Simulating improvements on mining compressed air systems

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It all starts here ™

Abstract

Title:	Simulating improvements on mining compressed air systems
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Degree:	Masters in Electrical and Electronic Engineering

As operational costs of deep level mines increases and gold ore grades decrease, profitability in the gold mining sector is becoming a challenge. Electricity tariff increases have contributed to a rise in the cost of operating mines. Compressed air systems are utilised on mines as they provide safe, reliable power for various underground machines. Compressed air is also used for emergency oxygen in refuge bays.

Compressed air systems utilise a significant portion of a mine's total energy. It has been shown that many deep level mine compressed air networks have inefficiencies. Improving the efficiency of these systems could result in a reduction of operational costs by reducing the energy required to produce compressed air. Additionally, an improvement in service delivery could be achieved.

Previous studies have shown the usefulness of simulations to develop improvements for deep level mining systems. However, these studies have not followed a structured methodology for developing compressed air simulation for deep level mines. Previous studies have also simplified compressed air models reducing the simulation precision and testable scenarios.

In this study a simulation methodology was therefore developed. Investigations into the compressed air systems are performed. A model is then developed in software to accurately recreate the system operation. Finally a proposed means of improvement is simulated, analysed and quantified in terms of improvements in energy savings and service delivery.

Two case studies were evaluated. For each case study a variety of scenarios were simulated.

In case study A by reducing air used by refuge bays in simulation, a reduction of 1 MW E.E. would be achieved with addition to a significant improvement of 18 kPa to system pressure. Drop tests implemented on the case studies validated the simulation with a precision of 5%.

The study showed that simulation is a important tool for identification improvements in large compressed air systems. By utilising a structured methodology to develop detailed compressed air simulations, inefficiencies and operational improvements were identified.

Keywords: Mining, Energy, Compressed air, modelling, Simulation, operational improvements

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Acronyms

CALDS	Compressed Air Leakage Documentation System
DSM	Demand Side Management
PI	Proportional-Integral
PLC	Programmable logic controller
SCADA	Supervisory control and data acquisition
SI	International System of Units
STB	Simulation Toolbox
THS	Thermal-hydraulic simulation
VFD	Variable Frequency Drive
VSD	Variable Speed Drive

Nomenclature

kilopascals	The international measure of pressure	kPa
polytropic coefficient	The thermodynamic coeificient used when describing the heat transfer due to compression or expansion	—
Tonne	The non-SI measure for 1000 kilograms	T
Watt	The SI measure of power	MW

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CHAPTER 1

Introduction and background

'*Quote.*' - Somebody

1.1 Preamble

This chapter firstly discusses background regarding deep level mining in South Africa. Next, the need to reduce costs of operation in the mining sector is examined. From this a focus in reducing energy consumption of compressed air systems is developed. Next, background on compressed air operation and energy interventions are discussed. Simulations and their value in industry is discussed leading to a problem statement and objectives of the study. Finally, an overview for the dissertation is provided.

1.2 Background on deep level mining

1.2.1 Mining profitability

Various technical, economic, social and operational challenges are posing a risk to the profitability of the South African mining sector. One of the challenges the sector faces is a rise in the cost of operation [1].

A considerable factor that is contributing to the rise of operational costs in South African gold mines has been the increase in electricity costs. As shown in figure 1.1, the general cost of electricity has increased at a rate greater than inflation since 2008 [2].

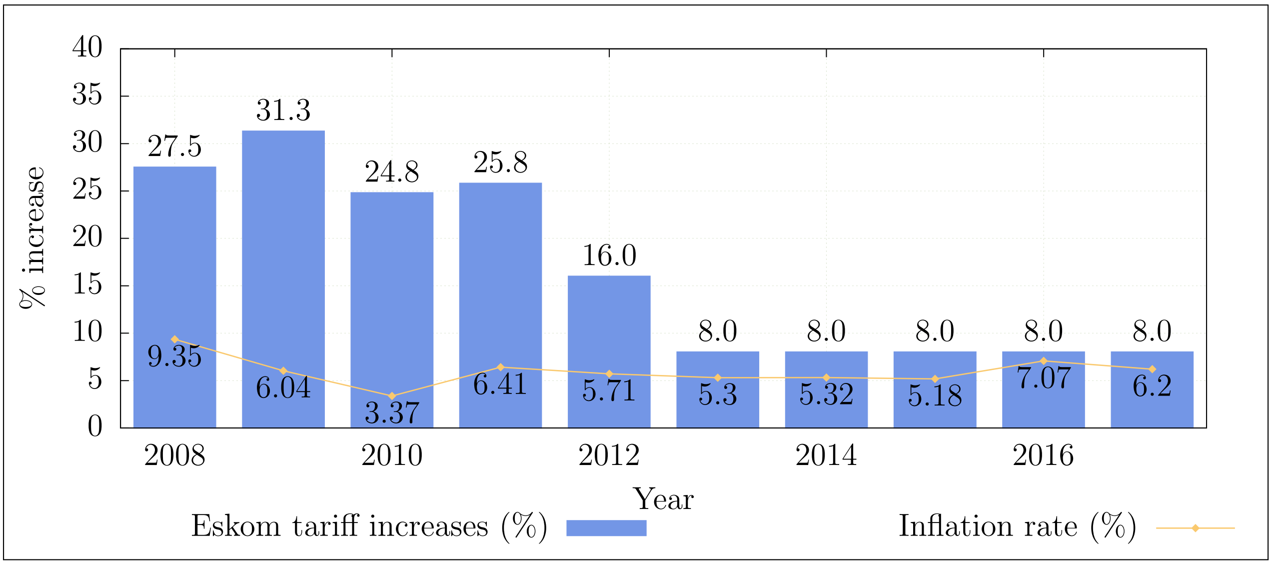

Figure 1.1: Electricity price increases between 2007 and 2017 [2] compared to the inflation rate in South Africa.[1]

[1]inflation.eu, "Historic inflation South Africa." [Online] http://www.inflation.eu/inflation-rates/south-africa/historic-inflation/cpi-inflation-south-africa.aspx, [Accessed 25 March 2017].

