Simulating improvements on mining compressed air systems

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Dissertation submitted in fulfilment of the requirements for the degree *Magister* in Electrical and Electronic Engineering at the Potchefstroom Campus of the North-West University

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July, 2017

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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

Contents

Acronyms

CALDS	Compressed Air Leakage Documentation System
DSM	Demand Side Management
E.E.	Energy efficiency
p.a	Per annum
P.C.	Peak-clip
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

Celcius	The SI measure for tempature	C
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	W

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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].

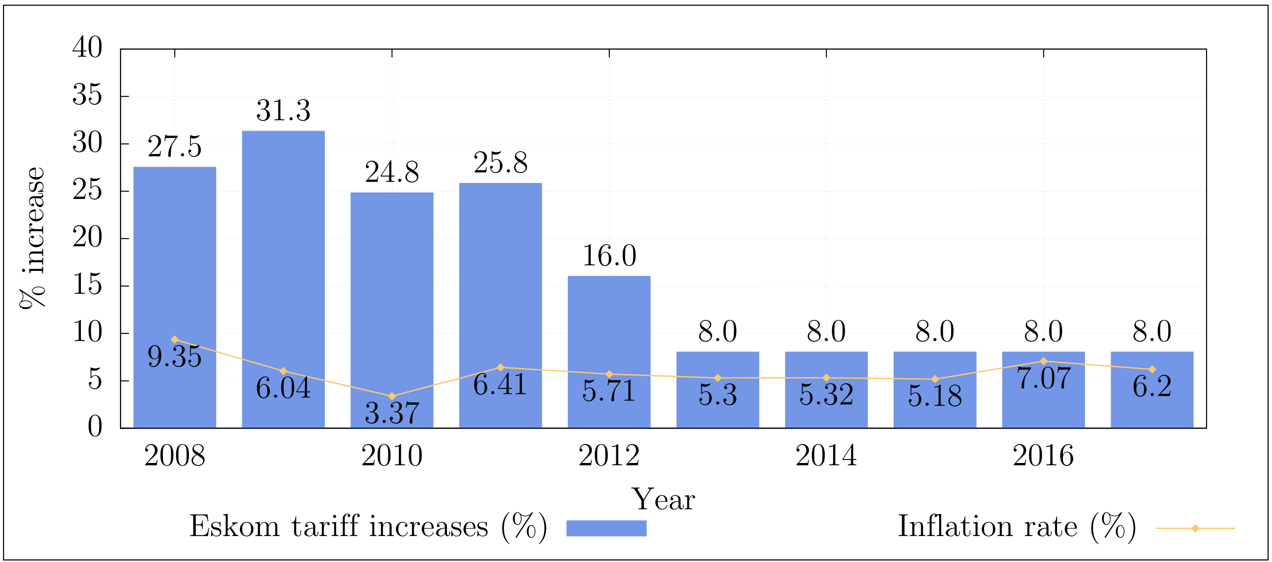

Figure 1.1: Electricity price increases between 2007 and 2017 [2] compared to the inflation rate in South Africa.[1]

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

[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].

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.

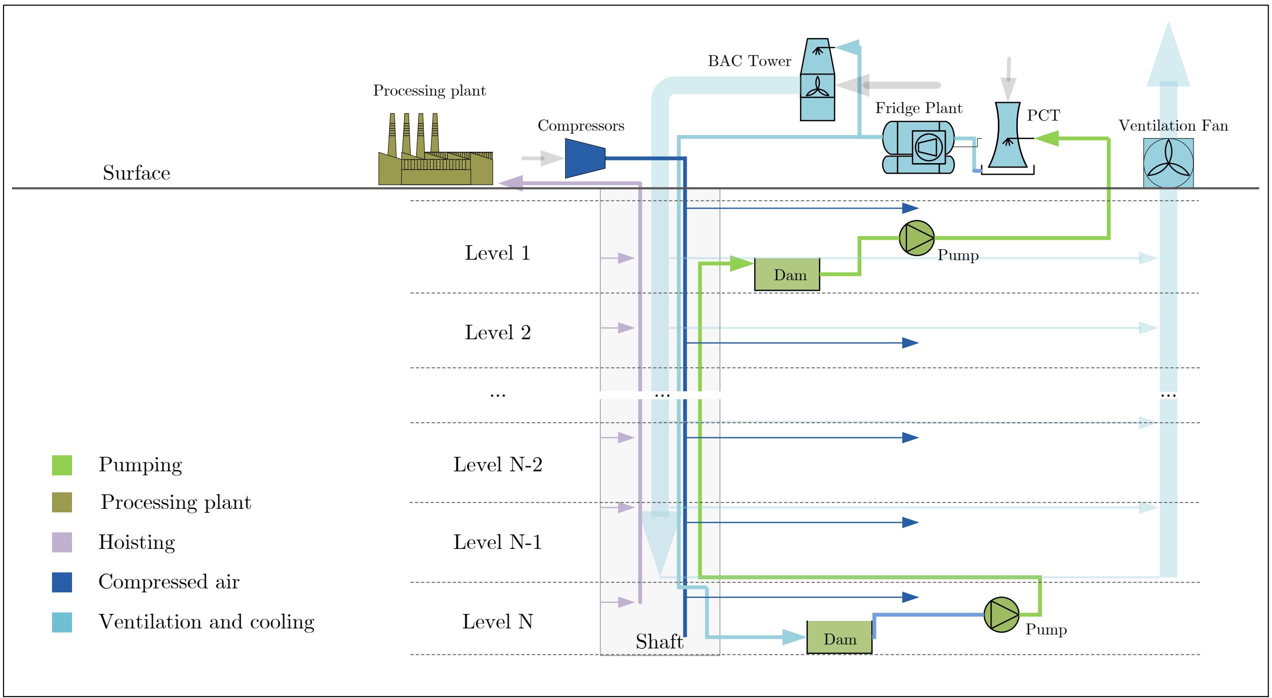

Figure 1.2: A layout showing the mining processes.

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.

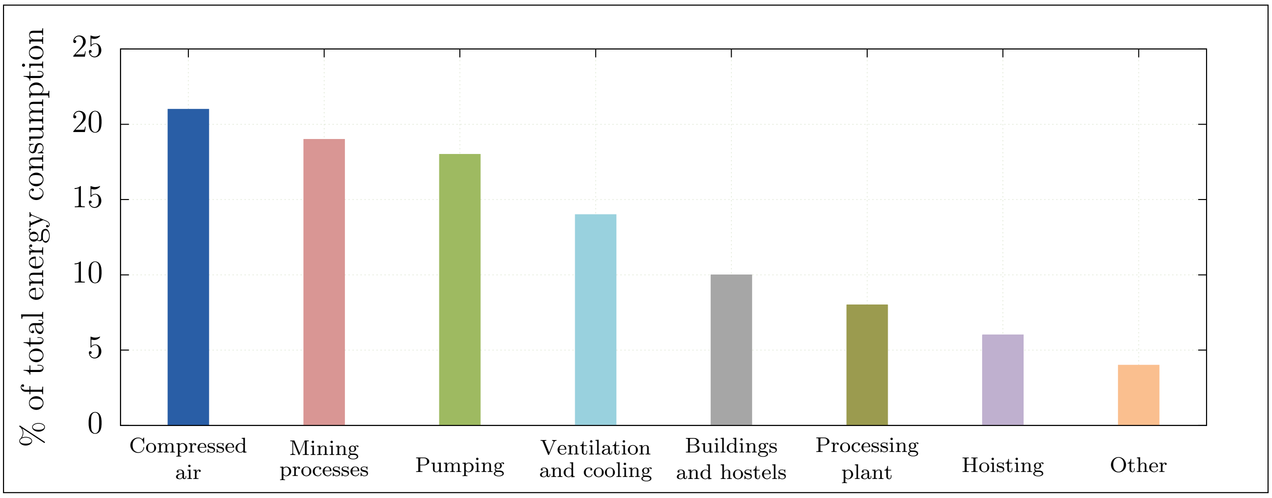

Figure 1.3: The energy consumption for each mining system [7].

1.3 Compressed air systems in mining

1.3.1 Compressed air in operation

Largely due to their reliability, 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 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 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 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.

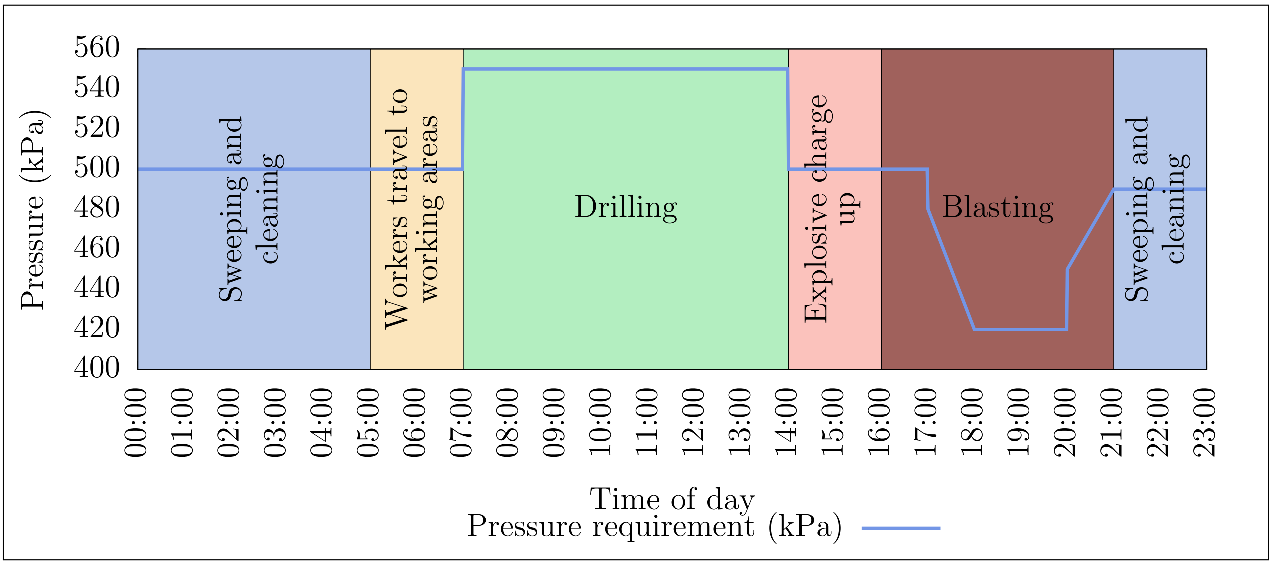

Figure 1.5: The typical operation schedule of a deep level mine [17].

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 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 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 to obtain energy savings through the identification of 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]

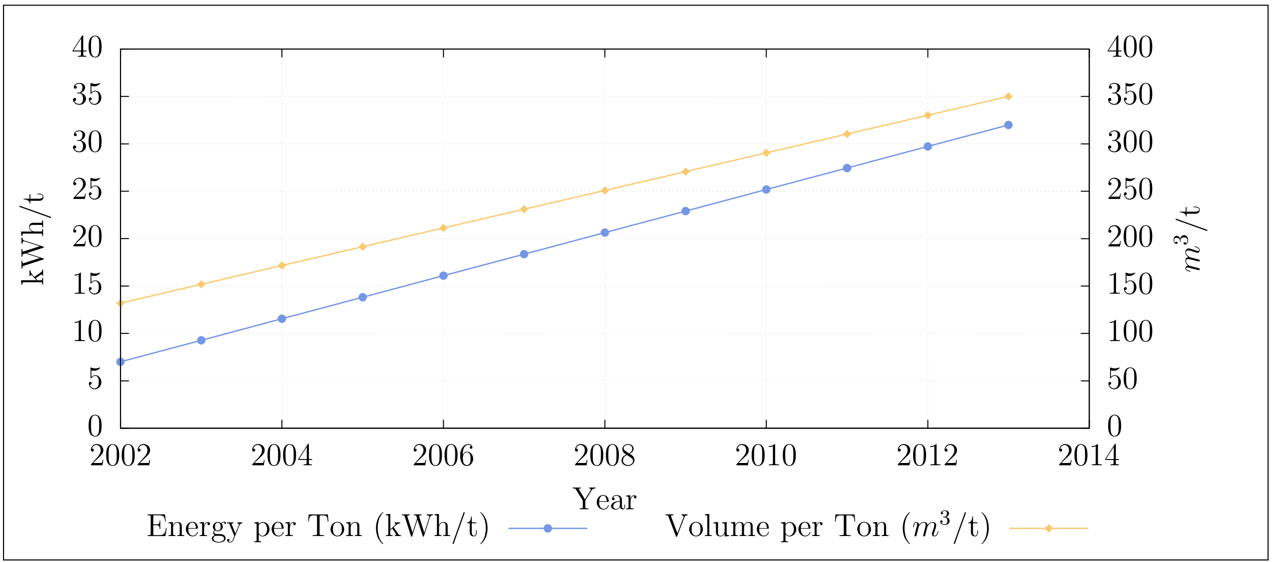

Figure 2.1: The Compressed air energy and flow consumed per T of ore produced. Adopted from Bester *et al.* [25].

