REDUCING ENERGY CONSUMPTION ON RSA MINES THROUGH OPTIMISED COMPRESSOR CONTROL

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at the Potchefstroom Campus of the North-West University

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ABSTRACT

Title: Reducing energy consumption on RSA mines through optimised compressor control

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Degree: Master of Engineering (Electrical)

South Africa experienced a severe shortfall in electricity supply during 2008. Eskom, the national electricity supplier, implemented several strategies to alleviate the situation. The Power Conservation Programme set the mining sector a mandatory target to reduce its annual power consumption by 10%. The quickest way to achieve these savings is by optimising the largest power consumers on the mines. Compressed air is one of these, constituting approximately 40% of total electricity consumption on platinum mines.

Several methods to reduce power consumption on compressed air systems were investigated. The investigation revealed that centrifugal air compressors on the mines are typically manually operated at a fixed delivery output. Attempts to reduce electricity consumption by reducing air demand will therefore not necessarily lead to savings. A control system that will enable the compressor to automatically match the supply with system demand is required. An optimised control strategy was then developed and implemented on three compressed air systems.

Measurements demonstrated savings between 13% and 49%. With the Eskom tariffs proposed for 2010, this implies a total saving of R 46 million per year for these three case studies. This will achieve, and may even exceed, the mandatory reduction in electricity consumption of the mines. These results demonstrate that one of the quickest ways to reduce energy consumption on South African mines is by implementing optimised compressor controls.
Suid-Afrika het in 2008 'n erge tekort aan elektrisiteit ervaar. Eskom, die nasionale elektrisiteitsvoorsieners, het verskeie strategieë toegepas ter verligting van hierdie tekort. Die *Power Conservation Programme* stel 'n verpligte 10% vermindering van jaarlikse kragverbruik aan die mynbousektor. Kragverbruik kan vinnig op myne verminder word deur te sorg dat die grootste kragverbruikers optimaal funksioneer. Pneumatiese stelsels is 'n voorbeeld van so 'n stelsel en is verantwoordelik vir byna 40% van die totale kragverbruik op 'n platinum myn.

Verskeie metodes is ondersoek om die kragverbruik van pneumatiese stelsels te verminder. Dit is duidelik uit hierdie ondersoek dat sentrifugale kompressors op myne hoofsaaklik met die hand beheer word en 'n vasgestelde uitset het. Die kompressor is dus nie daartoe in staat om die uitset na gelang van die behoefte te wysig nie. Pogings om die elektrisiteitsverbruik te verminder, deur die aanvraag na lug te verminder, sal dus nie 'n besparing kan meebring nie. Wat benodig word is 'n beheerstelsel wat die kompressor in staat stel om die stelselaanvraag en voorsiening automaties te laat strook. 'n Strategie vir optimale beheer van pneumatiese stelsels is dus ontwikkel en op drie stelsels toegepas.

Besparings tussen 13% en 49% is gevind. Met Eskom se voorgestelde tariewe vir 2010 sal die toepassing op hierdie drie stelsels 'n gesamentlike besparing van R46 miljoen per jaar teweeg bring. Dit sal dus die verpligte doelwit wat aan die myne gestel is, nakom. Hierdie resultate bewys dat die optimale beheer van kompressors een van die vinnigste maniere is om energieverbruik in Suid-Afrika te verminder.
ACKNOWLEDGEMENTS

This dissertation would not be complete without acknowledging all who contributed.

- I would firstly like to thank God for granting me the ability to complete this dissertation. Without His grace, I would not be able to achieve anything.

- To my parents Gerhard and Louïè Booysen, thank you for a lifetime of love and dedication. I would not have had this opportunity if it were not for your sacrifices. Thank you for always being an example to me, you truly inspire me.

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# NOMENCLATURE

## ABBREVIATIONS:

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSM</td>
<td>Demand Side Management</td>
</tr>
<tr>
<td>EAF</td>
<td>Energy Availability Factor</td>
</tr>
<tr>
<td>DME</td>
<td>Department of Minerals and Energy</td>
</tr>
<tr>
<td>PCP</td>
<td>Power Conservation Plan</td>
</tr>
<tr>
<td>MW</td>
<td>Megawatt</td>
</tr>
<tr>
<td>NERSA</td>
<td>National Energy Regulator of South Africa</td>
</tr>
<tr>
<td>GWh</td>
<td>Gigawatt hour</td>
</tr>
<tr>
<td>kPa</td>
<td>kilopascal</td>
</tr>
<tr>
<td>m³/h</td>
<td>Cubic metres per hour</td>
</tr>
<tr>
<td>US DOE</td>
<td>United States Department of Energy</td>
</tr>
<tr>
<td>FRL</td>
<td>Friction related losses</td>
</tr>
<tr>
<td>CAES</td>
<td>Compressed air energy storage</td>
</tr>
<tr>
<td>ASC</td>
<td>Air Systems Controller</td>
</tr>
<tr>
<td>HMI</td>
<td>Human-machine interface</td>
</tr>
<tr>
<td>CCV</td>
<td>Close-coupled valve</td>
</tr>
<tr>
<td>TCV</td>
<td>Throttle control valve</td>
</tr>
<tr>
<td>PID</td>
<td>Proportional Integral Derivative</td>
</tr>
<tr>
<td>VGD</td>
<td>Variable geometry diffuser</td>
</tr>
<tr>
<td>VSD</td>
<td>Variable speed drive</td>
</tr>
<tr>
<td>VTB</td>
<td>Virtual test bed</td>
</tr>
<tr>
<td>PLC</td>
<td>Programmable logic controller</td>
</tr>
<tr>
<td>SCADA</td>
<td>Supervisory control and data acquisition</td>
</tr>
<tr>
<td>M&amp;V</td>
<td>Measuring and verification</td>
</tr>
<tr>
<td>RPM</td>
<td>Revolutions per minute</td>
</tr>
<tr>
<td>IGV</td>
<td>Inlet guide vane control</td>
</tr>
<tr>
<td>SP</td>
<td>Set-point</td>
</tr>
</tbody>
</table>
**SYMBOLS:**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>Volume</td>
</tr>
<tr>
<td>T</td>
<td>Time</td>
</tr>
<tr>
<td>C</td>
<td>Air demand</td>
</tr>
<tr>
<td>P</td>
<td>Pressure</td>
</tr>
<tr>
<td>Ps</td>
<td>Pressure on suction side</td>
</tr>
<tr>
<td>Pd</td>
<td>Pressure on discharge side</td>
</tr>
<tr>
<td>Φ</td>
<td>Mass flow coefficient</td>
</tr>
<tr>
<td>Ψ</td>
<td>Pressure rise coefficient</td>
</tr>
<tr>
<td>k</td>
<td>Valve gain</td>
</tr>
<tr>
<td>L_i</td>
<td>Inlet duct length</td>
</tr>
<tr>
<td>l_c</td>
<td>Dimensionless compressor length</td>
</tr>
<tr>
<td>B</td>
<td>Greitzer's parameter</td>
</tr>
<tr>
<td>ρ</td>
<td>Ambient air density</td>
</tr>
<tr>
<td>a_s</td>
<td>Speed of sound</td>
</tr>
<tr>
<td>c</td>
<td>Valve capacity</td>
</tr>
<tr>
<td>L_e</td>
<td>Exit duct length</td>
</tr>
<tr>
<td>A_c</td>
<td>Compressor duct area</td>
</tr>
<tr>
<td>U</td>
<td>Mean rotor speed</td>
</tr>
<tr>
<td>R</td>
<td>Rotor mean radius</td>
</tr>
<tr>
<td>V_p</td>
<td>Plenum volume</td>
</tr>
<tr>
<td>ξ</td>
<td>Dimensionless time</td>
</tr>
<tr>
<td>u</td>
<td>Valve opening</td>
</tr>
<tr>
<td>L_c</td>
<td>Compressor and ducts length</td>
</tr>
<tr>
<td>a</td>
<td>Reciprocal time lag of compressor passage</td>
</tr>
<tr>
<td>Ψ_{co}</td>
<td>Compressor characteristics shut-off valve</td>
</tr>
<tr>
<td>W</td>
<td>Compressor characteristic semi-width</td>
</tr>
<tr>
<td>H</td>
<td>Compressor characteristic semi-height</td>
</tr>
<tr>
<td>N</td>
<td>Rotational speed</td>
</tr>
</tbody>
</table>
Chapter 1

Ongoing increases in the cost and demand for electricity worldwide have resulted in large-scale electricity conservation initiatives. A study of the major power consumers in South Africa has identified compressed air as an area with great potential to effectively reduce electricity consumption.
1 INTRODUCTION

1.1 The increase in electricity demand

1.1.1 Background

The global demand for electricity continues to increase because of growing populations and economies. The availability of non-renewable energy resources such as coal, natural gas and oil is therefore a constant concern. The major use of these fossil fuels to generate electricity has affected the environment negatively. A combination of these factors has resulted in a worldwide need for electricity conservation.

South Africa experienced a severe electricity supply shortfall during 2008 resulting in emergency load shedding [1.1] that significantly affected the South African economy. The national energy supplier Eskom launched various initiatives to reduce the growing demand for electrical energy. One of these initiatives is Demand Side Management (DSM). The goal of DSM is to lower the national electricity demand by motivating users to reduce or restrict their demand for electrical energy. By reducing the national demand, Eskom will be able to re-establish the required supply safety margin, thereby lowering the stress on the national grid and giving Eskom time to upgrade the supply system.

The mining sector is one of the largest consumers of electrical energy in South Africa and was one of the sectors most severely affected by the electricity supply shortfall [1.5], [1.6], [1.8]. Compressed air systems are one of the main consumers of electrical energy in the mining sector [1.9]. The majority of compressed air systems on the mines are inefficient and controlled by outdated technology and equipment. This presents a major opportunity for reducing energy demand by optimising the compressed air systems.
1.1.2 Global energy demand

According to the Office of Integrated Analysis and Forecasting in the United States Department of Energy (US DOE), the worldwide consumption of energy will increase by 50% from 2005 to 2030 [1.1]. The main contributors to the continuous growth are the expanding economies of developed countries and population growth in developing countries. Figure 1-1 illustrates this projected growth.

![Figure 1-1: Global energy consumption [1.1]](image)

Figure 1-2 shows the expected increase in consumption of various fuels. This figure shows that fossil fuels will remain the major energy resource for the immediate future. Dwindling supplies of non-renewable energy sources will inevitably result in increasing energy costs. Electrical energy is expected to remain the fastest growing source of energy consumed by end-users [1.1].
The increasing demand for energy, combined with rising costs has created the need for efficient and effective use of electricity. This presents the opportunity for new technologies to develop, which will not only pave the way for optimising the use of the energy available, but also have a positive impact on the environment.

1.1.3 South African electricity demand

Due to a series of problems experienced by Eskom during 2008, the demand for electricity briefly exceeded the supply. This shortage resulted in power failures throughout the country which affected several sectors of South African business and industry negatively.

Figure 1-3 illustrates Eskom’s energy availability factor (EAF) for the past ten years. The EAF measures generation plant availability and accounts for external energy losses. Figure 1-3 demonstrates the dramatic decrease in EAF in 2007 and 2008.
Figure 1-3: Energy availability versus annual target [1.1]

1.2 Electricity-saving initiatives

DSM implementation began in 2005. The objective of the PCP and DSM initiatives is to lower the expected 2008 - 2010 power demand by 3 000 MW. By increasing Eskom’s generation capacity and lowering the national demand, Eskom will again be able to operate within its 15% safety margin [1.1]. This would allow Eskom time for maintenance and upgrading of their systems [1.3].

Figure 1-4 illustrates the proposed impact of the planned reduction in demand.
By issuing existing users with a mandatory electricity-saving target, the PCP aims to control growth by encouraging changes in user behaviour while promoting the use of the DSM programme [1.4]. If the given target is not achieved, the user will be penalised. The PCP will also be used to manage new electricity connections, thereby managing consumption requirements in order to align with available capacity.

Presently there are three methods employed to reduce the amount of electricity used during peak times [1.1]. The first method is to move electricity demand away from peak demand time to a lower demand time; this method is termed load shifting. The second method is to reduce the amount of electricity used during peak time by limiting high electricity-consuming processes during this period; this method is referred to as peak clipping. A third method proposes to permanently reduce the energy consumption of several end-users or devices, resulting in overall energy efficiency [1.1].

![Figure 1-4: Estimated impact of the reduction in demand](image)
Introduction

Figure 1-5 shows the demand pattern experienced by Eskom during a typical 24-hour period. This figure clearly shows the peak morning, (07:00 to 10:00), and peak evening demand, (18:00 to 21:00), periods.