In addition to rising electricity costs, gold ore grades of South African mines have fallen substantially over the last few decades [3]. As ore grades decline, the energy utilised per unit of metal increases exponentially [4]. Therefore mines require significantly more energy per unit of metal produced. This combination of tariff increases and increased energy usage per unit have led to significant rises in mining operation costs.

1.2.2 Process of a deep level mine

South Africa's mines are some of the deepest in the world Some mine shafts are reaching depths deeper then 4000m below the surface [5]. The process of extracting ore at these depth is dependent on the essential services, mainly cooling and ventilation, pumping, compressed air and hoisting, as shown in figure 1.2.

Cooling and ventilation system are required to maintain safe working temperatures underground. Pumping is critical to remove service and fissure water, preventing flooding. Compressed air is needed to safely power underground drills and machines. Finally hoisting systems are used to bring the ore to the surface and to transport mine workers in the mine.

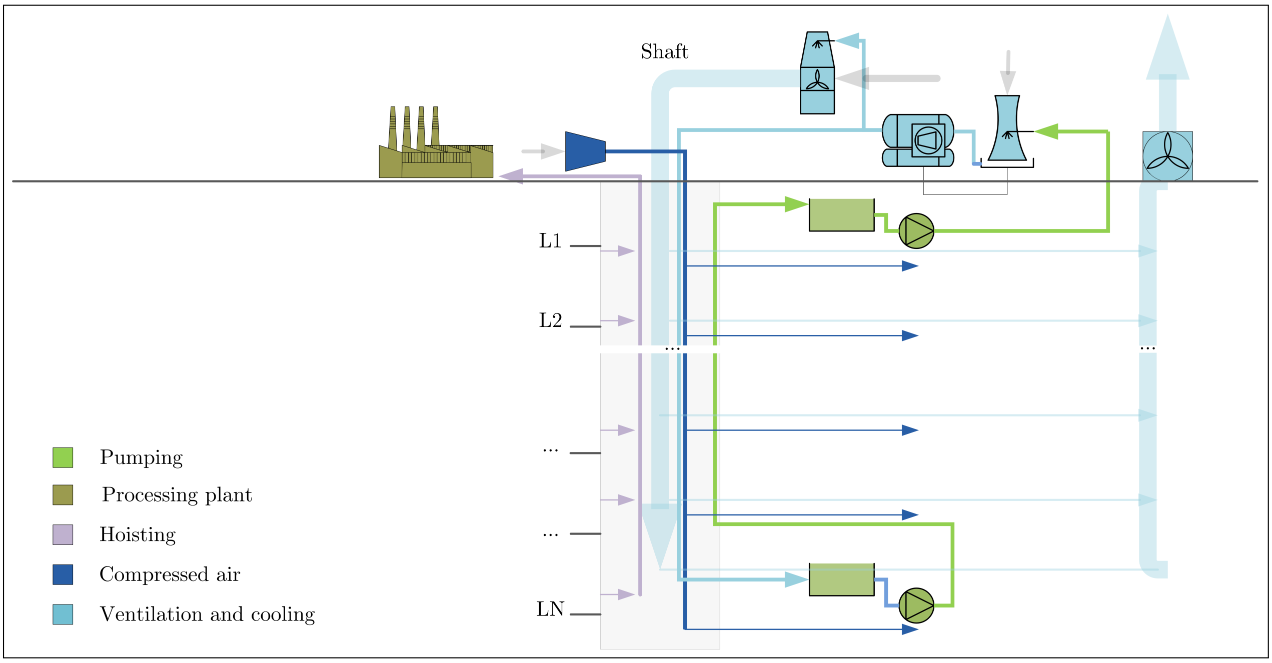

Figure 1.2: A layout showing the mining processes.

1.2.3 Mining Services

Energy usage

The mining industry uses extensive amounts of energy. In South Africa, the industry utilizes approximately 15% of the national electricity supplier's yearly output, of which, gold and platinum mines use 80%.[6]

Figure 1.3 shows the division of energy within the mining industry. The chart shows that compressed air systems utilizes the most energy within a mining industry. It is reasoned that energy can be most effectively reduced through the implementation of energy interventions on compressed air systems.

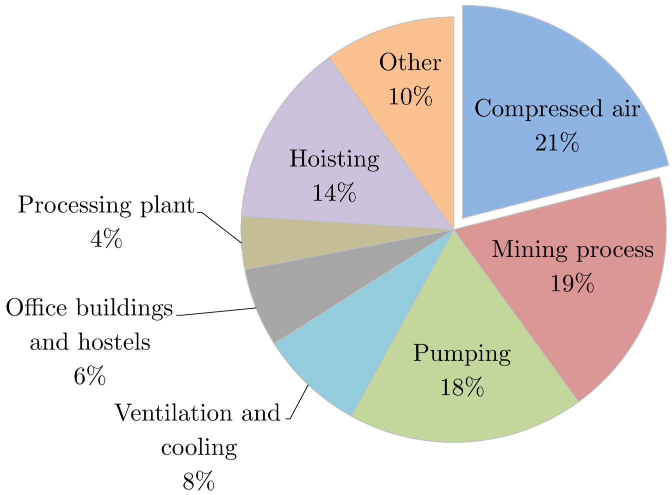

Figure 1.3: The energy consumption for each mining system [7].

1.3 Compressed air systems in mining

1.3.1 Compressed air in operation

Largely due to their reliability, versatilely and ease of use, the South African mining industry has installed extensive compressed air networks. These systems can have compressors with capacities of up to 15 Watt [8].However, the supply of compressed air is a highly energy demanding and costly process [9]. The energy used for compressed air production contributes to between 9% and 20% of the total mining energy consumption [6],[10].

