering 176 000 CFM of air [22]. Table 11 gives a brief summary of the compressors' ratings being used at Mine B [22].

Mine B Compressor Summary			
Shaft	**Compressor**	**Installed Capacity**	
		Power (kW)	**Airflow (CFM)**
1#	VK 10	1 050	10 000
	VK 10	1 050	10 000
	VK 28	2 600	28 000
	VK 28	2 600	28 000
	VK 50	5 100	50 000
	VK 50	5 100	50 000
Total	**6**	**17 500**	**176 000**

Table 11: Mine B compressor summary

All the compressors supplied air to a main manifold outside the compressor house. From there the main manifold split into two different sub-manifolds, supplying compressed air to

two different sections. The manifolds were linked via isolation valves [22]. These valves were left fully open with no control over the compressed air flowing between the manifolds [22].
As part of the existing control, the following hardware was installed [22]:

- volumetric flow meters and pressure transmitters on each compressor's outlet manifold;
- instrumentation was connected to relevant PLCs located in the compressor house; and
- PLCs were connected to the Mine's SCADA system via a communication network.

The connection with the PLCs ensured monitoring of instrumentation and compressor statuses [22]. The control room operators were also able to automatically stop/start the compressors from the local control room.

Investigations and purpose of study

Through investigation it was discovered that 1# and the gold plant were fully operational at the time of the study. Both 1# and the gold plant required a certain flow and pressure during normal mining weekdays. Relevant mine personnel were consulted to obtain information regarding the shaft and gold plant's daily mining schedules as well as their compressed air requirements [22].

The investigations identified the following compressed air requirements for 1# and the gold plant.

Mine B Compressed Air Requirement Schedule			
Shaft	**Activity**	**Time Period**	**Required Surface Pressure (kPa)**
1#	Peak drilling	09:00 – 15:00	440
	No activities	15:00 – 21:00 & 04:00 – 09:00	250
	Loading, tramming & hoisting	21:00 – 04:00	400
	Refuge bays	00:00 – 24:00	250
Gold Plant	Agitation	00:00 – 24:00	450 – 500

Table 12: Mine B compressed air requirement- and operating schedule

The actual air pressure required by the gold plant ranged between 420 and 450 kPa [22]. The higher requirement was due to pressure losses over the pipeline from the compressor house to the gold plant. The loss was due to large air dryers installed at the gold plant, through which air had to travel, before supplying the plant [22].

Compressed air was supplied to 1# and the gold plant from the same manifold at the compressors' outlet. Therefore, the minimum delivery pressure from the compressors was determined by the maximum requirement between 1# and the gold plant. The minimum and maximum pressure required from compressor outlets were 480 kPa and 530 kPa respectively [22]. These requirements were sufficient to satisfy 1# and the gold plant's compressed air demand.

As with the previous study, the purpose of this study was to determine the possibility to implement an EE strategy on Mine B's compressed air network. The basis of the strategy was to supply 1# and the gold plant with different, but sufficient compressed air pressures [22].

Proposed solution and control philosophy

After several investigations and calculations it was discovered that Mine B's network could be divided into two sections, namely [22]:

- low-pressure and high-airflow section (1#); and
- high-pressure and low-airflow section (gold plant).

It would be more efficient to supply each section with its own compressed air. This would allow the pressure supplied to 1# to be reduced below the minimum requirement of the gold plant during certain periods of the day [22].

Figure 23 is a simplified schematic layout of the proposed solution to optimise Mine B's compressed air network. According to Figure 23 the ESCO proposed the installation of four control valves, two pressure transmitters and one PLC. The control valves were used to create two separate supply manifolds [22]. Consequently, the compressed air supply to the gold plant was independent from the compressed air supply to 1#. The proposed infrastructure is highlighted in blue.