![Electricity demand patterns](image)

*Figure 1-5: Electricity demand patterns [1.1]*

Figure 1-6 is an illustration of the load-shifting technique. The electricity consumed in the morning and evening peaks is shifted to lower demand periods. This method has no impact on the total daily electric energy consumed. It only lowers the amount of electricity Eskom has to deliver during the peak demand periods.
Figure 1-6: An example of load shifting

Figure 1-7 illustrates the evening peak-clipping method. Peak-clipping only reduces electricity consumption during the peak demand period. The rest of the consumption during the day remains unaltered. The total electricity consumption of the system will therefore be less, with a reduction in electricity consumption only during peak demand period.

Figure 1-7: An example of peak clipping
Introduction

Figure 1-8 shows the effect of energy efficiency. Optimising existing equipment reduces overall power consumption. The energy profile remains the same and therefore production schedules are not affected.

![Energy efficiency graph](image)

*Figure 1-8: An example of energy efficiency*

Eskom has allocated funds to enable large consumers to implement DSM projects. In return, the customer will agree to sustain the selected DSM project for a stipulated period.
1.3 Major consumers of electricity

Areas where the application of electricity-saving projects will have the maximum effect must be determined.

Table 1-1: Eskom’s sales for 2007 and 2008 [1.1]

<table>
<thead>
<tr>
<th>Category</th>
<th>Customers1</th>
<th>Sold</th>
<th>Revenue</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number</td>
<td>Number</td>
<td>GWh</td>
</tr>
<tr>
<td>Redistributors</td>
<td>766</td>
<td>760</td>
<td>89 941</td>
</tr>
<tr>
<td>Residential2</td>
<td>4 016 689</td>
<td>3 829 986</td>
<td>10 423</td>
</tr>
<tr>
<td>Commercial</td>
<td>46 496</td>
<td>45 233</td>
<td>8 373</td>
</tr>
<tr>
<td>Industrial</td>
<td>2 966</td>
<td>2 955</td>
<td>61 510</td>
</tr>
<tr>
<td>Mining</td>
<td>1 153</td>
<td>1 127</td>
<td>32 373</td>
</tr>
<tr>
<td>Agricultural</td>
<td>83 722</td>
<td>82 583</td>
<td>4 848</td>
</tr>
<tr>
<td>Traction</td>
<td>510</td>
<td>510</td>
<td>2 990</td>
</tr>
<tr>
<td>International</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Utilities</td>
<td>7</td>
<td>7</td>
<td>4 553</td>
</tr>
<tr>
<td>End users across the border</td>
<td>3</td>
<td>3</td>
<td>9 355</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>4 152 312</strong></td>
<td><strong>3 963 164</strong></td>
<td><strong>224 366</strong></td>
</tr>
</tbody>
</table>

1 Customer numbers have been revised to take into account disconnected customers and homes that no longer exist as a result of floods and other reasons.
2 Prepayments and public lighting included under residential.
3 R45 million revenue, resulting from testing in 2007 at Camden power station, was capitalised to plant.

Table 1-1 illustrates Eskom’s power sales for 2007 and 2008. This table confirms that the mining and industrial sectors are major consumers of electrical energy in South Africa. The percentage of total energy consumption in 2008 is shown in Figure 1-9.
Introduction

Optimising the electricity consumption in the mining and industrial sectors will enable large electricity consumers to reach the PCP target without the need to reduce production.

In an effort to determine the areas in which the increased energy efficiency of the mining and industrial sectors will have the greatest impact, Eskom’s maximum demand figures in the Industrial sector were consulted [1.3]. Figure 1-10 illustrates the maximum demand in the industrial sector.
An analysis of industrial and mining compressed air systems indicated that compressors account for 9% of the total maximum industrial demand [1.3]. Compressors used in the platinum mines were responsible for up to 40% of total energy consumed at these mines [1.9]. Further investigation determined that the majority of compressed air systems in the mining industry are still operated by outdated technology and equipment.

The 10% reduction in electricity consumption demanded by the PCP severely affected the production of the major mining companies in 2008 [1.5], [1.6], [1.8]. Optimising the compressed air system will enable the mines to maintain full production while still complying with the PCP restriction.
1.4 Compressors as major electricity consumers

1.4.1 Cost components of compressor systems

An analysis of the five-year life cycle of a new compressed air system indicates that electricity consumption constitutes 80% of a compressed air system’s expenses [1.10]. Furthermore, a compressor system, including all its components and operations, can easily be responsible for 15% to 30% of a plant’s annual electricity costs [1.11]. Figure 1-11 illustrates the cost components of a typical compressor system.

![Cost components of a typical compressed air system](image)

*Figure 1-11: Cost components of a compressor system [1.10]*

Improving the energy efficiency of a compressor system will result in a reduction of electrical energy consumption.

1.4.2 Typical set-up of compressed air systems in industry

Compressor systems in the mining sector consist of several compressors connected to a complex supply network. In order to understand the interaction between the compressors and the operational equipment, investigation into the set-up of a typical compressed air system is required.
Figure 1-12 shows a simplified compressed air system.

![Diagram of a compressed air system](image_url)

*Figure 1-12: Layout of a small compressed air system [1.10]*

The correct operation of each component is critical to the efficiency of the compressed air system as a whole. Compressed air systems on the mines consist of several kilometres of underground piping running as deep as 3,000 metres below the surface. Some of these systems have been modified so many times, that very often there is no proper documentation of the existing system.

Mining sites often consist of several interconnected shafts. The main shafts usually consist of a local compressor house containing several compressors. These compressors will supply the bulk of the compressed air required by the activities of that particular shaft.

To increase the potential to deliver air to any one of the shafts on the site, the local compressor houses are all connected through a surface piping system, as illustrated in Figure 1-13.
Introduction

This piping system is referred to as a compressed air ring. The compressed air ring adds stability to the air system by enabling the network to supply air to a shaft from any of one of these compressors. This is a requirement when local compressors are unable to supply sufficient flow caused, for example, by a sudden increase in demand, compressor breakdown or planned maintenance.

![Figure 1-13: A typical compressed air ring](image)

Substantial losses occur when converting electric energy into compressed air and then piping the air underground. These losses are persuading the mines to investigate alternative energy sources for underground operations, such as replacing pneumatic drills with electric drills [1.13]. Owing to the high cost of installing new infrastructure, the ideal solution is to optimise existing infrastructure.
1.4.3 Operation constraints

The compressors connected to the air ring must maintain the system output so that the operational constraints are met at all the stations. The major constraints in the compressed air system are air pressure and air flow.

Pneumatic tools are designed to operate using air within a specified pressure range. Each piece of equipment has different requirements for operating efficiently [1.14]. If the pressure is too low, the equipment will not work properly and if the pressure is too high, the equipment may suffer damage or operate in a manner that is energy inefficient.

Normally hand-held pneumatic tools require only small volumes of air flow [1.15]. However, the large number and size of the equipment used in mining requires large volumes of air output from the compressors. Therefore, compressor output must be able to produce the required pressure and volume flow to meet all the operational requirements of each piece of equipment.

Table 1-2 presents the typical pressure and flow requirements of equipment used in the mining sector. This table indicates that the highest design pressure is 600kPa. The pressure output of the compressed air plant on the surface must be greater than 600kPa to compensate for system losses and leakages.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Pressure requirements (kPa)</th>
<th>Flow requirements (m³/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock drills</td>
<td>400 – 600</td>
<td>310 - 430</td>
</tr>
<tr>
<td>Mechanical loaders</td>
<td>400 – 500</td>
<td>Up to 1010</td>
</tr>
<tr>
<td>Fans</td>
<td>400 – 500</td>
<td>70 -680</td>
</tr>
<tr>
<td>Diamond drills</td>
<td>400 – 500</td>
<td>Up to 510</td>
</tr>
<tr>
<td>Agitation</td>
<td>300</td>
<td>Up to 1700</td>
</tr>
</tbody>
</table>

It is essential to specify equipment with design pressure specifications that are similar. If the equipment used has a wide range of pressure requirements,
additional energy losses will be created because some equipment will be supplied with excess pressure.

The total air consumption of a system can be calculated if the number and consumption of each piece of equipment is known. An example of the typical calculation to determine maximum demand of air flow is presented in Appendix A. Calculating the actual requirement of the entire system accurately will enable optimal compressor selection.

In addition to air pressure and air flow, there are other criteria to be considered. These include components such as bleed valves and water traps. Friction losses and leaks in the system piping must also be considered. Furthermore, the schedule of equipment usage should be taken into account. For example, rock drills and rock breakers are not used during the same shift, which will significantly influence the maximum air demand of the system. After taking all these criteria into consideration, the system requirements can be estimated.

1.4.4 Methods to reduce compressed air system electricity consumption

Several methods are available to optimise compressor systems [1.16]. Most optimisation initiatives focus on a single aspect of the system without considering the system as a whole. Some examples of existing energy savings procedures are discussed below.

- **Reduction of inappropriate use**

Compressed air energy is a clean, easy to use and readily available energy source. This leads to several forms of abuse in the industry. Examples of such abuse in the mining sector [1.17]:

- An open tube is used as a tool to cool, clean or dry certain applications [1.18].
- Personnel cooling.
- Diaphragm pumps are often installed without proper regulators and speed controls resulting in air wastage.
Introduction

- Equipment continuously operating at maximum system air pressure.
- Abandoned equipment is often found underground in the mine, particularly when the specific area is no longer used, but still connected to the supply network.

Some mines have already reduced their energy consumption by removing air equipment such as Venturi pumps and blocking off pipe sections that are no longer used. The use of compressed air by illegal mining activities also has a significant effect on compressed air consumption.

- **Reduction of system leaks**
  Systems that are not subjected to regular maintenance result in a 20% loss of the total air produced, due to system leaks [1.17], [1.19].

- **Control of pressure drop and system pressure**
  Ideally, a system should not experience a pressure loss of more than 10% from the compressor discharge to point of use [1.17]. When the compressor discharge pressure is increased, losses through leaks and unregulated equipment will also increase [1.17].

Figure 1-14 illustrates system pressure drop from compressor output up to the end users underground.

---

1 Hennie de Winnaar Amandelbult Mine.
2 Dawie Peters Rustenburg Platinum Mine (RPM).
3 Henk Viljoen Evander Mine.
System pressure losses can be reduced by regular maintenance. Pressure losses at points of use can be kept to a minimum by using the correct specification filters, regulators and lubricators. Reducing the system pressure loss to below 10%, the compressor delivery pressure can be reduced. This will in turn result in a reduction of the overall energy consumption [1.19] [1.18]. The lower system pressure will also reduce the amount of air lost due to leaks.

Figure 1-15 shows the air loss as a function of orifice size at different pressures [1.20].
A generally accepted estimation is that compressor energy efficiency can be increased by 1% for every 14kPa that the output set point can be lowered [1.21].

- **Storage of compressed air**
  One of the methods available as a renewable energy source is through compressed air energy storage (CAES) [1.22]. This ability to store energy enables the system to adjust its energy consumption/generation profiles in order to achieve load shifting [1.23].

  Several mines converted unused underground cavities into air receivers. The sheer volume of air required to accommodate system requirements and safety concerns resulted in these experiments being discontinued.

- **Heat recovery on compressed air systems**
  The production of compressed air results in the generation of heat [1.17]. By using a well-designed heat recovery unit, 50% to 60% of the heat energy can be recovered and applied to alternative uses such as the heating of water [1.24].
Introduction

Tshepong Mine, the excess heat from the compressors is used to heat water for use in the change house\(^4\).

- **Opportunities at component level**

  By improving a specific component, the efficiency of the entire system can be improved \([1.19]\) \([1.18]\). There are several component sub-systems that can be investigated \([1.17]\); examples of these are:
  - electrical motor;
  - controls;
  - air treatment equipment;
  - air distribution; and
  - end-user equipment.

Anglo Gold Ashanti’s Tau Tona Mine replaced its standard pneumatic drills with electric drills. The removal of the pneumatic drills resulted in lower air consumption and pressure requirements, resulting in fewer losses and increased compressor efficiency \([1.13]\).

- **Compressor control**

  Reducing system air consumption alone will only marginally reduce the electricity consumption of the system. In order to reduce electricity consumption significantly, compressor output should be compatible with the demands of the system. Air compressors should be able to continually adjust output to meet system requirements.

  There are several software packages available to facilitate the automation and control of air compressors, including specifically developed Wonderware \([1.25]\) and Ingersoll Rand’s Air System Controller (ASC) \([1.26]\). This software includes programmes to facilitate human-machine interface (HMI), data acquisition and performance management. The systems have already been implemented to optimise plant and workshop compressors \([1.27]\).

\(^4\) Tony Kleinschmidt *Tshepong mine.*
Many mines are presently engaged in various efforts to reduce the energy waste of their compressed air systems. Research indicates that efforts have concentrated mainly on reducing inappropriate usage, repairing system leaks and lowering the required system pressure. There is no available information on the successful implementation of automated control systems in the South African mining sector.