Large compressed air systems are likely inefficient. Internationally, the expected energy savings potential of a large compressed air network is 15% [11]. Marais [12] showed that energy savings of up to 30% and 40% can be attained through various interventions.

Pneumatic rock drills

Drilling is mainly performed in the production areas or stopes of a mine. Drill machines are used to drill holes into the rock face. Once the holes have been drilled, explosives are then installed to break up the rock [13].

Compressed air is used to power pneumatic rock drills within a mine. Pneumatic rock drills run at an efficiency of 2%. This is low when compared to alternative rock drills such as electric, oil electro-hydraulic and hydro-powered drills that run at an efficiency of between 20-31% [14],[15].

Refuge bays

Refuge bays are installed underground in deep level mines to provide safety to miners in the event of an emergency. To satisfy the safety criteria, most mines will utilize compressed air to deliver cool air to the chamber [16]. Figure 1.4 shows an example of a compressed air inlet at an underground refuge bay. A muffler is installed to the end of the inlet air pipe to reduce noise.

Figure 1.4: An example of compressed air inlet in an underground refuge bay chamber of a mine.

The provision of 1.42 l/s of air per person at a pressure between 200 and 300 kilopascals is required to provide oxygen and prevent any poisonousness gas entering the refuge [16].

Airflow in the refuge bays can be controlled with a manual valve within the chamber. Often, this valve is often misused by mine workers who open the valves fully in order to cool the bay through decompression of the air.[CitationNeeded]

Processing plants

Processing plants are constructed near gold and mines. They are used to extract metal from the ore obtained from the mining operation. These plants utilize compressed air for various systems, processes and equipment.

To save costs, processing plants often share compressed air network with mine [8]. The plants use relatively low amounts of air compared to mines, however plant processes have pressure requirements that differ from the rest of the air network. If the plant is not isolated from the mine air network, compressed air optimizations on the mine can be complicated.

Other compressed air uses

Due to the availability underground, compressed air is utilised for a number of other applications. These usages include, pneumatic loaders or rock shovels, pneumatic cylinders, dam sediment agitation, cooling and ventilation and many other applications. This vast variety of of applications also leads to misuse of compressed air this leads to inefficient operation.

Operation schedule

On a typical mine, various operations will take place at different times of the day. Depending on the activity taking place, many mines will control the pressure to meet the requirements [17],[8]. Figure 1.5 shows the schedule and pressure requirement on a typical deep level mine.

As shown in the figure, the pressure requirement changes depending on the activity taking place. The drilling shift typically has the highest pressure requirement whilst blasting shift requires the lowest. Schedules and operation philosophies can differ between mines. Different operational schedules require alternative pressure requirement profiles.

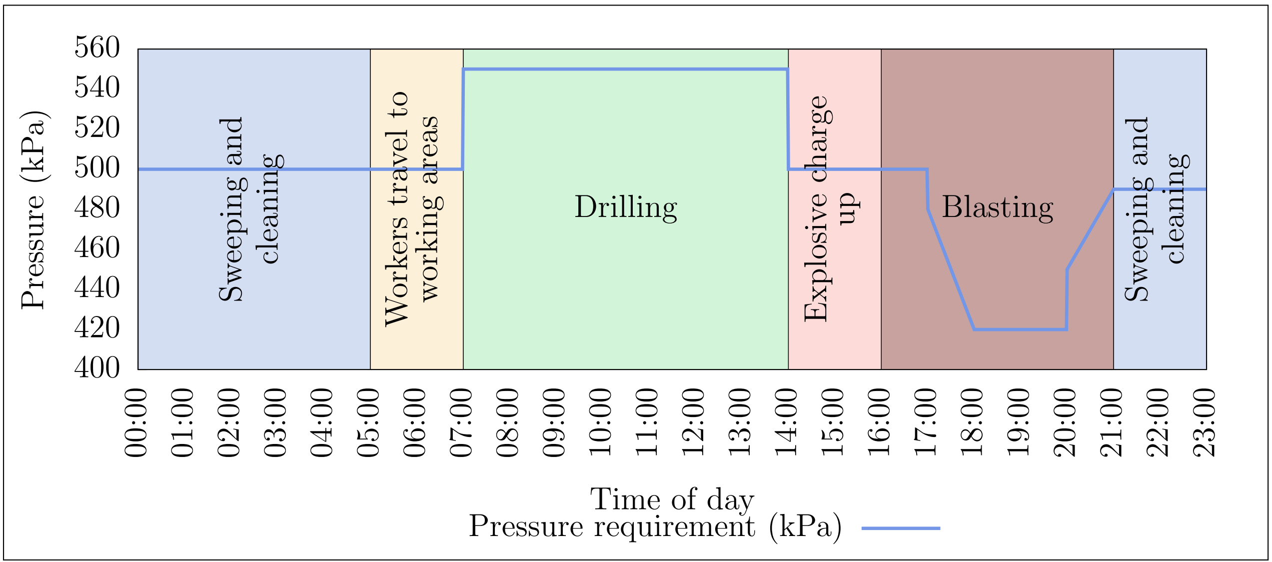

Figure 1.5: The typical operation schedule of a deep level mine [17].

1.3.2 Characteristic inefficiencies of compressed air systems

Compressed air distribution networks in the mining industry consist of multiple compressors and working areas up to eight kilometres away from the source [8]. Due to their size and complexity, these systems are prone to large energy losses.

Compressed air leakage accounts for as much as 35% of the energy losses of a compressed air network [18]. Other systemic losses include, faulty valves, pipe diameter fluctuations, obstructed air compressor intake filters and inefficient compressors.

1.3.3 Instrumentation and measurements

For large industrial systems, thorough instrumentation is necessary in order to monitor performance and equipment condition throughout the system. In a mining compressed air network, instrumentation is installed to monitor flows, pressures, temperatures ,etc.. Electrical instrumentation is also installed for sensing currents, power factors, voltages and power. On control valves, input/output pressures, flows and valve position are usually measured with instrumentation.