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

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

Developing a simulation methodology

'*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.

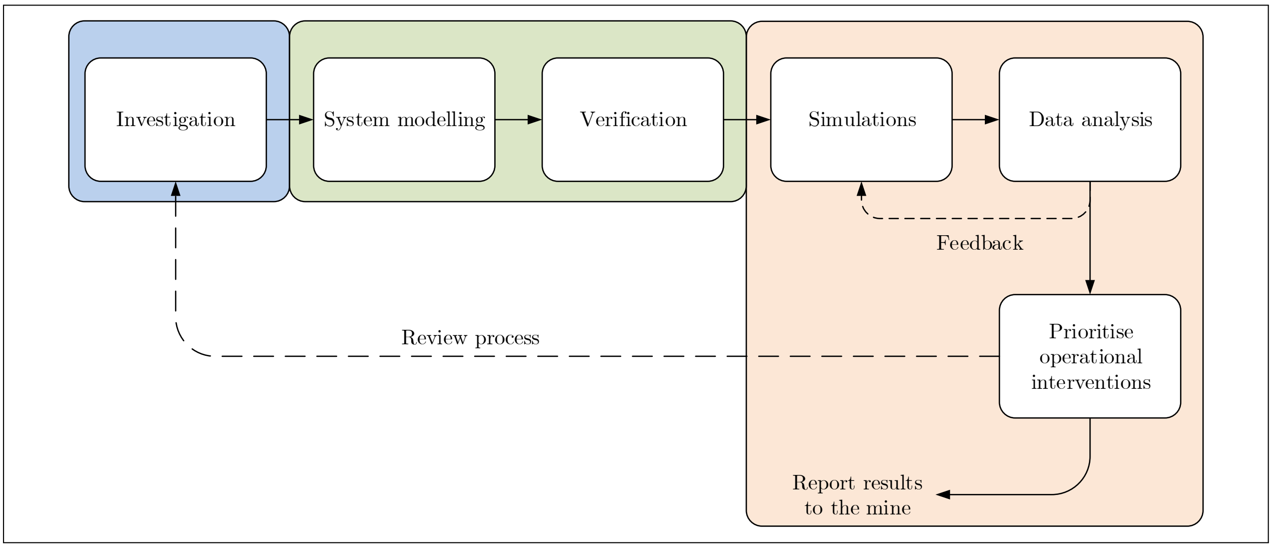

Figure 3.1: Flow diagram of the methodology for this study.

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..

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*[1]:

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

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

Where the pressure difference ΔP is a function of:

Parameter	Definition
f	Friction coefficient
L	Pipe length (m)
D	Pipe diameter (m)
ρ	Air density (kg/m^3)
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 3.2 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

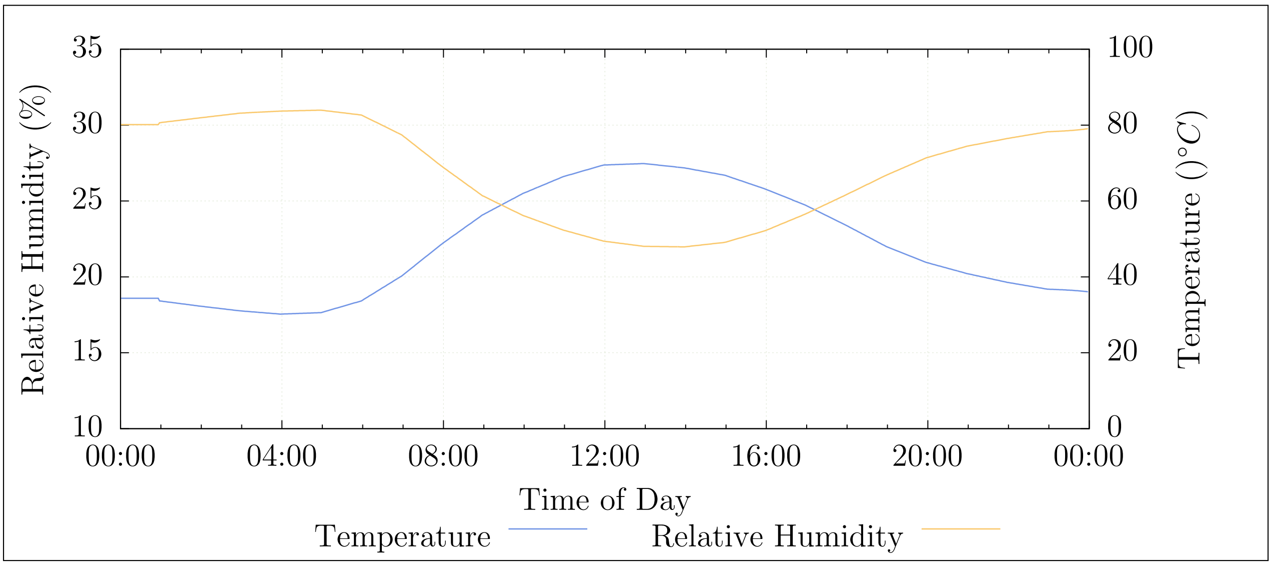

Figure 3.2: Average summer ambient air conditions at a South African gold mine.

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
- 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 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 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 3.3 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.

Once the models are accurately calibrated, the compressor component is integrated to the air network in the arrangement shown in figure 3.4. 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.

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.

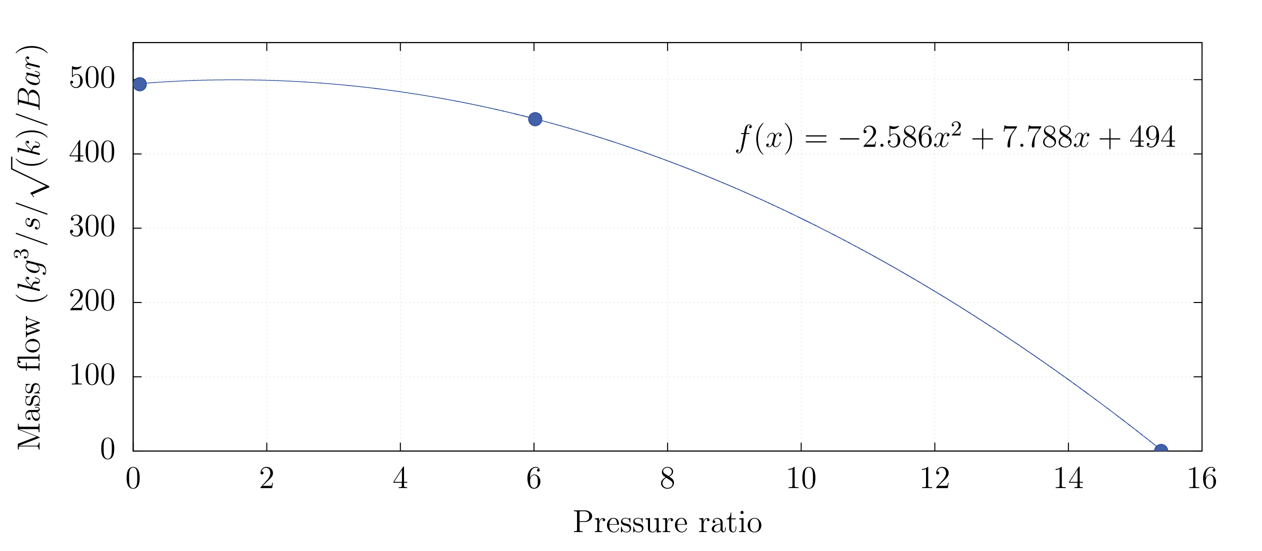

Figure 3.3: Estimating the characteristic curve of a compressor by fitting a quadratic function to points of operation.

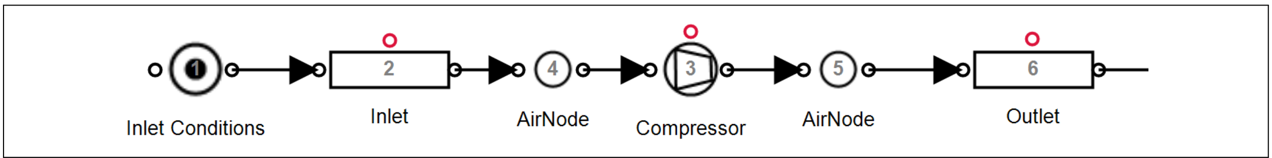

Figure 3.4: Integrating the compressor component into the simulation.

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

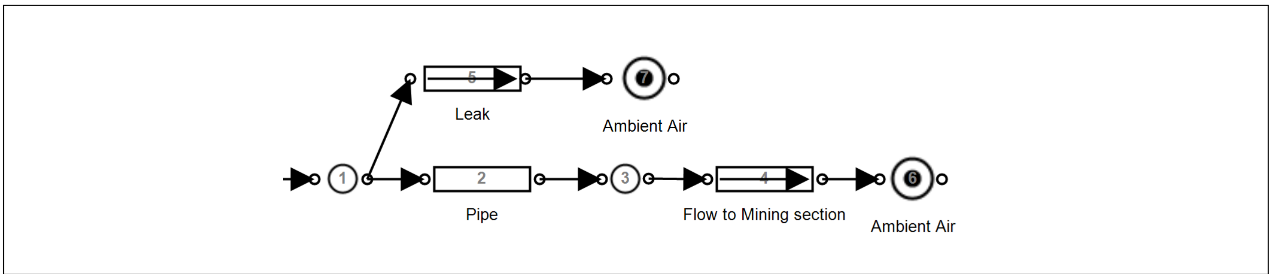

Figure 3.5: Implementing flow demands and leaks into the simulation.

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 3.6 where discharge pressure is used as feedback for the controller. Guide vains are most commonly used in mining to control

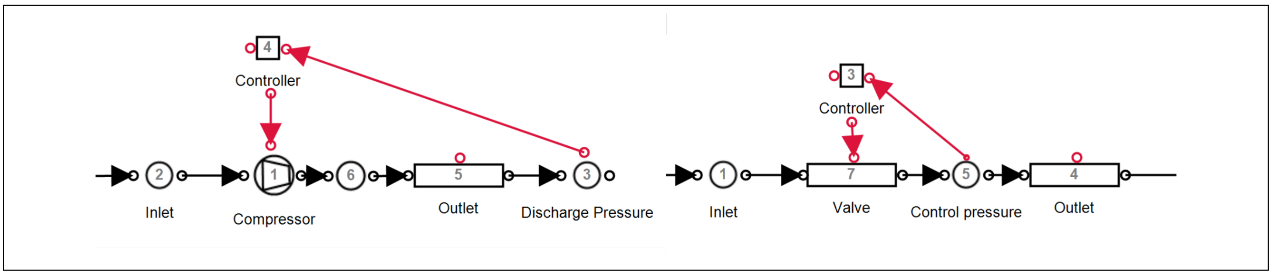

Figure 3.6: Control components in STB.

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 3.7 shows the relationship between power and guide vain position. This can be modeled 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.

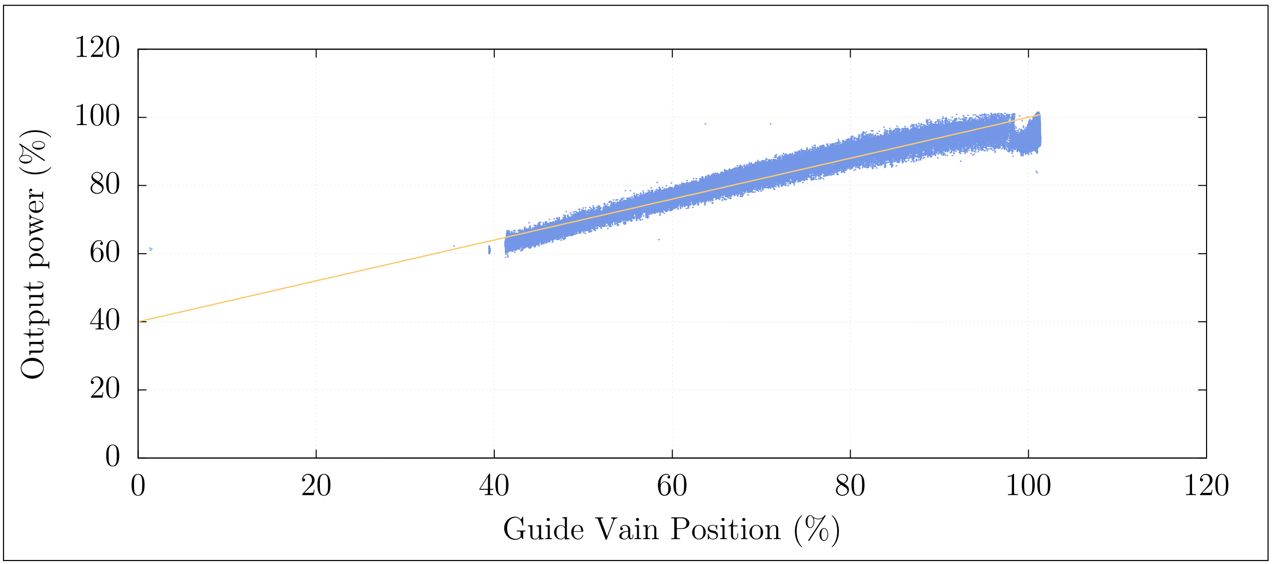

Figure 3.7: Modeling the compressor control from a guide vain

A guide vain controller is modelled using a PI controller component. However, the limitations of guide vain control, as represented in figure 3.7, 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 3.7 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 3.6 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 3.8: An example of a compressed air control valve[31].

