Modelling the effect of changes in mining compressed air networks on refuge chambers

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In his essay titled, The World as I See It, Albert Einstein said:

"A hundred times every day I remind myself that my inner and outer life are based on the labours of other men, living and dead, and that I must exert myself in order to give in the same measure as I have received and am still receiving."

This dissertation would not have been possible without the help, support and guidance of my peers. It is thanks to them that I was able to complete this degree to the best of my abilities and I, therefore, dedicate this section to giving thanks to those who made a remarkable impact on my journey.

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ABSTRACT

Keywords: Mining Health and Safety, Compressed Air, Process Simulation, Refuge Chamber

Health and safety are major talking points in the South African mining sector. Various systems are in place to ensure the safety of all mining personnel underground. One such safety device is refuge chambers. Refuge chambers are underground havens where personnel can go to escape toxic gases and smoke build-up. Refuge chambers make use of compressed air to supply safe, breathable air to the occupants of the chamber.

Several studies have been done on the minimum compressed air requirements of a refuge chamber. However, there has not been adequate research done on supplying this compressed air in large and complex mining networks or what effect any changes to the network will have on the supply. With that said, studies have shown that process simulations can accurately predict what the effects of changes to a compressed air network will have on the energy consumption of the mine. Therefore, it stands to reason that process simulations could be used to predict what effect changes to a compressed air network will have on the supply of compressed air to all refuge chambers on the network.

This study aimed to develop a simulation-based methodology to investigate the effects of various compressed air network configurations on the supply to the refuge chambers and then to verify the results with data acquired from a mining case study.

The methodology followed to accomplish this was to gather the necessary information required to build the baseline simulation, which was then calibrated using actual data from the mine in the case study. This baseline simulation was then used to simulate and analyse various proposed changes to the network to ascertain whether the minimum supply to all refuge chambers would be met if the new configuration would be implemented. Once a suitable configuration was found it was then implemented on the mining network and the accuracy of the simulation was validated.

During the case study, two possible changes to the compressed air network were identified and both changes were implemented and analysed independently. After implementation, the actual results were compared with the simulation results and Configuration 1 had a mean absolute error of 4.65% and a mean square error of 0.94 kg^2/s^2 and Configuration 2 had a mean absolute error of 0.78% and a mean square error of 0.40 kg^2/s^2. The simulation did, however, tend to underestimate the flow of compressed air to the refuge chambers, but this was not detrimental

to the results as the simulation was used to ensure that the flow to the refuge chamber was above a minimum requirement and as a result this added an additional safety factor to the results.

These results proved that the methodology developed, could be used to estimate what the effects on the compressed air supply to refuge bays will be, if changes to the compressed air network are introduced. This methodology can thus be used as an aiding tool in decision making and give one enough confidence to implement changes. It is also a valuable tool to test various scenarios without the need to physically perform them which is not only beneficial from a safety point of view, but also from a financial one.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

Symbol	Description	Units
a	Fan pressure curve coefficient	-
A	Actual value	-
b	Fan efficiency curve coefficient	-
C	Concentration	-
C_p	Specific heat	kJ/(kg·K)
d	Inner pipe diameter	m
$Err_{\%}$	Error percentage	%
f	Friction factor	-
F	Part load fraction	-
g	Gravitational acceleration	m/s^2
h	Vertical distance	h
k	Polytropic coefficient	-
L	Length of vertical pipe	m
m	Mass flow	kg/s
M	Volumetric flow	L/min
n	Timestamp	-
N	Total number of timestamps	-
P	Pressure	kPa
Q	Corrected mass flow	$kg \cdot K^{0.5}/(s \cdot bar)$
r^2	Coefficient of determination	-
S	Simulated value	-
t	Time	min
T	Temperature	K
U	Change in concentration	L/min
v	Flow velocity	m/s
V	Volume	L
W_e	Electrical power	kW
X	Initial concentration (CO_2)	-
Y	Initial concentration (O_2)	-
Z	Upper safety concentration	-

Greek

η	Efficiency	-
ρ	Density	kg/m^3

LIST OF ABBREVIATIONS

DMR	Department of Mineral Resources
ERS	Emergency refuge station
GP	Gold plant
MAE	Mean absolute error
MHSA	Mine Health and Safety Act of 1996
MSE	Mean square error
OHSA	Occupational Health and Safety Act of 1993
PI	Proportional-integral
PTB	Process toolbox
RSA	South Africa
SCADA	Supervisory control and data acquisition

CHAPTER 1 INTRODUCTION AND LITERATURE REVIEW

1.1 Background

Health and safety regulations in South African (RSA) mines have made large improvements over the last 27 years. In 1993 there were 638 casualties and 8 593 injuries across all mining sectors. Since then there has been a 93% reduction in fatalities and a 73% reduction in injuries resulting in only 51 casualties and 2 406 injuries in 2019 [1].