A Supervisory control and data acquisition (SCADA) system is used to monitor and control processes throughout the mine from a control room. The SCADA centralises instrumentation data from Programmable logic controllers (PLCs) throughout the mine. The SCADA can also be used to control machines and instrumentation by sending control signals to the relevant PLC. Communication to the underground PLCs is achieved using a substantial fibre optic network.[19]

1.3.4 Inefficiency identification methods

Leakage and inefficiency detection strategies is not often pursued in the South African mining industry [15]. Many mines do however perform leak inspections either internally or by a outside company. In these inspections, an ultrasonic detector is used to locate the leak. Alternatively, some mines employ the “walk and listen” method to identify leaks from the audible sound that it produces [15]. Once the inspection is completed, the findings, including the locations and estimated costs of all identified leaks, are reported.

1.3.5 Compressed air savings strategies

Strategies to reduce energy on compressed air systems can be summarised as follows [20]:

- Reducing leaks.
- Reducing demand.
- Reducing unauthorised usage.
- Increasing supply efficiency.
- Optimising supply.

Often a combination of energy strategies will lead to the most savings [8]. Specific energy saving measures that have successfully reduced energy on mine compressed air systems will be discussed in Chapter 2.

1.4 Use of simulation in industry

1.4.1 Background in industrial simulation

Continuous improvements in computing hardware has led to major advancement in software technology. Consequently the use of computational simulation has become an increasingly valuable tool for many industries.[21]

In *Handbook of simulation: principles, methodology, advances, applications, and practice*, the advantages of the use of simulation in industry are discussed as follows [22]:

- The ability to test new policies, operating procedures and methods without causing a disruption to the actual system.
- The means to identify problems in complex systems by gathering insight in the interactions within the system.
- The facility to compress or expand time to investigate phenomena thoroughly.
- The capability to determine the limits and constraints within a system.
- The potential to build consensus with regard to proposed designs or modifications.

1.4.2 Simulation usage in mining

Simulation has been used to test and identify energy and operational improvements in mining systems. However, existing tools require to much data to model the systems accurately [CitationNeeded]. New tools such the STB software, have made it possible to develop accurate, detailed simulations for mining systems. This allows for testing of more complex intervention scenarios, leading to more improvements for the mine than could be previously obtained.

1.5 Problem statement and objectives

1.5.1 Problem statement

Rising costs and falling ore grades are driving in the mining industry to reduce operational inefficiencies. Large energy savings can be made in Compressed air systems in the mining industry. However manual testing of interventions can be cumbersome.

Computer modeling and simulation of compressed air systems can be used to quantify and priorities operational interventions that improve efficiency. These interventions can be evaluated with minimal risk. However simulations have not been utilized to their full potential in the mining industry. With new tools that allow for more detailed simulation models of mining systems could allow for of identification of more effective energy savings measures for mines.

1.5.2 Research objectives

The main objective of this dissertation is achieve energy savings and identify operational improvements in mining compressed air systems. A simulation process to will be developed to achieve this goal.

1.6 Dissertation overview

`Describe (in approximately one sentence each) the contents of each of the dissertation chapters. No results here.`

CHAPTER 2

Overview of simulation and compressed air applications

‘*Quote.*’ - Somebody

2.1 Introduction

2.2 Methods to identify operational improvements

2.2.1 Preamble

2.2.2 Identifying areas for improvement

(Kriel Masters) -Investigation

-Measurements

-Simulated impact of the proposed intervention

2.2.3 Measurements

2.2.4 Leakage detection

(Van Tonder masters) - Inspections

- Audible sounds (by ear)

- Ultrasonic

- Intelligent leakage detection (instrumentaion SCADA)

- Alternatives (pigging, soap water, Dyes load/unload test)

- CALDS (Compressed air leakage document system)

2.2.5 Estimation techniques

- Snyman estimated improvements using historical data.[20]

- Marais estimation through simplified estimation, simulation [8, 12].

2.2.6 Summary

2.3 Review of compressed air energy interventions in industry

2.3.1 Preamble

(Kriel Masters) - Supply and demand strategies (improving compressor efficiency vs reducing/improving demand)

Marais et al investigated increased energy savings through the use of Compressed Air Leakage Documentation System (CALDS) [23].

2.3.2 Strategies to improve compressed air supply

- Control Strategies
- Relocating compressor. reconfiguring networks - Bredenkamp
- Compressor schedules
- Variable speed drives
- Compressor selection
- Marais showed compressed air saving potential through an expert control system.[24]

2.3.3 Strategies to reduce/optimise compressed air consumption

- Reducing leaks
- Control Valves - Pascoe
- Marais PhD

- Snyman - investigated various Compressed air demand reduction and efficiency optimisations [20].

Pneumatic rock drills efficiency

Reduced pressure to the drill will cause it to run even less efficiently. A study by Bester *et al.* showed that between 2002 and 2013 compressed air and energy consumption per tonne of ore produced had steadily increased as shown in figure 2.1. The increase in consumption per Tonne was a result of a reduction in air pressure at the mining stopes. Measurements indicated that the pressure was as low as 300 kilopascals. This reduced the efficiency of the rock drills. Before 2002 pressure was maintained above 500 kilopascals at the stopes. .[25]