1.5 Research objectives

The initial investigation to reduce electricity consumption on the mines identified compressed air as an area with significant electricity-saving potential. There are various approaches to reduce compressed air consumption. Significant electrical energy savings can be achieved by accurately controlling the output air supply to match the system demand.

The objectives of this study are to:

- investigate present compressor control methods and strategies;
- develop an optimised compressed air control strategy;
- simulate the new strategy;
- validate the results by implementing the strategy in the mining environment.
1.6 Overview of chapters

A brief overview of the following chapters is given below.

Chapter 2: Study of compressor control.

Chapter 3: New concepts for controlling compressed air systems and the development of an optimised control strategy.

Chapter 4: Implementation and verification of the optimisation strategy in actual compressor systems.

Chapter 5: Discussion of the results from the new optimisation strategy and recommendations for future studies.
1.7 References


Introduction

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Date of access: 15 Nov. 2009.)


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Introduction


Chapter 2: A study of compressor control
2 COMPRESSOR BACKGROUND

2.1 Introduction

A brief discussion on compressor operation is given in this chapter. The aim will be to provide a basic insight and understanding of compressor performance and the interaction of the various components. This is critical for developing an improved control strategy to reduce the overall electric power consumption of compressed air systems.

2.2 Compressors in industry

Several types of compressors are available for the various requirements of industry. Each type of compressor has unique characteristics that influence its control and performance. Table 2-1 presents some basic compressor characteristics.

*Table 2-1: Compressor characteristics [1.10]*

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Reciprocating</th>
<th>Rotary Vane</th>
<th>Rotary Screw</th>
<th>Centrifugal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency at full load</td>
<td>High</td>
<td>Medium – high</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Efficiency at part load (power as % of full load)</td>
<td>High due to staging</td>
<td>Poor below 60%</td>
<td>Poor below 60%</td>
<td>Poor below 60%</td>
</tr>
<tr>
<td>Efficiency at no load (power as % of full load)</td>
<td>High (10%-25%)</td>
<td>Medium (30%-40%)</td>
<td>High-Poor (25%-60%)</td>
<td>High-Medium (20%-30%)</td>
</tr>
<tr>
<td>Noise level</td>
<td>Noisy</td>
<td>Quiet</td>
<td>Quiet if enclosed</td>
<td>Quiet</td>
</tr>
<tr>
<td>Size</td>
<td>Large</td>
<td>Compact</td>
<td>Compact</td>
<td>Compact</td>
</tr>
<tr>
<td>Oil carry over</td>
<td>Moderate</td>
<td>Low-Medium</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Vibration</td>
<td>High</td>
<td>Almost none</td>
<td>Almost none</td>
<td>Almost none</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Many wearing parts</td>
<td>Few wearing parts</td>
<td>Very few wearing parts</td>
<td>Sensitive to dust in air</td>
</tr>
</tbody>
</table>
### Compressor background

<table>
<thead>
<tr>
<th>Mass flow capacity</th>
<th>Low – high</th>
<th>Low - medium</th>
<th>Low – high</th>
<th>Medium – high</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>Medium – very high</td>
<td>Low – medium</td>
<td>Medium – high</td>
<td>Medium – high</td>
</tr>
</tbody>
</table>

Figure 2-1 illustrates the typical application ranges of different compressor types. This figure shows that the multistage centrifugal compressor is a more general purpose compressor, supplying high pressure air at an acceptable flow rate.

![Figure 2-1: Typical application ranges of compressor types [2.6]](image)

The centrifugal compressor is most widely used in the mining sector [1.14]. Because this study specifically focuses on the use of compressors in the mining sector, only aspects of the centrifugal compressor and pertinent issues are discussed.
2.3 Centrifugal compressors

Centrifugal compressors have unique characteristics that make them suitable for use in the mining sector. The compressors have the ability to produce the required air flow while maintaining a stable high system pressure. Furthermore, the compressors are mechanically simple, consisting of very few moving parts. The simplicity of these compressors makes them easier to operate and maintain.

The basic centrifugal compressor consists of an impeller mounted on a shaft. The shaft and impeller is positioned inside a housing consisting of an inlet duct, a volute and a diffuser. Figure 2-2 shows a backswept impeller.

Figure 2-2: Backswept impeller blade geometry [2.2]

Figure 2-3 illustrates the basic operation of a simple single stage centrifugal compressor used to compress refrigerant [2.3], [2.4]. Air is drawn into the rotating impeller eye and whirled outwards, increasing angular momentum. Inside the impeller, both static pressure and velocity are increased. The air then passes through diffuser vanes. The diffuser converts the kinetic energy of the air into pressure energy [2.1].
A higher compression ratio centrifugal compressor will usually consist of several impellers in series. The air is compressed through each stage resulting in improved efficiency and higher compression ratios [1.17]. Multistage compressors are required to meet the high-pressure requirements of the mining sector. Figure 2-4 is a cutaway diagram of a multistage centrifugal compressor.
A simplified diagram illustrating the air flow through a multistage centrifugal compressor similar to the compressor illustrated in Figure 2-4 is shown in Figure 2-5. After exiting the impeller the air flow enters a diffuser, where the kinetic energy of the air is converted into pressure energy. Each stage flow is collected in a volute where it enters the inlet of the following stage and further compression takes place [2.7].

Figure 2-5: Air flow through a multistage centrifugal compressor [2.6]

2.4 Compressor control

2.4.1 Methods of controlling output

There are several basic methods used to control the output of a centrifugal compressor. The standard methods of operation presently used are [1.17]:

- **Start and stop**
  The most basic output control of a compressor is to start or stop the electric motor driving the compressor [1.10]. This control works well with small compressors. Large compressors used in the mining sector are stopped only when the system demand reduces to such an extent that the continued operation of an extra compressor is no longer required.
Compressor background

Repeated start and stop cycles of compressors driven by large electric motors will cause the armature to overheat and result in equipment damage. When a compressor is stopped it can only be started up again after a sufficient time delay. This will allow the armature of the electric motor to cool down to a safe temperature.

• **Load and unload**
A better method to prevent excess air pressure is to simply off-load the compressor from the system [1.17], [2.6]. Centrifugal compressors can be off-loaded by isolating the compressor from the supply network. The compressor blow-off valve can then be opened to allow the compressor to run freely. The motor powering the compressor will therefore only need sufficient power to overcome basic friction within itself and the compressor. Table 2-1 shows that a centrifugal compressor operates at 20% to 30% of full load power while in the off-load state [1.10].

• **Variable output**
To accurately match compressor flow output with system demand, the output of a compressor must be controllable within various pressure delivery parameters. A large control range will ensure that the system requirements are accurately maintained. There are several methods that can be used to regulate the output of a compressor [1.10], [2.6], [1.19]. Whichever method is selected, the range of output will still be restricted [2.11].

The operational range of a centrifugal compressor’s output can be obtained from the compressor’s performance map. An example of a performance map is shown in Figure 2-6. The area of safe operation is limited by the surge line and the choke line.
Compressor output can be varied to meet the demand, as long as the performance lies within the stable operating region.

### 2.4.2 Compressor surge

Surge is a phenomenon characterised by oscillations in system pressure and flow. These undesirable oscillations could result in severe compressor damage. The output of a centrifugal compressor is controlled in order to ensure safe operation. Several controls exist to ensure optimal system performance while still preventing surge [2.12], [2.13], [2.14], [2.15].

Figure 2-7 is a characteristic curve of pressure ratio as a function of mass flow rate for various rotational speeds of a typical centrifugal compressor. Under normal operating conditions, the compressor will be running in a region situated to the right of the red surge line. Consider now the operation of the compressor at some
Compressor background

point to the left of the surge line where the slope of the constant speed curve is positive. At a constant rotational speed, a small reduction in mass flow will result in a lower delivery pressure. The pressure of the downstream air is still at a higher pressure and will tend to reverse its direction. Downstream pressure will eventually decrease and normal flow direction is again possible. This cycle is repeated at a high frequency, resulting in unstable air flow as well as extremely high compressor blade stresses [2.12].

Traditional control systems ensure that the compressor operation operates to the right of the “Surge Control Line” as shown in Figure 2-6. This approach restricts the operational area of the compressor. The development of more advanced control methods enables a controller to actively suppress, rather than avoid surge, improving overall system performance [2.16]. Actively suppressing surge will enable stable compressor operation in regions left of the surge line previously avoided [2.17]. Figure 2-8 illustrates the shift in surge line due to surge detection and active control.

Figure 2-7: Typical compressor surge line and performance map [2.12]
Figure 2-9 shows how the performance map for a multi-stage centrifugal compressor is developed to incorporate the surge points of all the individual stages. The first stage of the compressor is most likely to surge, due to the higher volume flow rates [2.12].
Before commissioning the compressor, the surge line will be verified by running the compressor under actual operational conditions. Several verification methods are employed but will not be covered in this dissertation.

### 2.4.3 Defining choke

When the air flow velocity in a passage reaches the speed of sound the flow is said to choke [2.11] and no further increase in mass flow is possible [2.18]. The choke limit illustrated in the compressor map is an indication of when this will happen. The effects of choke will not be studied further in this dissertation.
2.4.4 Variable structure control

The output of certain compressors can be varied because the compressors are designed to operate in several partially loaded conditions [1.17]. This enables the compressor to regulate the output without the need for start/stop or load/unload sequences [2.19].

The output of a centrifugal compressor operating at constant speed can be controlled by actuating the close-coupled valve (CCV) or the throttle control valve (TCV) [2.13]. The position of these valves is illustrated in Figure 2-10.

![Figure 2-10: A compressor model with a close-coupled valve and throttle control valve [2.13]](image)

The operation of the CCV and TCV can be controlled using several control techniques. Integrating the operation of these valves ensures that the output of the compressor can be optimally controlled. By utilising surge suppression techniques and varying the structure of the control techniques, the stable operation area of the compressor can be extended while still suppressing surge under various conditions [2.13].
Compressor background

An alternative method of incorporating variable structure control is the use of variable geometry diffusers (VGD). The flow though the centrifugal compressor can be controlled by changing the geometry of the compressor's diffuser [2.20]. The application of VGD improves the operational efficiency of the compressor at partially loaded conditions.

2.4.5 Drive speed control

The concept of drive speed control is to actively suppress surge in a centrifugal compressor. The output speed of the motor can be varied using variable speed drives, (VSD), which also serves as surge control, eliminating the need for various actuators [2.14], [2.21], [2.22], [2.23].

The control achieved with drive speed control is very effective and efficient. The cost of installing VSD systems on compressors in the mining sector is however extremely high because of the high powered electric motors used - typically 3 MW to 13 MW.

2.4.6 Inlet guide vane control

At very high impeller rotational speeds, the angle of air flow relative to the impeller becomes large enough for the flow to break away from the convex face of the impeller [2.8]. To improve performance, the air flow into the compressor can be changed by introducing pre-whirl [2.8]. This is achieved by introducing inlet guide vanes, (IGV), at the inlet section of the compressor. The purpose of the IGVs is to reduce the velocity of the air relative to the blade.

Figure 2-11 shows the influence of the IGV on velocity triangles of the air flow into the compressor. Correct positioning of the IGV reduces the relative air velocity, for a given axial velocity and impeller rotational speed.
In addition to improving the efficiency of the compressor, IGVs can also be used as a control medium. By controlling the vanes between fully open and fully closed, a compressor can be loaded/unloaded in order to satisfy system pressure demands.

Centrifugal compressors connected to complex systems often experience large fluctuations in airflow rates. To be able to satisfy the required parameters the compressor operation point needs to be shifted. Automatically adjusting the IGVs will enable the compressor to actively adjust to the changing parameters while maintaining good efficiency [2.25].

Figure 2-12 shows the results of performance tests conducted on a compressor with variable IGV (VIGV) [2.26]. The influence of IGV position on compressor performance at different rotational speeds, N, can be clearly seen.
Controlling the IGV to match compressor output to system demand will allow a compressor to operate at 40% of its rated output [1.17]. The range of IGV control is still limited by the potential for surge and minimum throttling capacity. Changes to various components such as the diffuser will also influence the control limit [2.24]. It is therefore typical practice to regulate a compressor down to only 60% of its rated flow [1.19].

In order to assist the IGV controller with surge control, a bleed or blow-off valve is also used [2.15]. The blow-off valve is used to reduce air mass flow in the compressor by bleeding off compressed air into the atmosphere. Figure 2-13 shows the power consumption of several compressor configurations. This figure illustrates that IGV control is an energy efficient means of controlling a compressor.
Figure 2-14 illustrates the results of a test conducted on a Sulzer compressor with a rated output of 51 000 m$^3$/h. The compressor is driven by a 5.3 MW electrical motor and has a basic IGV controller installed. The goal of the test was to determine how far the IGV controller can reduce the compressor output. The manual pressure set-point was steadily reduced from 600kPa to 465kPa.
System pressure could be successfully maintained until the set-point was lowered below 495kPa. The IGV controller was unable to reduce the compressor output any further. When the pressure set point fell below 495kPa the controller opened the blow-off valve of the compressor. The test was abandoned and the controller set-point was returned to the original setting of 600kPa.

