

# Simulating improvements on mining compressed air systems

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# Abstract

**Title:** Simulating improvements on mining compressed air systems  
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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%.

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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

## Acknowledgements

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## Acronyms

CALDS	Compressed Air Leakage Documentation System
DSM	Demand Side Management
PI	Proportional-Integral
PLC	Programmable logic controller
PTB	Process Toolbox
SCADA	Supervisory control and data acquisition
SI	International System of Units
SP	Set-Point
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 coefficient 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	$W$

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# CHAPTER 1

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## Introduction and background

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*'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].

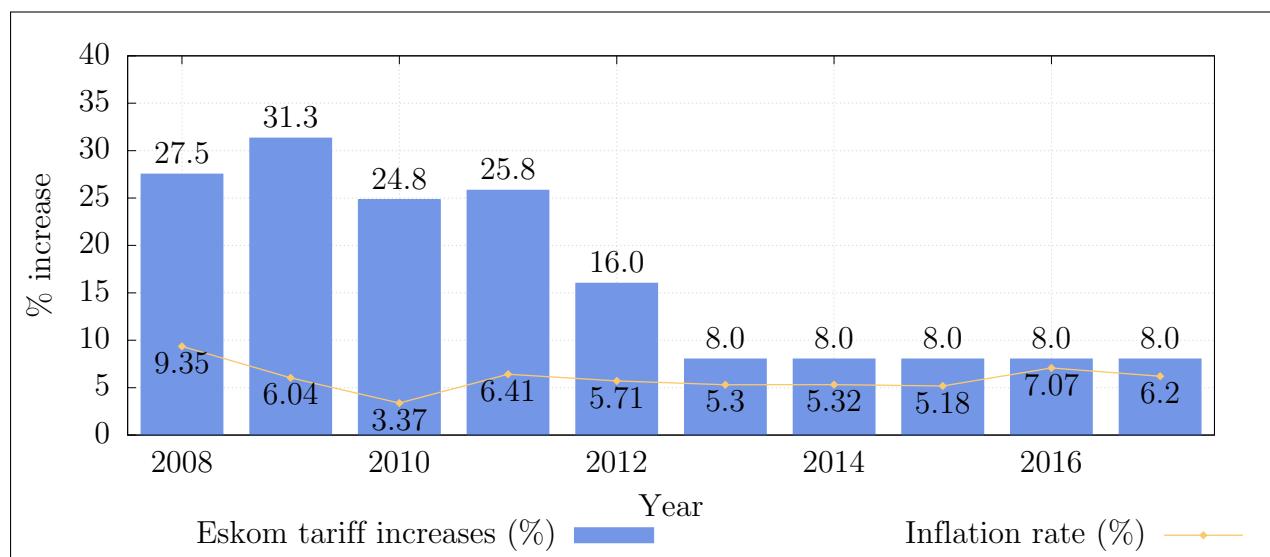


Figure 1.1: Electricity price increases between 2007 and 2017 [2] compared to the inflation rate in South Africa.<sup>1</sup>

In addition to rising electricity costs, gold ore grades of South African mines have fallen

<sup>1</sup>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].

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 than 4000m below the surface [5]. The process of extracting ore at this 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 a safe working temperature 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.

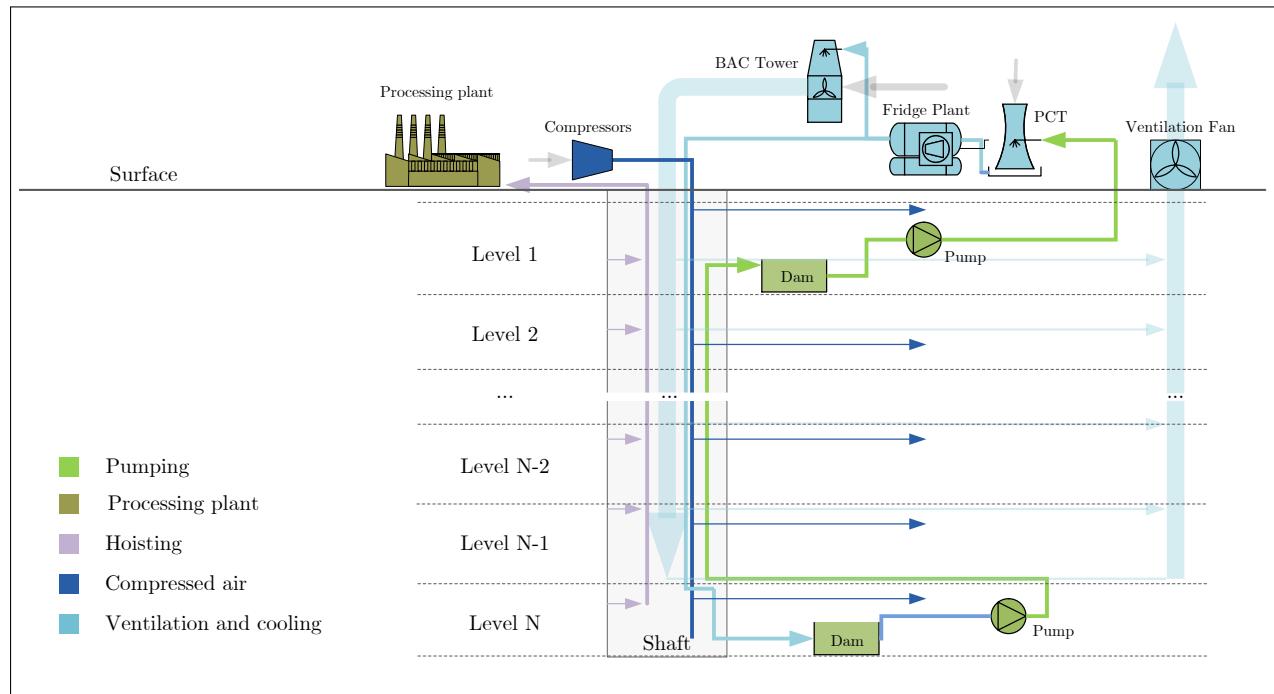


Figure 1.2: A layout showing the mining processes.

### 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.

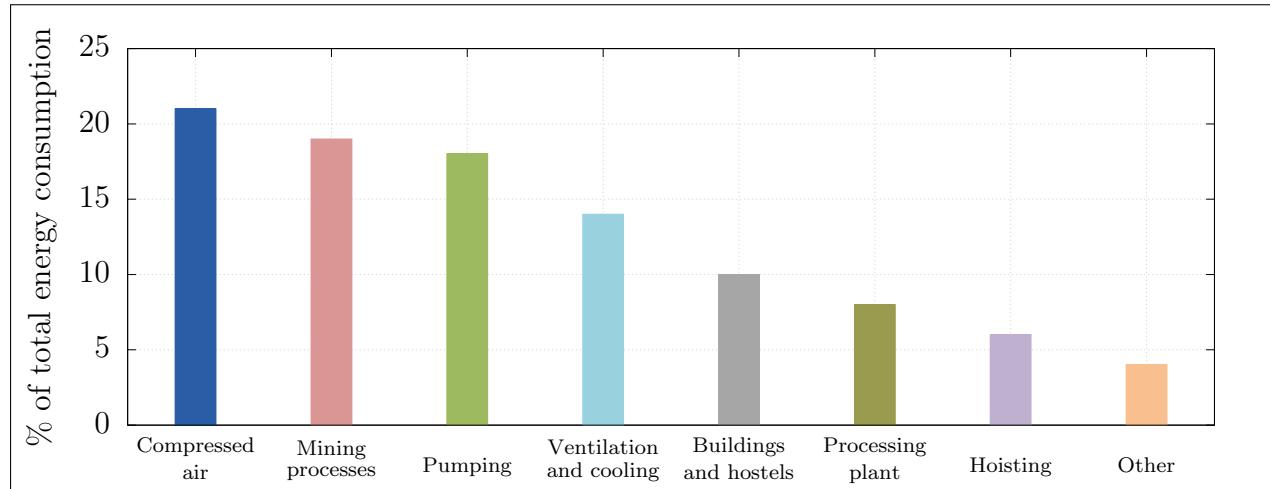


Figure 1.3: The energy consumption for each mining system [7].

## 1.3 Compressed air systems in mining

### 1.3.1 Compressed air in operation

Largely due to their reliability, versatility 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 MegaWatt (*MW*) [8]. \*\*\* compress process inefficient \*\* 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  $1.42 \text{ l/s}$  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 when extracting metal from the ore that is obtained from the mining operation. These plants use 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 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.

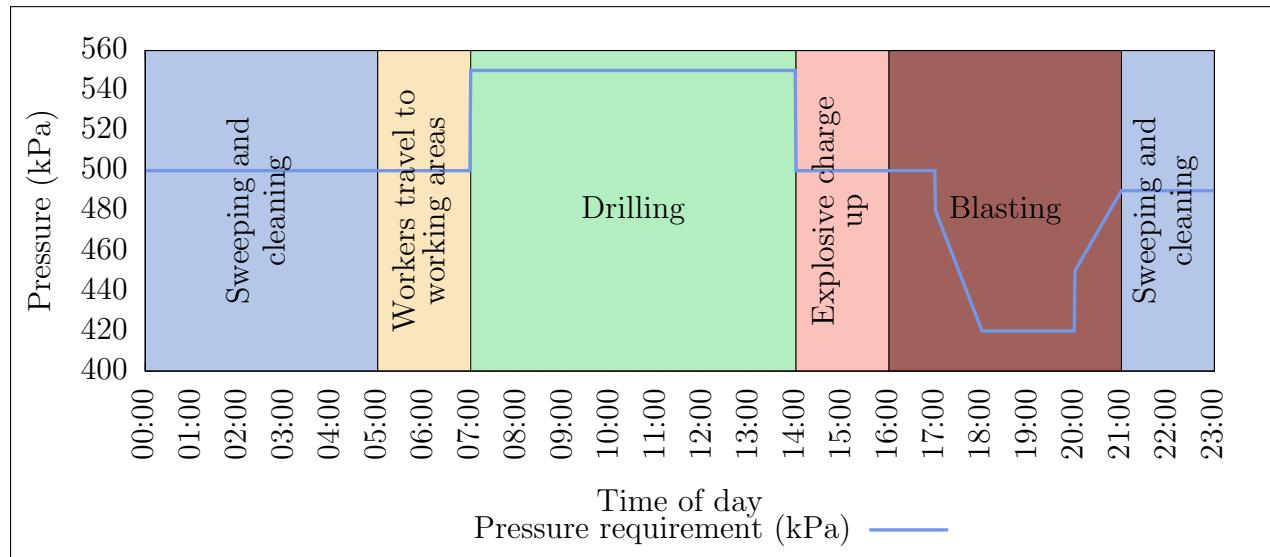


Figure 1.5: The typical operation schedule of a deep level mine [17].

### 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 too much data to model the systems accurately [CitationNeeded]. New tools such the Simulation Toolbox (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 modelling and simulation of compressed air systems can be used to quantify and prioritize 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 identification of more effective energy savings measures for mines.

### **1.5.2 Research objectives**

The main objective of this dissertation is to obtain energy savings through the identification of operational improvements in mining compressed air systems. A simulation process 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

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## 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 (instrumentation 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]

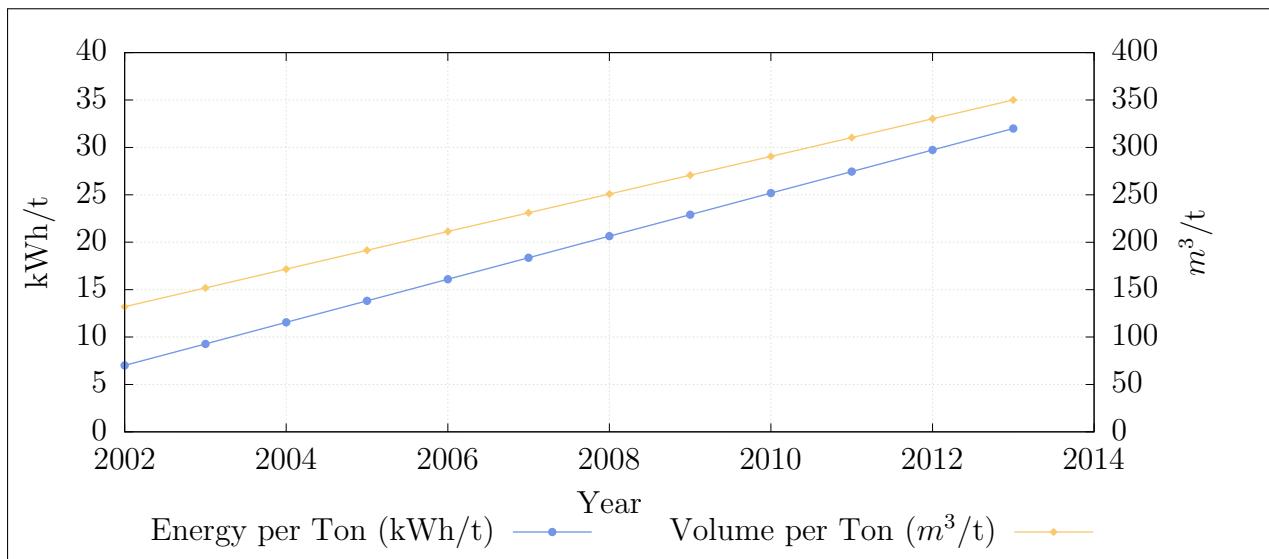


Figure 2.1: The Compressed air energy and flow consumed per T of ore produced. Adopted from Bester *et al.* [25].

### 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

Variable Speed Drives (VSDs) (or Variable Frequency Drives (VFDs))

-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

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## Developing a simulation methodology

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*'Great Design is iteration of good design.'* - Dr M. Cobanli

## 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 divided into three steps as shown in the flow diagram, Figure 3.1. 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. In the final step, scenarios are tested using simulations and the results are quantified and prioritised. After the process has been reviewed, a simulation report is then produced and passed to the mine.

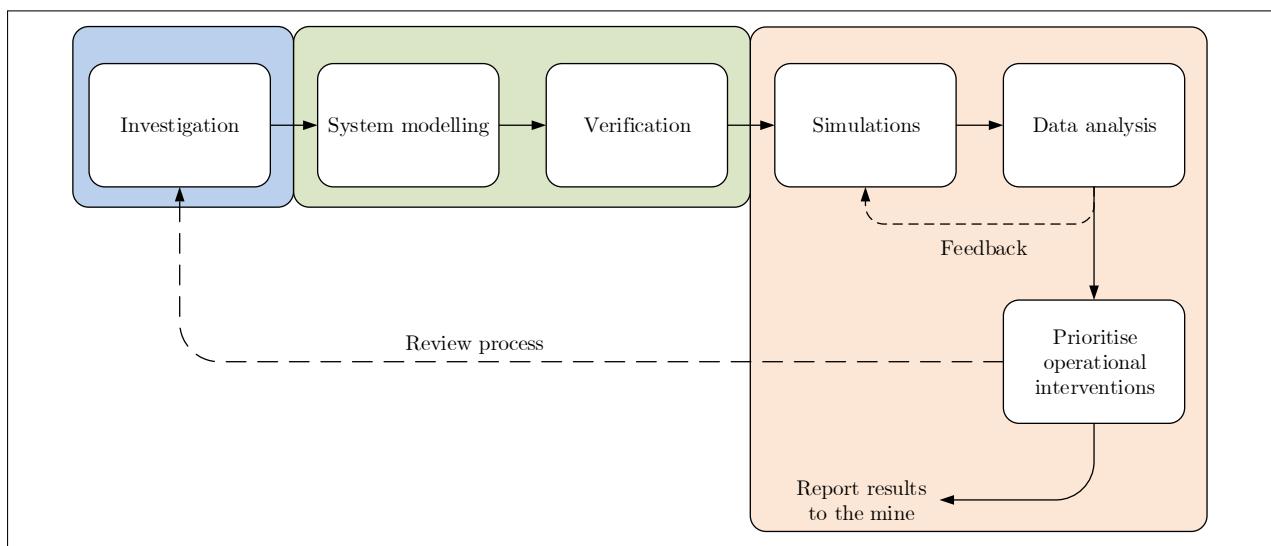


Figure 3.1: Flow diagram of the methodology for this study.