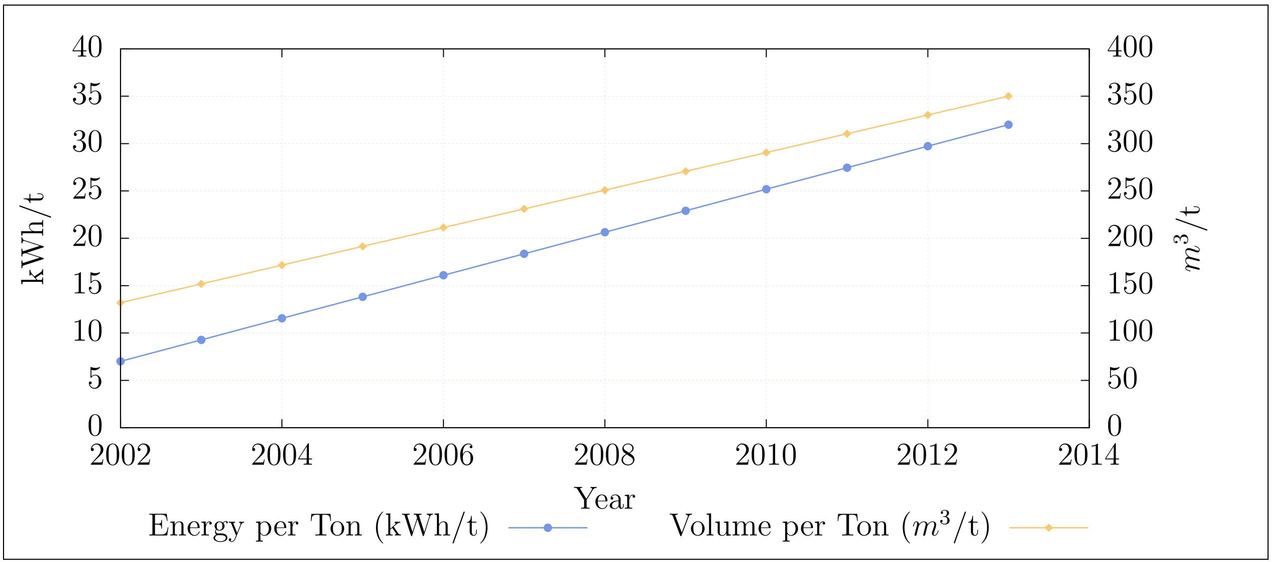

Figure 2.1: The Compressed air energy and flow consumed per T of ore produced. Adopted from Bester *et al.* [25].

2.3.4 Summary

2.4 Use of simulations to identify improvements in mining systems

2.4.1 Preamble

2.4.2 Value of simulation in DSM projects

(Van Niekerk M)

- Compressed air

- Cooling systems

- Dewatering

- Design optimisations using simulation

- KYPipe's gas simulation engine

- De Coning - simulations to investigate the opportunity to optimise the control strategy of a compressed air network by rescheduling the compressors.

2.4.3 Simulation procedures

-Kriel masters

-Pascoe

Periodic simulation

2.4.4 Verifying simulations

- Holman - van Niekerk masters

- Kriel masters (validation)

- Calibrating -pascoe - determining accuracy - pascoe - Du2015Development - comparisons with models - comparison with actual - First principles

2.4.5 Shortcoming of previous studies

2.4.6 Summary

2.5 Conclusion

CHAPTER 3

Developing a simulation methodology

'*Quote.*' - Somebody

3.1 Introduction

This chapter details the implementation methodology of simulations to optimize mining compressed air systems. The methodology discussed in this chapter will utilize insights from previous studies. Improving on shortcomings discussed in section 2.4.5.

Implementation of a simulation is split into three steps. Firstly, an investigation on the specific air network to is performed. The data acquired from this investigation is then utilized to develop and verify a simulation model. Finally scenarios are implemented using the simulations and the results are quantified and ranked. A simulation report is then produced and passed to the mine.

3.2 System investigation method

3.2.1 Preamble

Developing a detailed simulation model of a compressed air network requires thorough comprehension of the inner workings of the system. This section will discuss the investigations needed to obtain the required understanding.

3.2.2 Acquiring data

The first step of the system investigation is to acquire the data and understanding that will be required to model compressed air system's function. This will requires access to mine resources such as data storage systems, instrumentation, and communication with relevant engineers and personnel.

Comprehensive and up to date layouts illustrate a compressed air network's unique set-up, scale and location of instrumentation. More detailed layouts can provide per-level air consumption breakdowns of the network, locations of refuge bays, mining cross-sections and identified inefficiencies. This is vital to understand the operation and identify what data parameters will be required for the model.

3.2.3 Mining schedule

A critical aspect to developing an accurate model of a mining compressed air system is understanding the the operational philosophy of the mine. The schedule for operations such as drilling, blasting or cleaning can have a major impact on compressed air requirements at different times of the day. By utilizing the operational schedule, simulation scenarios can be optimized for the air requirements throughout the day.

3.2.4 Data accuracy and verification

3.2.5 Solutions to unavailable data

Parameters that are required to develop the simulation model, such as flows, pressures, may not be actively logged by mine systems. To obtain this data it is necessary to investigate alternative sources. At points where instrumentation is absent, estimations can be made from assumptions made using instrumentation on the network or spot inspections.

Air network specifications such as piping sizes, technical layouts, major leak locations or specifications is often outdated or not recorded. Critical data should be obtained through audits and inspections of the system. If manual inspection is not possible, estimations should be made using the available data or approximation techniques discussed in literature.

3.2.6 Summary

3.3 Model development and verification

3.3.1 Preamble

Compressed air networks are comprised of components such as compressors, valves, pipes, etc. This section will discus the development, calibration and verification of component models that make up a compressed air simulation is.

3.3.2 Compressed air component models

Air pipes

Pressure losses occur over compressed air networks due to friction in the pipe, these losses should be taken into account in the simulation for large piping sections. A pipe model is used to account for these losses which are defined by the *Darcy-Weisbach equation*[1]:

$$\Delta P = \frac{fL\rho V^2}{2D}$$

Where the pressure difference ΔP is a function of:

f	Friction coefficient
L	Pipe length (m)
D	Pipe diameter (m)
ρ	Air density (kg/m^3)
V	Average velocity (m/s)

The pipe component can be used as a valve by controlling the open fraction between 0 and 1. Modelling the valve flow characteristics is discussed in 3.3.2 *Controllers*.

Ambient conditions

Ambient air condition underground and on surface change the characteristics of the air, effecting the operation of the system. Figure 3.1 shows the average summer air conditions. If no data is available for the specific simulation period, the conditions can be estimated by scaling this profile. The assumption is made that underground conditions remain constant at each mining level. Pressure and temperature increases with depth as a result of auto compression and rock face temperature. Therefore the conditions can be estimated using only the depth at each level.