This test confirmed that the system remained stable at lower output pressures and that IGV control can successfully reduce compressor output. The power consumption of the compressor is reduced to 71% of installed capacity, while still maintaining system demand requirements.

Data for a similar Sulzer compressor was gathered. The IGV controller was set to automatically maintain a fixed system pressure. The IGV controller would therefore control the compressor output to compensate for any change in system demand. Figure 2-15 shows the compressor power as well as the changes in system pressure.
The significant dip in power consumption (11:00 – 15:00) can be attributed to the sudden increase in system pressure. During this time the compressor is set to maintain system pressure at 520 kPa. Once system pressure increased above the set-point, the compressor reduced output in an attempt to lower system pressure. The reduced output resulted in the reduced power consumption.

The IGV controller managed to reduce the output to 57% of the rated output. This is 14% lower than the minimum reduction recorded during the manual test. The compressor is also operating, on average, at a lower output. This is because the compressor only needs to maintain the system pressure, consuming less energy compared to the previous setup.

The data shows considerable improvement when active IGV control is implemented. Active IGV control will also ensure that the actual system demand is achieved and maintained at all times, subject to the limitations of the controller. IGV control is the most widely used method of control in the mining sector. The majority of centrifugal compressors investigated already had IGV installed.
Compressor background

Actively controlling compressor pressure and flow, while dynamically suppressing surge by automation of the existing IGV, will improve compressor efficiency. Optimising the control of the existing manually controlled IGV, will greatly reduce the cost of implementation. The improved performance obtained through IGV control together with a lower cost of automation makes it a more popular control method than, for example, a VSD system.

2.4.7 Non-linear bleed valve control

Experiments, using non-linear control on compressors, indicated that surge and stall can be prevented by implementing two-dimensional actuation on a ring of inter-stage bleed valves [2.27]. The use of open-loop non-linear control allows for control where the exact parameters required for a closed loop linear control system are difficult to ascertain [2.28]. The exact operational parameters, of a typical mining compressor system, are difficult to determine.

The concept of non-linear bleed valve control is however not widely used.

2.4.8 Mixed capacity control

Compressor systems in the mining sector often consist of several different centrifugal compressors varying in size and capacity. Optimal selection of an individual compressor can significantly affect overall system efficiency [2.29].

Various methods, (such as neural networks, linear programming and generic algorithms), can be used as aids in selecting optimal compressor operation. The following parameters should be taken into account [2.30]:

- system demand;
- compressor performance and controllability;
- cost of operating specific compressors;
- maintenance costs.

By analysing the various components of the compressed air system, the optimal operation of the various components can be adapted, to optimise efficiency. As an example, consider a basic compressed air network consisting of two similar
Compressor background

compressors. One with only load/unload functionality and the other with the ability to modulate its output by utilising IGV control [2.31].

The fully loaded compressor together with the modulating compressor will be able to regulate the output when the system is near full load. When the system has lower demand, the first compressor can be unloaded, leaving the modulating compressor to meet system demand.

2.5 Simulation models

There are several crucially important factors in a compressed air system, each of which makes the system unique. The different types of compressors, components, control techniques and system requirements make it possible to design an optimal solution that will meet the requirements of a particular system. The many different options available, however, create the problem of determining the optimal combination. It is because of these many variables that the requirement for simulation of compressors and compressed air systems arises. There are several methods used to determine the characteristics of a component or system, three of these methods are discussed below.

2.5.1 Experimental method

The oldest method used to determine the characteristics of a component is the experimental method. In the experimental set-up, a system with known parameters is used to determine the characteristics of a component. The characteristics are determined by changing the parameters of the specific component and observing the effect these changes have on the known system parameters [2.32].

2.5.2 Numeric and mathematical method

The modern approach is to simulate a system by deriving a mathematical model of the system [2.33]. The actual performance under various conditions can then be estimated by simply changing the variables of the mathematical model [2.34]. The
Compressor background

Simulation model can be used to test and develop control algorithms without the need to design and construct physical equipment.

Appendix B shows an illustration of the Moore–Greitzer model which was developed to predict surge and describe a compressor's flow dynamics [2.13]. Epstein, Williams and Greitzer first introduced active surge control in 1989.

2.5.3 Integrated environments and dynamic models

The most advanced methods of simulation integrate experimental and statistical data with numeric and mathematical models. This data can be simulated in a virtual test bed (VTB) computational environment. This enables the simulation of all possible situations, system set-up, operating parameters and compressor types [2.35]. The result is a processing method that can, for example, model air flow, conduct vibration analysis, determine optimal blade profiling and export the results to computer-aided design [2.36]. These systems can be used to determine the dimensions and design specifications by incorporating all the various requirements and characteristics. Figure 2-16 presents an illustration of all the components of a conceptual design system.
There are various methods that can be applied to simulate the performance of a compressor and compressed air system. The limiting factors however are the amount of time and money available to determine the optimum characteristics.
2.6 Problems with the method of present systems

The effect of automatic control on compressor operation and the actual operation of compressor systems required onsite investigation. Investigations were conducted on several sites operated by prominent mining companies. These investigations determined that various factors influence the inefficient operation of the system, namely:

- Human control;
- Lack of real-time information;
- Pressure set-points that are higher than required;
- Excessive compressor blow-off;
- Inefficient compressor selection.

These factors are discussed in the following sections.

2.6.1 Human control

A basic set-up for this type of compressor control is to assign an operator to a compressor house. The operator is responsible for starting and stopping the compressors according to a pre-determined time schedule or when requested by a senior manager or engineer. This method of operation results in incorrect service delivery and inefficient use of energy.

2.6.2 Lack of real-time information

Compressor delivery pressure was the only available parameter and was displayed on an analogue pressure gauge at each shaft. The lack of instrumentation made it difficult to determine the mass flow of air consumed by each shaft. It was also not possible to determine the typical system pressure and the pressure drop from compressor discharge to the end-users. This resulted in oversupply and a significant waste of energy.
2.6.3 Set-points that are higher than needed

The compressors investigated were all set to a constant delivery pressure set-point of approximately 650kPa. This would ensure that underground equipment would be supplied with a minimum pressure of 550kPa. The 15% difference, was required to compensate for the pressure drop from compressor discharge to the end-users.

Equipment demanding the highest system pressure usually operates for a single shift, usually lasting only 8 hours per day. The fixed pressure set-point results in the system running at a higher pressure than required for most of the day.

2.6.4 Excessive compressor blow-off

The compressor characteristics demonstrated that compressors would start to blow-off excess air when the system pressure increased above the maximum delivery pressure set-point. Onsite investigation determined that several compressors often operate in the blow-off state for extended periods resulting in a significant wastage of energy. One of the factors contributing to unnecessary blow-off is the manual operation.

2.6.5 Inefficient compressor selection

Compressed air system design, type and size were different at every site. It was evident that the combination and efficiency of compressors used had a significant influence on system performance and efficiency.

Normal system operation dictates that a shaft should be supplied with air from the compressor house closest to the shaft. Additional compressors are started up when required. This operation selects compressors based on location, rather than efficiency, resulting in energy wastage.
2.7 Conclusion

The operation and control of the compressors were studied in detail. This investigation concluded that IGV control is the most efficient mode of control for centrifugal compressors. Onsite investigations determined specific areas in which the control of the compressed air system is inefficient.
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Compressor background


Compressor background


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Chapter 3
Development of a new control strategy to reduce energy consumption on mining compressed air systems
3 OPTIMISED CONTROL STRATEGIES

3.1 Introduction

Chapters 1 and 2 determined that the present methods implemented to control compressors in the mining sector resulted in energy inefficient operation. Several alternative control methods to improve centrifugal compressor operational efficiency were identified. This Chapter will focus on developing a new strategy to supply compressed air more efficiently and reduce overall energy consumption.

3.2 Optimising system control

3.2.1 Background

Figure 3-1 illustrates a simple flow chart depicting the proposed process of optimising compressor control. The optimisation strategy entails:

- controlling compressor pressure and flow supply electronically by monitoring and controlling the varying system requirements;
- recording real-time data from appropriate locations in the system;
- centralising the control and data systems;
- developing an optimised control strategy to satisfy system parameters efficiently through optimal pressure delivery and compressor selection;
- simulating or testing an optimised strategy in order to verify that the new optimised control will satisfy system requirements; and
- implementing the new strategy.
Optimised control strategies

Enable compressor control

Acquire real-time measurements

Centralise control and data systems

Develop control strategy

Pressure delivery

Compressor selection

Simulate/test control strategy

Simulation results satisfactory?

Yes

Implement control strategy

No

Figure 3-1: A flow chart depicting the optimisation strategy
3.2.2 Automation of compressors

The first step to facilitate optimised control is to automate the compressor system. Automating the IGV control on centrifugal compressors regulates the output capacity of the compressor efficiently to accurately match compressor supply with system demand.

Figure 3-2 indicates schematically the basic components of an automated compressor system. The IGV controller will optimise compressor mass flow based on data received from the compressor PLC and Supervisory Control and Data Acquisition (SCADA), systems. Primary control will regulate the IGV angle to suppress compressor surge and stall. The secondary function is to regulate compressor flow output, depending on system demand.

Full automation of the electrical drive unit and IGV control is expensive. However, this will allow the PLC to start and stop the compressor without requiring human intervention. A less expensive alternative is to implement automatic control on the IGV alone. This will require manual control of the compressor motor start and stop operation. The IGV controller will still be able to regulate compressor flow output from no-load to full load requirement.
Figure 3-3 shows the improvement in efficiency after implementation of automatic IGV control. Optimised control will result in significant energy and cost savings.

![Compressor curves illustrating control](image)

*Figure 3-3: Manual versus automated compressor control*

### 3.2.3 Real-time measurements

Installing pressure and flow transmitters strategically throughout the system will supply essential data on the system performance. This will significantly increase the accuracy of an automatic controller.

Figure 3-4 shows a compressed air ring with manual valves installed at each of the four shafts. South D shaft is approximately 5.055 km from the compressor house. Each valve is fitted with a flow and pressure transmitter. The instrumentation at the shaft will provide information on the pressure drop between the compressor house and the shaft.
3.2.4 Centralised control system

The electronic compressor control components as well as system parameter information can be integrated into a single SCADA system. Control and monitoring of the entire compressed air system can be managed from a single dedicated control room. Figure 3-5 illustrates a compressed air ring with a centralised control system.
Centralising the data and control systems has the benefit of:

- **Sustainability**, where a dedicated individual or department is responsible for monitoring the performance of the system.
- **Robust performance** because information on the operation of all system components is immediately available to the controller. The controller can react to any unexpected events, such as compressor failure.
- **Precise control** which allows the system to supply sufficient air to meet all the system requirements.
- **Various combinations of system components** can be used in several combinations to improve system performance.
3.2.5 Development of control strategies

After the system has been fully automated and all control components centralised, the individual responsible for the system will have full control of each of the components. It is essential that the system is controlled and operated in an efficient manner. This requires the development of new control strategies. The power output of the compressed air system can be reduced by implementing various strategies:

- Regulation of the compressor flow output will ensure that no excess air is produced or wasted. This is achieved by automating the IGV.
- Reducing system output pressure will reduce compressor power consumption. The ideal system pressure should be continually regulated according to equipment requirements.
- Optimal use of the most efficient compressors will produce the maximum air output per kW.
3.3 Pressure delivery

3.3.1 Concept

Pressure remains the most important parameter of the compressed air system. The new automated control system will be able to control system pressure dynamically. Optimised pressure delivery is achieved through integrating the requirements of each individual piece of equipment. System pressure will be continually regulated according to the actual demand. Figure 3-6 presents an example of the varying system pressure requirements throughout a typical mine production day.

![System pressure requirements](image)

*Figure 3-6: Optimised pressure set-points for a typical production day*

In order to maintain an optimised system pressure, compressor output must be dynamically controlled. Figure 3-7 presents a flow chart that illustrates the method used to control the output of the compressor system.
Figure 3-7: Flow chart illustrating compressor control approach
A system consisting of several compressors will usually have some compressors running at full capacity. The remaining compressors are used as trimming compressors to optimally regulate the system demand pressure.

The flow chart of Figure 3-7 can be explained as follows:

- The system set-point, maximum pressure and minimum pressure will change according to schedule; system flow will fluctuate according to demand.
- IGV control will regulate trimming compressor flow output in order to maintain the scheduled system pressure.
- If the IGV control is unable to sufficiently lower system pressure, a compressor will be temporarily off-loaded.
- The compressor will remain in an unloaded state to allow time for the system pressure to stabilise.
- If the system pressure remains stable, the compressor will be shut down completely, otherwise the compressor will be placed on-line again to stabilise the system.
- In the event of low system pressure, the controller will bring the unloaded compressor back on-line.
- When all running compressors are loaded, the trimming compressor IGV control will adjust the blade angle and increase the output.
- If the IGV is already positioned for maximum output, an additional compressor will be started.