These regulations for the safety of RSA miners are formalised in the Occupational Health and Safety Act of 1993 (OHSA) and the Mine Health and Safety Act of 1996 (MHSA). The MHSA primarily governs the regulations pertaining to the health and safety of RSA miners. Whereas the OHSA primarily governs the regulations pertaining to factories in RSA. The OSHA act is however referred to by the mining industry, with regards to areas which are not specifically or clearly governed by the MHSA.

Figure 1 illustrates the positive effect that these regulations have had on the safety of miners [1]. The bar graph shows the total fatalities per year from 1993 to 2019 and the line graph shows the decrease in fatalities per million hours worked from 0.5 in 1993 to less than 0.1 in 2019.

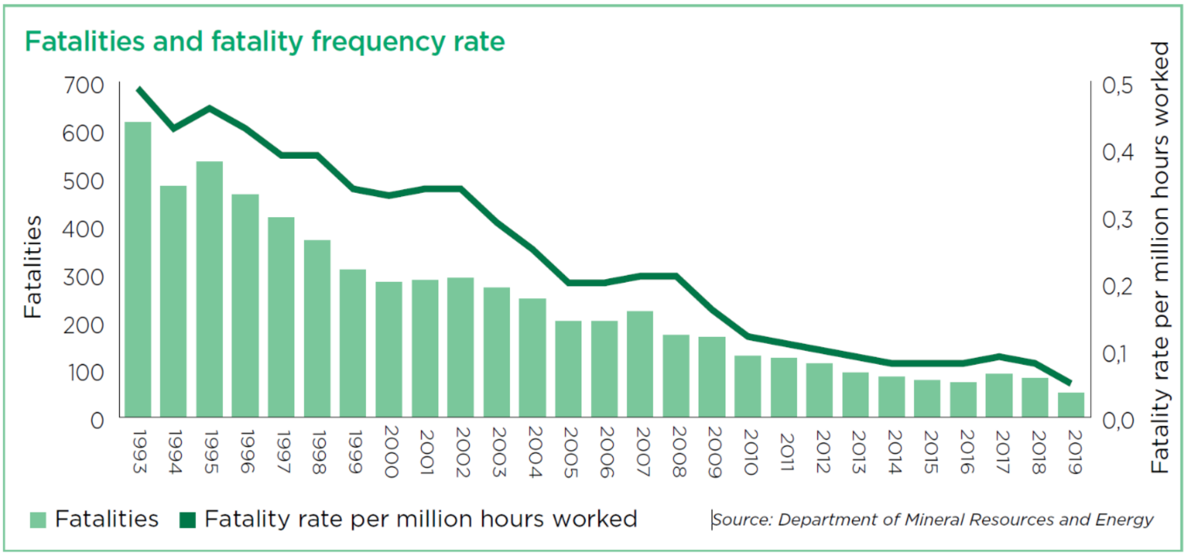


Figure 1: Fatalities and fatality rate in RSA Mines from 1993–2019, sourced from [1]

The year 2017 saw the first increase in mining-related fatalities in ten years and sparked a radical change in how safety in mines was viewed. This change is known as the Khumbul'ekhaya strategy which means "Remember Home". This strategy was developed by the

CEO Zero Harm Forum whose main goal is to eliminate all mining-related fatalities. This strategy's main focus is to increase the focus on safety culture in the mining sector by reminding all that each fatality not only effects the mine but also the families back home [1].

Studies focussed on Sweden's mining sector have shown that the adoption of broader safety management strategies has had a significant effect on the safety of their miners [2]. The Khumbul'ekhaya strategy aims to change the attitude of all personnel to have a safety-first philosophy and increase their focus on safety cultures to ensure the safety of all miners.