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.

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

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

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. Figured 3.9 shows an example of a changing compressor schedule where an input parameter would need to be updated in the simulation.

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

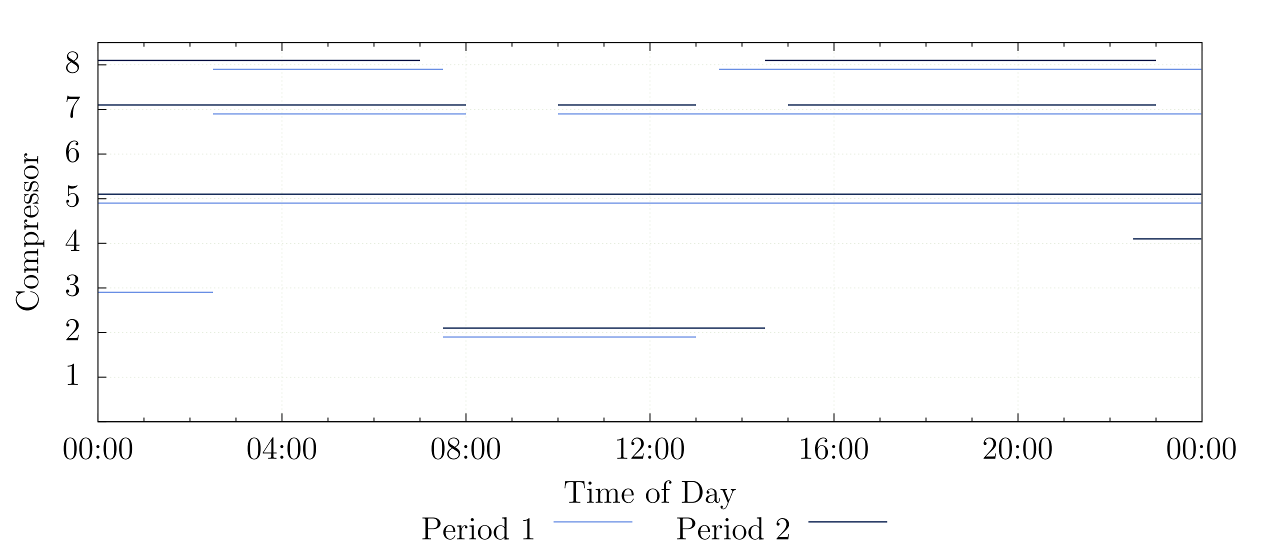

Figure 3.9: An example of two baseline periods, showing a changed compressor schedule.

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.

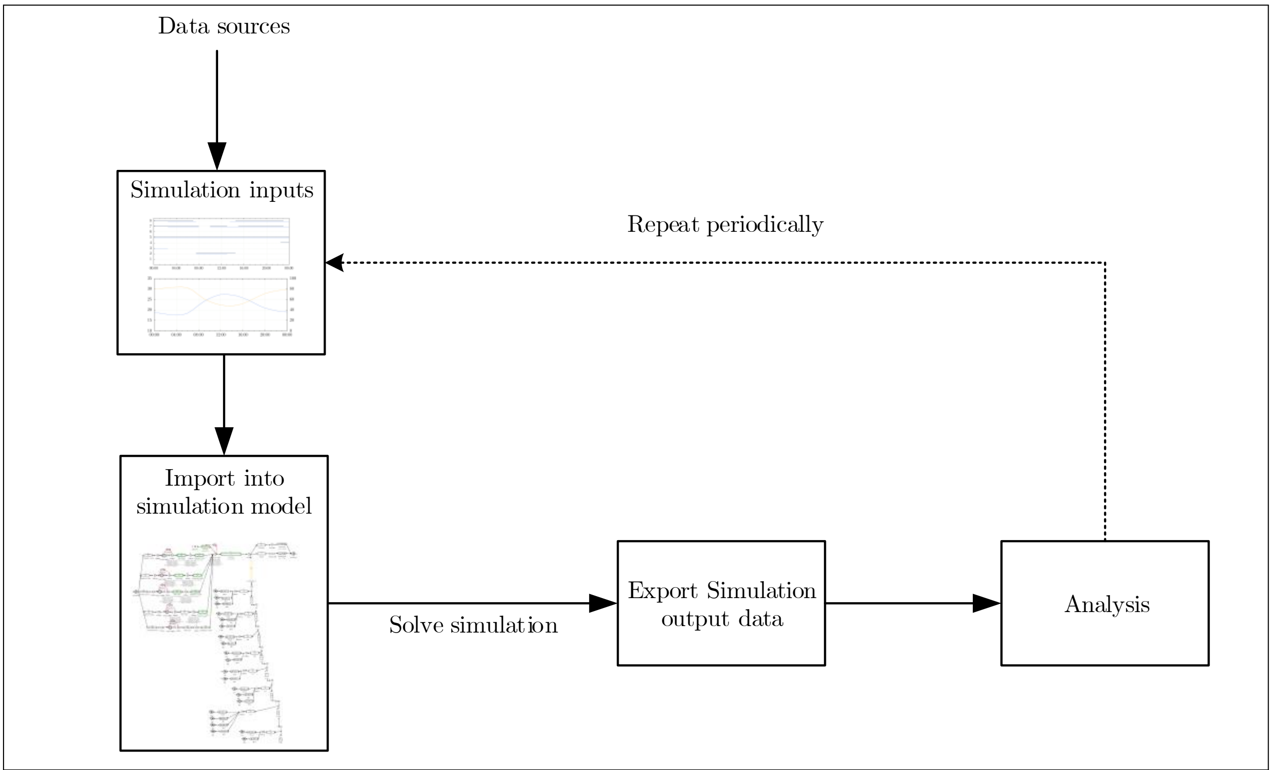

Figure 3.10: The periodic simulation process that was followed in this analysis.

3.3.7 Summary

Unfinished

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 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

Results and validation

‘*Quote.*’ - Somebody

4.1 Introduction

This section will discuss the results of the implementing the simulation methodology on various case case study. Further, the result of various simulated scenarios will be discussed. Finally validation of the the simulated scenarios using actual measurable tests will be discussed.

4.2 Case study A (Beatrix 123)

4.2.1 System investigation

Case study A represents a group of three gold mining shafts and a gold processing plant in the Free state that share a compressed air network. Prior to this study, efforts were made to optimise the system through Demand Side Management (DSM) energy projects. An investigation into the system was performed to identify potential energy and operation improvements strategies that are still available.

An air distribution layout was developed for the system, the simplified diagram is shown in Figure 4.1.From this along with information from the mine personal and system data, an understanding of the operation philosophy was obtained.

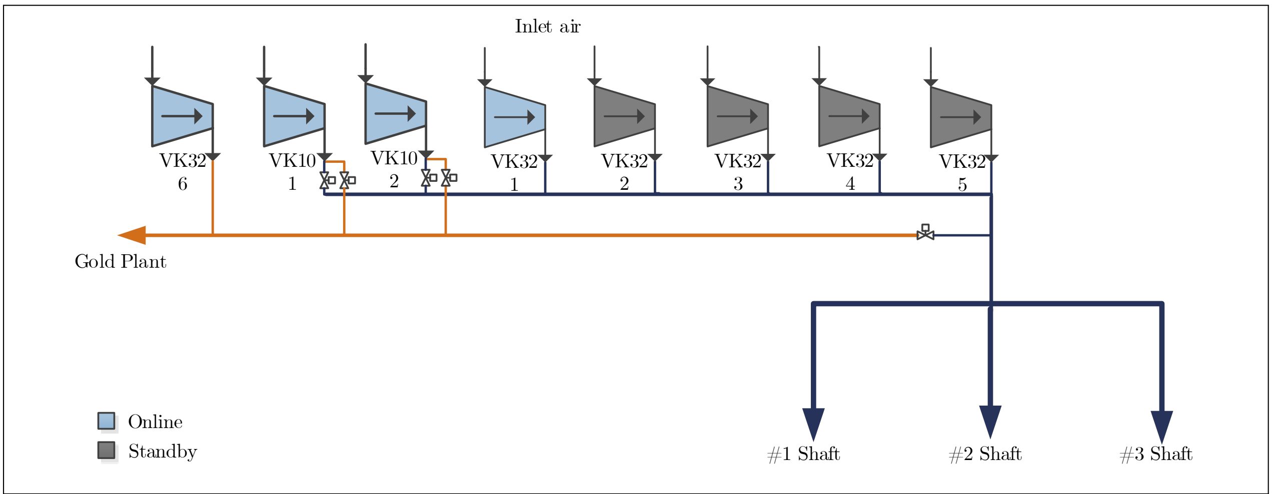

Figure 4.1: Simplified process flow chart of the compressed air network.

The system typically uses 5 MW of power, which increases by a 1 MW during the drilling shift. The average weekday power profile is shown Figure 4.2. Seven compresses are available in the system. Five large compressors (VK32s) rated at 2.9 MW each and two smaller compressors (VK10) with a power rating of 1.1 MW each. The system is normally operated with a combination of two VK32 compressors and two VK 10 compressors. The other compressors serve as standby.

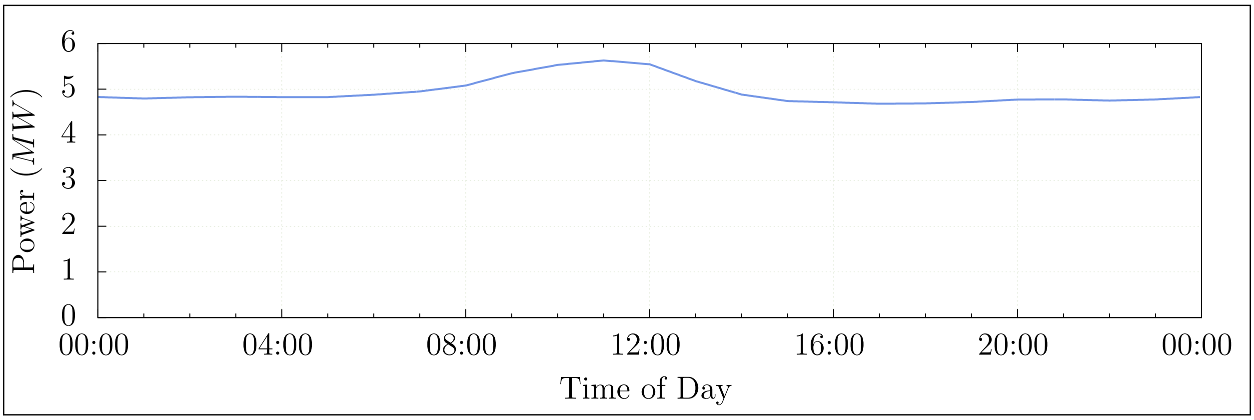

Figure 4.2: Average power profile

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 f 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 utilising the surface control valves and a specific configuration of compressors. The mine prefers not to operate this way.

4.2.2 Model development

With the data and understanding of the gathered from the investigation, a model was developed in the Process Toolbox (PTB) tool using the methodology discussed in Chapter 3. First the simulation boundary was selected to include the measured flows to each level as well as the processing plant. As data was only available in half an hour intervals, the simulation step size was was set to 30 minutes to match the available data.

Component models were developed using the respective methods discussed in chapter 3. The following assumption were made to simplify the development the model:

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

The model components was calibrated so that the simulated outputs matched data from the real system.