By varying system pressure according to system requirements, a significant decrease in compressor energy consumption will be realised. Reducing the pressure for long periods of the day will generate additional savings by minimising air losses caused by system leaks.
3.3.2 Implementation

The new optimised system pressure schedule is only an indication of the ideal system pressure schedule. The actual system pressure will vary significantly depending on the nature and size of the specific compressed air system. Figure 3-8 illustrates the proposed system pressure schedule, as well as an example of the variation in the actual system pressure within the control constraints.

![System pressure regulation graph](image)

*Figure 3-8: Illustration of required system pressure versus actual regulated system pressure*

The output of the compressors will be controlled to keep the actual system pressure profile as close to the proposed profile as possible. The control constraints are specified by the mine to ensure continuous and safe operation of all equipment and processes.
Guide vane control

IGV control will regulate compressor flow output to allow for small fluctuations in system demand. The typical mine compressor system will consist of a set of base-load compressors and trimming compressors. Figure 3-9 illustrates the change in system pressure and the corresponding regulation of a trimming compressor IGV as a function of time.

Control of the IGVs is discussed in the following steps, using the system pressure line shown in Figure 3-9, as an example:

1) System pressure is below the required set-point. The trimming compressor (and all base load compressors) operate at 100% in an attempt to increase system pressure.

2) As system pressure approaches the required pressure, the controller starts to reduce the trimming compressor output by gradually changing the IGV angle. The rate at which the angle is changed depends on the rate of system pressure response.
3) The system pressure initially overshoots the required system pressure demand. The IGV controller will continue to adjust the IGV angle, limiting the output of the compressor to approximately 60% of its rated output.

4) The reduction in compressor flow will result in lowering of the system pressure.

5) As the system pressure approaches the target pressure, a control signal is sent to adjust the IGV angle which will reduce the rate at which the system pressure changes. The system pressure finally stabilises at the target system pressure.

Figure 3-10 illustrates the effect of IGV control on the power consumption of the trimming compressor. Prior to automation, the compressor would have continued to run at 100% output. The control optimises energy consumption by regulating compressor flow output to maintain the system pressure set-point although the compressor continues to rotate at a constant speed.
• **Off-load control**

Large fluctuations will sometimes require a more aggressive IGV control where one or more compressors will be required to be shut down or started up. Figure 3-11 illustrates IGV control when an off-load event occurs.

![Off-load control](image)

*Figure 3-11: Illustration of off-load control*

An example of the controller management is described in the following steps with reference to Figure 3-11:

1) System pressure is rapidly rising from the stable system pressure set-point. The rate at which the pressure is rising will cause the controller to command a maximum reduction in the output of a trimming compressor.

2) The system pressure continues to increase, reaching and exceeding the maximum pressure limit. This will prompt the controller to reduce the output of a second trimming compressor. The output of this trimming compressor is reduced to 80%, stabilising the system pressure.
3) The system pressure however remains higher than the maximum pressure limit and the trimming compressor will be taken off-line. The output of the second trimming compressor will be increased to compensate for the reduced pressure supply.

When the system pressure drops below the maximum pressure limit the second trimming compressor will use IGV control to regulate the system pressure and maintain the required system pressure.

4) System pressure drops below target even though the trimming compressor is running at 100% supply. The decreasing system pressure will signal the first compressor to come on-line again and stabilise the system pressure.

Figure 3-12 demonstrates the influence of off-loading a compressor on power consumption.

![Graph](image)

*Figure 3-12: The influence of off-load on compressor power consumption*
**Shutdown control**

System pressure can be successfully regulated using IGV control and placing compressors off-line or on-line. The changes in system demand during a typical production day will sometimes require the control system to shut down one or more compressors. The controller must stabilise the system appropriately in order to prevent compressors that have been shut down from being started up moments later. Figure 3-13 illustrates shutdown control.

![Figure 3-13: Illustration of shutdown control](image)

The controller operation can be explained as follows with reference to Figure 3-13:

1) System pressure increases prompting a trimming compressor to reduce its output by adjusting the IGV angle.

2) The system pressure continues to increase above the maximum pressure limit. This prompts the trimming compressor to reduce its output to a minimum. The second trimming compressor will be prompted to reduce output as well.
3) The reduced output of both trimming compressors reduces the total system pressure. However, system pressure still remains above the maximum pressure limit.

4) A trimming compressor is taken off-line and the output of the second trimming compressor stabilises the system.

5) The output of the operating trimming compressor will remain below 100% while the system pressure remains above the pressure set-point. A continual steady pressure state will allow the off-load compressor to be shut down.

Figure 3-14 demonstrates the power consumption of the trimming compressor.
Optimised control strategies

- **Start-up control**

  If the system pressure drops below the minimum limit, with all the operating compressors running at 100% output, an additional compressor must be started. Figure 3-15 illustrates the start-up control.

![Figure 3-15: Illustration of compressor start-up control](image)

In a similar manner, this control management is discussed with reference to Figure 3-15:

1) A drop in system pressure prompts the controller to increase the output of a trimming compressor up to 100%. The system pressure continues to fall below the minimum pressure limit.

2) The controller will send a signal to start an additional compressor. The start-up sequence of a compressor requires the electrical drive and all the auxiliary systems to be running before the compressor can be loaded.
3) As soon as the compressor is on line, the output can be steadily increased by controlling the IGVs.

4) As soon as the system pressure has been stabilised, the pressure can be regulated using IGV control of the newly started compressor.

Figure 3-16 illustrates the power consumption of both the extra compressor, brought on-line to sustain system pressure and the trimming compressor.

![Figure 3-16: The influence of compressor start-up on power consumption](image-url)
3.4 Compressor selection

3.4.1 Compressor size and efficiency

A typical mine compressed air system will consist of several compressors with different operational specifications. Different definitions, including adiabatic, overall and mechanical, are used to describe the efficiency of a compressor. The compressor performance map can be used to determine the optimal efficiency at a constant rotational speed. By selecting the optimal combination of compressors to produce the base-load air, the overall system power consumption can be further reduced.

Figure 3-17 presents a compressor operational schedule for a typical production day. Compressors 1, 2 and 3 are the most efficient compressors and will be selected to supply base-load air. Compressors 4 and 5, which are less efficient, will only be used during the shorter, high demand periods, to maintain the required system pressure.

![Compressor schedule](image)

*Figure 3-17: Optimal compressor selection*
3.4.2 Optimal flow delivery

The proposed new system pressure control will influence the air consumption of the system as a whole. The total system air flow may change, due to the effects discussed in Chapter 1 section 1.4.4.

Apart from efficiency, the selection of a compressor will be determined by the output capabilities of the trimming compressor. The compressed air system must incorporate a trimming compressor that will be able to vary its output to compensate for varying system demand. In order to determine the optimal compressor combination, typical air flow requirements of the system must be considered.

The airflow requirement of the system, at the correct operating pressure, can be calculated by estimating the flow required by all the pneumatic equipment used on site. However, if this method is applied to a typically large mining operation, the results may not be very accurate. The accuracy will be influenced by leaks, unidentified equipment and possible alternative uses of the air that cannot be quantified. To determine the air flow required on a site, the actual air flow used must be measured.

Figure 3-18 shows a 24-hour flow demand of a compressed air system for a typical production day. This figure shows that there is a considerable increase in air flow requirement between 06:00 and 15:00 which is due to the drilling shift. The shift is repeated on a production-day schedule. This information can be used to schedule the optimal combination of compressors to run according to projected demand.
3.4.3 Implementation

As an example, consider a compressed air system with five automated compressors, supplying air at the same pressure. The air flow requirement for a typical production day must first be obtained by analysing data received from installed instrumentation. The flow capabilities of the compressors, in descending order of efficiency are:

- 1 x 600 m$^3$/h (most efficient);
- 2 x 500 m$^3$/h; and
- 2 x 300 m$^3$/h (least efficient).

The compressors can be operated in various combinations. These combinations take into account compressor efficiency and capacity to provide the required air flow. Based on these considerations, the optimal combination of compressors can be selected.

Figure 3-19 shows the compressor schedule for a typical production day base-load output with the 600 m$^3$/h compressor selected to run at full capacity. The 500 m$^3$/h
compressor was selected as the trimming compressor with predicted baseline flow requiring the trimming compressor to run at 70% of its capacity.

![Base-load compressor selection and flow delivery](image)

*Figure 3-19: Base-load compressor selection and flow delivery at the required pressure*

IGV control will regulate the output of the trimming compressor between 60% and 100%, resulting in improved energy efficiency and cost savings.

Because the trimming compressor in Figure 3-19 is running at a reduced output capacity, it can easily respond to any variance in system pressure demand. This configuration allows the system to supply compressed air at reduced power, without compromising flow or pressure delivery.

Figure 3-20 illustrates the compressor selection for the drilling shift, which will also be the maximum flow demand period for the production day. The three most efficient compressors are selected to operate as base-load compressors. One 300 m³/h compressor is used as the trimming compressor.
Typical air flow demand will require the trimming compressor to run at 80% output. The compressor will therefore be able to react to any change in system demand, within 20% of its operating output.

Figure 3-21 shows a typical day with an optimal compressor selection scheduled. The figure illustrates a schedule in which the most efficient compressors were selected to supply base-load air. The trimming compressors were selected so that they would operate between 60% and 100% output, while ensuring optimal flow and pressure output.
Figure 3-21: Optimal compressor selection and flow delivery

Figure 3-22 shows a situation with an inefficient compressor selection scheduled. The base-load is partially achieved by the two smallest compressors. A third compressor, in addition to these two compressors is required to satisfy the base-load air flow demand.

Figure 3-22: Inefficient compressor selection and flow delivery
The compressor selection has resulted in excess air delivery during the drill shift. The trimming compressor will have to be off-loaded regularly to avoid exceeding the system set-point pressure.

3.5 Simulating optimised control

3.5.1 Background

The proposed control strategy takes into account system pressure, compressor output, efficiency and an estimated typical flow demand. By efficiently controlling these parameters, the compressed air system can be successfully optimised.

Implementing changes to the compressed air supply system may severely effect overall mining production and other activities. The effects of these changes must first be analysed experimentally. In order to ensure optimal strategy development, proposed solutions are first tested and analysed using a simulation model. The simulation is used to investigate the influence of changes on the overall compressed air system. The strategies that are successfully simulated will be implemented in an actual mining compressed air system.

3.5.2 Simulation model

Various compressor simulation models have been evaluated and implemented. The majority of these models focus solely on modelling the performance of an individual compressor. An Excel based simulation model was developed to determine the effect of parameter changes on the power consumption of a compressed air system. The simulation is also used to determine optimal compressor selection that will still satisfy system air flow requirements.

The existing system pressure set-point was compared to the proposed pressure set-point. Figure 3-23 shows the present and proposed system pressure set-points for a typical production day.
The automation of the system enables compressor flow output to be controlled according to system demand and pressure set-point. If the air flow required by the system remains unchanged, even though the system pressure is changing, the effect of the reduction in delivery pressure can be estimated. The effect can be estimated by taking the influence of reduced output pressure on compressor power consumption into account (as discussed in Chapters 1 and 2).

The simulation uses the existing power profile of the system to calculate the optimised profile. Figure 3-24 shows the results of this simulation.
Optimising system pressure delivery may also have the beneficial effect of being able to reduce the number of compressors required to ensure sufficient airflow. This would result in an additional saving. The simulation programme will therefore also calculate the amount of compressors required to produce sufficient air flow while maintaining sufficient system pressure.

The simulation considers both the flow capacity and the efficiency of the compressor. By determining the correct combination of compressors to satisfy system airflow and pressure supply, the total system power consumption can be greatly reduced.
3.6 Conclusion

Based on the research, described in Chapter 1 and 2, a new optimisation strategy was developed. The simulation model predicts reduced system energy consumption by optimising compressor control.

The optimisation strategy consists of:

- full system control by automating compressor output;
- the measurement of system parameters in real time to determine system status and performance;
- the centralisation of all control and data systems;
- the development of a control strategy to optimise system performance; and
- the simulation of the strategy to ensure functionality.
VERIFICATION OF THE INTEGRATED OPTIMISATION STRATEGY

Chapter 4
Verification of the optimisation strategy by implementation of the optimised control on actual compressor systems
4 VERIFICATION OF THE INTEGRATED OPTIMISATION STRATEGY

4.1 Introduction

The strategy to improve energy efficiency, through optimised compressor control, was implemented at three mining sites. The compressor systems varied in complexity. Due to confidentiality agreements these mines cannot be named and will be referred to only as Mine A, Mine B and Mine C.