## 3.2 Investigate the system

### 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 Acquire 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 require 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.

A baseline period that best represents the typical operation of the mine. Additionally, availability of data should be considered. The length of the baseline period is selected based on the scenarios that are to be tested, this can be changed later. For calibrating a compressed air system a 24 hours period of normal operation is usually sufficient. A longer period may be needed to verify the model. Next data

### 3.2.3 Investigate mining schedules

A critical aspect to developing an accurate model of a mining compressed air system is apprehension of 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 Verify data accuracy

Data verification is the process where data is evaluated to ensure accuracy. It is important to verify data that is used for model development as an accurate representation of the operation

of a system can only be achieved utilising data of high quality [26]. The factors that influence a data-set's quality, accuracy and integrity summarised as follows:

- Conversion of measurement value [27]
- Storage and collection of the system [28],[29]
- Traceability of measurement sources [29]
- Measurement equipment accuracy and malfunctions [26]
- Data abnormalities [26]

Therefore a data verification methodology is utilised to ensure datasets are of high quality.

### **3.2.5 Resolve 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 Develop and verify a simulation model

### 3.3.1 Preamble

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

### 3.3.2 Select the system boundaries and simulation parameters

The simulation boundaries determine the detail that the system is modelled. For a simple compressed air model, the boundaries can be set around the compressor house. This model would then only include the compressor components, inlet and outlet airflows. Alternatively a more complex model can be developed by choosing boundaries to include more aspects of the system such as mining levels, processing plants etc.

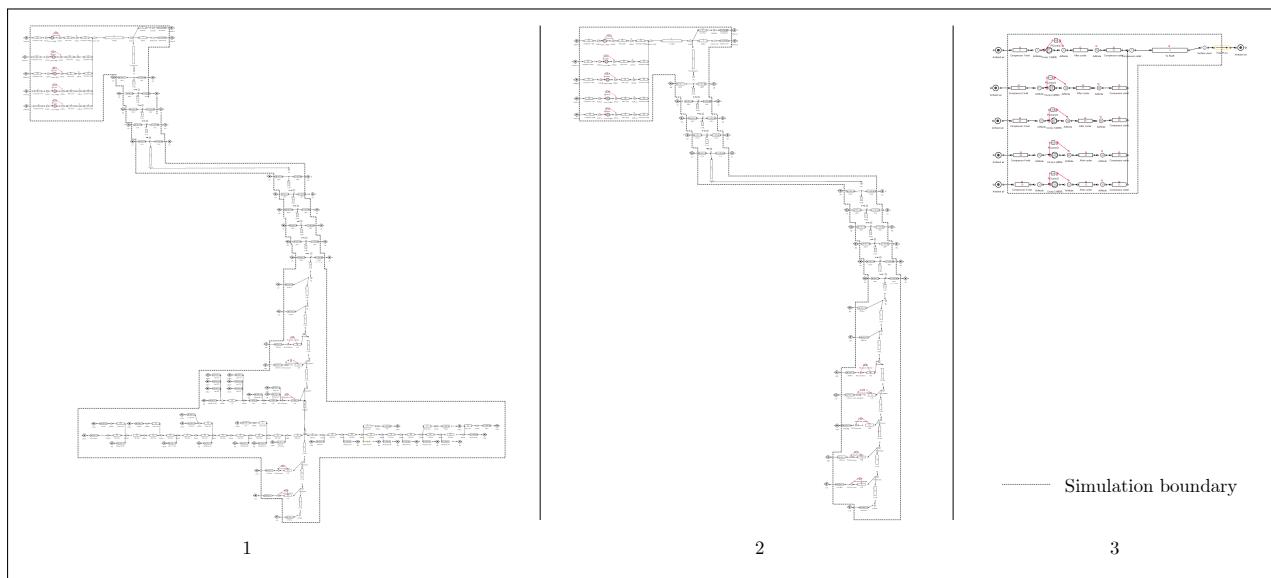


Figure 3.2: Model boundary selection examples.

The boundaries should be chosen based on the input data available, required accuracy n and available time and resources. A more detailed model will lead to more accurate simulation, however it may take more time and resources to obtain the data required. Figure ?? shows an example of different boundary selection for the same system.

The period and step size selected for the simulation is just as important. The period of the simulation should be determined to ensure a scenario is fully tested. Most commonly, a 24 hour period is chosen as daily parameters are normally very similar. The simulation step size should be selected with the resolution of the available data in mind. Smaller step size

selection can lead to a more accurate simulation model.

### 3.3.3 Model compressed air network component

#### 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*<sup>1</sup>:

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

Where the pressure difference  $\Delta P$  is a function of:

Parameter	Definition
$f$	Friction coefficient
$L$	Pipe length (m)
$D$	Pipe diameter (m)
$\rho$	Air density (kg/m <sup>3</sup> )
$V$	Average velocity (m/s)

Table 3.1: Air pipe component model parameters.

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 3.3.3 *Controllers*.

#### Ambient conditions

Ambient air condition underground and on surface change the characteristics of the air, effecting the operation of the system. Figure 3.3 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:

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

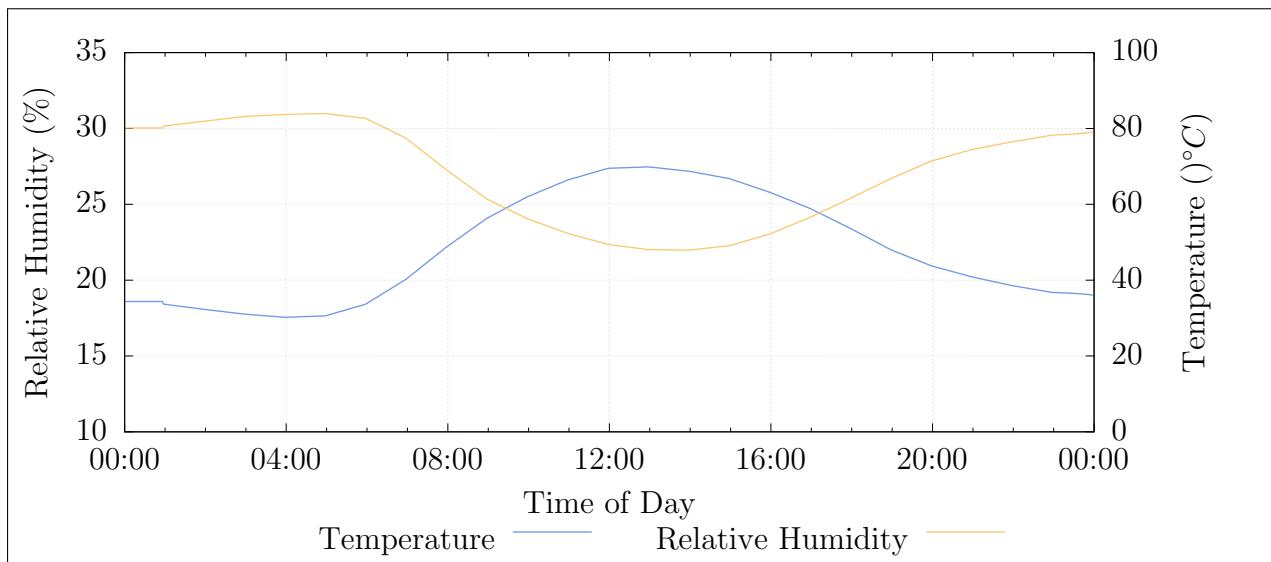


Figure 3.3: Average summer ambient air conditions at a South African gold mine.

- Air compressor
- Dynamic compressor
- Positive displacement compressor

The air 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 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 than 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 3.4 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.

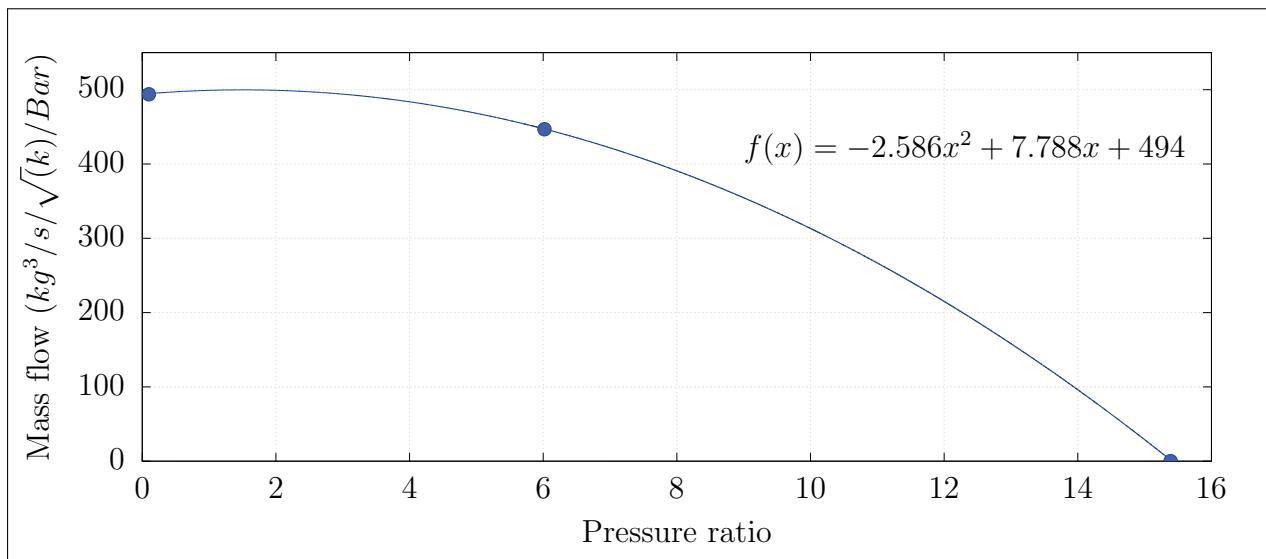


Figure 3.4: Estimating the characteristic curve of a compressor by fitting a quadratic function to points of operation.

Once the models are accurately calibrated, the compressor component is integrated to the air network in the arrangement shown in figure 3.5. 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 to allow the inlet and outlet parameters and conditions to be monitored and controlled.

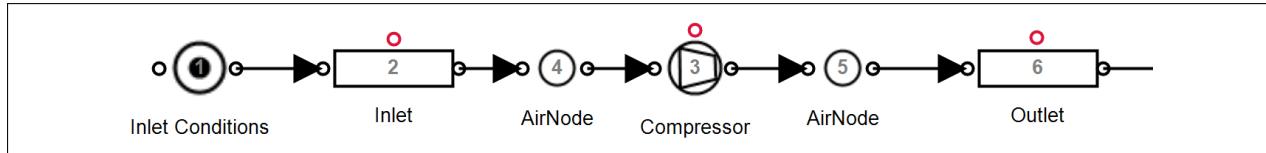


Figure 3.5: Integrating the compressor component into the simulation.

### 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 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 3.6 shows how a calibrated air demand or leak is integrated into the simulation.

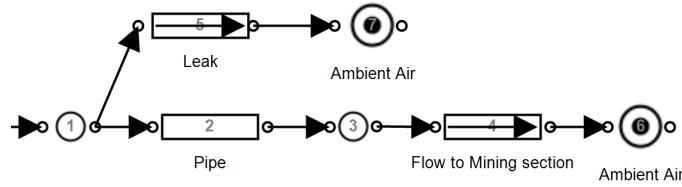


Figure 3.6: Implementing flow demands and leaks into the simulation.

### 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 VSDs (or VFDs) and guide-vain control. VFDs provides a wide range of power control and can be estimated using a Proportional-Integral (PI) controller as in figure 3.7 where discharge pressure is used as feedback for the controller. Guide vains are most commonly used in mining to control

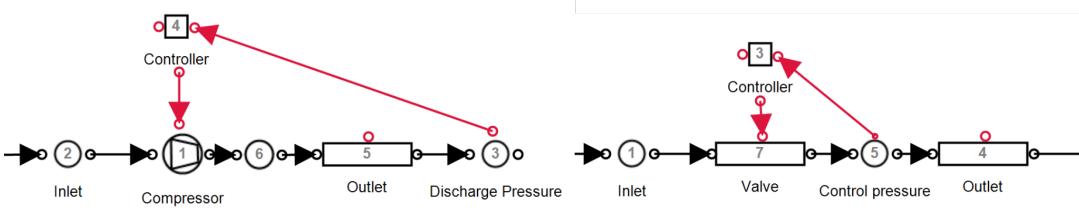


Figure 3.7: Control components in PTB.

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 affect the power the compressor inputs into the system. Figure 3.8 shows the relationship between power and guide vain position. This can be modelled as a linear function where a guide vain position of 40% relates 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.

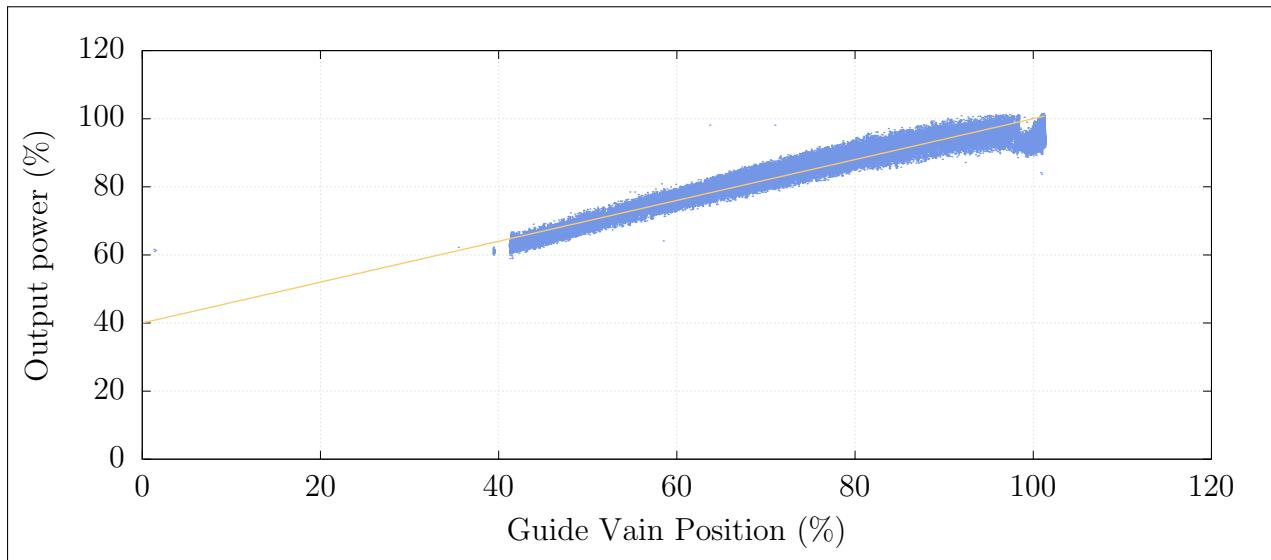


Figure 3.8: Modeling the compressor control from a guide vain

A guide vain controller is modelled using a PI controller component. However, the limitations of guide vain control, as represented in figure 3.8, 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 3.8 would have a minimum control output of approximately 60%.

Mines utilize control valves at underground sections to control the pressure at individual mining stations independently [30]. Controlling of valve components is performed similarly as control of the compressor components. As shown in figure 3.7 the outlet pressure is used as feedback for a pi controller. The controller output is mapped to the valve fraction of a pipe component.



Figure 3.9: An example of a compressed air control valve[31].

Parameter	Definition	Unit
$A$	The heat transfer area	$m^2$
$UA$	Heat transfer coefficient	$kW/\text{°}C$
$T_{amb}$	Ambient air temperature	$\text{°}C$

Table 3.2: The input parameters for the after-cooling simulation model .

### 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, 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 out of the compressors. This cooling can have an effect on the operation 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. The heat transfer parameters shown in Table 3.2 should be calibrated such that the air temperature matches after-cooled air temperature measurements. An assumption of 40 °Celcius can be used if no measurements are available.