Compressors

Three compressor models were investigated, each with varying complexity. The models are: air compressor, dynamic compressor and positive displacement compressor. The air

[1] B. Glenn, 'The Darcy–Weisbach Equation,'[Online] `https://bae.okstate.edu/faculty-sites/Darcy/DarcyWeisbach/Darcy-WeisbachEq.htm`, [Accessed 20-05-2017]

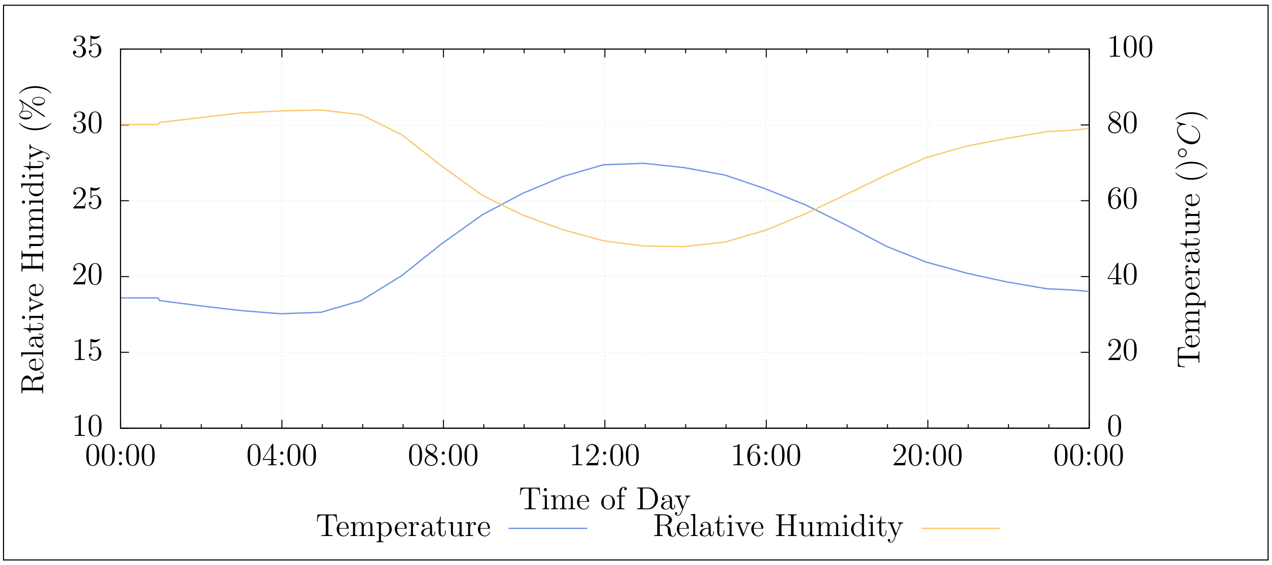

Figure 3.1: Average summer ambient air conditions at a South African gold mine.

compressor is a general, simplified model. It requires minimal user inputs by making several assumptions. This is useful when parameters for a compressor are not available. Or when doing a quick preliminary simulation. However it is not ideal for detailed simulations which require more precision.

The dynamic compressor components are is more complex, taking into account factors such as heat generated by polytropic

coefficient and inefficiencies within the process. Hence the model can be used more accurately and for more complex simulations then the general compressor model. However, it should be noted that the dynamic compressor is simplified by several assumptions, for example, a constant efficiency at varying loads.

For most scenarios, the dynamic compressor model is most suitable. This component is modelled by fitting a quadratic curve through three points of operation to obtain an equation for corrected mass flow as a function of the pressure ratio. This characteristic curve of compressor as shown in figure 3.2 can be accurately estimated even when only one data point is available by making approximations for the zero flow and pressure points on the curve. Once the flow characteristics of the compressors are set, the efficiency and polytropic coefficient parameters are calibrated such that the output power and air temperature match the actual or estimated outputs of the compressor.

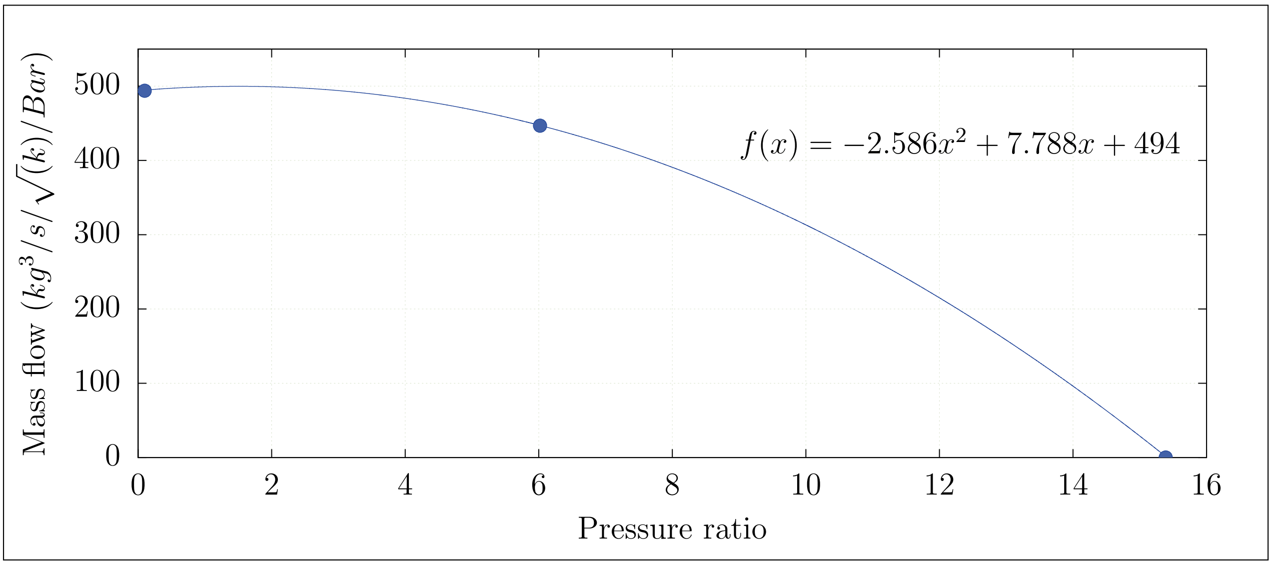

Figure 3.2: Estimating the characteristic curve of a compressor by fitting a quadratic function to points of operation.