- Mine A has seven identical compressors, installed in a central compressor house.
- Mine B has eight compressors, all installed in a central compressor house.
- Mine C has thirteen compressors, located at three different sites.

The implementation at each mine is discussed separately, below.

4.2 Mine A: Simple layout, identical compressors

4.2.1 Layout and operation

The optimised control was first implemented at a platinum mine. Figure 4-1 is a schematic of the basic layout of the mine. Compressed air for the entire mine is supplied from a single compressor house. The air is then delivered to the three active shafts using a compressed air ring. The South Shaft is not operational and is isolated from the compressed air supply.
The compressor house contains seven identical Centac 2 600kW compressors. However, the electricity supply can only feed six of the compressors simultaneously. One compressor will always serve as a standby unit.

The system pressure, prior to any intervention was measured. Data over several production days was recorded and analysed. This data was used to calculate the average pressure profile for a typical production day. The profile obtained is defined as the baseline pressure. Figure 4-2 shows the 24-hour production day baseline pressure.
A minimum compressor output pressure of 620kPa is required to ensure that the underground equipment is supplied with air at the correct pressure. The baseline pressure profile clearly shows that the compressors are unable to maintain the required system pressure during the peak air demand time. The maximum amount of drilling typically takes place during what is called the drill shift from 08:00 to 16:00. It is during this time slot that the compressors are unable to maintain the required system pressure.

The power consumption of the compressors was electronically logged over a period of approximately three months. A new power consumption baseline was subsequently developed. Figure 4-3 shows this new 24-hour production day power consumption profile.
Figure 4-3: Baseline power consumption profile of Mine A

A typical production day power consumption at the site indicated that a minimum of three compressors are required to maintain the base-load. Supplementary compressors must be brought on-line during the drill shift.

Figure 4-4 illustrates the individual compressor power consumption for a specific production day. The compressors have basic anti-surge control. However, the system pressure cannot be adjusted or controlled without the intervention of the compressor operator.
Without automatic IGV control the compressors are unable to reduce output when the system pressure increases above the set-point pressure. The compressors will regulate the system pressure by opening blow-off valves and release compressed air into the atmosphere.

Figure 4-5 shows individual power curves of a production day during which a compressor was temporarily shut down to regulate system pressure.
The operation of these compressors will be significantly improved by implementing automatic control. The optimisation will reduce power consumption by accurately regulating system pressure to meet the actual end-user requirements.

4.2.2 Optimisation of the system

- Implementing automatic control

The data, obtained from Mine A, showed clearly that there was significant scope for optimising compressor control. To implement the optimised control strategy, the following installations and upgrading would be required:
  - installing IGV controls to automatically control compressor output;
  - installation of appropriate electronic metering in mine shafts and on the compressors;
  - linking all components with wireless radio communication systems;
  - establish a central control room; and
  - installation of SCADA and control systems in the control room.
Figure 4-6 illustrates the basic layout of the mine with the new equipment installed.

![Diagram](image)

**Figure 4-6: Installations and upgrading on Mine A**

- **Development of the control strategy**
  The system pressure baseline indicated a clearly noticeable pressure drop during the drilling shift. Investigations revealed that the underground pneumatic drills, operating during the drill shift, required the highest air pressure for proper operation. However, no noticeable operational deterioration in drilling operation was experienced when the system pressure fell to below 550kPa. This indicates that the pressure at the end user is still within the equipment’s operational range and the present system set-point of 620kPa may therefore be unnecessarily high. The new proposed system pressure schedule took into account that different equipment would be used during the different shifts. Figure 4-7 shows the proposed optimised system pressure schedule (red line).
Verification of the integrated optimisation strategy

Figure 4-7: Proposed optimised pressure schedule of Mine A

Figure 4-8 shows the result of the simulation, after applying the proposed pressure changes.

Figure 4-8: Proposed power profile versus actual profile of Mine A
Verification of the integrated optimisation strategy

Results of the simulation indicated that the optimised system would reduce daily energy consumption by approximately 14 MWh. This is an average daily reduction of 590 kW, including a peak clip of 630 kW, with projected annual savings of R 1.6 million.

- **Implementation of the strategy**

  The proposed pressure set-point schedule was implemented at the mine. Performance tests were conducted and the system pressure profile was analysed. The results of this analysis showed that the system pressure could be reduced even further without affecting the efficiency of the equipment. Figure 4-9 shows the final optimised pressure schedule implemented at the mine. The pressure set-point was changed to 500kPa. This lower pressure set-point would still ensure satisfactory operation of the underground drills and loading boxes.

![Implemented optimised pressure schedule](image)

*Figure 4-9: Implemented optimised pressure schedule of Mine A*

The reduced pressure set-point during the Eskom evening peak period allowed for lower compressor pressure output. This resulted in increased cost saving for the mine and a reduction in the evening peak electricity demand.
Figure 4-10 shows the power curves of the automated compressors for a specific production day during which the system experienced compressor cycling. This results when a specific system demand cannot be matched to any combination of compressor output and compressors are turned on and off at frequent intervals.

The post-drill shift air demand on Mine A required that two compressors be operated at full capacity. This operation was still unable to supply sufficient air flow and pressure. Bringing a third compressor on-line resulted in the system pressure rising above the maximum limit, prompting the controller to switch this compressor off again. The system continued to switch between two and three compressors until the system demand changed. Figure 4-10 shows the multiple start and stop cycles of compressor 1. This can be very destructive for the compressor and electric motor, due to the increased wear created by repeated start and stop cycles.

The problem of rapid compressor cycling was solved by increasing the off-load delay time before shutting the compressor down. Extending the time a compressor remains in the off-load state allows the system more time to stabilise, limiting
Verification of the integrated optimisation strategy

compressor cycling. Figure 4-11 illustrates the optimised control with increased off-load delay.

![Individual power curves](image)

*Figure 4-11: Individual compressor power curves illustrating optimised control for Mine A*

Figure 4-11 shows that compressor 3 is off-loaded several times, (for approximately 30min at a time), and that the IGV control of the operating compressors is adjusted to ensure minimum compressor flow output. The improved control regulates the system without incurring unnecessary stress on equipment.
4.2.3 Results

An independent measuring and verification (M&V) team monitored the performance of the project. Data for November 2008 and January 2009 was used to determine the performance after implementation. December 2008 was excluded because the holiday period does not accurately reflect typical mine operation schedules.

Figure 4-12 shows the new average production day optimised pressure profile and the baseline pressure. The figure clearly illustrates the reduction in system pressure which, when combined with automated output control, results in increased system efficiency.

![Mine pressure profiles](image)

Figure 4-12: Actual optimised pressure profile and baseline pressure profile of Mine A

The effect of the improved control on the system’s average production day power consumption is illustrated in Figure 4-13.
Verification of the integrated optimisation strategy

The power profiles in Figure 4-13 show the:

- Optimised power consumption: Energy presently consumed by the system;
- Baseline power consumption: Energy consumed by the system before intervention; and
- Scaled baseline power consumption: Energy the system would have consumed had there been no intervention.

The aim of baseline scaling is to allow for any increase or decrease in mine production and incorporate this into the baseline. The scaled baseline for a specific day would therefore indicate the amount of power the mine would have used on that day before intervention. This provides a clearer indication of the actual effect of the intervention.

The baseline for Mine A was scaled according to the average energy consumed during the peak drill period from 09:00 to 12:00. If the mine increases production, the energy consumed during the peak drill period will increase proportionately. The baseline will then be scaled, using an appropriate factor. This will give a new
average peak drill period energy baseline which will have the same profile as the actual peak drill period energy for that particular day.

The intervention at Mine A allowed for a reduction of system supply pressure, resulting in an overall increase in system efficiency. Automatic compressor control also reduced the operating time of additional compressors required to maintain system pressure during a drill shift. This is clearly evident from the graphs shown in Figure 4-13.

The M&V team confirmed that an average power reduction of 1.07 MW was achieved at Mine A on a typical production day. This resulted in an estimated annual energy cost saving of R 3 million. Furthermore, the Eskom evening peak demand period was reduced by 1.25MW.

4.3 Mine B: Simple layout, various compressors

4.3.1 Layout and operation

Mine B is a gold mine. Optimised control was also implemented at this mine. This mine uses compressors with two different power ratings. Out of a total of eight installed compressors, six are rated at 2 900kW and the remaining two at 1 090kW giving a total of 19 500kW. The large power capacity presents an ideal opportunity to investigate the energy efficiency potential and system performance at this mine. The basic layout is illustrated in Figure 4-14.
The procedures described in section 4-2 to obtain the necessary data are similar to the methods used at Mine B. Therefore, only significant procedural differences will be pointed out and discussed. The profile in Figure 4-15 shows the variation in system pressure during an average production day.
The power consumption baseline, shown in Figure 4-16 at mine B, is representative of a typical production day.

![Mine baseline power consumption profile](image)

*Figure 4-16: Baseline power consumption profile of Mine B*

Figure 4-17 shows the accumulative power consumption profile for a typical production day. It can be seen from this figure that the six 2900kw, VK 32, compressors are used as base-load compressors. The two 1090kW, VK 10, compressors are only used during higher demand periods.
None of these compressors are automated and the compressors operate continuously at full capacity. The system presents an ideal opportunity for implementing energy efficient optimisation.

4.3.2 Optimising the system

- **Enabling of automatic control**

The system upgrade was similar to the upgrade performed on Mine A. However, at Mine B, additional underground measuring and control equipment was required and installed. This consisted of flow and pressure metering equipment, as well as control valves strategically placed on levels with high air consumption.

The underground metering equipment will provide accurate information on the various parameters of the system and ensure control that is more precise. Underground valves are electrically controlled depending on the flow or pressure requirement at each level.
Verification of the integrated optimisation strategy

Figure 4-18 illustrates the installation and upgrade of equipment on Mine B.
Development of the control strategy

The new control system will be used to optimise system pressure control. Shaft #1 and #2 are the major air users. Shaft #3 is a hydro-powered shaft that uses compressed air only for control purposes, for example opening and closing of valves.

Similar to Mine A, the baseline pressure indicated that the mine experienced a significant pressure drop during the drill shift. The equipment was however still able to function properly during the drill shift indicating that a system pressure of 550kPa will not affect production.

A proposed system pressure set-point of 575kPa was selected with a permissible small drop to 550kPa during the Eskom evening peak demand period. Figure 4-19 shows this new optimised pressure schedule.
In order to facilitate peak electricity clipping, the underground valves will be closed automatically during the Eskom evening peak demand period. Closing the underground valves isolates the air consumers at the extremities of each underground level. This will help to maintain system pressure of the remaining air consumers during the evening peak.

A stable system pressure enables the control system to reduce output, making further savings possible. Figure 4-20 shows the result of the simulation, incorporating the proposed pressure changes.

![Proposed power profile vs. actual power profile](image)

*Figure 4-20: Proposed power profile and actual power profile of Mine B*

The simulation demonstrated that the optimised system would reduce daily energy consumption by approximately 5 MWh giving an average daily power reduction of 210 kW. A peak clip of 460 kW is also realised with an annual saving of R 460 000.
• **Implementation of the strategy**

The control system was developed and designed to maintain system pressure supply for the optimised profile. Figure 4-21 shows the individual compressor power curves for a typical production day. These curves show that the two 900kW, VK32, compressors are operating at a much-reduced rate of 70% to 90% of their installed capacity, after implementing IGV control.

As a result, the VK 10, 1090kW, compressors were not required to operate as frequently as before. The combination of reduced system pressure set-point and installed underground valves, allowed the controller to shut down a VK32 compressor during the peak evening demand period. This results in a further reduction in evening peak power consumption.

![Individual power curves](image)

*Figure 4-21: Individual compressor power curves illustrating new control of Mine B*

The control system was optimised even further by regulating compressor schedules and pressure set-points. Figure 4-22 shows a typical production day where improved control allows two VK32 compressors to be switched off for a period of 2 hours in the early morning and almost 2 hours during the evening peak
period. The lower power consuming, VK10 compressor, is started to help sustain system pressure during the evening peak.

![Individual power curves](image)

*Figure 4-22: Individual power curves illustrating additional savings achieved for Mine B*

### 4.3.3 Results

An independent M&V team also verified the performance of this project. In contrast to the operation at Mine A, this mine continued with production throughout the December holidays. Data recorded from the beginning of December 2008 to the end of February 2009 was used to determine the performance. Public holidays were taken as non-production weekend days. This ensured that the actual performance would not be biased because of the larger number of public holidays during December.