Verification of model

Verification was performed to ensure that simulated output accuracy was ¿95%. Figure 4.3 and Figure 4.4 compare the to total simulated and actual power and flow respectively. The average accuracy was 97.34% for system power and 97.01% for system flow. Both these parameters were well within the target 95% accuracy.

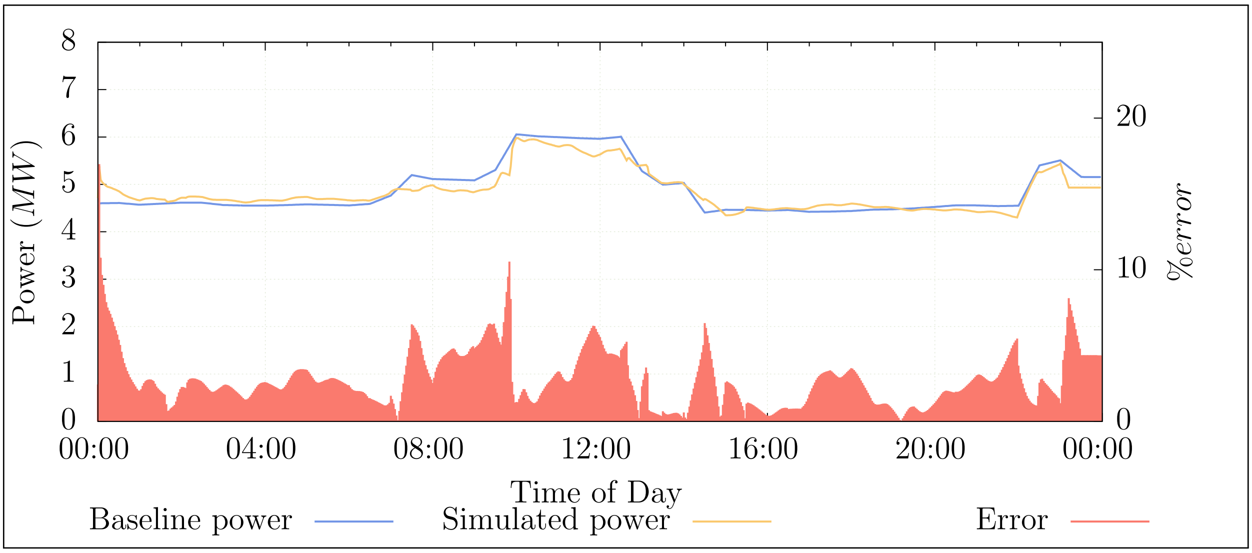

Figure 4.3: The simulated power compared to the actual measured power

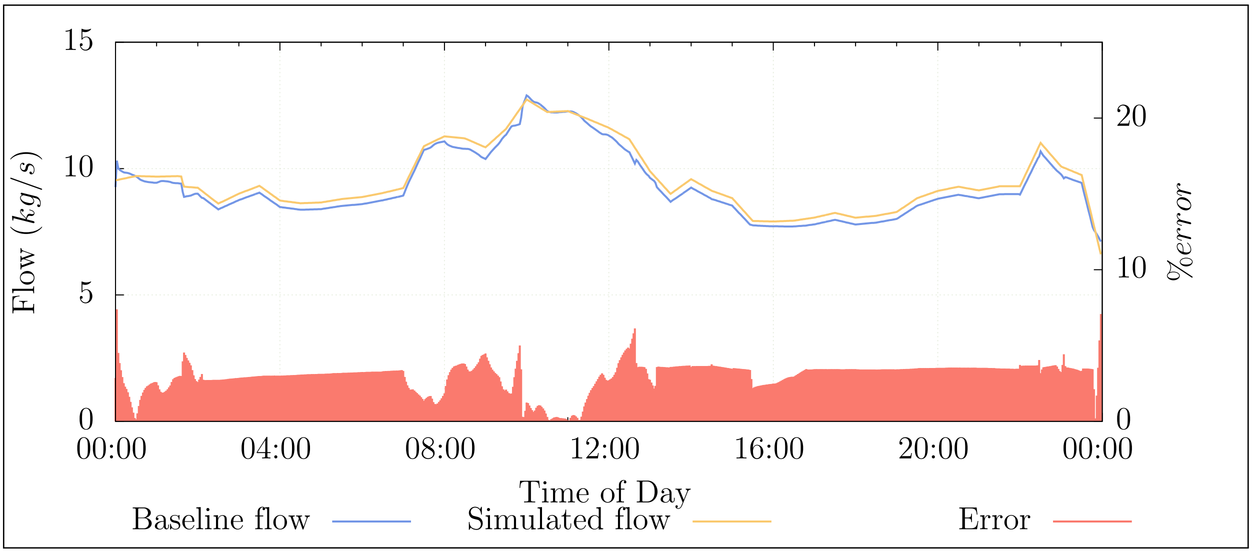

Figure 4.4: The simulated flow compared to the actual measured flow

The same check was performed for the compressor outlet pressure. Figure 4.5 compares the actual measured and simulated pressures. The accuracy of the outlet pressure was 99.1%. The high accuracy of the simulated pressure was expected as the mine uses a constant pressure set-point for the compressors.

The accuracy of the model was checked in more detail to ensure that each modelled parameter

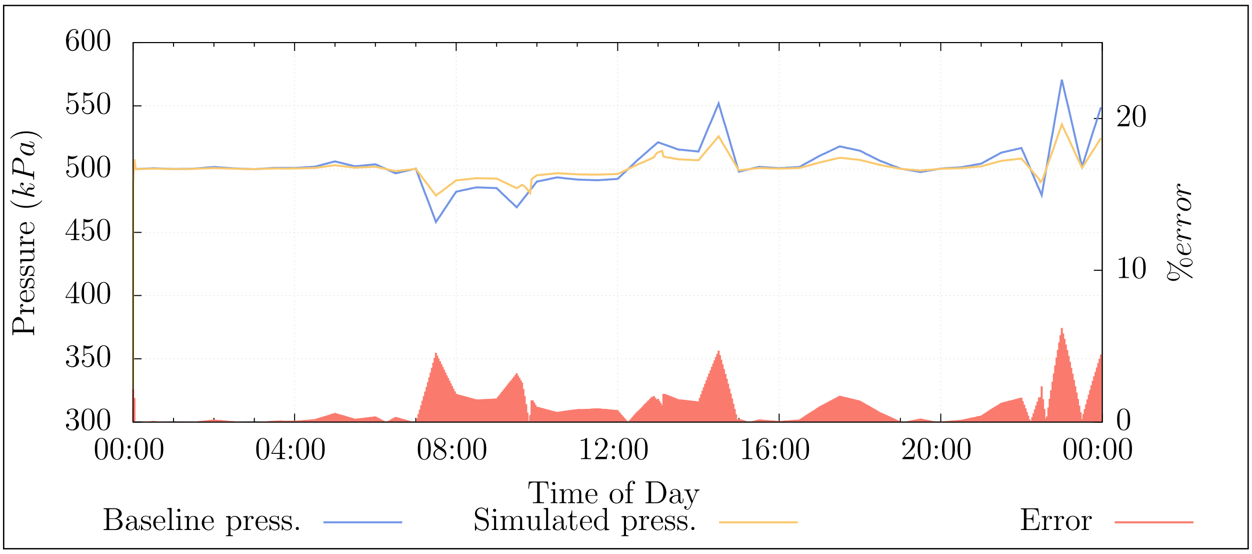

Figure 4.5: The simulated Pressure compared to the actual measured pressure

matched the actual measurement with high accuracy. Table II.1 shows the accuracy each measured simulation output in the model.

4.2.3 Scenario 1. Compressor set points

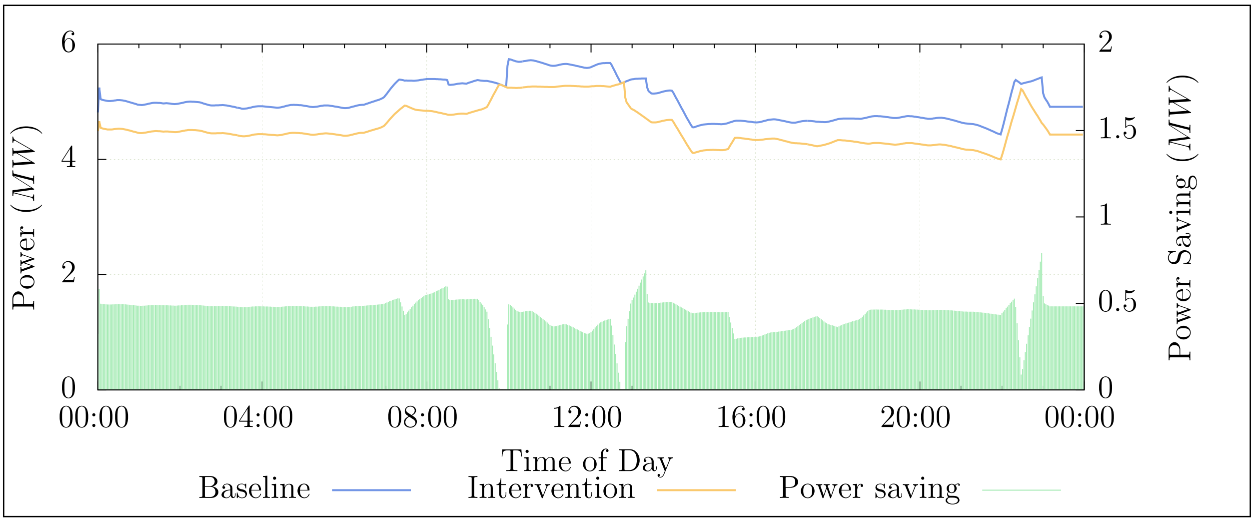

Figure 4.6: Power savings

4.2.4 Scenario 2. Control valves set points

Per annum (p.a)

4.2.5 Comparison of scenario results

Scenario	Power saving	Cost saving p.a	Additional benefit

Table 4.1: Comparison of the simulated scenarios

4.2.6 Validation of results

4.2.7 Summary

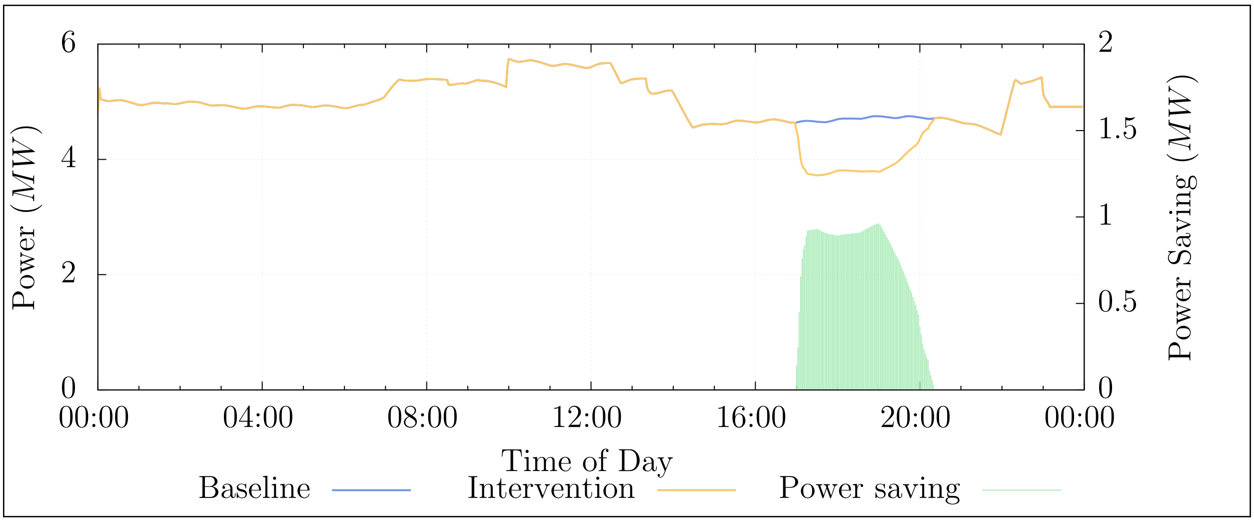

Figure 4.7: Power savings

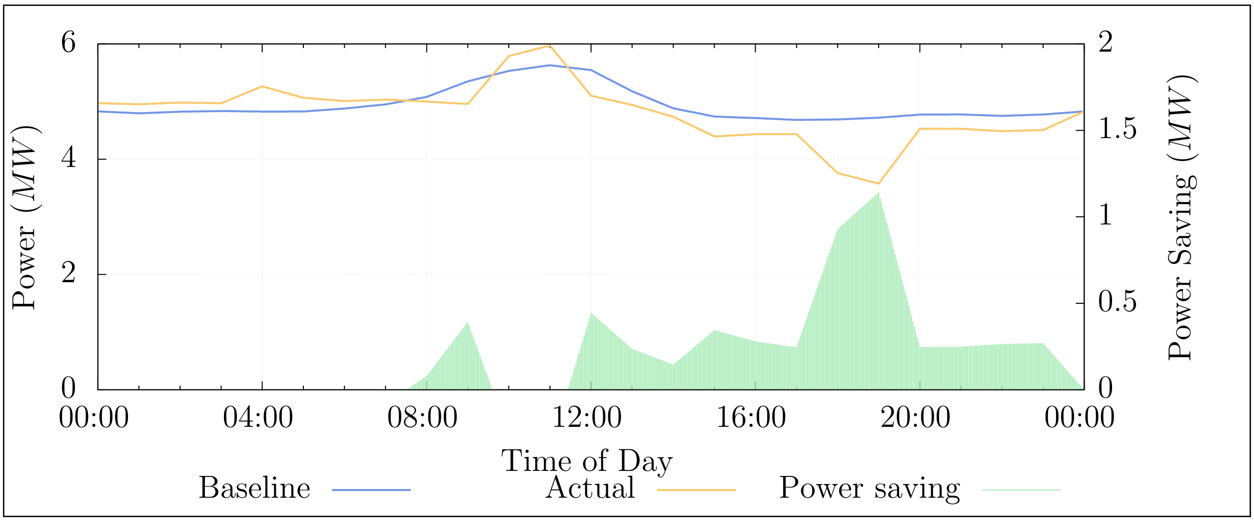

Figure 4.8: Actual power savings achieved on the system

4.3 Case study B (Kusasalethu)

4.3.1 System investigation

Case study B is another 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.