Depending on the accuracy requirement, after-cooling can be excluded from the simulation. Post aftercooling, compressed air is normally still warmer then ambient conditions. Air temperatures underground can be accurately matched by including heat transfer for compressed air pipelines.

#### 3.3.4 Verify simulation model

- Steps to validate the model accuracy - Compare parameters to actuals
- First principles - Comparison to other models

#### 3.3.5 Select 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:

- Surface ambient conditions
- Machine operation schedules
- Air demands

- Operational changes

Changing the simulation baseline period for a calibrated simulation should only require the updating of the input parameters. Figure 3.10 shows an example of a changing compressor schedule where an input parameter would need to be updated in the simulation.

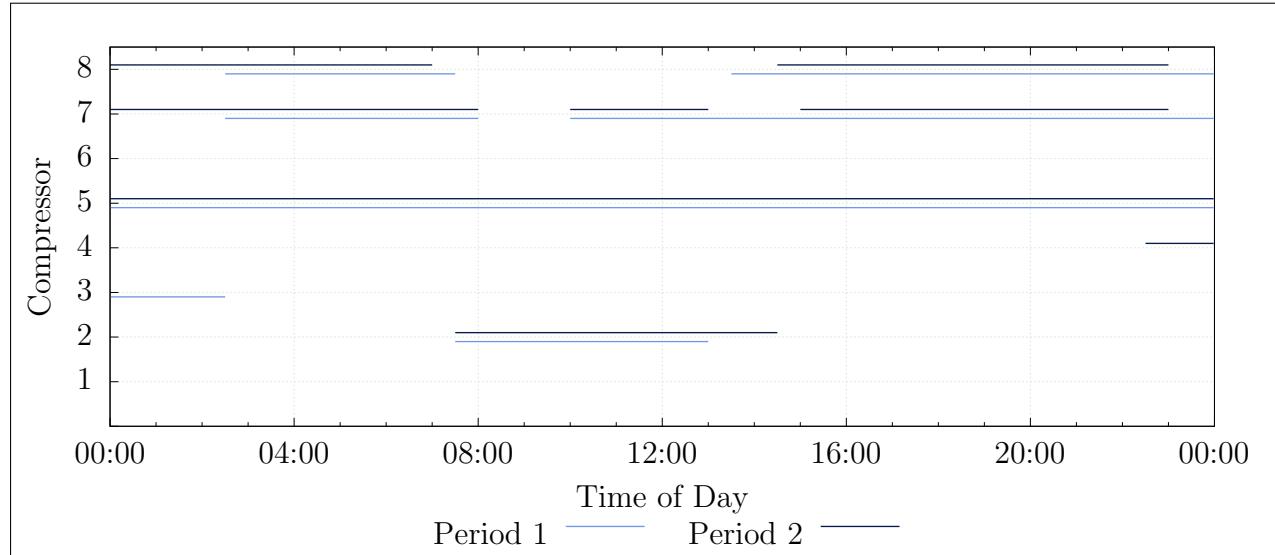


Figure 3.10: An example of two baseline periods, showing a changed compressor schedule.

### 3.3.6 Periodic simulation

Period simulation refers to the repetition of simulations over subsequent periods to determine the sequential accuracy of the model. This is important to verify the model is valid in general and not just a single period. This simulation will also indicate where operation changes have occurred as the simulation accuracy will be reduced.

The following process is followed to implement periodic simulation: Simulation input data is collected periodically for each simulation interval, this data includes only inputs that vary day to day such as schedules, air conditions and measured flows. Once the input values are collected, they are then imported into the compressed air model. The simulation performed and the output data is exported for analysis. The simulated data is then compared with the actual operation of the system and major discrepancies are identified. This process is triggered periodically.

### 3.3.7 Summary

*Unfinished*

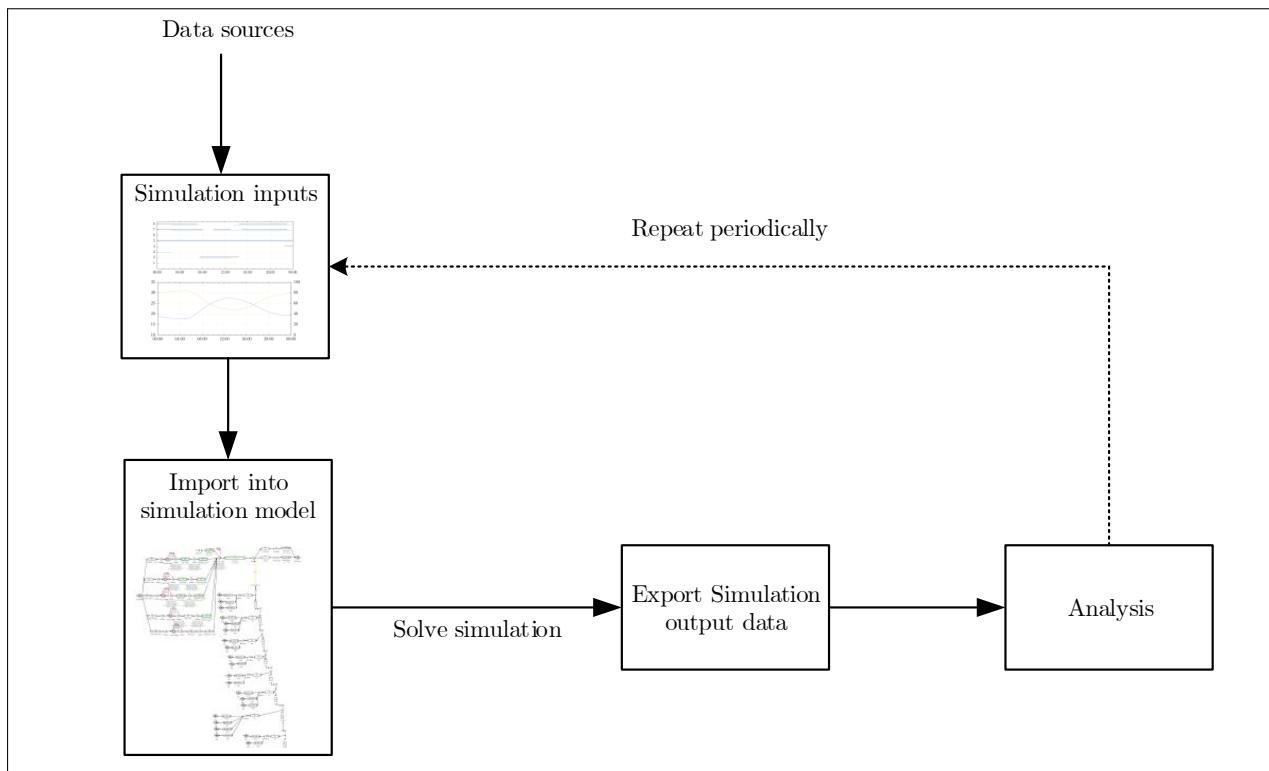


Figure 3.11: The periodic simulation process that was followed in this analysis.

## 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 implementing the simulation methodology, and analysis of interventions will be discussed.

### 3.4.2 Analyse data

- Baseline vs Optimised analysis
- identification of further improvements

*Unfinished*

### 3.4.3 Quantify operational improvements

- Estimating cost savings
- Reporting feedback to the mine

*Unfinished*

### 3.4.4 Summary

## 3.5 Conclusion

# CHAPTER 4

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## Results and validation

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*'Not everything that can be counted counts, and not everything that counts can be counted.'* -  
Albert Einstein

## 4.1 Introduction

This section will validate the simulation methodology through case studies. Mining compressed air systems were chosen as case studies based on the availability of data and the scope for energy and operational improvement. Two different mines were selected for the studies.

Three case studies were performed. In case study 1 and 2, improvements were simulated on mine A and mine B respectively. In Case study 3 periodic simulation analysis is implemented using the simulation developed for case study 2. From the results in the case studies, the potential benefits compressed air simulations for the South Africa mining industry is estimated and discussed.

## 4.2 Case study 1. Simulated improvements on mine A

### 4.2.1 System investigation

Mine A represents a group of three gold mining shafts and a gold processing plant in the Free state province. The mine shafts and gold plant share a compressed network. Prior to this study, efforts had been made to optimise the system through Demand Side Management (DSM) energy projects. However, there may still be potential for further optimisation. An investigation was performed to gather data and understanding of the system and to identify potential energy and operation improvement strategies.

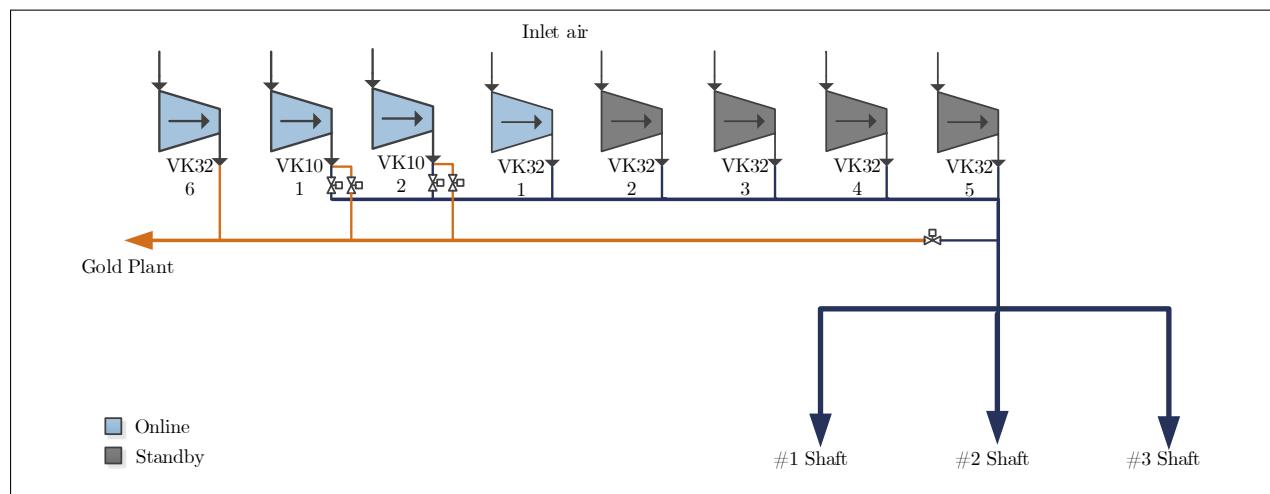


Figure 4.1: Simplified process flow chart of the compressed air network.

An air flow distribution layout was developed for the system, a simplified layout is shown in Figure 4.1. From this along with information from the mine personal and data, an understanding of the air network's operation was obtained. The system typically utilises 5 MW of power. During the drilling shift the demand increases to 6 MW. Figure 4.2 show

the average weekday power profile between January and May 2016.

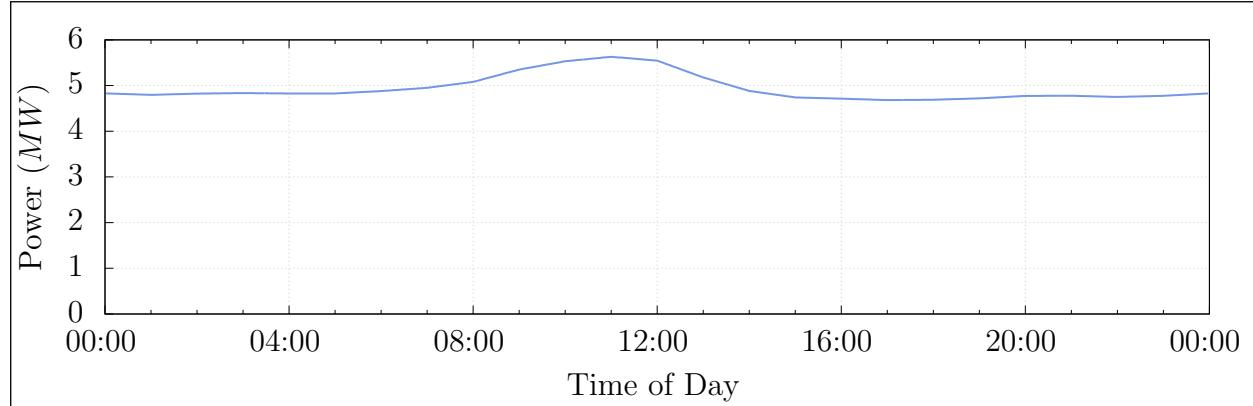


Figure 4.2: Average power profile

Seven compressors are available in the system. Five large compressors (VK32) rated at 2.9 *MW* each and two smaller compressors (VK10) with a power rating of 1.1 *MW* each. No more than 4 compressors are required at any time, the other compressors are therefore on standby. Air is supplied to the sections in three mining shafts as well as a gold processing plant on the surface.

The mine normally operates the compressors with a constant pressure set-point of 500 kilopascals. The set-point is kept this high as the gold processing plant requires constant high pressure throughout the day. This makes it difficult to reduce the set-points of the compressor. It is possible to control the air supply pressure to the gold plant independently from the rest of the network. This is performed by controlling the surface valves.

The evening Eskom energy peak time was identified as a period where savings could be obtained. During this time, air is not required underground as blasting is scheduled. Due to the energy tariff structure, interventions during the energy peak also maximises the financial benefit for the mine. Compressor set-point control and underground valve control were identified as strategies to achieve these savings. Due to the risk of loss of production, the mine would not allow practically testing the scenario on the actual system. Simulation was therefore required to accurately calculate and analyse the benefits of the compressor set points. A model was developed to test these scenarios.

#### 4.2.2 Model development

With the data and understanding of the gathered from the investigation, a model was developed using the PTB tool and the methodology discussed in Chapter 3. First, the

simulation boundary was selected to include the measured flows to each level underground, as well as the surface processing plant. For highest accuracy, the simulation step size was set to 30 minutes to match the available data resolution.

The simulation component models were developed and calibrated using the respective methods discussed in chapter 3. The following assumptions were made to simplify the model development:

- The effect of compressed air after-cooling is negligible
- Heat transfer over the pipe length is negligible
- Underground temperature and humidity remained constant for each level
- Surface ambient air conditions followed normal summer trend

The model components was calibrated so that the simulated outputs matched data from the real system. The process flow diagram for the simulation is shown in Figure II.1. The model data inputs and outputs are described in Table 4.1.

Inputs	Outputs
Level measured flows	Compressor powers
Compressor schedules	Network flows
Compressor set-points	Network pressures
Underground valve set-points	

Table 4.1: Data inputs and outputs for the Case study 1 simulation model

### 4.2.3 Verification of model

Verification was performed to ensure that simulated output accuracy was > 95%. Figure 4.3, 4.3 and 4.5 show the to total simulated power ,flow and outlet pressure of the compressors compared to the system. The average accuracy for the power and total flow was 97.34% and 97.01% Respectively . Both these parameters were well within the target 95% accuracy. The accuracy of the outlet pressure was 99.1%. This was expected simulated pressure was expected as the mine uses a constant pressure set-point for the compressors.

Accuracy of the model was checked in more detail to ensure that each modelled parameter matched the actual measurement with high accuracy. Table III.1 shows the accuracy each measured simulation output in the model.