Figure 4-23 shows the baseline pressure profile and the improved average pressure profile of the optimised system. Improved control reduces the overall system pressure. A further reduction in system pressure during the early morning and the Eskom evening peak demand period resulted in further savings.
Figure 4-23 shows the effect of the optimised pressure control on the overall system power consumption where the greatly reduced optimised power consumption profile is evident. Automation of the compressors resulted in an increase in overall efficiency by lowering the system pressure. The scheduled pressure reduction allowed the shutdown of additional compressors, resulting in increased morning and evening savings.
The independent M&V team confirmed a daily reduction of 5.4MW at Mine B. This resulted in an estimated annual energy cost saving of R 16 million. An average peak clip of 7.29 MW during the Eskom evening peak demand period was achieved.
4.4 Mine C: Complex layout, various compressors

4.4.1 Layout and operation

Optimised control was implemented at Mine C, which is a gold mine consisting of three shafts. The compressed air system supplies air directly to each shaft which are interconnected. However the shafts are closed off from one another and no air can flow between the shafts. Each shaft has a dedicated compressor house to meet the air requirements of the specific shaft. Figure 4-25 illustrates the layout of Mine C.

![Figure 4-25: Basic site layout of Mine C](image)

The compressors, (labelled C1 to C13 in Figure 4-25), are summarised in Table 4-1. The different installed capacities make it possible to use various combinations of compressors to supply the required air pressure and flow.

<table>
<thead>
<tr>
<th>Compressor</th>
<th>Installed capacity (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1 – C2 (BTH)</td>
<td>3766</td>
</tr>
<tr>
<td>C3 – C6 (BB)</td>
<td>4030</td>
</tr>
<tr>
<td>C7 – C8 (Sulzer)</td>
<td>5900</td>
</tr>
</tbody>
</table>
Similar procedures to those applied at the previous two mines were followed to obtain the required data. Figure 4-26 illustrates these power consumption baselines.

The power consumption baselines of the three shafts were integrated to form a single baseline representing the total compressor power consumption of the mine. Figure 4-27 illustrates this integrated compressor power consumption baseline of the mine.
Verification of the integrated optimisation strategy

The baseline pressure profiles for the individual shafts are displayed in Figure 4-28. Optimising the compressor control of this mine was a greater challenge than the previous two mines. Compressors with four different power ratings are used. This project was divided into two phases that took several months to complete. The first phase comprised automation of the compressors at the M- and TT-shafts, while automation of the compressors at S-Shaft formed the second phase. Data acquisition for S-Shaft could only be obtained much later.
4.4.2 Optimising the system

- **Implementation of automatic control**
  
  Similar methods used at Mines A and B were applied. In addition the valves splitting the surface compressed air reticulation system were opened, interconnecting all the shafts.

**Development of the control strategy**

The control strategy at Mine C differed from the previous two mines. At Mine C the system pressure could not simply be reduced to improve compressor efficiency. Figure 4-28 shows that the highest individual shaft pressures were in the range of 450kPa. This pressure range is significantly lower than the optimised pressure profiles of Mines A and B. Because the system pressure is already relatively low, the strategy for Mine C was to reduce energy consumption by selecting the most efficient method to supply the compressed air ring. The piping network between the shafts were opened to enable compressed airflow throughout all the shafts.
Verification of the integrated optimisation strategy

Figure 4-29 shows the optimised system pressure profile. This profile indicates a system pressure slightly higher than the baseline pressure, during certain periods of the day. A higher pressure was required to compensate for the additional system losses experienced when changing to the proposed open compressed air supply option.

![Optimised pressure schedule](image)

Figure 4-29: Proposed optimised system pressure schedule of Mine C

The investigation concluded that the air demand at the mine could be regulated to implement the following compressor schedule:

- C7 and C8 (T- Shaft): base-load;
- C9 to C12 (M- Shaft): base-load and auxiliary;
- C6 (S- Shaft): auxiliary; and
- C1 to C5 and C13: reserve.

Figure 4-30 shows the predicted and baseline power requirement as well as the scheduling simulation. The vertical bars indicate the simulated, individual compressor scheduling selection.
Verification of the integrated optimisation strategy

The simulation predicted that the optimised system would reduce daily energy consumption by approximately 177 MWh. This corresponds to an average efficiency of 7.4 MW, including a peak clip of 8.8 MW, which will result in an annual saving of R20 million.

Figure 4-30: Planned compressor scheduling of Mine C
• **Implementation of the strategy**

The compressors at the TT-Shaft are the largest and most efficient compressors on the mine. These compressors were selected to define the system base-load air supply. The two compressors are however not able to provide sufficient air to maintain system pressure. Some of the compressors at M- and S-shafts must be used to augment the supply of air. Figure 4-31 shows the power profiles of the compressors at Mine C during a typical production day.

![Individual power curves illustrating improved control of Mine C](image)

The entire pneumatic system of the mine can be supplied using fewer compressors by keeping the compressed air supply line valves open. This has a significant impact on the overall power consumption of the system. Using the most efficient compressors, at all times, to supply air also increases the efficiency of the system. The lower system pressure set-point during the Eskom evening peak demand period allows an additional compressor to be stopped, resulting in a further peak-clipping saving.
4.4.3 Results

An independent M&V team determined and verified the improved performance. Figure 4-32 shows the average TT-shaft and M-shaft baseline pressure profile and the pressure profile of the optimised system. This figure shows that the system pressure was increased for the greater part of the production day. The pressure set-point was only reduced during the Eskom evening peak to facilitate increased evening peak clipping.

![Mine pressure profiles](chart)

*Figure 4-32: Actual optimised pressure profile and baseline pressure profile of Mine C*

The total energy savings of the system was not realised by lowering the system pressure. Rather, the savings were realised by opening the compressed air ring, allowing use of the most efficient compressors to supply base-load air. The operation of the ring was improved to such an extent that the entire compressed air system could be operated with a reduced number of compressors at S-Shaft. The compressors at S-Shaft are only used to sustain system pressure during the drill shift or during periods when some compressors are taken off-line. Figure 4-33 illustrates the power savings realised by the optimised compressor control. The figure shows the considerable reduction in system energy consumption due to optimised compressor control.
The project was able to clip an average of 17.34 MW from the Eskom evening peak demand period. The system also achieved a reduction of 19.3 MW in the average daily power consumption. This resulted in an estimated annual energy cost reduction of R 27 million.
4.5 Extension of this research to other mines

The optimised control strategy was successfully implemented at three different mines, each with unique characteristics. Investigation into the operation of these mines confirmed the potential to reduce energy consumption. The reduction in air used and thus energy required by the compressed air system was achieved by improving compressor control.

Reducing energy consumption on the mines, through optimising compressor control, could therefore be implemented at any mine. The extent of the potential savings to justify the costs could be the only possible reason to inhibit the implementation of energy efficiency on compressed air systems. Table 4-2 shows the average energy and cost reduction at ten mines where optimisation strategies have already been implemented.

<table>
<thead>
<tr>
<th>Mine no.</th>
<th>Daily reduction during Eskom evening peak (MW)</th>
<th>Annual energy reduction (GW hour)</th>
<th>Cost reduction (million Rand/year), using 2008 tariffs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13.95</td>
<td>96.452</td>
<td>27.0</td>
</tr>
<tr>
<td>2</td>
<td>11.51</td>
<td>43.805</td>
<td>12.3</td>
</tr>
<tr>
<td>3</td>
<td>7.97</td>
<td>64.247</td>
<td>18.0</td>
</tr>
<tr>
<td>4</td>
<td>4.49</td>
<td>17.846</td>
<td>5.0</td>
</tr>
<tr>
<td>5</td>
<td>5.8</td>
<td>58.956</td>
<td>16.5</td>
</tr>
<tr>
<td>6</td>
<td>6.2</td>
<td>2.470</td>
<td>0.7</td>
</tr>
<tr>
<td>7</td>
<td>3.45</td>
<td>31.494</td>
<td>8.8</td>
</tr>
<tr>
<td>8</td>
<td>2.3</td>
<td>17.778</td>
<td>5.0</td>
</tr>
<tr>
<td>9</td>
<td>1.25</td>
<td>10.538</td>
<td>3.0</td>
</tr>
<tr>
<td>10</td>
<td>6.6</td>
<td>32.188</td>
<td>9.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>63.52</strong></td>
<td><strong>375.775</strong></td>
<td><strong>105.22</strong></td>
</tr>
</tbody>
</table>
4.6 Conclusion

Implementation of the optimisation strategy developed during this study was applied at three different mines in South Africa. All three projects realised satisfactory results.

The power consumption at Mine A was reduced by improving control of the system pressure. The results were an average peak clip of 1.25 MW and reduction of 1.07 MW in average power consumption on a typical production day.

Power consumption saving at Mine B was achieved by similar methods applied at Mine A. The optimisation was further improved by installing additional underground measuring equipment. The underground control valves enabled the system to clip additional energy from the evening peak. An average reduction in peak power of 7.29 MW and average 5.4 MW overall on a typical production day was achieved.

The system pressure at Mine C was already lower than the air pressure supply at Mine A and Mine B. Any improvement in the energy consumption of the system could not be achieved by further lowering the system pressure. The compressed air system at Mine C consisted of three shafts operating in isolation of each other.

The compressed air ring was modified so that all three shafts could be supplied by air from any compressor. Selection of the most efficient compressors was then possible and significant savings were achieved. These savings were achieved even though the actual system pressure set-point was increased. The results showed an average peak clip of 17.34 MW and a average reduction of 19.3 MW in power consumption for a typical production day.
The simulations for all three mines predicted that cost savings were possible. Actual savings proved to be better than the simulation predictions. This can be attributed to:

- reduced compressor blow-off due to improved control;
- lower system pressure set-points which reduced flow losses through leaks and unregulated equipment;
- primary use of efficient compressors; and
- use of information on system performance to identify and manage problem areas.

The reduction in power consumption can be directly attributed to the improved compressor control. This study has shown that an optimised, energy efficient control strategy, can be successfully implemented on mine compressed air systems.

Penalties linked to the PCP have not yet been implemented. The impact of the PCP on the cost of electricity will drastically reduce the payback period of these optimisation projects. Presently, some DSM projects are too expensive to vindicate the potential savings required by Eskom.

However, the risk of paying PCP penalties and the large increase in electricity tariffs will make these projects more viable. The sustainable reduction in electricity consumption will assist the mining sector in achieving the mandatory 10% reduction in consumption. This will also significantly reduce the future cost of operation.
CONCLUSION AND RECOMMENDATIONS

Chapter 5:
Conclusion on findings of the new optimisation strategy, as well as recommendations for future work
5 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Several electrical energy-intensive mining systems were investigated to identify areas of potential energy reduction. Compressed air systems were identified as having great potential for significantly reducing energy consumption. Various methods were studied to determine the most suitable technique to reduce power consumption on compressed air systems.

Compressor control was identified as the most viable approach. Various compressor control methods were studied. Based on these investigations, IGV control was identified as the most cost effective means of controlling centrifugal compressor output. Optimising system performance using IGV compressor control encouraged further investigation into other system requirements.

The investigation concluded that a dynamic pressure delivery control system would provide optimum results. Actual system pressure requirements would always be satisfied and a significant increase in system efficiency would be realised. The system efficiency can be further improved by scheduling optimal compressor combinations.

A strategy, to reduce energy consumption on South African mines, was developed by optimising compressor control. The strategy entailed:

- automation of compressors;
- installation of equipment to record real-time data measurements;
- centralisation of recorded data on a central SCADA system; and
- development of control strategy, focusing on:
  - optimal pressure delivery;
  - optimal compressor selection; and
  - optimal flow delivery.
Conclusion and recommendations

A simulation model, using actual data from the mines, was developed to determine the potential effects of the changes on the compressed air system. The optimisation strategy was implemented at three different mines in order to verify whether optimising control would have a beneficial effect on system power consumption. The implementation at all three mines was successful, resulting in a significant reduction of power consumption. Table 5-1 presents the savings achieved.

<table>
<thead>
<tr>
<th>Mine</th>
<th>Average daily efficiency (MW)</th>
<th>Evening peak clip (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mine A</td>
<td>1.1</td>
<td>1.25</td>
</tr>
<tr>
<td>Mine B</td>
<td>5.4</td>
<td>7.29</td>
</tr>
<tr>
<td>Mine C</td>
<td>19.3</td>
<td>17.34</td>
</tr>
</tbody>
</table>

Simulated savings were less than the actual savings achieved. This difference can be attributed to the simulation model only calculating the influence of system pressure change. Several other factors, including real-time information that could provide better management of the system, for example, limiting compressor blow-off, were not taken into account. Actual system performance demonstrated that energy consumption can be reduced by optimising compressor control. These results also confirmed that optimising compressed air control can play a major role in achieving the mandatory 10% reduction in electricity consumption set by Eskom.
5.2 Recommendations for further work

The optimisation of compressor control achieved savings by accurately matching compressed air supply with system demand. Computerised control ensured that system pressure output was never greater than the demand. This resulted in improved equipment efficiency and reduced pipeline resistance. Because of the lower delivery pressure, smaller amounts of air, due to system leaks, were lost.