A basic air distribution layout was obtained, as shown in Figure 4.9. The figure indicates available meters and instrumentation as well as typical airflow splits to various sections and levels of the mine.

To understand the operation of the system, schedules and set-points as well as critical limits

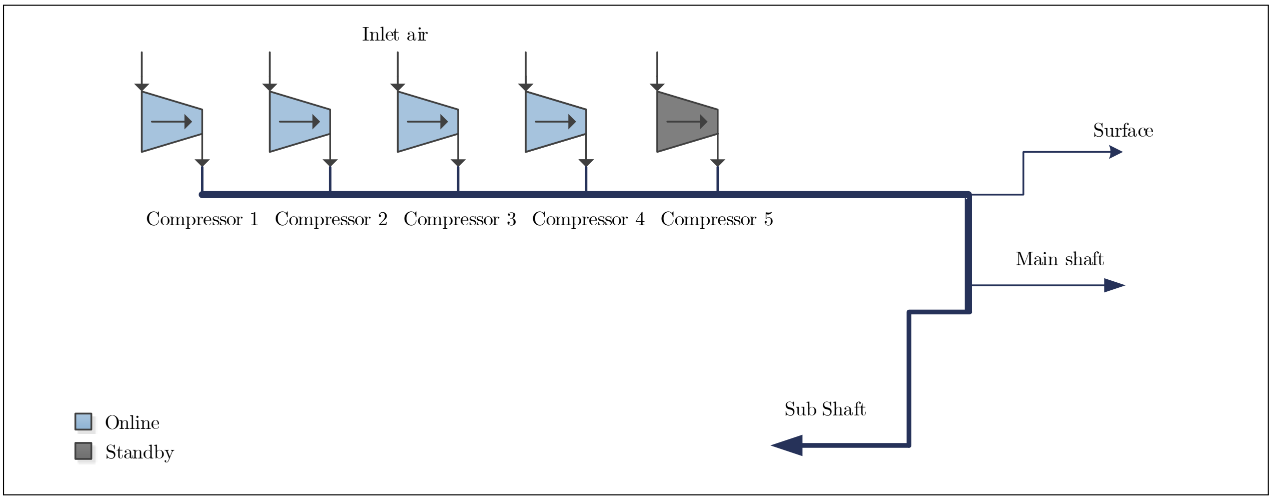

Figure 4.9: Basic layout of the compressed air network.

such as minimum and maximum pressures were obtained from various personal and from the SCADA. Important data parameters such as Powers, pressures, flows, etc. for the system was gathered from the SCADA and other data sources. This data will be used to develop and calibrate the simulation model

An in-depth investigation was performed on the significant mining levels to map the locations of mining cross-sections, refuge bays, major leaks and other compressed air consumers on each level as well as measure the usages. An example of a resultant schematic from the underground investigation is shown in Figure ??

4.3.2 Model development

Using the data obtained from the investigation of the system, a simulation model was developed in software. The modelling methodology described in Chapter 3 was then utilised to develop a model for the system. The entire model is shown in Appendix ?? Figure I.2. The model parameters were then calibrated to match the actual data from the mine.

Verification of baseline simulation

Using the verification methodology, the simulation model was performed by comparing the simulation outputs to actual measured values. To simplify the model, the actual measured 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 measured system as shown in Figure 4.10.

With the pressure set, the power and air flow outputs for components throughout the model 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

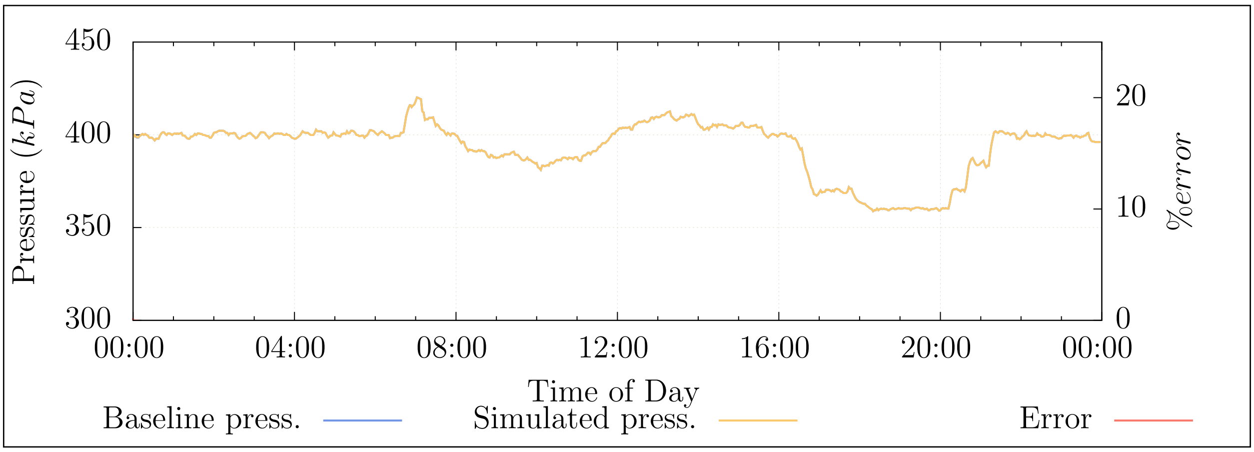

Figure 4.10: Comparing the pressure response of simulation to the actual measured pressure

accuracy for these parameters compared to the real system was 98.7% and 99.0% respectively. This was regarded as acceptable accuracy.

Once all the power and flow parameters were checked calibrated with minimal error, the system's response to the pressure set-points was checked. The compressor models were replaced with the pressure set-point profile instead of the measured outlet pressure profile. The simulated outlet pressure was then compared to the actual measured outlet, this is shown in Figure 4.12.

4.3.3 Scenario 1. Refuge bay optimisation

From investigations that were conducted on the mines compressed system, 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 a reduction refuge bay leaks, by closing the valves would lead to a air saving of 0.05 kg/s per refuge bay at typical operational pressures. This measurement was conservative as not all the refuge bays on the level could be closed for the test.

Extending these tests to include the rest of the mining sections was not practical due to the size of the mine and high resourse requirement . Therefore, the benefits bay 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 detail was selected to recreate the scenario within 2% error. To model auto-compression, the depth of each compressed air component was included into the simulation. Using the per-level layouts obtained from the investigation the location of

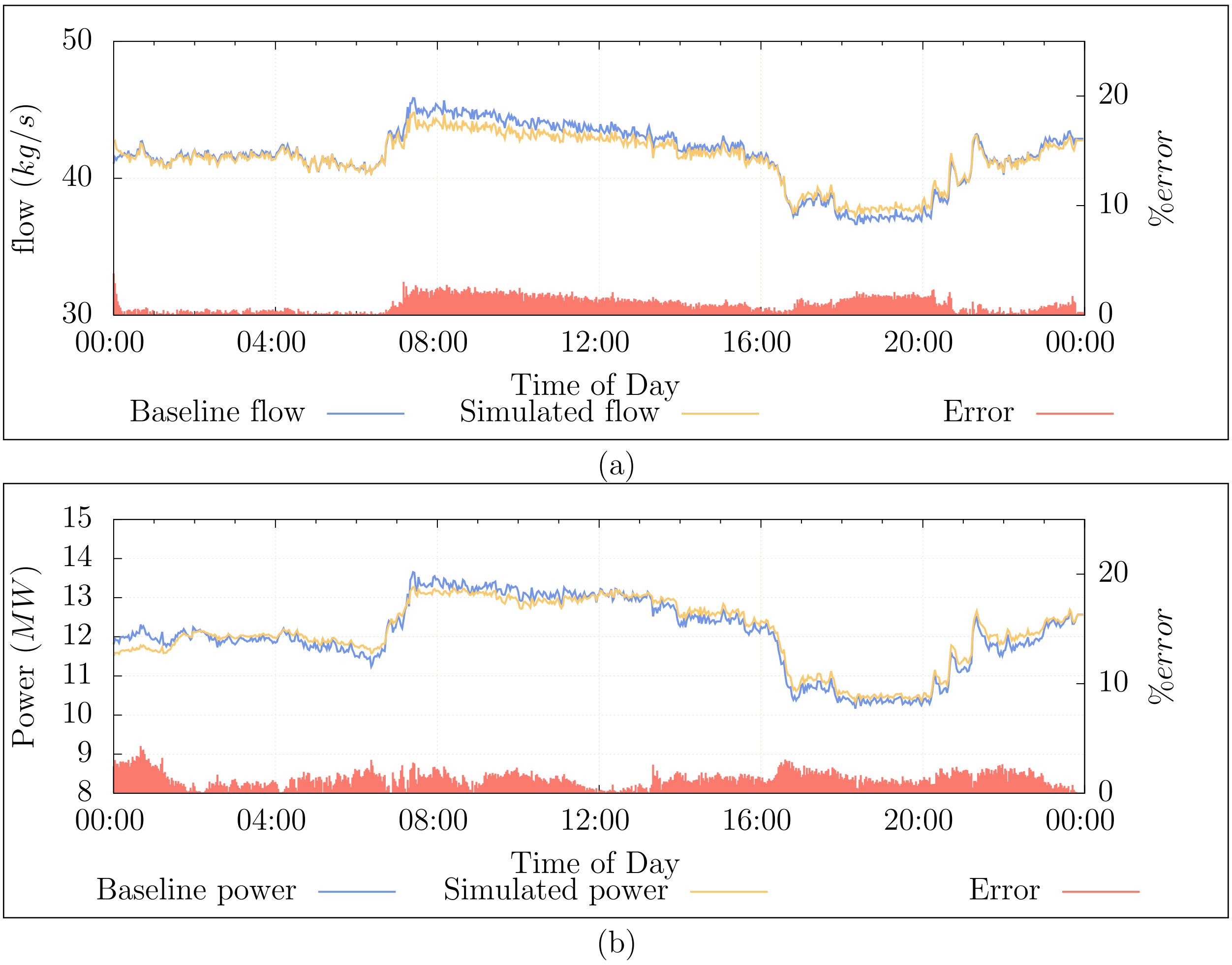

Figure 4.11: Verification of the total (a) flow and (b) power of the system using the actual pressure profile.

refuge bay components were identified. Refuge bay leak components were then added to the simulation to replicate the measured leak from each refuge bay. 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 keap the model accurate. The simulation was verified with an accuracy of 98% using actual data from the mine. The full simulation process flow diagram is shown in Figure I.3 in Appendix I.

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

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 the 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.