Once the models are accurately calibrated, the compressor component is integrated to the air network in the arrangement shown in figure 3.3. The Compressor is connected to the inlet air source via an inlet pipe and air node and to the rest of the network via an air node and outlet pipe. This is is to allow the inlet and outlet parameters and conditions to be be monitored and controlled.

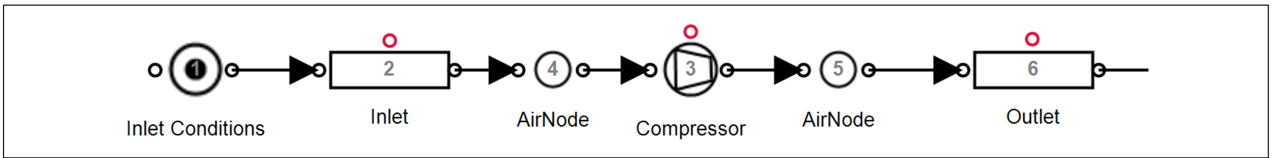

Figure 3.3: Integrating the compressor component into the simulation.

Demand/leak

A flow demand represents any air flow leaving the network. This includes equipment that uses air such as drills and agitators etc. as well as inefficiencies like leaks and open pipes. Generally the air flow is dependent on pressure and the specific resistance to flow of the outlet.

The specific resistance of the flow demand can be obtained using the inlet pressure, outlet pressure and flow. If the flow is not known, a reasonably accurate estimation can be made by calculating the expected flow from the size of the outlet. The air demand may vary throughout the day. For example, a mining section may utilise more machines during certain periods of the day. A schedule is used to replicate this in the simulation. Figure 3.4 shows how a calibrated air demand or leak is integrated into the simulation.

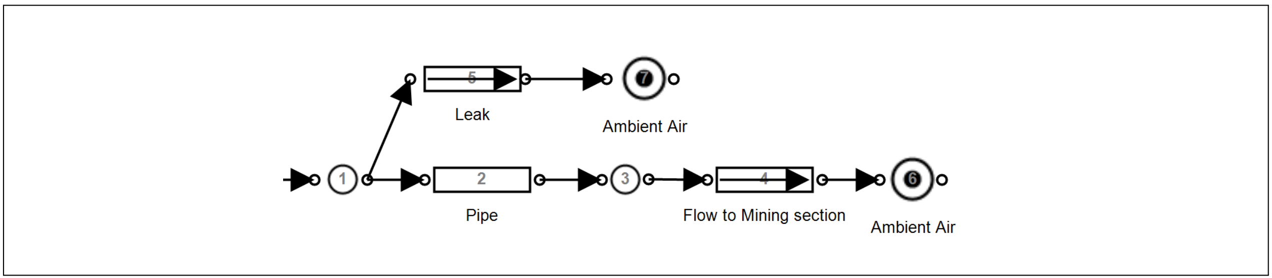

Figure 3.4: Implementing flow demands and leaks into the simulation.

Compressed air control

Simulation components need to be dynamically controlled as in the actual air network. Control is typically implemented on compressors and valves throughout the network to follow certain set-points and schedules. It is important to not only include the controllers in the simulation, but to replicate the non-linearities, limitations and responsiveness related to their use. This ensures the model reacts in the same way the actual network would, improving accuracy.

On a typical mine, compressors power is controlled to ensure that the discharge pressure matches a specified set-point. This control is achieved through either Variable Speed Drives (VSDs) (or Variable Frequency Drives (VFDs)) and guide-vain control. VFDs gives a wide range of power control and can be estimated using a Proportional-Integral (PI) controller as in figure 3.5 where discharge pressure is used as feedback for the controller.

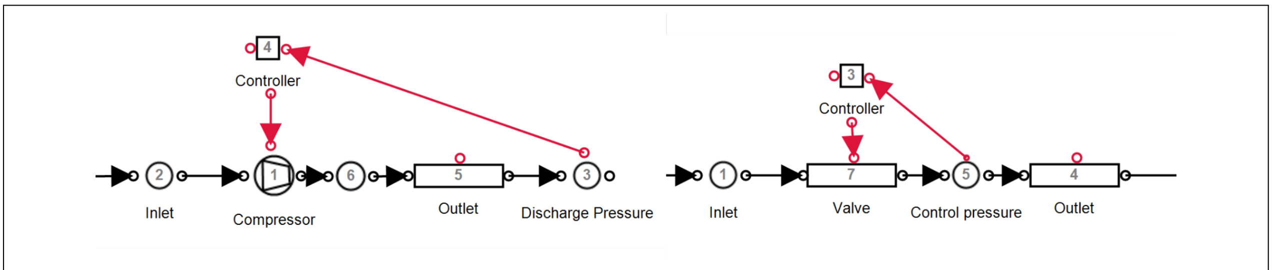

Figure 3.5: Control components in STB.

Guide vain control is most commonly used in mining to control compressors. This entails controlling the position of the inlet guide vain . The guide vain is opened or closed to control the compressors discharge pressure. Manipulating the guide vain position will effect the power the compressor inputs into the system. Figure 3.6 shows the relationship between compressor power and guide vain position. This relationship can be approximated as a linear function. A guide vain position of 40% maps to an output power of about 60% of the maximum power. When more pressure is required than can be obtained with the guide vains fully opened, another compressor is needed to operate.