A recommendation for further work is to investigate other methods that could further reduce pressure and flow requirements on the demand side. A lower pressure demand on a system where the supply side is already optimised will result in a further reduction in power consumption.

Suggested areas of investigation are:

- Incorporation of additional underground measuring instrumentation to give a clearer picture of actual end user demands;
- Implementing artificial intelligence, neural networks or fuzzy logic in the control of the system;
- Influence on system requirements if some pneumatic equipment is replaced with equipment powered by alternative sources such as hydro, hydraulic and electric power;
- Effects of using smaller capacity compressors to power isolated high pressure equipment;
- Using system information for early detection and repair of system leaks; and
- Use of underground valves to control and sustain system pressure and flow.
Improve the simulation model to predict more accurate results by introducing the following additional parameters:

- influence of varying system pressure on leaks, pipe resistance and pressure drop;
- influence of control valves on system performance; and
- compressor runtime and equipment maintenance.
APPENDIX A

CALCULATION OF FLOW REQUIREMENTS

Appendix A
Calculation of flow requirements
APPENDIX A: CALCULATION OF FLOW REQUIREMENTS

The methods and examples discussed are an extract from the Hard Rock Miner’s Handbook [1.15].

The flow generation capacity required from a new mine’s compressed air system can be determined by three methods:

1) use of a mathematical formula to calculate the required capacity;
2) comparison of the characteristics of the new mine to other existing mines, in which the existing mines’ air consumption data is used to estimate the new mine’s consumption;
3) detailed analysis of the equipment on the mine in order to calculate the total air flow requirement.

Example 1: Use of a mathematical formula to calculate required capacity

\[ C = 140 \ T^{0.5} \ \text{(O’Hara)} \]  \hspace{1cm} (B.1)

Where:
C = new plant capacity in cubic feet per minute (cfm); and
T = short tons of ore mined daily (tpd).

If the new mine were to produce 3000 tons of ore daily, the estimated plant capacity will be:

\[ C = 140 \ T^{0.5} \]
\[ = 140 \times (3000)^{0.5} \]
\[ = 7700 \ \text{cfm} \]

To convert cfm to m\(^3\)/h multiply by 1.699011.
# Example 2: Use of actual mine data to estimate consumption

<table>
<thead>
<tr>
<th>Mine</th>
<th>Production (tpd)</th>
<th>Plant capacity (cfm)</th>
<th>Ratio (cfm/ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2300</td>
<td>7000</td>
<td>3.04</td>
</tr>
<tr>
<td>2</td>
<td>2500</td>
<td>9000</td>
<td>3.60</td>
</tr>
<tr>
<td>3</td>
<td>1400</td>
<td>4000</td>
<td>2.86</td>
</tr>
<tr>
<td>4</td>
<td>1650</td>
<td>5200</td>
<td>3.15</td>
</tr>
<tr>
<td>5</td>
<td>3310</td>
<td>16000</td>
<td>4.83</td>
</tr>
<tr>
<td>6</td>
<td>1380</td>
<td>4500</td>
<td>3.26</td>
</tr>
<tr>
<td>7</td>
<td>1200</td>
<td>4400</td>
<td>3.67</td>
</tr>
<tr>
<td>8</td>
<td>2425</td>
<td>8400</td>
<td>3.46</td>
</tr>
<tr>
<td>9</td>
<td>2500</td>
<td>5900</td>
<td>2.36</td>
</tr>
<tr>
<td>10</td>
<td>2400</td>
<td>6000</td>
<td>2.50</td>
</tr>
<tr>
<td>11</td>
<td>6615</td>
<td>20000</td>
<td>3.02</td>
</tr>
<tr>
<td>Average</td>
<td>2516</td>
<td>8218</td>
<td>3.266</td>
</tr>
</tbody>
</table>

Data from mines similar to the new mine will indicate the amount of air a typical compressed air system will be required to produce. If the new mine were to produce an average of 3 000 tons a day, the required plant capacity would be \(3.266 \text{ cfm/ton} \times 3000 \text{ ton} = 9800 \text{ cfm}\).
Example 3: Detailed analysis of the equipment on the mine

<table>
<thead>
<tr>
<th>EQUIPMENT</th>
<th>MAX. No. EMPLOYED</th>
<th>OPERATING HOURS/SHIFT</th>
<th>OPERATING PER CENT UTILIZATION</th>
<th>SINK No.1 SHAFT</th>
<th>PREPROD. DEVELOP.</th>
<th>PROD. 3000 TPD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Slope</td>
<td>1</td>
<td>60</td>
<td>50%</td>
<td>16</td>
<td>34</td>
<td>80</td>
</tr>
<tr>
<td>Collar Doors</td>
<td>1</td>
<td>40</td>
<td>20%</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Dump Doors</td>
<td>5</td>
<td>75</td>
<td>10%</td>
<td>2</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>Collar Tuggers hoist</td>
<td>1</td>
<td>150</td>
<td>10%</td>
<td>2</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>Station Tuggers hoist</td>
<td>3</td>
<td>150</td>
<td>10%</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chutes</td>
<td>3</td>
<td>50</td>
<td>20%</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Cylinder (underground)</td>
<td>5</td>
<td>50</td>
<td>20%</td>
<td>30</td>
<td></td>
<td>30</td>
</tr>
<tr>
<td>Boosts Monitor</td>
<td>1</td>
<td>1500</td>
<td>95%</td>
<td>2850</td>
<td>1425</td>
<td></td>
</tr>
<tr>
<td>Coilwound Monitor</td>
<td>0</td>
<td>1500</td>
<td>100%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blow Pipes 2&quot;</td>
<td>1</td>
<td>1060</td>
<td>15%</td>
<td>38</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>Pumps</td>
<td>0</td>
<td>180</td>
<td>0%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sprinklers</td>
<td>6</td>
<td>180</td>
<td>75%</td>
<td>233</td>
<td>306</td>
<td></td>
</tr>
<tr>
<td>Jacklegs</td>
<td>6</td>
<td>180</td>
<td>75%</td>
<td>233</td>
<td>306</td>
<td></td>
</tr>
<tr>
<td>Air Diamond Drills</td>
<td>5</td>
<td>300</td>
<td>0%</td>
<td>60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hoist Diamond Drills</td>
<td>6</td>
<td>0</td>
<td>80%</td>
<td>0.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shotcrete Machine</td>
<td>2</td>
<td>750</td>
<td>100%</td>
<td>469</td>
<td>938</td>
<td></td>
</tr>
<tr>
<td>Air movers</td>
<td>6</td>
<td>40</td>
<td>100%</td>
<td>120</td>
<td>240</td>
<td></td>
</tr>
<tr>
<td>Raise Boosts RB 40'</td>
<td>2</td>
<td>600</td>
<td>20%</td>
<td>210</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Raise Boosts 6LB, 7LB</td>
<td>2</td>
<td>900</td>
<td>20%</td>
<td>140</td>
<td>140</td>
<td></td>
</tr>
<tr>
<td>Raise Boosts 82R</td>
<td>0</td>
<td>900</td>
<td>20%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air AirushMotor</td>
<td>1</td>
<td>90</td>
<td>100%</td>
<td>70</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>Air AirushMotor - Diesel</td>
<td>2</td>
<td>400</td>
<td>100%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LT 250 Locusts</td>
<td>0</td>
<td>900</td>
<td>0%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Haggard Cut</td>
<td>0</td>
<td>480</td>
<td>0%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mobile Trolley (Hydr.)</td>
<td>1</td>
<td>0</td>
<td>0%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mobile Trolley</td>
<td>2</td>
<td>0</td>
<td>0%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vent Ratings Station</td>
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<tr>
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<td>Hoist, Rackbreaker</td>
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<td>0</td>
<td>0%</td>
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</tr>
<tr>
<td>ITH Slope drills 10&quot;</td>
<td>4</td>
<td>900</td>
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<tr>
<td>ITH Slope drills 9&quot;</td>
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<td>350</td>
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<td>444</td>
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<tr>
<td>ITH Slope drills 6&quot;</td>
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<tr>
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<td>0</td>
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<tr>
<td>Top Hammer drills 2.5&quot;</td>
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<td>250</td>
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<tr>
<td>Hydr. Top hammer drills</td>
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<tr>
<td>Air Welder</td>
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<td>500</td>
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<tr>
<td>Air Lifts</td>
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<tr>
<td>Air Lights</td>
<td>0</td>
<td>500</td>
<td>0%</td>
<td></td>
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</table>

| SUBTOTAL                  | 2689              | 3470                   | 4495                          |                 |                   |                |
| Contingency (10%)         | 259               | 347                    | 449                           |                 |                   |                |
| SUBTOTAL                  | 3177              | 3817                   | 4944                          |                 |                   |                |
| Late Losses (Loss)        | 159               | 572                    | 929                           |                 |                   |                |
| SUBTOTAL                  | 3336              | 4389                   | 5933                          |                 |                   |                |
| DESIGN CAPACITY           | 3200              | 4500                   | 6000                          |                 |                   |                |
| STANDBY CAPACITY          | 1100              | 1500                   | 2000                          |                 |                   |                |
| PLANT CAPACITY            | 4000              | 6000                   | 8000                          |                 |                   |                |

The analysis presented in the table takes into account every piece of equipment, operating at nominal air consumption. The data is normalised to consider operating hours and utilisation. The result indicates that the new plant must be able to generate 8,000 cfm in order to supply the mine with sufficient air.
THE MOORE–GREITZER MODEL
APPENDIX B: THE MOORE–GREITZER MODEL

Figure B-1 illustrates the Moore–Greitzer mathematical model. The model was developed to predict surge and describe a compressor’s flow dynamics. The model and equations below is an extract from “Variable structure surge control for constant speed centrifugal compressors”.

The mathematical formulas describing the model are given below [2.13].
The Moore-Greitzer model

\[
\frac{d\Phi_c(\xi)}{d\xi} = \frac{1}{l_c} \left( \frac{\Psi_c(\Phi_c) - \Psi_v(\Phi_c) - \Psi_p(\xi)}{\Psi_c(\Phi_c)} \right),
\]

\[
\frac{d\Psi_p(\xi)}{d\xi} = \frac{1}{4B^2l_c} (\Phi_c(\xi) - \Phi_t(\Psi_p) - \Phi_{tcv}(\Psi_p)),
\]

where

\[
B = \frac{U}{2a_0} \sqrt{\frac{V_p}{A_c}} \quad \text{and} \quad l_c = l_i + \frac{1}{a} + l_e,
\]

\[
\Phi = \frac{m}{\rho A_c U}, \quad \Psi = \frac{\Delta p}{\rho U^2}, \quad \xi = \frac{U}{R} t, \quad l_i = \frac{L_i}{R}, \quad \text{and} \quad l_e = \frac{L_e}{R}
\]

\[
\Psi_c(\Phi_c) = \psi_{c0} + H \left[ 1 + \frac{3}{2} \left( \frac{\Phi_c}{W} - 1 \right) - \frac{1}{2} \left( \frac{\Phi_c}{W} - 1 \right)^3 \right].
\]

The characteristics of the CCV, the throttle, and the TCV are given respectively, by

\[
\Psi_v(\Phi_c) = \frac{1}{k^2_v} \Phi_c^2 \quad \text{and} \quad k_v = c_v u_v > 0,
\]

\[
\Phi_t(\Psi_p) = k_t \sqrt{\Psi_p} \quad \text{and} \quad k_t = c_t u_t > 0,
\]

\[
\Phi_{tcv}(\Psi_p) = k_{tcv} \sqrt{\Psi_p} \quad \text{and} \quad k_{tcv} = c_{tcv} u_{tcv} > 0,
\]
Symbols/parameters:

Φ  Mass flow coefficient
Ψ  Pressure rise coefficient
k  Valve gain
L_i  Inlet duct length
l_c  Dimensionless compressor length
B  Greitzer’s parameter
ρ  Ambient air density
a_s  Speed of sound
c  Valve capacity
L_e  Exit duct length
A_c  Compressor duct area
U  Mean rotor speed
R  Rotor mean radius
V_p  Plenum volume
ξ  Dimensionless time
u  Valve opening
L_c  Compressor and ducts length
a  Reciprocal time lag of compressor passage
Ψ_{co}  Compressor characteristics shut-off valve
W  Compressor characteristic semi-width
H  Compressor characteristic semi-height
Subscripts

\begin{align*}
c & \quad \text{Compressor} \\
t & \quad \text{Throttle} \\
d & \quad \text{Desired} \\
r & \quad \text{Error} \\
s & \quad \text{Surge line} \\
p & \quad \text{Plenum} \\
o & \quad \text{Initial} \\
x & \quad \text{Range extension} \\
v & \quad \text{Close-coupled valve} \\
e & \quad \text{Equivalent compressor} \\
tcv & \quad \text{Throttle control valve}
\end{align*}