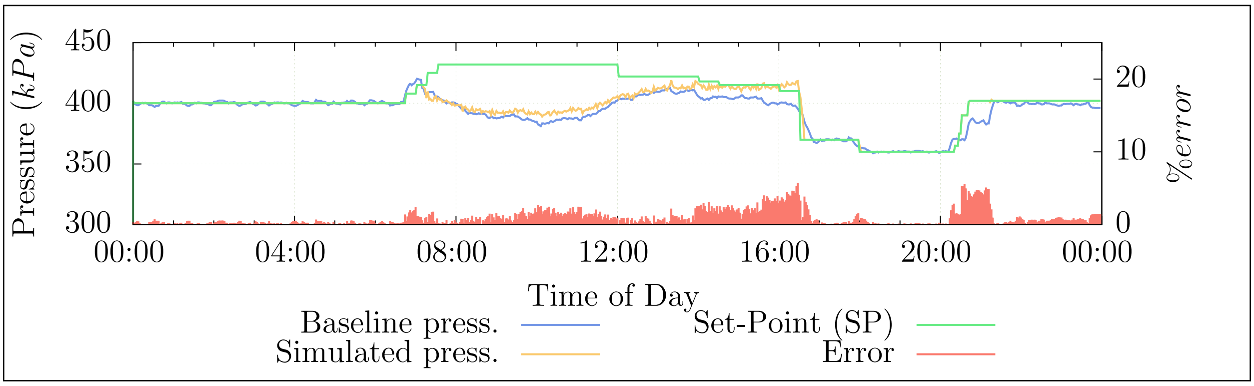

Figure 4.12: Verifying the Pressure response of the system give the pressure set points as inputs

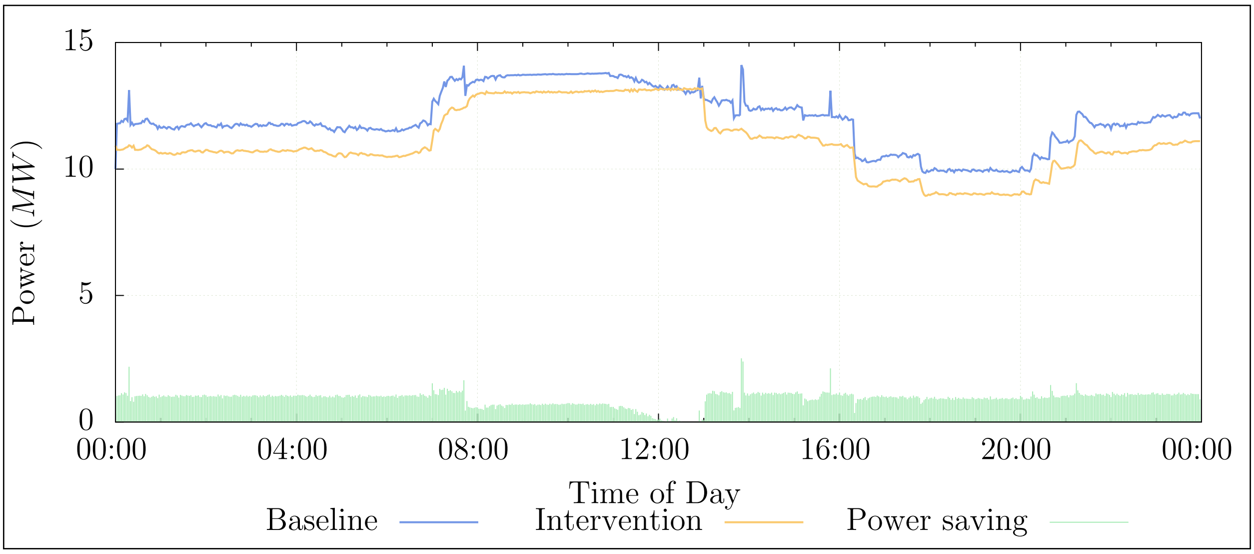

Figure 4.13: The Baseline system power compared to the system power when refuge bay leaks are reduced.

The effect of in-stope control 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 investigations. This is shown in the simulation diagram shown in Figure For comparison, station isolation and the combination of in-stope control and station isolation were simulated.

Peak-clip (P.C.) Energy efficiency (E.E.)

4.3.5 Comparison of interventions

4.3.6 Validation of results

- awaiting results on manual tests

4.3.7 Summary

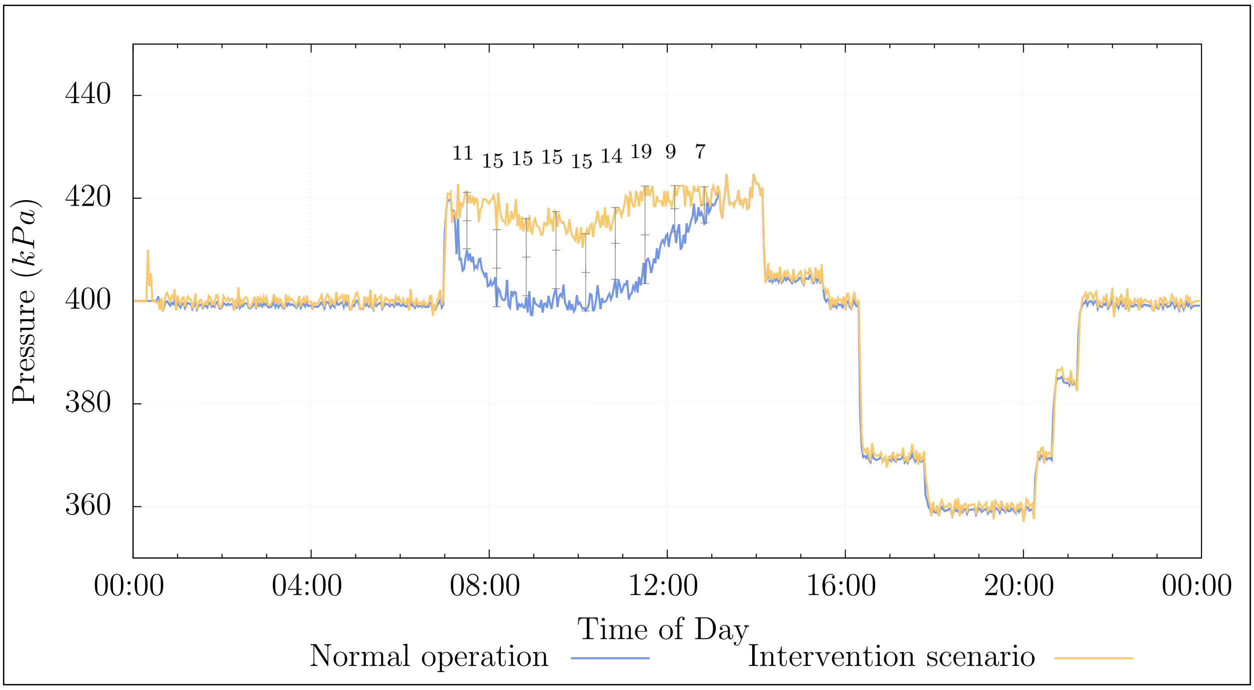

Figure 4.14: The Baseline system pressure compared to the system pressure when refuge bay leaks are reduce.

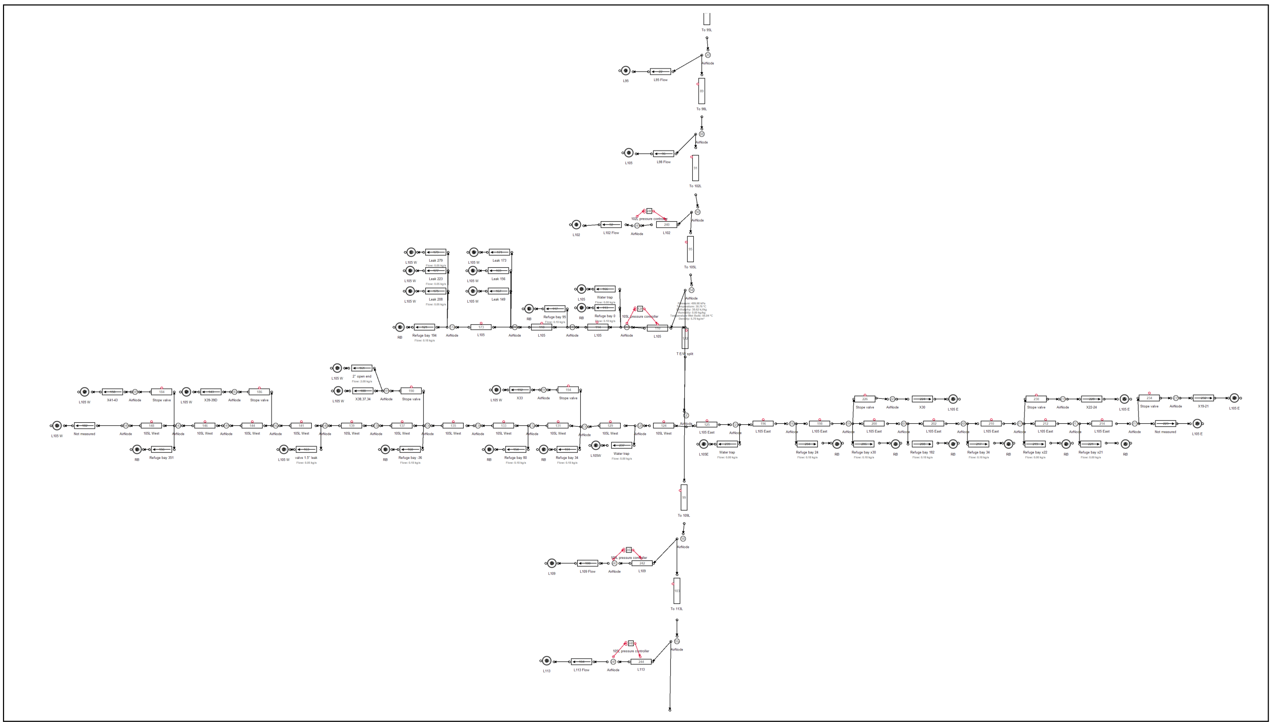

Figure 4.15: Underground level layout.

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

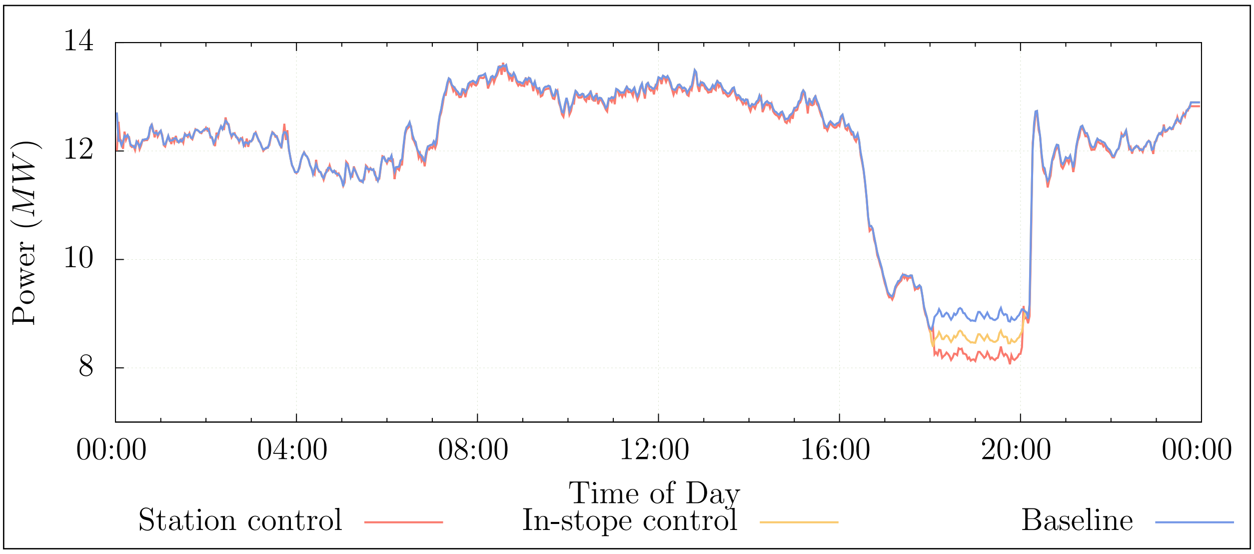

Figure 4.16: Comparing simulated pressure interventions at the stopes and the station of 105L.