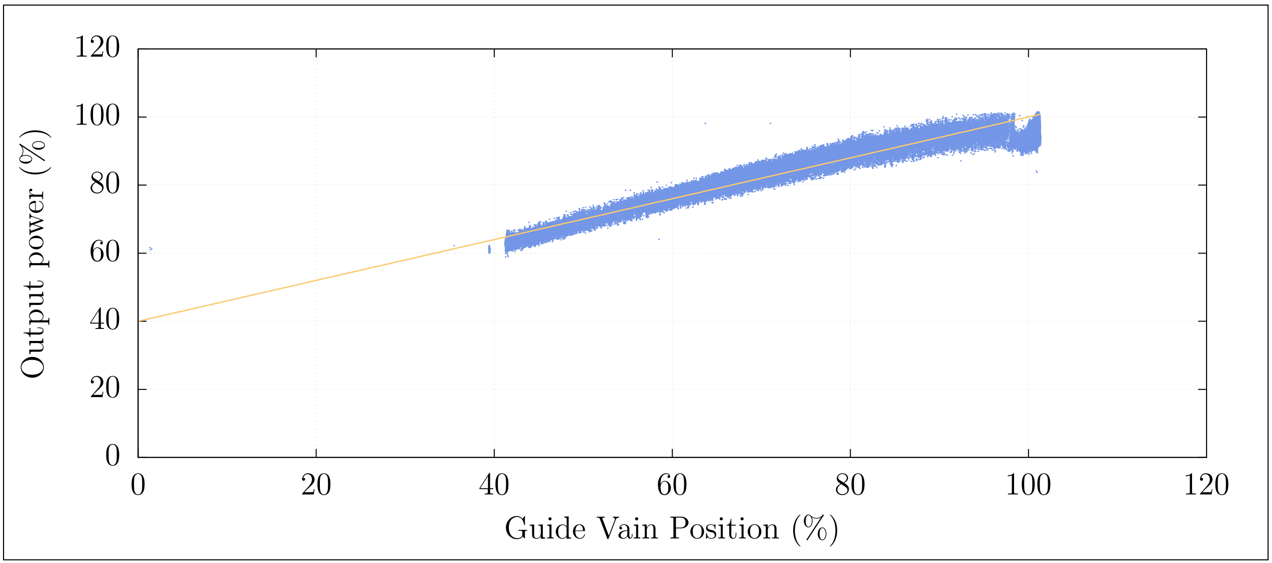

Figure 3.6: The relation between guide vain position and compressor output power.

A guide vain controller is modeled using a PI controller component. However the limitations of guide vain control, as represented in figure 3.6, must be implemented in the controller. This is done by using a minimum output that would match the minimum power reduction the guide vain achieved by closing the guide vain. For example, a PI controller for the compressor from figure 3.6 would have a minimum control output of approximately 60%.

Mines utilise control valves underground sections to control the pressure at individual mining stations independently [26]. Controlling of valve components is perfomed similarly as control of the compressor components. As shown in figure 3.5 the outlet pressure is used as feedback for a pi controller. The controller output is mapped to the valve fraction of a pipe component.

Compressed air after-cooling

The air compression process generates significant heat. Compressed air at high temperatures contains a large amount of water vapour. To prevent condensation later in the air network,

Figure 3.7: An example of a compressed air control valve[27].

improve the system capacity and protect equipment from excessive heat, after-coolers are installed to the outlet of the compressor [19].

After-cooling reduces the compressed air temperature to within a margin of ambient. This cooling could have a large effect on the performance of the network. Hence including after-cooling to the simulation model should improve accuracy.

To replicate this effect, a heat transfer node can be added to the outlet of the compressor component. STB utilizes the following heat transfer parameters of the air node to solve for outlet temperature:

$Area$	The heat transfer area (m^2)
UA	Heat transfer coefficient ($kW/°C$)
T_{amb}	Ambient air temperature ($°C$)

3.3.3 Verification of simulation model

- Steps to validate the model accuracy .

- Compare parameters to actuals

- First principles

-

3.3.4 Simulation inputs

The inputs of a simulation are any parameters that do not remain static, or follow the same profile in day to day operation of the system. Examples of such parameters in a compressed air simulation are:

- Simulation period
- Surface ambient conditions
- Compressor selection and schedules
- Flow demands
- Operational changes

Changing the simulation baseline period for a calibrated simulation should only require the updating of the input parameters. Figured ??? shows an example of a changing compressor schedule where an input parameter would need to be updated in the simulation.

3.3.5 Summary

3.4 Implementation of simulation method

3.4.1 Preamble

Once a simulation has been developed and verified, the implementation of interventions and scenarios follows. In this section, the approach of implementation, and analysis of interventions in simulation will be discussed.

3.4.2 Analyses of data

- Baseline vs Optimised comparison

3.4.3 Quantifying operational improvements

- Estimating cost savings

3.4.4 Summary

3.5 Conclusion

CHAPTER 4

Results and validation

‘*Quote.*’ - Somebody

4.1 Introduction

4.2 Case study: Mine A (Kusasalethu)

4.2.1 Preamble

4.2.2 Scenario 1. Refuge bay simulation

Tested scenario where all excessive leaking valves are removed. refuge bays savings 1MW E.E.

4.2.3 Verification of baseline simulation

Validation of results

4.2.4 Scenario 2. Closing off levels/stopes

4.2.5 Summary

4.3 Case study: Mine B (Beatrix 123)

4.3.1 Preamble

4.3.2 Scenario 1. Compressor set points

4.3.3 Scenario 2. Control valves set points

4.3.4 Summary

4.4 Periodic simulation analysis

4.4.1 Preamble

4.4.2 Summary

4.5 Potential benefit for SA mines

4.6 Conclusion

CHAPTER 5

Conclusion

‘*Quote.*’ - Somebody

5.1 Conclusion

5.2 Limits of this study

5.3 Recommendations for future studies

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APPENDIX A

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APPENDIX B

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