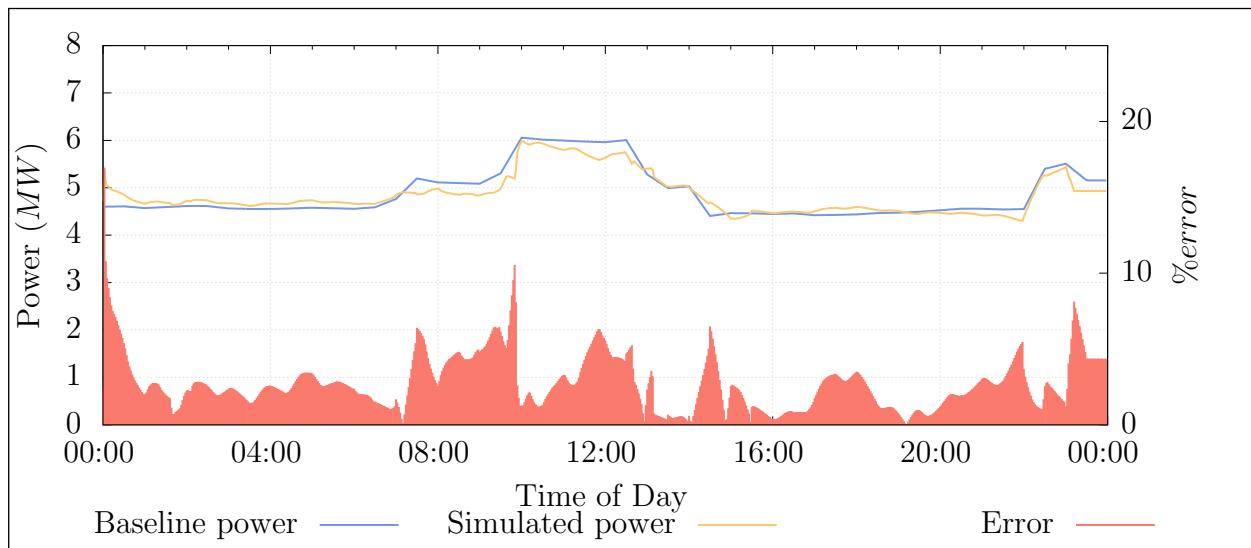


Figure 4.3: The simulated power compared to the actual measurement

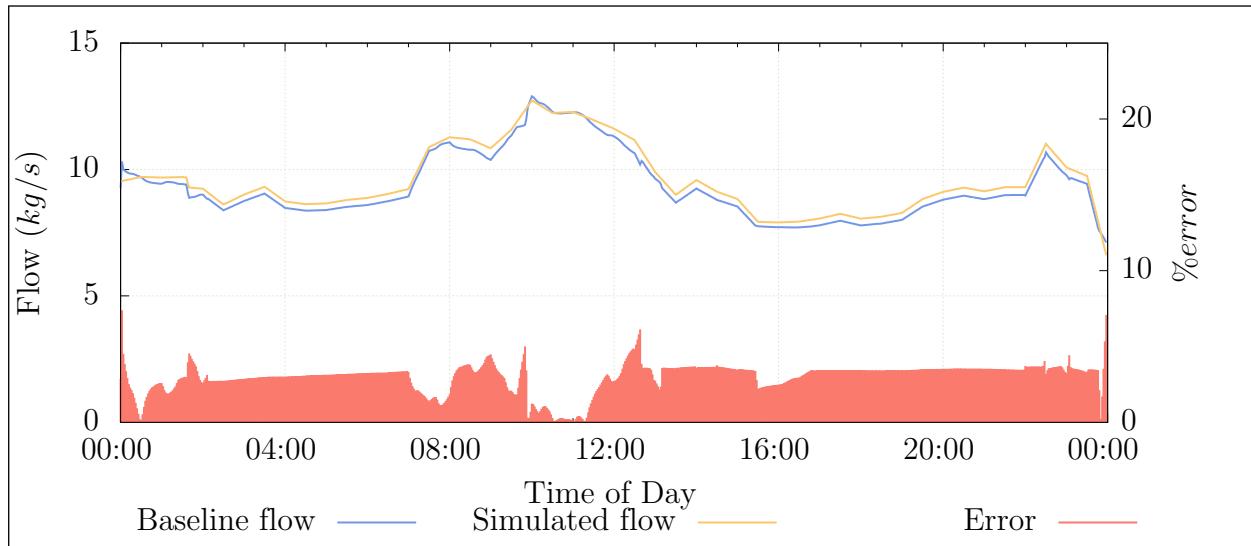


Figure 4.4: The simulated flow compared to the actual measurement

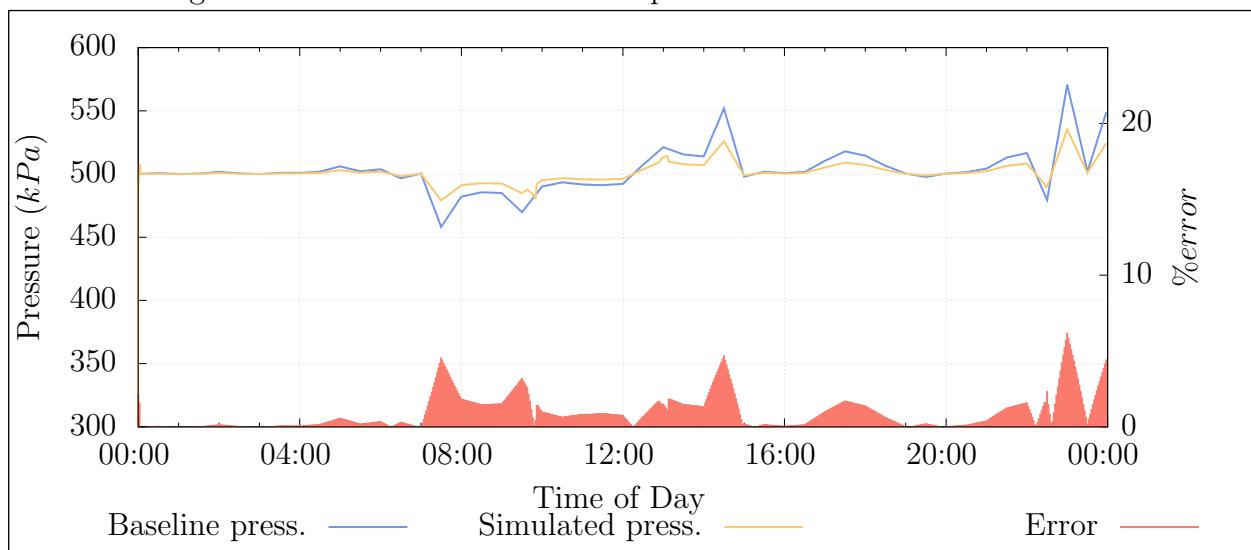


Figure 4.5: The simulated Pressure compared to the actual measurement

#### 4.2.4 Scenario 1. Compressor set points

The Eskom evening peak tariff time occurs during the blasting shift. During this shift, the pressure requirements underground are lower than the rest of the day. Reducing pressure in the network reduces power as less work is required from the compressors. Additionally, losses caused by leaks, open valves, etc. are reduced. However, lowering the pressure set-point of the compressors requires independently controlling the air to the gold plant.

Using the verified simulation model, the compressor set-points were reduced to 420 kilopascals, the minimum allowed compressor set-point during the drilling shift. The compressor schedule was changed to allow independent control of the gold plant pressure. Gold plant pressure was maintained at 490 kilopascals.

The results of the simulation, shown, in Figure 4.6, indicated an average power reduction of 0.46 MW Peak-clip (P.C.). This energy optimisation relates to a R0.37 M Per annum (p.a) energy cost saving to the mine.

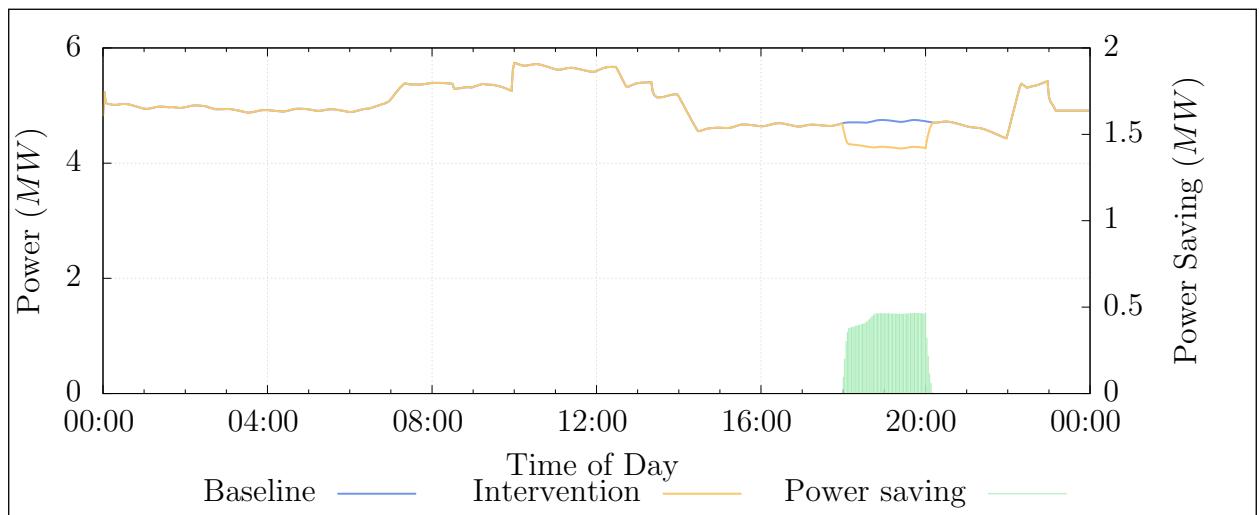


Figure 4.6: Energy savings by reducing compressor set-points

#### 4.2.5 Scenario 2. Control valves set points

An alternative scenario is to reduce the pressure at the control valves at each level. By reducing pressure at the control, set-points can be lowered to the minimum requirement per level. This can lead to higher savings than could be achieved through compressor set-points. This scenario would be relatively easy to implement as it does not require any changes to the compressor control schedule.

Air pressure set-points were reduced to 300 kPa at the underground control valves during the

evening peak period. Analysis of the simulation results showed a 1MW average P.C. saving. The intervention would lead to an annual cost saving of R0.91M.

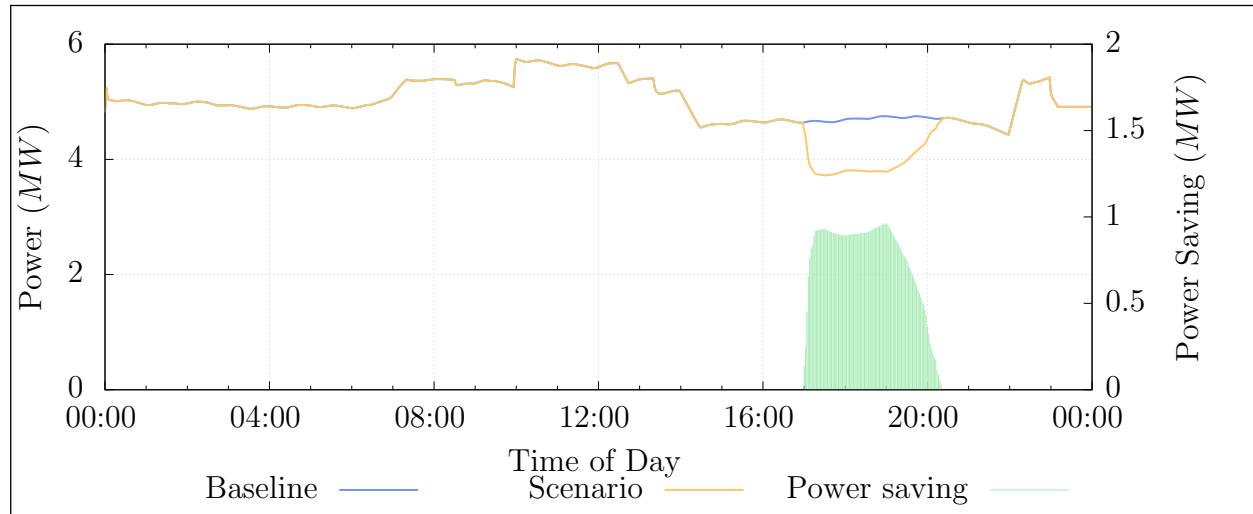


Figure 4.7: Power savings

#### 4.2.6 Comparison of scenario results

Comparing the scenarios in Table 4.2 showed that Scenario 2 had a larger peak energy impact than scenario 1. Further savings could be achieved through a combination of the two scenarios as well as investigating set-point reductions during other periods of the day.

Scenario	Power saving	Cost saving p.a
<b>Scenario 1 results</b>		
Reducing compressor set-points	0.46 MW P.C.	R0.37M
<b>Scenario 2 results</b>		
Reducing underground pressure during evening peak	1.0 MW P.C.	R0.91M

Table 4.2: Comparison of Mine A's simulated scenarios

#### 4.2.7 Validation of results

Scenario 2 was implemented on the actual compressed air system. An energy saving of just under 1 MW P.C. was recorded when compared with the 2016 power baseline profile. These results matched the simulated scenario closely. Figure 4.8 shows the practical result compared with the simulated and baseline power profiles.

#### 4.2.8 Summary

A case study was implemented mine compressed air network in the Freestate. Following the simulation methodology, An investigation was performed to gather data and identify potential interventions. A simulation model was developed to test scenarios. The tested

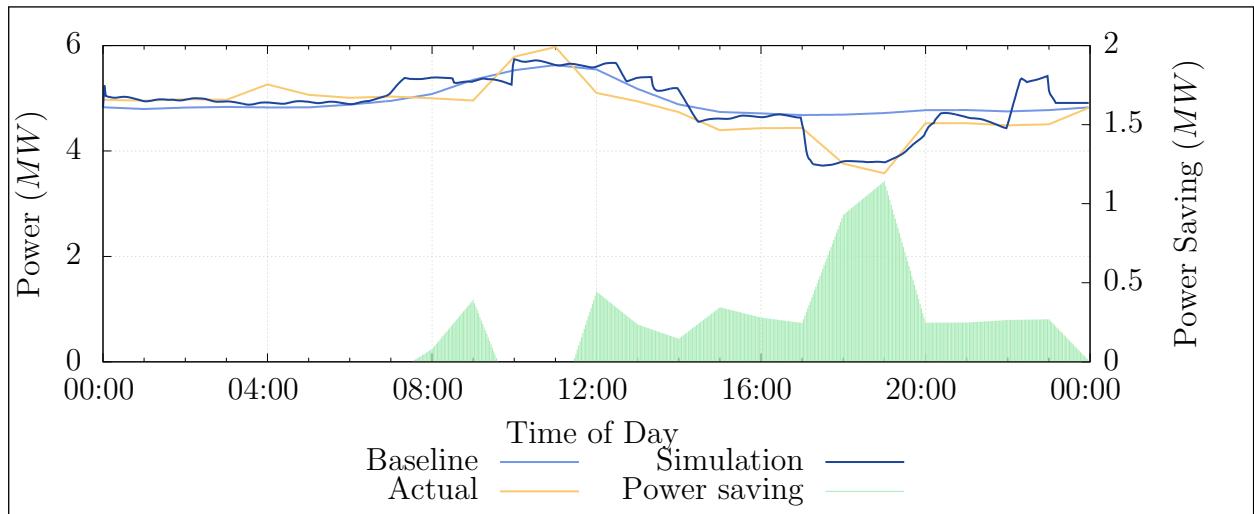


Figure 4.8: Actual power savings achieved on the system

interventions showed a P.C. saving of 1 MW which would result in a cost saving of R0.9M. The simulated was validated by implementation on the actual system leading to similar results.

## 4.3 Case study 2: Simulated improvements on mine B

### 4.3.1 System investigation

Case study B is large South African gold mine. The mine utilises five compressors supply compressed air to various surface and underground operations. An investigation was performed to gather the data and information required to build a simulation model of the network. As well as to identify potential simulation scenarios.