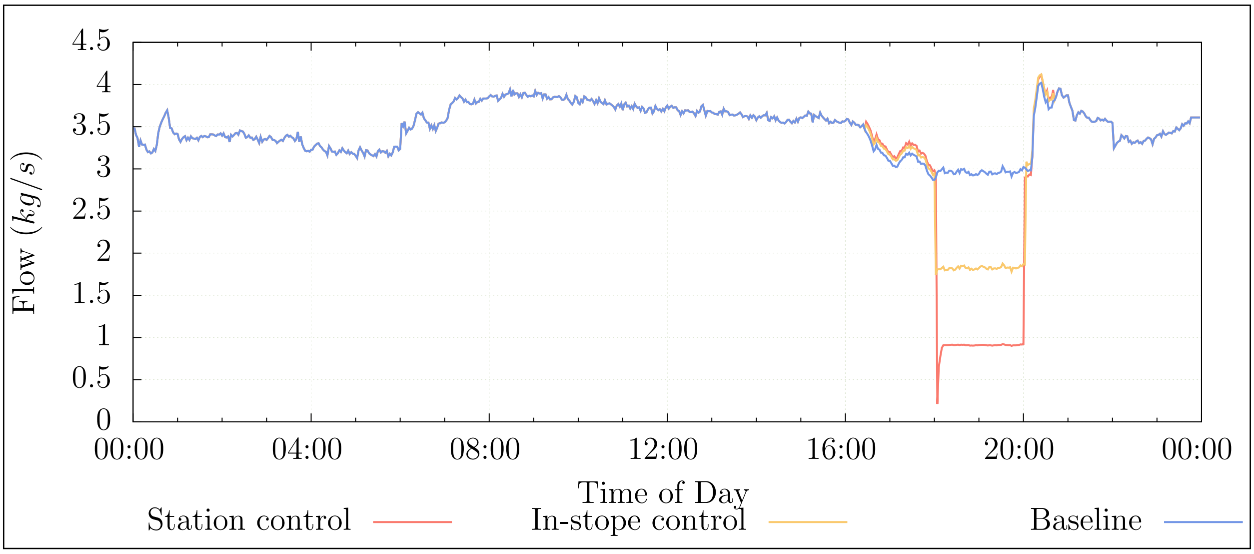

Figure 4.17: Flow reduction during blasting period for 105 level

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 4.3.

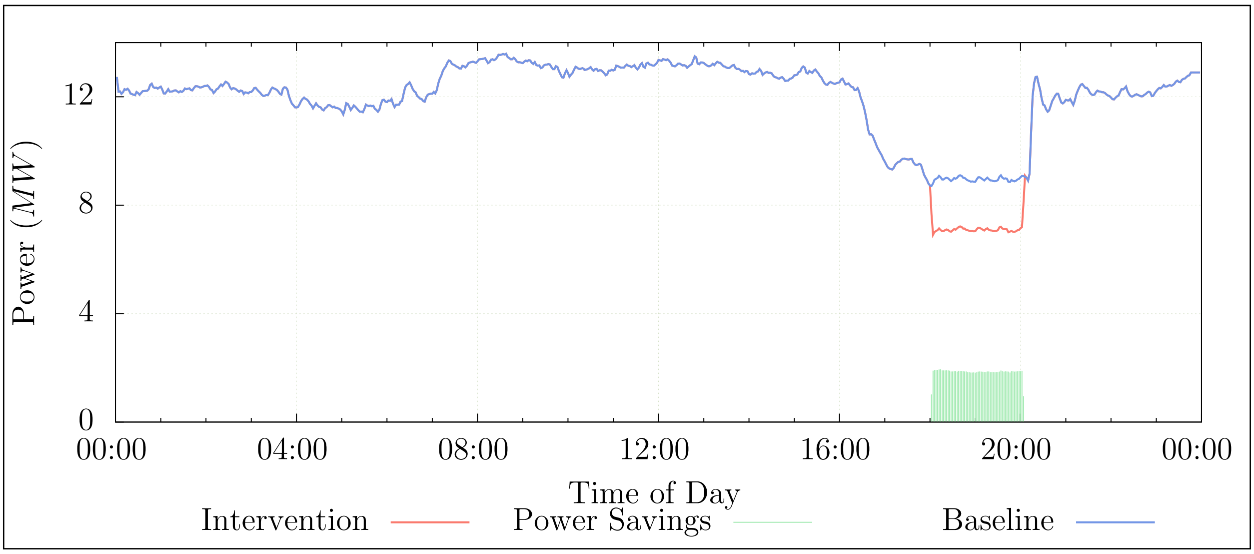

Figure 4.18: Saving achieved by extending peak time station control to other mining levels

Scenario	Power saving	Cost saving (p.a)	Additional benefit
Scenario 1 results			
Refuge bay leakage reduction	-	-	Increase in drilling pressure
Scenario 2 results			
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 4.2: Comparison of the simulated scenarios

4.4.2 Results

The process was triggered daily. For each period, data inputs shown in table 4.3 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.

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

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

Table 4.3: Data inputs and outputs for the simulation

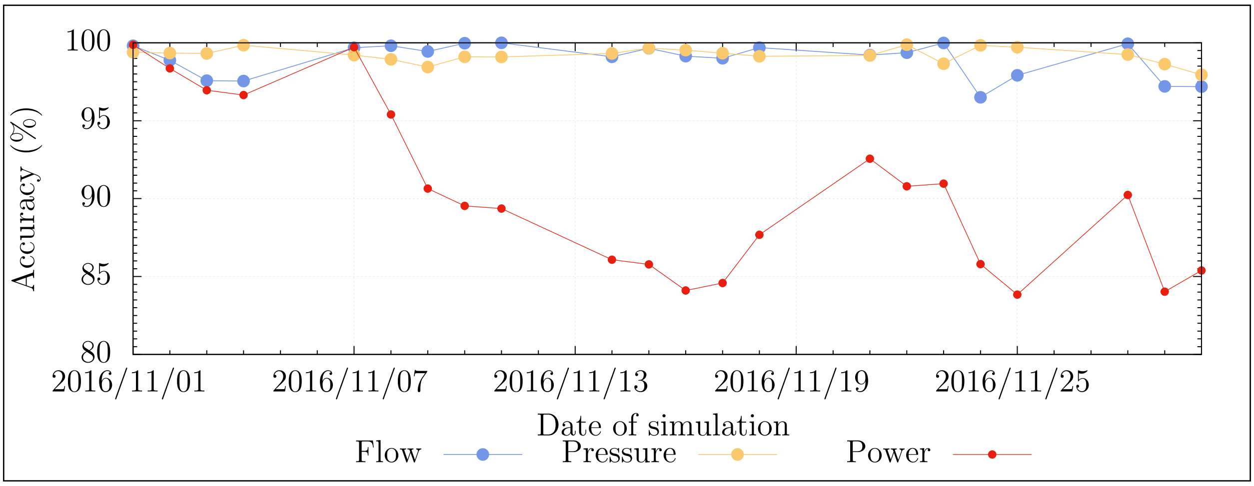

Figure 4.19: The flow, pressure and power error percentages for daily periodic simulations over a month.

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

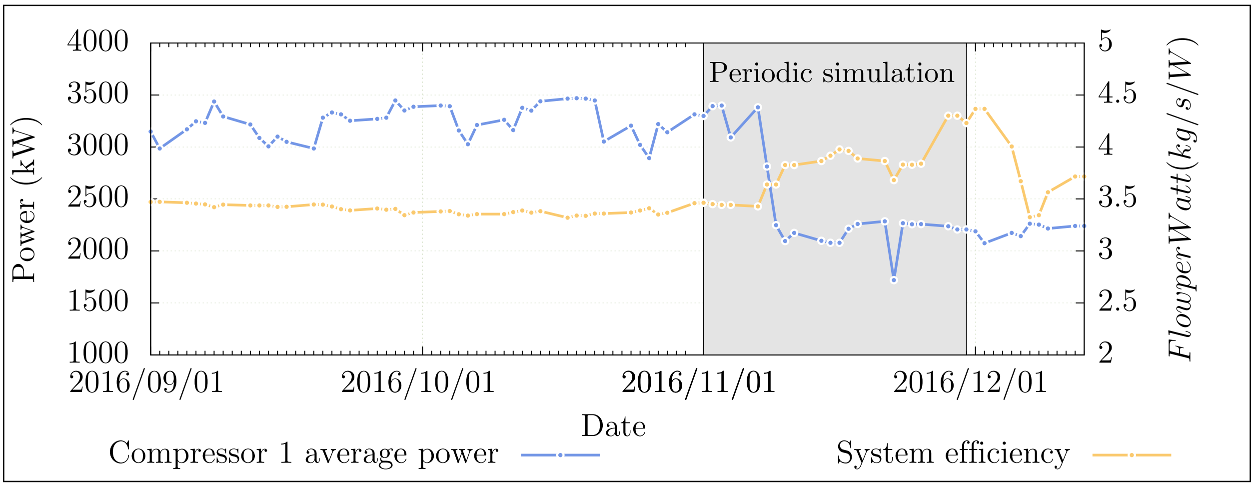

Figure 4.20: Supply efficiency and Compressor 1's average power output over the time of the periodic analysis.

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 validate that the change identified using periodic simulation was caused by the power meter, data from the substation was compared to the combined individual compressors meters. This comparison is shown in Figure 4.21. The comparison shows that the substation power measurement strays from the compressors at the same time that compressor 1 average daily power drops.

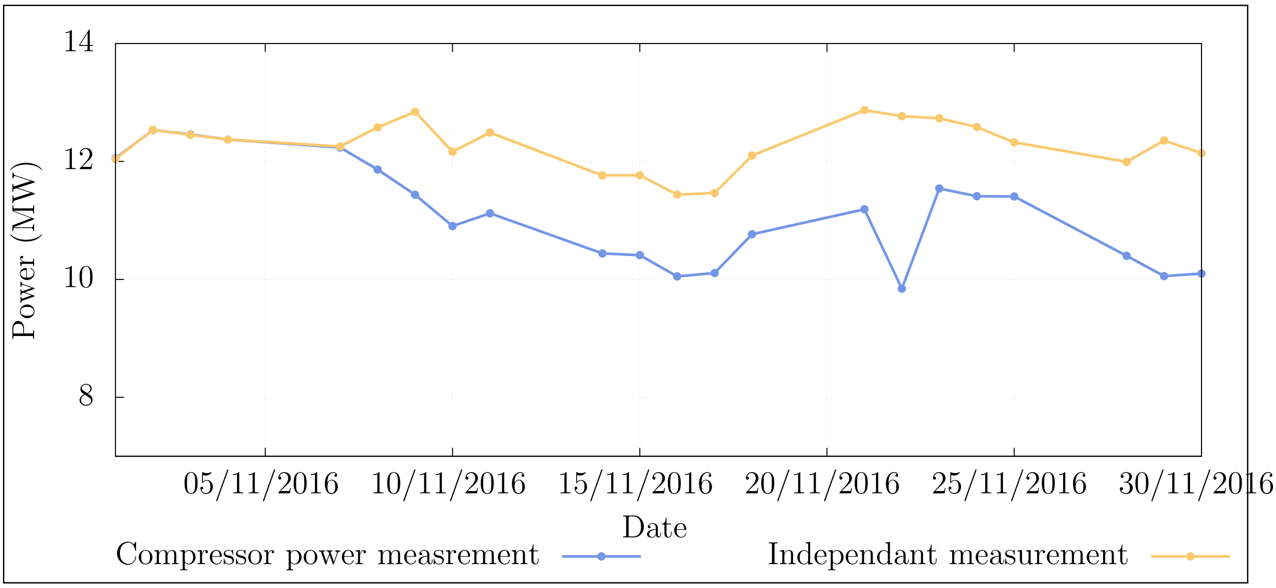

Figure 4.21: Comparison using alternative power source.