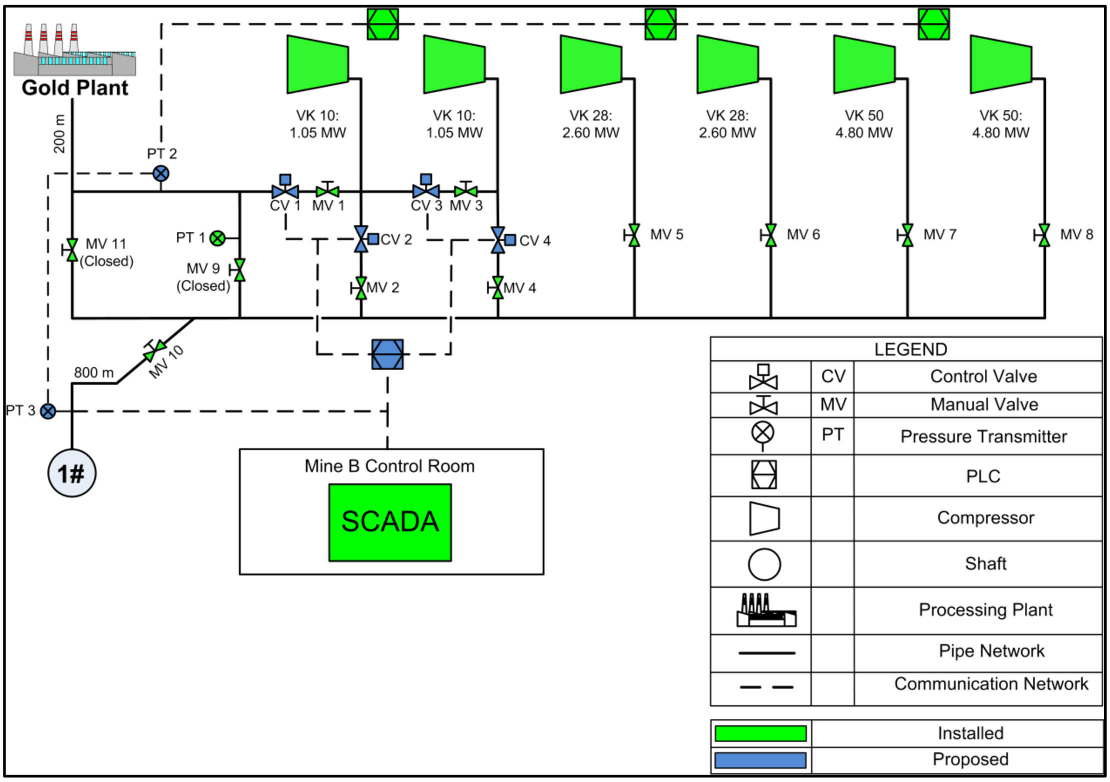

Figure 23: Proposed compressed air network layout for Mine B

According to the control philosophy, manual valve (MV) 11 and MV 9 were closed. The VK 10 compressors had to be used as baseload compressors to supply the gold plant with sufficient compressed air. The remaining compressors had to be used to supply 1#. One of the remaining compressors could also be stopped if excess air was supplied to 1#. The delivery set points of the VK 10 compressors had to be set according to the minimum pressure requirement of the gold plant. The remaining compressors' set points had to be set according to the minimum pressure requirement of 1#.

All the control valves (CV 1, CV 2, CV 3 and CV 4) had to be controlled according to the pressure requirements of the gold plant. CV 2 and CV 4 should be controlled according to the pressure reading from pressure transmitter (PT) 2 [22]. The valves should open if the average reading goes above the pressure set point of the gold plant [22]. This would allow any excess air to be supplied to the manifold supplying 1# with compressed air [22].

Implementation and results

Figure 24 illustrates the effect of the EE initiative on the power consumption of Mine B's compressors. However, Figure 24 displays the total power saved due to all the optimisation strategies, previously discussed in the background of this study. For the purposes of this study, only the separation strategy is of importance.

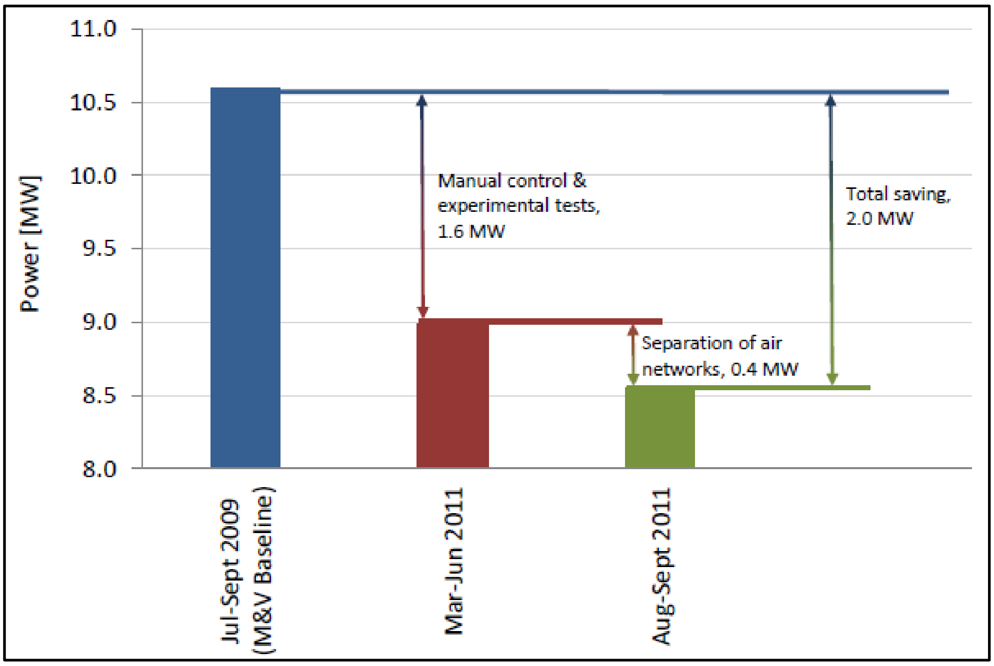

Figure 24: Effect of the DSM strategy on Mine B's compressor power consumption [22]

According to Figure 24, an average weekday power saving of 0.4 MW was realised during August 2011 and September 2011 [22]. This saving was due to the separation of the compressed air supply manifolds, which allowed mining personnel to reduce the pressure and flow supplied to 1# during low demand periods [22]. The compressors were also able to supply each section of Mine B individually with compressed air.

2.6 Conclusion

This chapter investigated basic mining operations and their compressed air requirements. Inefficient air supply, distribution and the technologies used to address these inefficiencies were discussed. Basic compressed air network fundamentals and calculations were researched. The information gathered in this chapter will be used to simplify the reconfiguration process, discussed in the following chapter.

An overview of two previously implemented DSM projects, related to the reconfiguration of mining compressed air networks, were given. However, the studies focused on reconfiguring a network by optimising the distribution of compressed air. This study will now focus on reconfiguring the physical layout of the reticulation network for optimal operation.