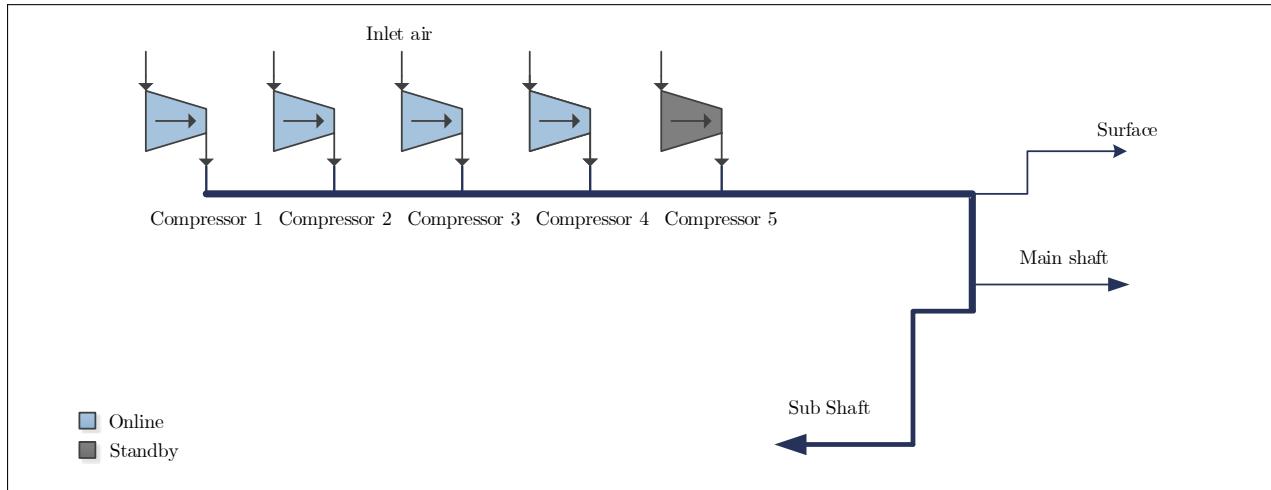


Figure 4.9: Basic layout of the compressed air network.

A basic air distribution layout was developed for the system. Figure II.?? illustrates the system in detail, indicating instrumentation, meters as well as normal airflow splits to various sections and levels of the mine.

Data related to the mines scheduling as well as critical limits and set-points of the compressed air system was obtained from various mine personnel. From this a general understanding of the operation was obtained. Important data parameters such as Power, pressures and flows of the system were gathered from the SCADA as well other data measurement sources. This data will be used to develop and calibrate the simulation model

Per-level investigations were performed on the significant mining levels to map and measure the locations and air usage for the cross-sections, refuge bays, major leaks and other compressed air consumers on each level. An example of a resultant schematic from the underground investigation is shown in Figure I.1. The information gathered from the system investigations was then utilised to develop and calibrate a simulation model.

### 4.3.2 Model development

Using the data obtained from the investigations on the network, a simulation model was developed in PTB. The methodology described in Chapter 3 was utilised in this process. . The following assumptions made to simplify the model development:

- After cooling reduced compressed air temperature from  $60^{\circ}$  Celcius to  $40^{\circ}$  Celcius
- Underground temperature and humidity remained constant for each level

The boundaries of the baseline simulation were selected based on the available data for the network. The developed simulation model is shown in Figure II.2. For maximum accuracy, the simulation step size was set to the two minutes intervals to match the resolution from the data source. The model components was calibrated so that the simulated outputs matched data from the real system. The process flow diagram for the simulation is shown in Figure II.2. The model data inputs and outputs are described in Table 4.1.

Inputs	Outputs
Level measured flows	Compressor powers
Compressor schedules	Network flows
Set-points	Network pressures

Table 4.3: Simulation inputs and outputs

#### Verification of baseline simulation

Using the verification methodology, the simulation model verified by comparing the simulation outputs to actual measured values. The compressors outlet pressure often does not match the set-point. To simplify the verification, the measured outlet pressure is temporarily used as set points for the compressors. This ensured that the pressure in the network is identical to that of the actual system as shown in Figure 4.10.

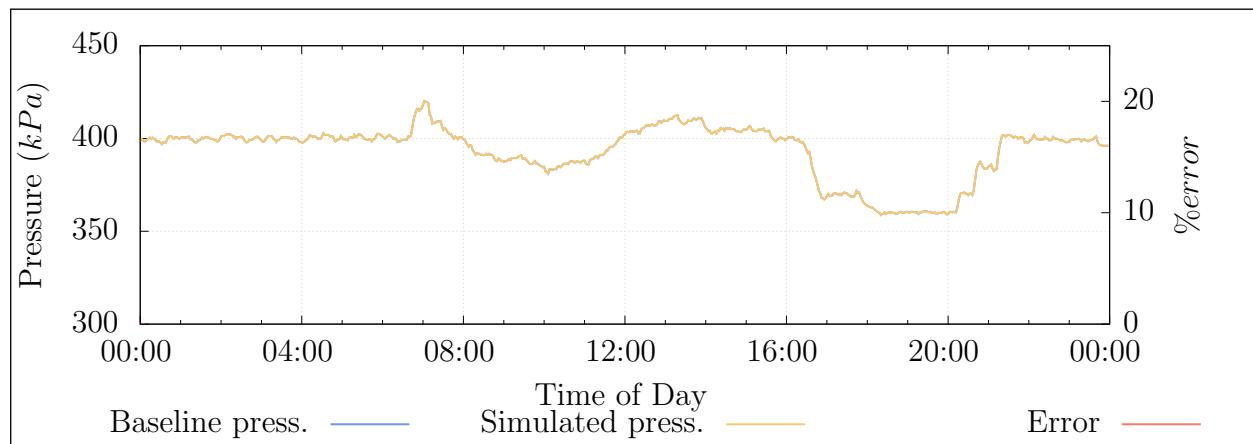


Figure 4.10: Comparing the pressure response of simulation to the actual measured pressure

With the simulated pressure identical to the actual, the power and air flow outputs were

compared with their relative actual values. Figure 4.11 shows the comparison of the total power and flow of the system with the actual measure values for that same period. The accuracy for these parameters compared to the real system was 98.7% and 99.0% respectively. This was within the acceptable error.

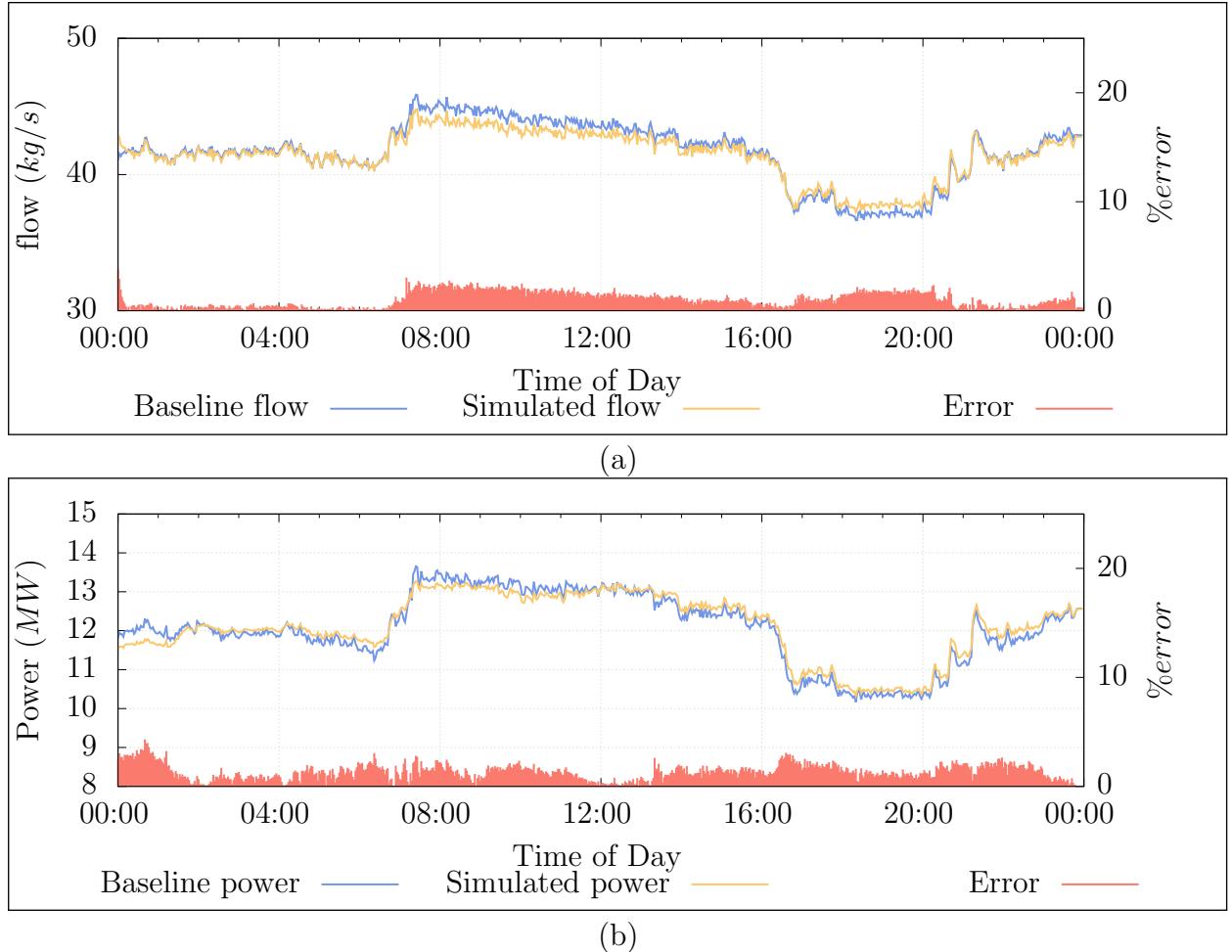


Figure 4.11: Verification of the total (a) flow and (b) power of the system using the actual pressure profile.

Once the power and flow parameters were verified with acceptable error, the actual pressure set-point profile was imported to the compressor controllers. The simulated outlet pressure was then compared to the actual measured pressure and set-point, this is shown in Figure 4.12. The accuracy of the compressor outlet pressure was acceptable at 99.02 %. To ensure the model accuracy, all measured flows and pressures were compared to the simulated outputs. This comparison is shown in Table III.2.

### 4.3.3 Scenario 1. Refuge bay optimisation

From investigation, unnecessary refuge bay leaks were identified as a significant inefficiency that can be reduced. A test on a single mining level was performed to measure the potential flow saving of reducing refuge bay leaks. The test showed that reducing refuge bay leaks, by

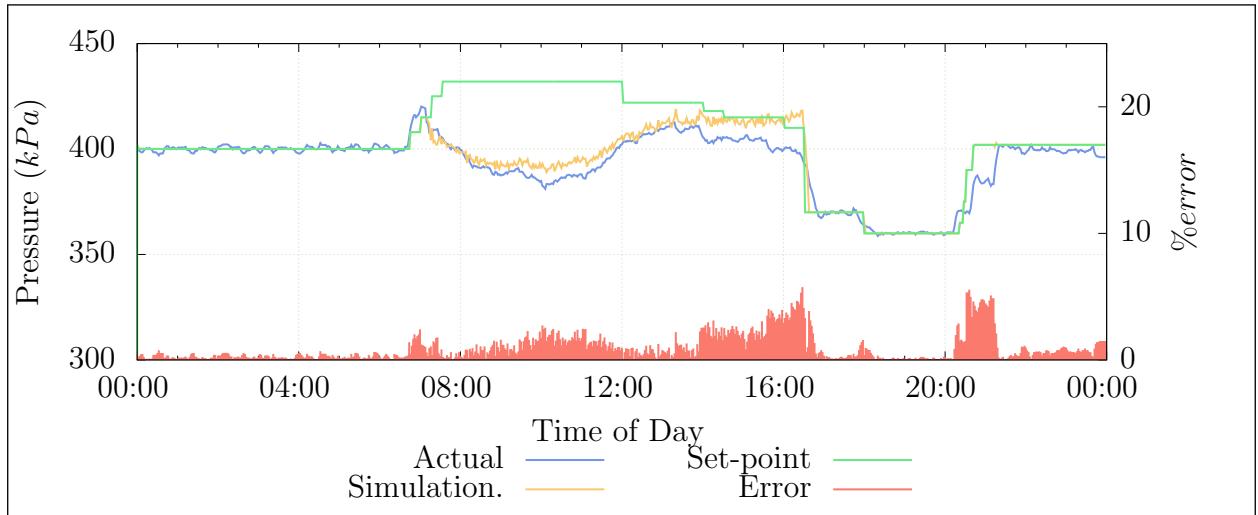


Figure 4.12: Verifying the Pressure response of the system given the pressure set points as inputs

closing the valves, would lead to an average air saving of  $0.05 \text{ kg/s}$  per refuge bay at typical operational pressures. This measurement was conservative as it was not possible to close all the refuge bays on the level for the test.

Due to the size of the mine, extending these tests to include the rest of the mining sections was not practical. Therefore, the benefits of an intervention on the entire mine could not accurately be determined from practical tests. Using simulation the typical operation with can be accurately compare with the intervention scenario to quantify the potential financial and operational benefits throughout a given period.

The simulation model boundaries was updated to include refuge bay leaks on each level. For each refuge chamber, a air leak was added to the model by utilising per level layouts indicating locations of refuge bays. These leaks were modelled as flow demands using the data from the initial refuge bay tests. The overall mass flow of the system was maintained to ensure model accuracy. By adding the flow component in the actual location in the process, the pressure to each chamber is correctly modelled. The full simulation model is shown in Figure II.3. The updated simulation model was re-checked to ensure accuracy. This model was used as a baseline to quantify saving for the scenario.

To create the optimised scenario, the refuge bay flow components were set to  $0 \text{ kg/s}$ . The simulation was performed and the output data compared ot the baseline. Figure 4.13 shows the baseline power compared to the optimised scenario. The comparison showed a potential  $0.92 \text{ MW}$  improvement in Energy efficiency (E.E.) through optimisation of refuge bay leaks. The optimised scenario would lead to a R5.13M energy cost saving for the mine.

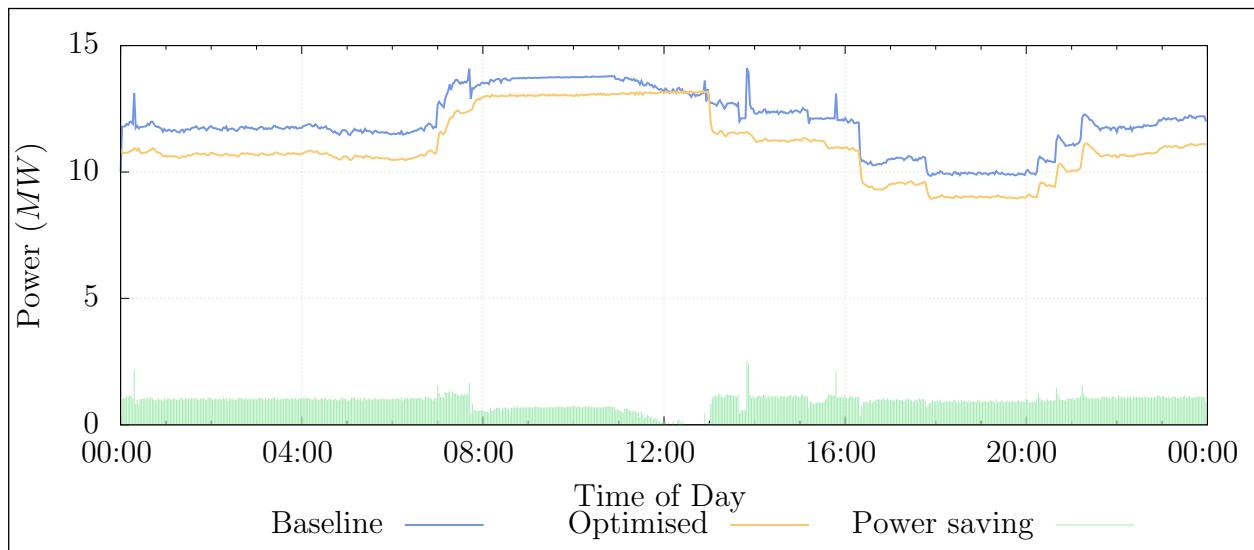


Figure 4.13: The Baseline system power compared to the system power when refuge bay leaks are reduced.

An additional pressure benefit was identified during the drilling shift, shown in Figure 4.14. The reduced flow lead to a pressure increase of about 15 kpa. The pressure increase could lead to an increase in drilling efficiency.