4.4.4 Summary

4.5 Potential benefit for SA mines

Using

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 I

Process Flow diagrams

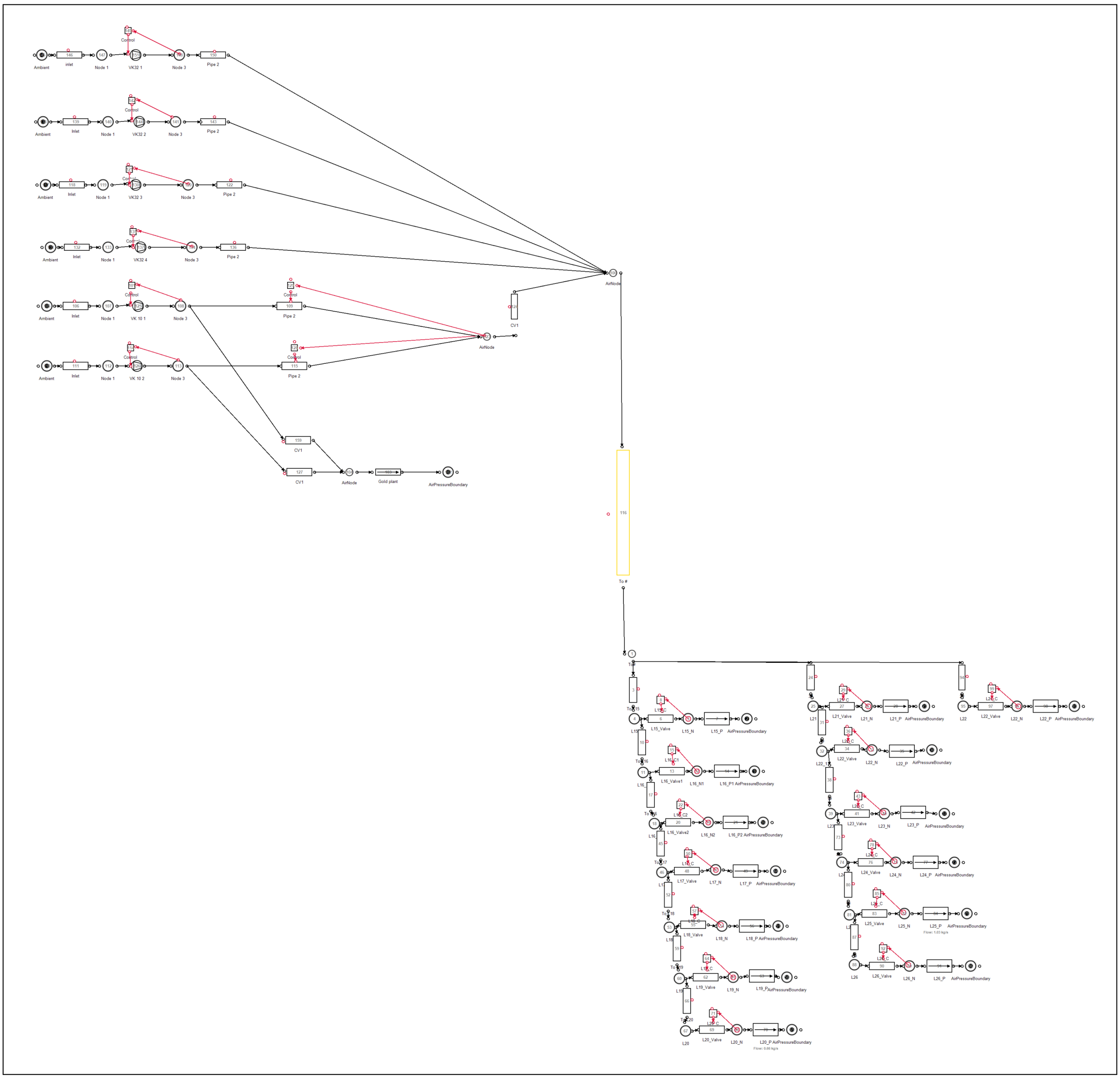

Figure I.1: Mine A: Simulation model diagram

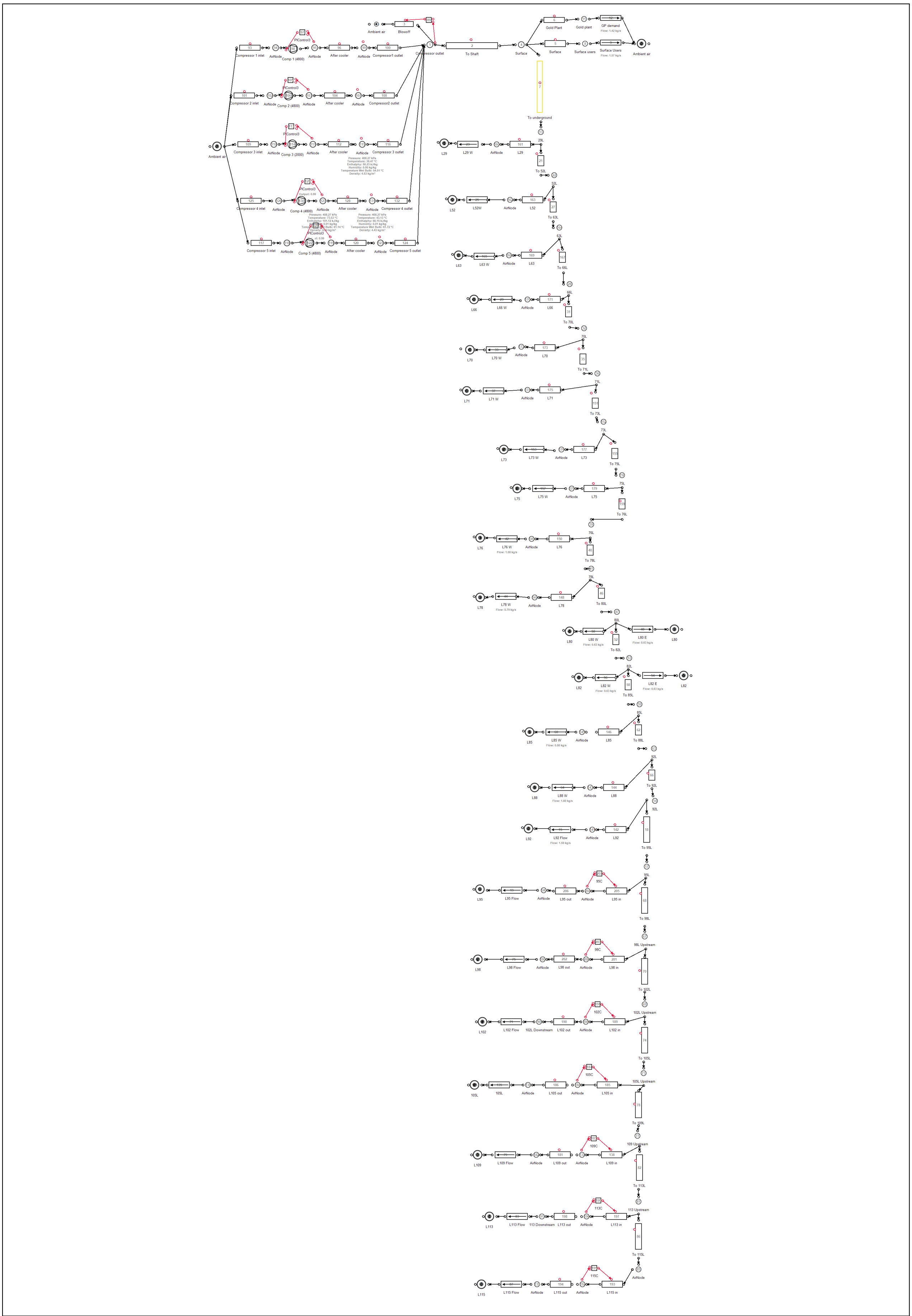

Figure I.2: Mine B: Baseline simulation model diagram.

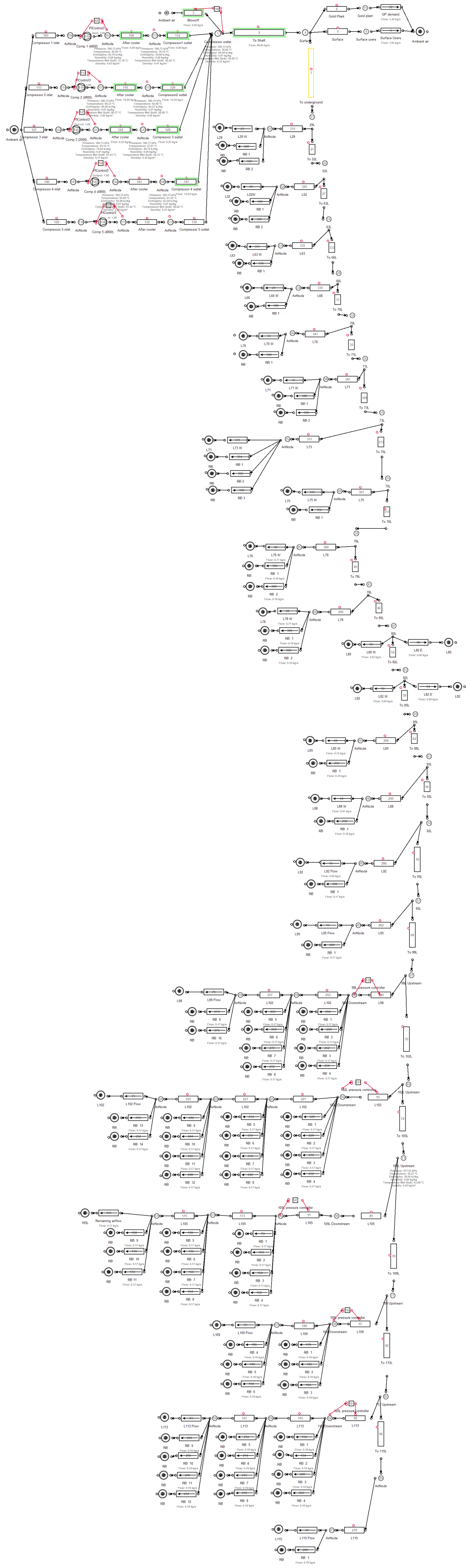

Figure I.3: Mine B: Simulation model diagram for the refuge bay scenario.

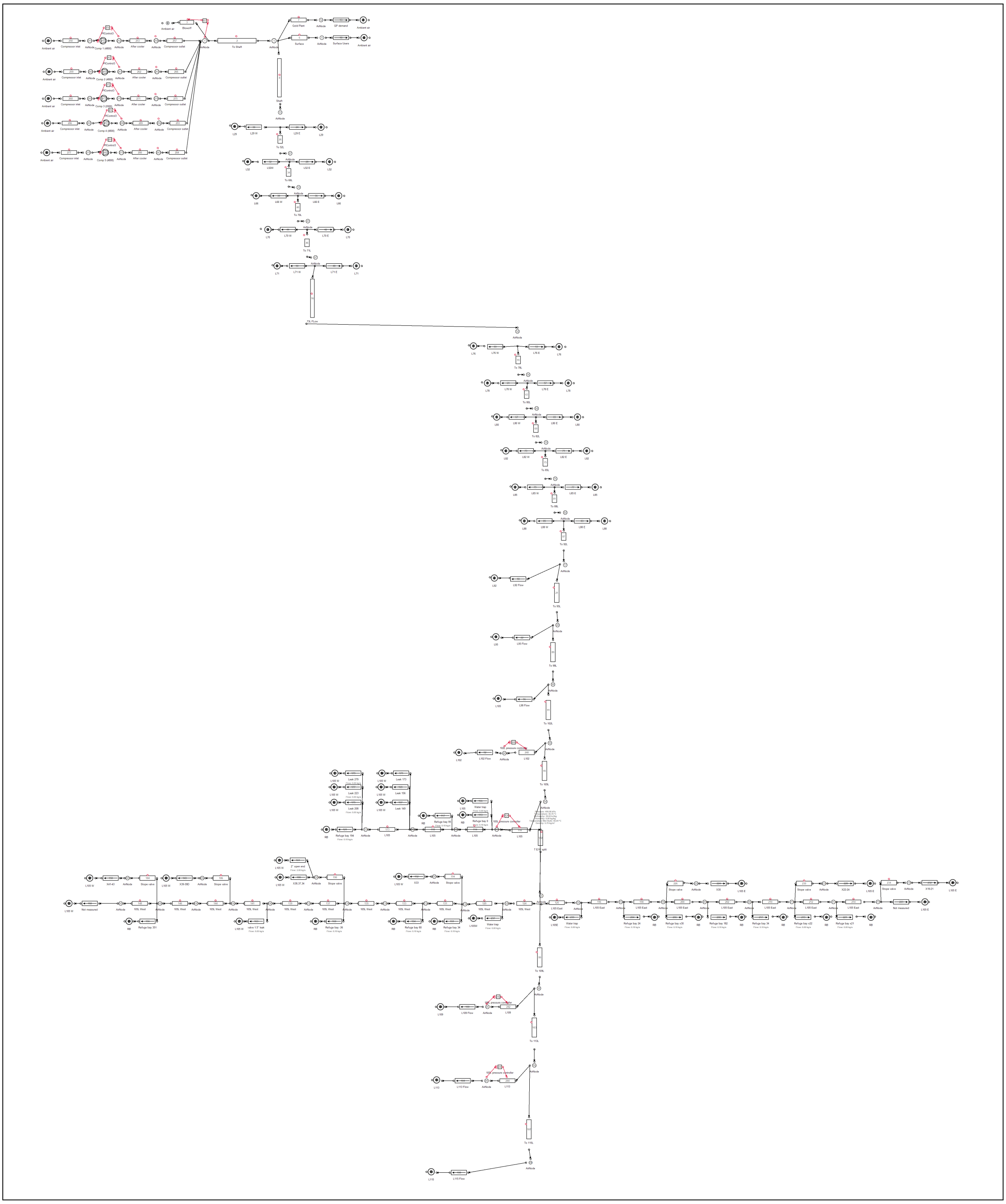

Figure I.4: Mine B: Simulation model diagram for the station isolation stope control.

APPENDIX II

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 II.1: Case study A: Model verification

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 II.2: Case study B: Model verification