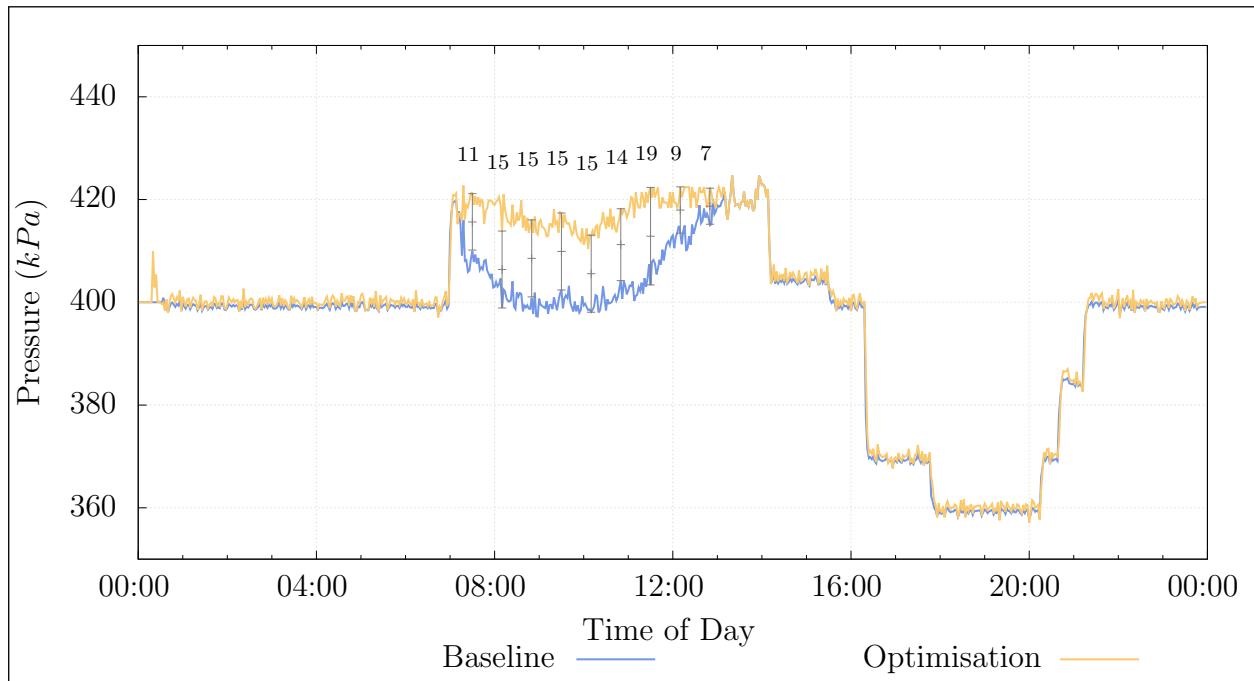


Figure 4.14: The Baseline system pressure compared to the system pressure when refuge bay leaks are reduce.

#### 4.3.4 Scenario 2. Closing off levels and inactive work areas

Due to the high prevalence of compressed air misuse, leaks and open valves, significant amounts of air is still used during periods where it is not required. Reducing pressure to areas during these times may lead to a major power and cost saving. Using simulation, tests can be done to identify the benefits of reducing pressure to inactive mining sections.

Strategies to reduce airflow during peak times was simulated for level 105L. The level was modelled to include all major leaks, refuge bays and drilling sections that were manually identified from the level investigation. This is shown in the simulation diagram shown in Figure 4.15. Station control, in-stope control and a combination were simulated were all

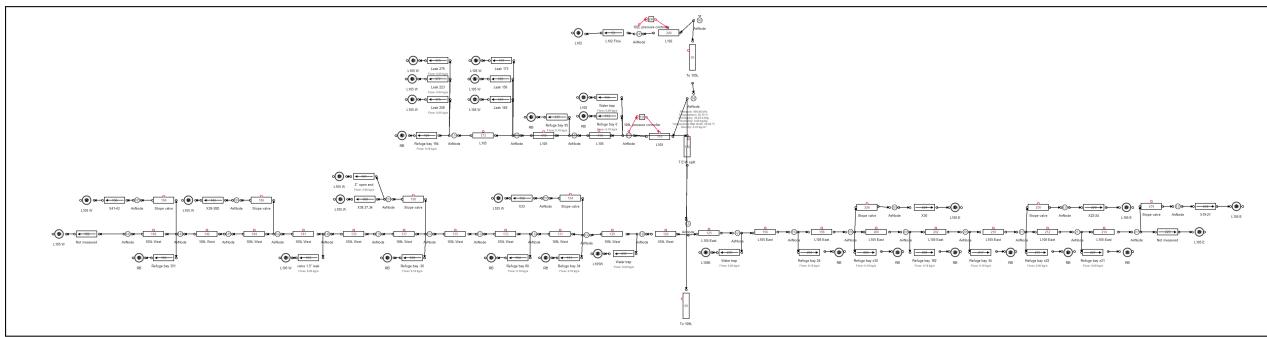


Figure 4.15: Underground level layout.

simulated for 105L. Station control means control of the pressure of at the station of the level. In-stope control is control of the is cut the airflow to the mining section during certain periods. Figure 4.16 shows the effect the varios interventions have on the flow for 105L compared to the baseline.

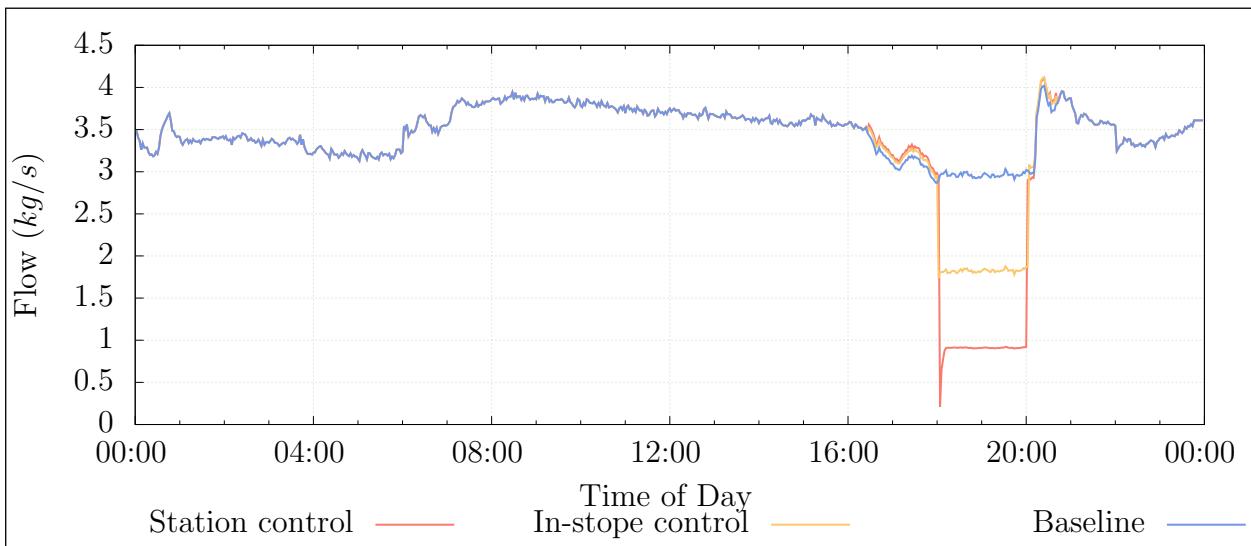


Figure 4.16: Flow reduction during blasting period for 105 level

Station control had the largest impact on the flow usage for the level. This reflects with the

power reduction achieved for each intervention shown in Figure 4.17. The impact was 0.4 and 0.7 MW for the stope and station intervention respectively.

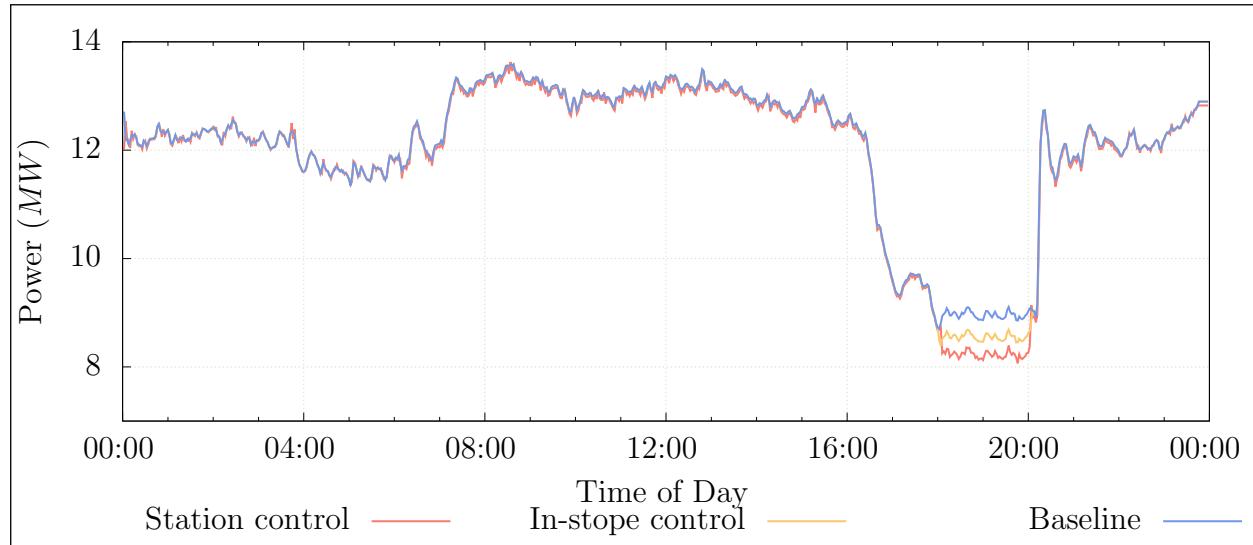


Figure 4.17: Comparing simulated flow interventions on 105L.

A simulation was done to estimate the potential savings of extending the evening station control to other levels. This was performed by updating the flow demands for levels 95- 115 to match the flow saving achieved in the 105L simulation. The savings achieved for the general station control were 2.0 MW P.C., shown in Figure 4.18. It was calculated that this would lead to a annual energy cost saving of R2.5M.

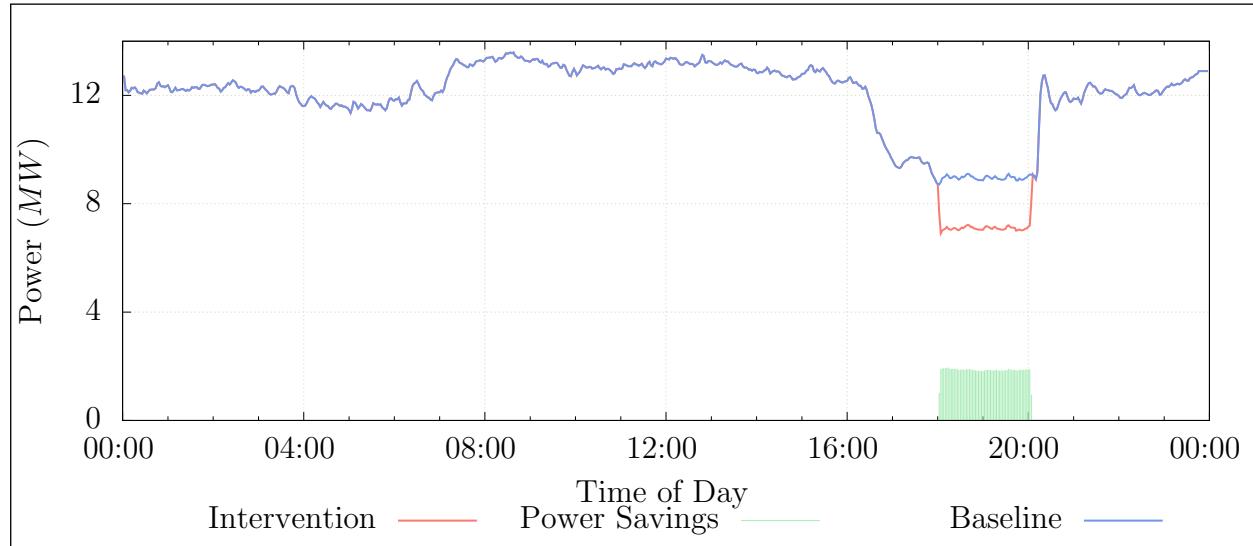


Figure 4.18: Energy saving achieved by general peak time Station control

### 4.3.5 Comparison of interventions

The interventions were then compared for feedback to the mine. The refuge bay intervention is recommended as it will achieve the highest energy cost saving.

Scenario	Power saving	Cost saving (p.a)	Additional benefit
<b>Scenario 1 results</b>			
Refuge bay leakage reduction	0.92 MW E.E.	R5.17M	Increase in drilling pressure
<b>Scenario 2 results</b>			
105L peak time in-Stope control	0.4 MW P.C.	R0.3M	-
105L peak time Station control	0.7 MW P.C.	R2.5M	-
General peak time Station control	2.0 MW P.C.	R2.5M	-

Table 4.4: Comparison of the simulated scenarios

### 4.3.6 Validation of results

- Awaiting results on manual tests -

### 4.3.7 Summary

- Unfinished

## 4.4 Case study C: Periodic simulation analysis

### 4.4.1 Preamble

Updating the inputs of a simulation periodically could be used to verify simulation model accuracy. If the precision of simulation outputs remains for subsequent days, this would indicate that the model is correctly calibrated. Additionally, this process could be used to identify significant operational changes that occur within the system. This would cause the simulation outputs to differ from the actual measured parameters.

A daily periodic simulation analysis was implemented between 2016/11/01 and 2016/11/30 using the periodic simulation methodology discussed in Chapter 3. The simulation model developed for case study A was used for the analysis. The simulation receives the data inputs shown in table 4.5.

Inputs	Outputs
Ambient air conditions	Compressor power
Measured flows	Flows
Compressor schedules	Pressures

Table 4.5: Data inputs and outputs for the simulation

### 4.4.2 Results

The process was triggered daily. For each period, data inputs shown in table 4.5 were imported into the model, the simulation was then processed and the outputs are compared with the real system parameters. Figure 4.19 shows the average daily accuracy of the simulated total system power, flow and the shaft pressure per period.

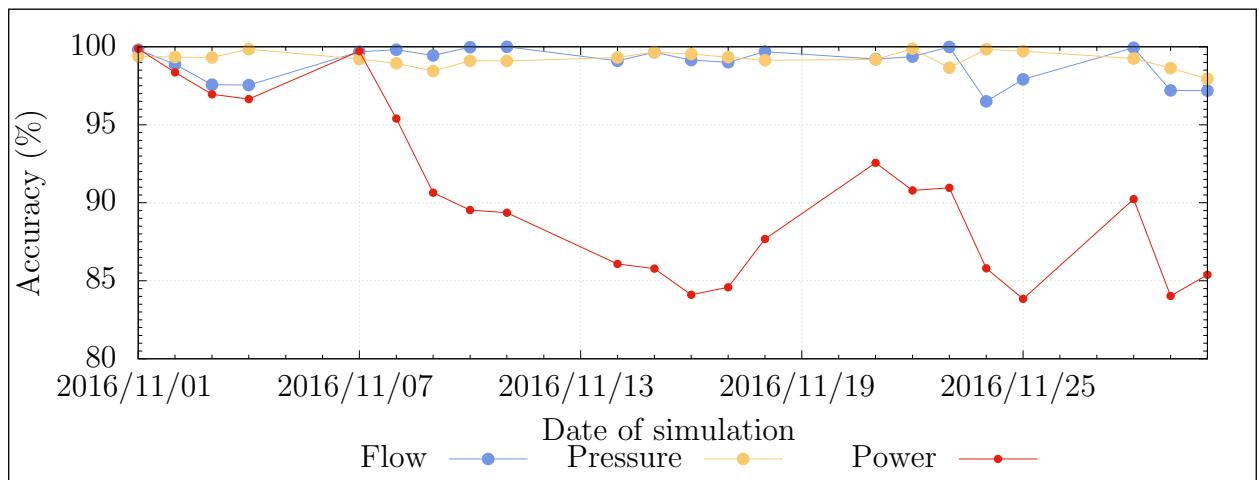


Figure 4.19: The flow, pressure and power error percentages for daily periodic simulations over a month.

The accuracy of the process parameters of the simulation was within 5% for the duration of the periodic simulation. However, From the 2016/11/07, the accuracy of the simulated power dropped by between 10 and 15 percent. The daily average power of the system up to the point was approximately 12.5 MW, a 15% simulation error therefore relates to 1.9 MW difference between simulated and actual parameters. This suggests a major shift in operation of the system.

An analysis was done to try determine the source of the discrepancy. From the data it was identified that the simulated power for compressor 1 was the source of the different A look at the actual power measurement for compressor 1 show drop compared to normal operation by almost 2 MW. At the same time the power used per kg/s of air seemed to have dropped. Figure 4.20 shows the average daily power for compressor 1 (blue), compared to the air mass flow per Watt(yellow). As a 2 MW shift in power is not likely from, the results seem to

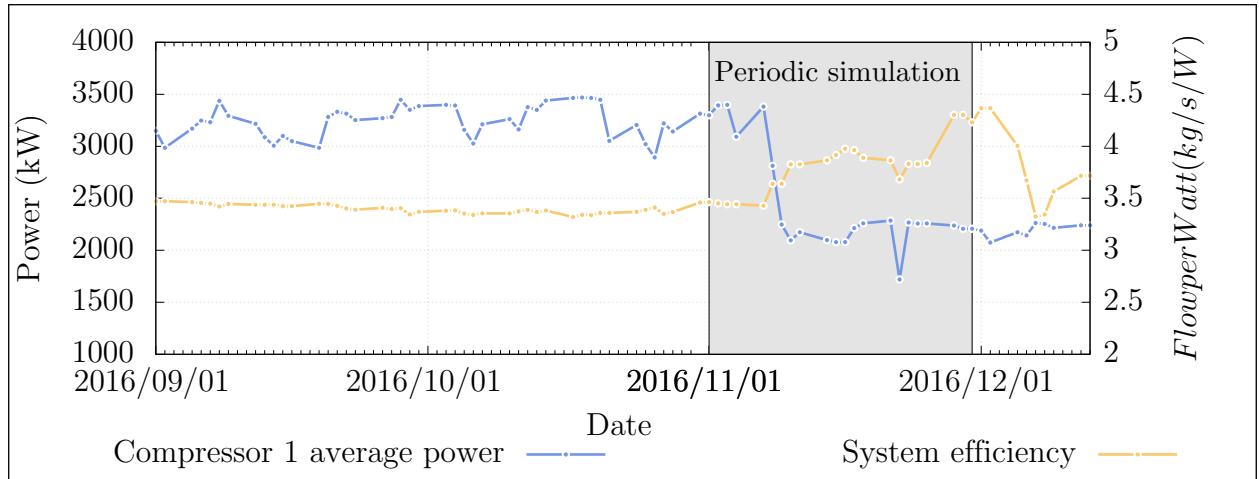


Figure 4.20: Supply efficiency and Compressor 1's average power output over the time of the periodic analysis.

show that there was a fault in the power metering starting from 2016/11/07. This explains the perceived increase in efficiency over the same period as a less power is measure then is actually being provided. In this situation the simulated power measurement is actually a more accurate metric for compressor 1's power over this period.

#### 4.4.3 Validation

To validation of misreadings from the power meter from comparing independent power data for the substation to the combined individual compressors meters. This Figure 4.21 shows the measured power from the two sources. By comparing the compressor power to the independent data, it is clear that there is an error in measurement as hypothesised.

#### 4.4.4 Summary

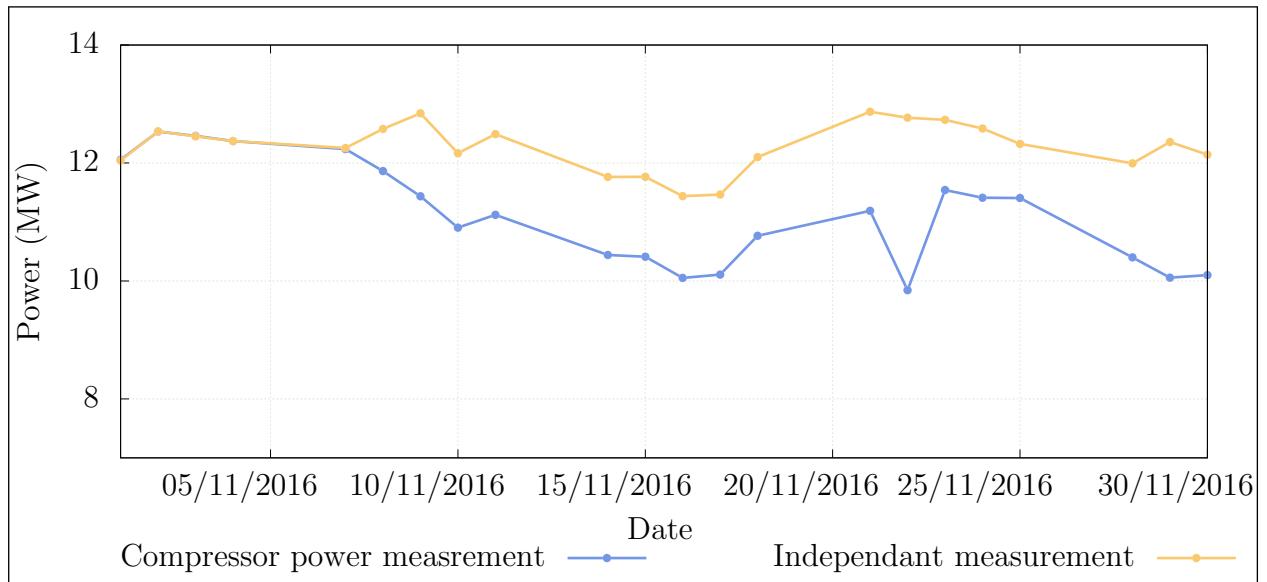


Figure 4.21: Comparison using alternative power source.

## 4.5 Potential benefit for SA mines

There are approximately 75 operational gold and Platinum group metal (PGM) mines in South Africa, as illustrated in Figure 4.22<sup>1,2</sup>. Each mine utilises compressed air for underground processes. By utilising the compressed air simulation methodology in this study, the mines could collectively achieve significant energy and cost savings for the industry.

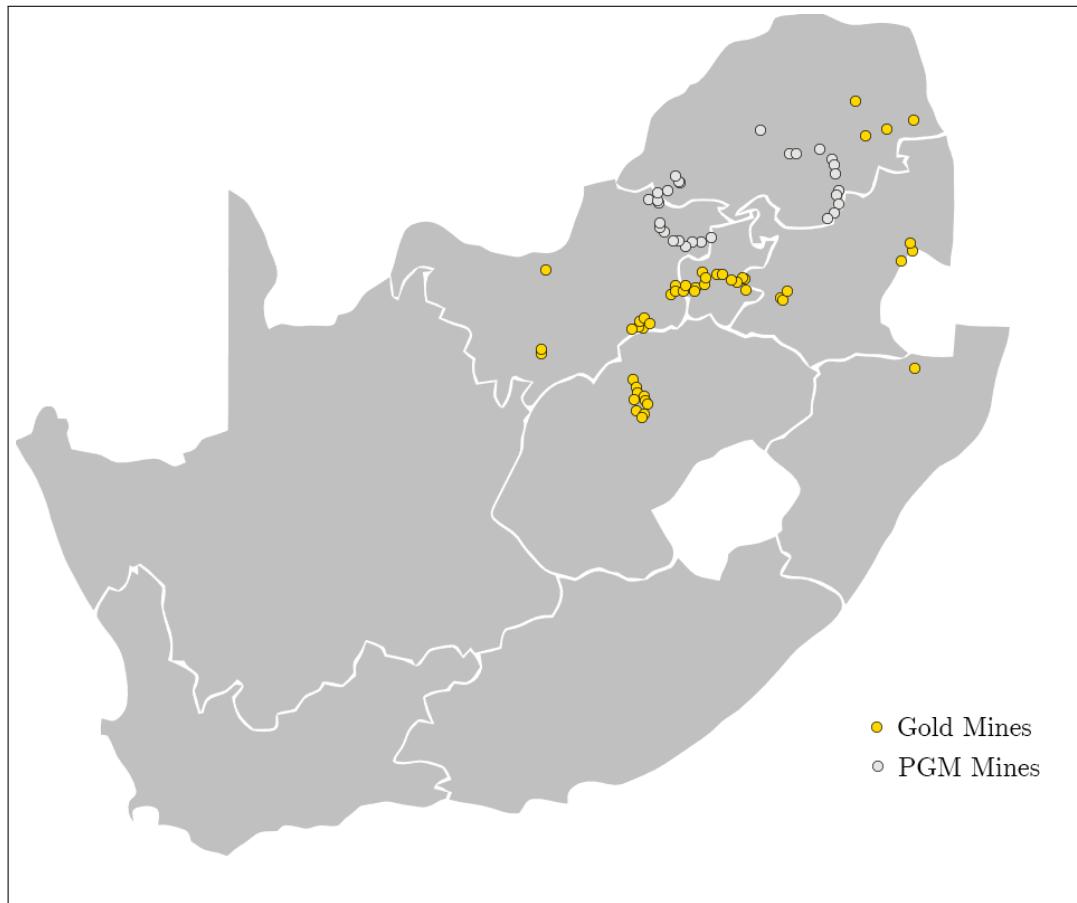


Figure 4.22: Gold and PGM mines in South Africa<sup>1,2</sup>.

In this study, the simulated interventions resulted in savings of (on average) 0.69 MW E.E. or 1.025 MW P.C.. Assuming similar intervention were identified, through simulation for all gold and platinum mines. A potential energy saving of approximately 50 MW E.E. or 75 MW P.C. could be achieved. The combined cost saving for these interventions would amount to up to R400M p.a.

<sup>1</sup> Chamber of Mines, [Online] <http://www.chamberofmines.org.za/sa-mining/gold>, [Accessed 16-06-2017]

<sup>2</sup> Chamber of Mines, [Online] <http://www.chamberofmines.org.za/sa-mining/platinum>, [Accessed 16-06-2017]

## 4.6 Conclusion

- Unfinished

# CHAPTER 5

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## Conclusion

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*'Quote.'* - Somebody

## **5.1 Conclusion**

### **5.2 Limits of this study**

### **5.3 Recommendations for future studies**

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# APPENDIX I

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## Network layout diagrams

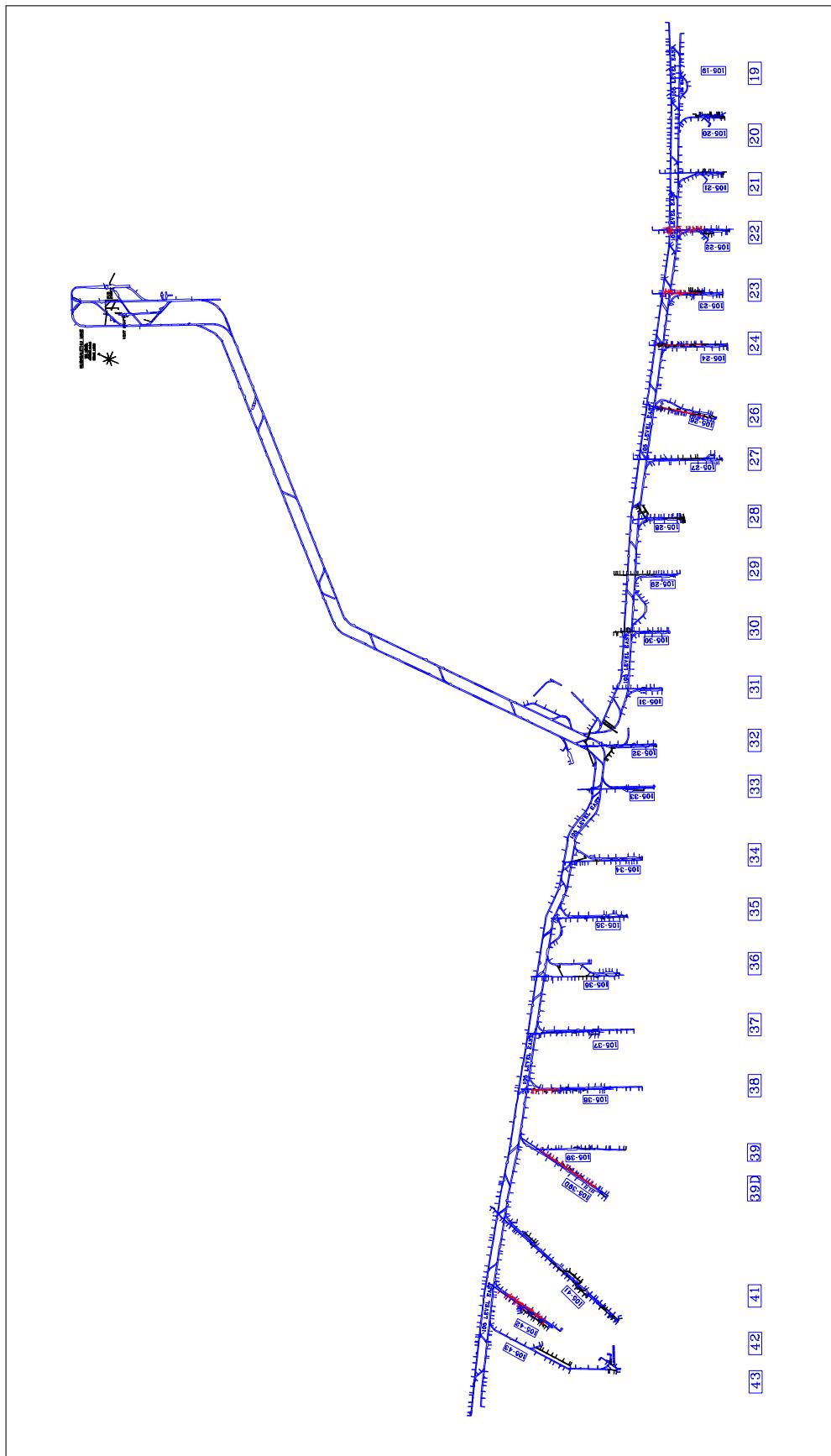


Figure I.1: Underground level layout.

## **APPENDIX II**

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### **Simulation process Flow diagrams**

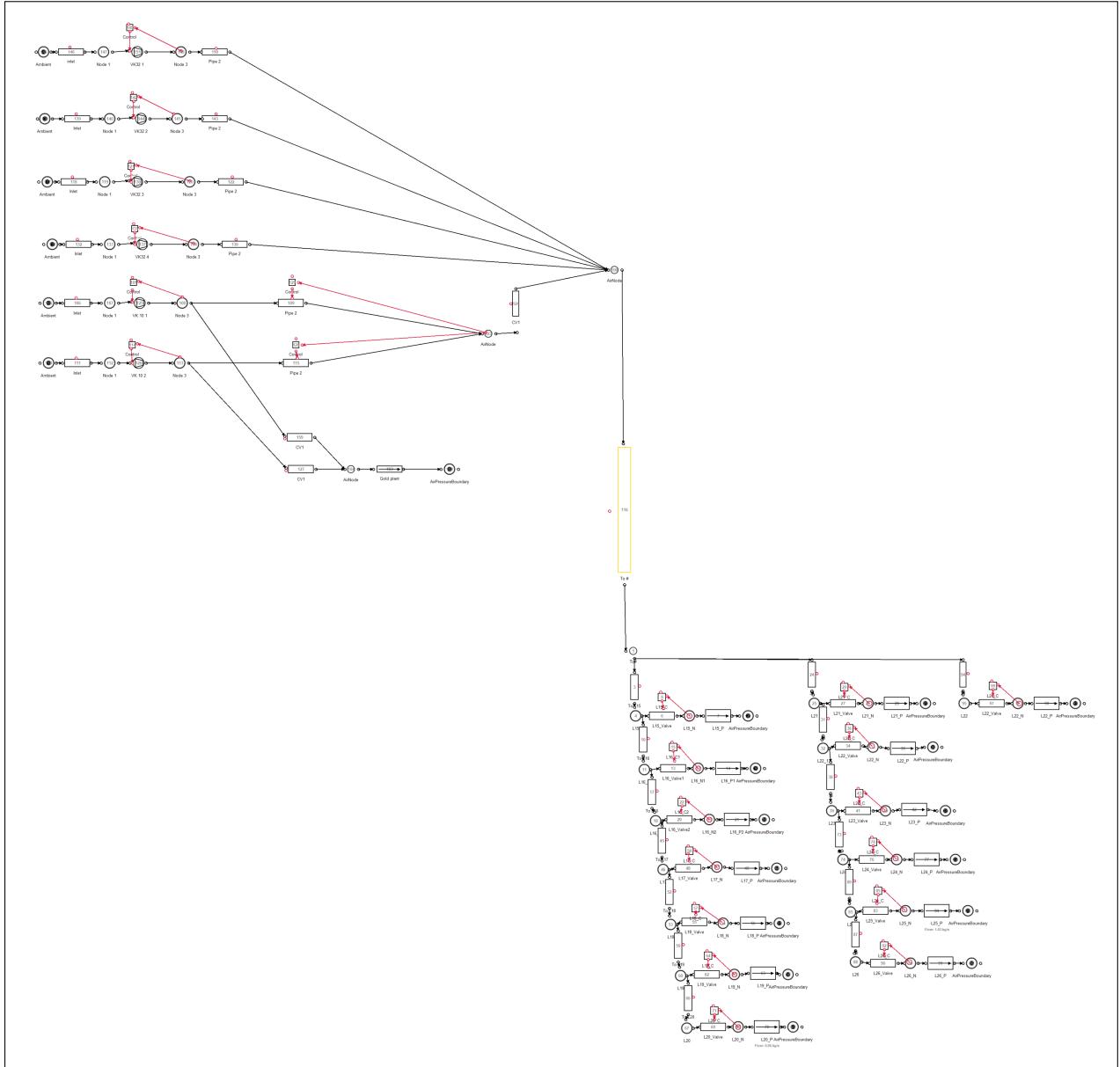


Figure II.1: Mine A: Simulation process Flow diagrams

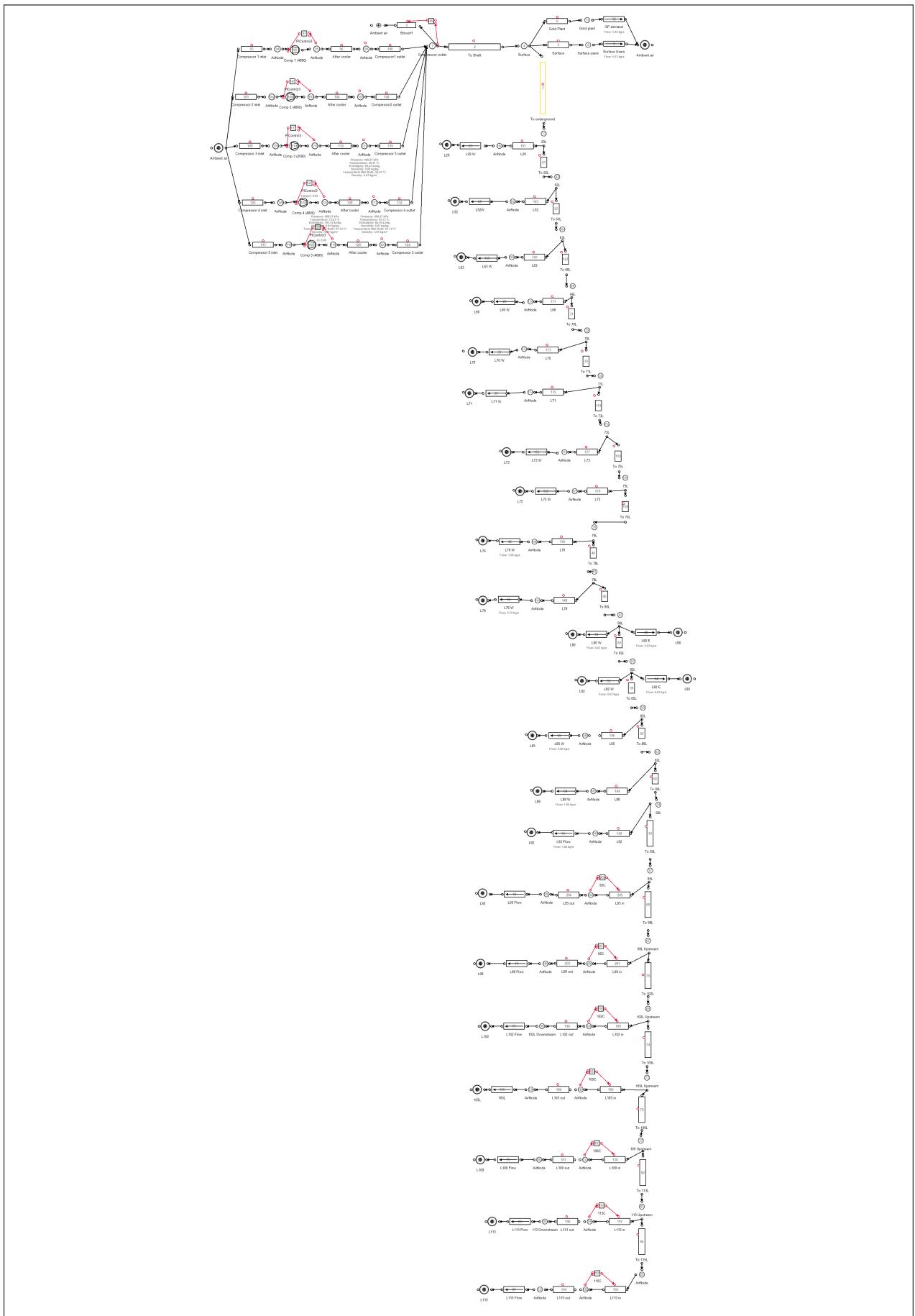


Figure II.2: Mine B: Baseline process Flow diagram.

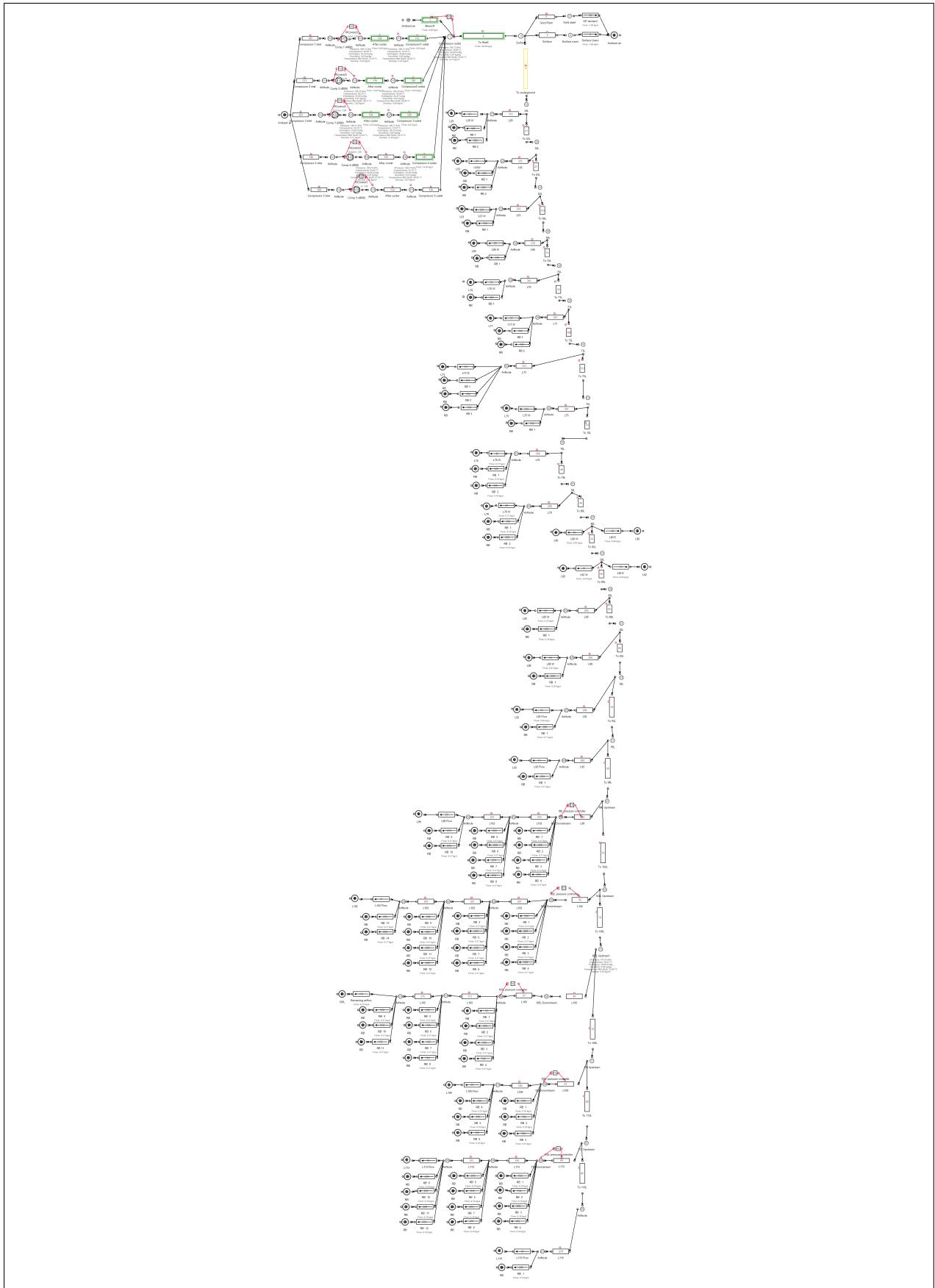


Figure II.3: Mine B: Simulation process Flow diagrams for the refuge bay scenario.

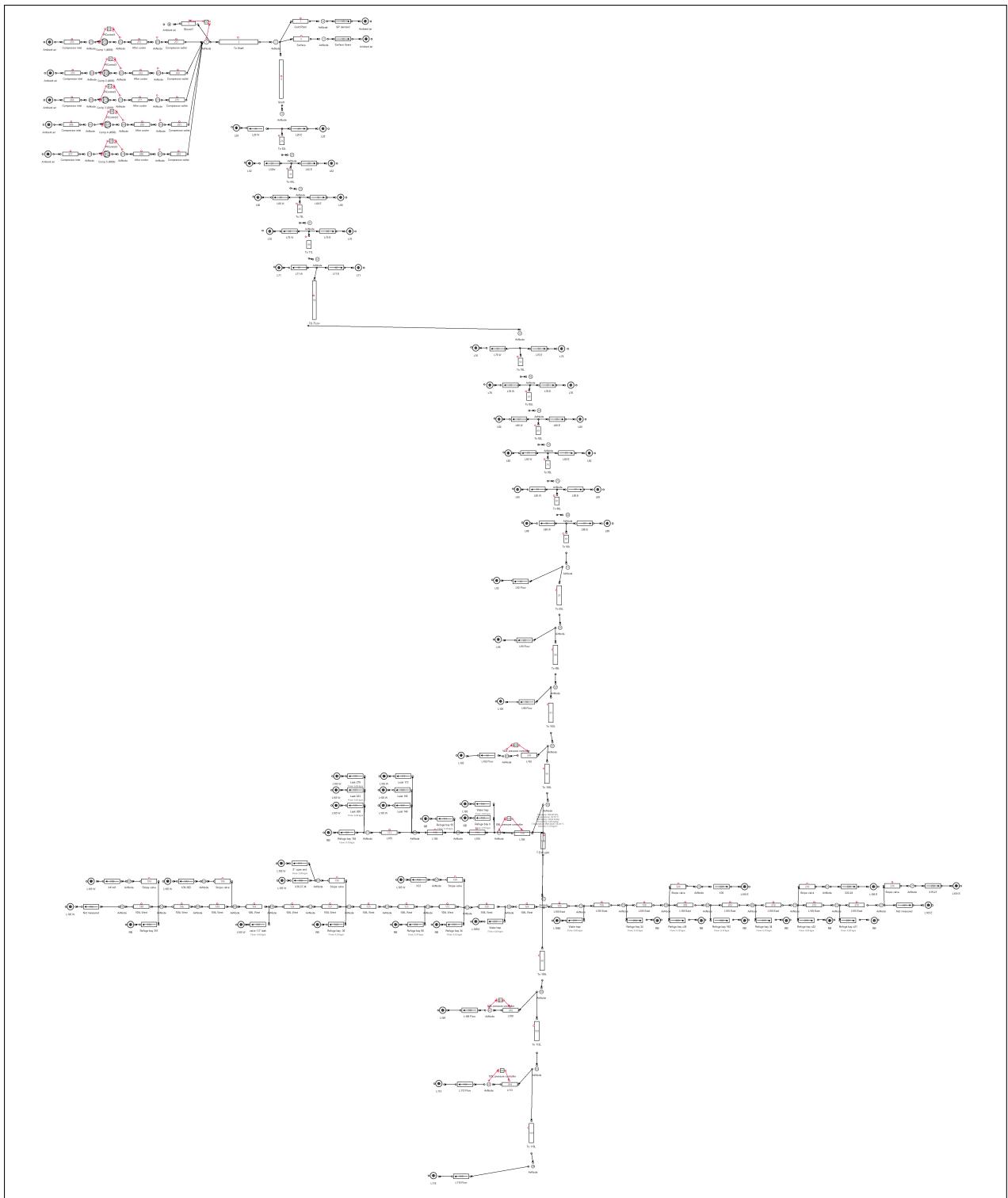


Figure II.4: Mine B: Simulation process Flow diagram for the station isolation stope control.

## **APPENDIX III**

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### **Model component verification tables**

Component	Actual Ave.	Simulated Ave.	Accuracy
Power ( $kW$ )			
VK-32 1	0	0	100%
VK-32 2	460	477	96.35%
VK-32 3	142	117	82.31%
VK-32 4	428	408	95.45%
VK-32 5	1813	1903	95.03%
VK-32 6	732	725	99.01%
VK-10 1	744	745	90.02%
VK-10 2	687	635	92.24%
System	4940	4911	97.34%
Flow ( $kg/s$ )			
1# 15L	1.45	1.42	97.87%
1# 16L	2.15	2.18	98.48%
1# 17L	0.34	0.35	97.30%
1# 18L	0.38	0.39	97.39%
1# 19L	0.31	0.31	98.77%
1# 20L	0.12	0.13	92.65%
2# 23L	1.31	1.35	96.69%
3# 21L	0.67	0.66	98.68%
3# 22L	0.74	0.67	89.54%
3# 23L	0.04	0.04	98.72%
3# 24L	0.11	0.11	98.76%
3# 25L	0.33	0.33	99.95%
3# 26L	0.45	0.47	95.07%
Gold Plant	2.59	2.48	95.72%
Total	9.32	9.51	97.01%
Pressure ( $kPa$ )			
1# 15L	394	384	98.55%
1# 16L	421	419	99.61%
1# 17L	345	344	99.81%
1# 18L	336	336	99.99%
1# 19L	311	309	99.53%
1# 20L	368	368	99.90%
2# 23L	365	327	91.25%
3# 21L	303	302	99.92%
3# 22L	332	301	95.42%
3# 23L	332	332	99.98%
3# 24L	413	409	99.10%
3# 25L	413	409	99.01%
3# 26L	515	509	98.99%
Surface	502	501	99.95%

Table III.1: Case study A: Model verification

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Component	Actual Ave.	Simulated Ave.	Accuracy
Power ( $kW$ )			
Compressor 1	3406	3669	92.37%
Compressor 2	3911	3668	93.92%
Compressor 3	1440	1453	99.05%
Compressor 4	0	0	100%
Compressor 5	3299	3274	99.22%
System	12057	12103	98.73%
Flow ( $kg/s$ )			
95L	1.51	1.42	93.95%
98L	3.75	3.53	93.99%
102L	2.97	2.79	98.72%
105L	5.65	5.71	98.84%
109L	3.57	3.37	94.27%
113L	5.09	4.84	95.05%
Gold Plant	1.41	1.35	95.14%
Sub-shaft total	34.12	34.76	98.09%
Total	41.65	41.43	98.96%
Pressure ( $kPa$ )			
Surface	393	396	99.02%

Table III.2: Case study B: Model verification