The MHSA defines an emergency as "a situation, event or set of circumstances at a mine that could threaten the health or safety of persons at or off the mine, and which requires immediate remedial action, such as the evacuation, rescue or recovery of persons, to prevent serious injury or harm, or further serious injury or harm, to persons" [3].

Mavhura [4] identified several possible emergencies or hazards associated with mining activities. These hazards are:

- Fires
- Fall of ground
- Working at heights
- Flooding
- Explosions
- Machinery (mobile and fixed)
- Noxious gases and fumes
- Noise
- Dust

Power failures can also be added to this list as this is a common occurrence in the RSA. During a power failure, the ventilation system of the mine will be offline which means that no cooling is taking place within the mine and fresh air is no longer circulated which leads to hazardous conditions underground. These hazards are present in all mines across the world and certain measures need to be in place to mitigate the risks associated with these hazards.

Most of these hazards could affect the air quality underground to such an extent that personnel will have to proceed to refuge chamber for health and safety reasons. It is for this reason that refuge chambers are one of the most important safety devices in a mine.

Chapter 16 of the MHSA, Rescue, First Aid and Emergency Preparedness and Response, states that all incidents of explosions, fires and flooding need to be reported. All personnel who go underground need to be issued with a self-contained self-rescuer that can supply the wearer with breathable air for up to two hours and rescue teams need to always be on standby to act on these emergencies [3]. These self-contained self-rescuers are issued purely to provide breathable air to underground employees such that they can safely get to the refuge chambers during certain emergency conditions.

In February of 2018, a power failure at a mine near Welkom caused 955 mine workers to be trapped underground for over 30 hours [5]. Due to the power failure, breathable air could not be supplied by conventional methods and self-contained self-rescuers can only supply breathable air for up to two hours. Therefore, they had to make use of refuge chambers for breathable air.

1.2 Refuge chambers

The purpose of a refuge chamber is to protect all users from irrespirable atmospheres and to sustain life [6]. Refuge chambers provide a haven underground for when accidents occur such as:

- Fires
- Explosions
- Loss of ventilation
- Flooding
- Gas leakage
- Fall of ground

These areas are used to wait for either the atmosphere to become safe to breathe or to be rescued [7]. These rescues can possibly take more than 24 hours to occur and therefore refuge chambers must be able to cater for their occupants for these extended periods of time [8].

Figure 2: Exterior (left) and interior (right) of a refuge chamber[1]

Figure 2 pictures both the exterior and interior of an underground mining refuge chamber. The refuge chamber is sealed-off with a door to separate miners from the outer atmosphere. Pipes enter the refuge chamber to supply breathable air and water to the occupants of the chamber. Electrical and communication cables also enter to provide power to the lighting and to provide communication with the surface.

Brake, Fellow and Bates set up the standard design criteria for emergency refuge stations (ERS) in Australia back in 2001 and is still used to this day by various government entities around the world [9]. In RSA the two main bodies who create the regulations used currently are the Department of Mineral Resources (DMR) and the Mine Ventilation Society of South Africa.

Section 16.6(2) of the MHSA also sets out several regulations in terms of refuge chambers. These regulations are as follows [3]:

> *16.6(2) The employer must take reasonably practicable measures to ensure, that having regard to the number of persons likely to be present in the area served by the refuge bay, every refuge bay complies with at least the following:*
>
> *a) is of sufficient size;*
> *b) is equipped with means for the sufficient supply of respirable air;*
> *c) is equipped with a sufficient supply of potable water;*
> *d) is equipped with sufficient ablution facilities;*
> *e) is equipped with sufficient illumination;*
> *f) is equipped with sufficient first aid equipment;*
> *g) is equipped with efficient means to communicate verbally to the surface;*

[1] "Refuge Station – RED LAKE REGIONAL HERITAGE CENTRE." Internet: *https://www.redlakemuseum.com/refuge-station.html,* [2021/02/18]

h) is situated, where practicable, in an area not being used for storage of combustible material or close to such an area;

i) is constructed in such a way that air containing noxious smoke, fumes or gases will not enter the refuge bay;

j) a plan of the escape route is displayed in the refuge bay, indicating the position of the refuge bay in relation to the shaft or any other egress or access way to the surface;

k) a sign is displayed in the refuge bay, setting out the emergency procedures to be followed in the refuge bay and relevant emergency phone numbers; and

l) has a means to facilitate clear identification of the location of the refuge bay from the outside in poor visibility.

Additional regulations include that the ERS must be large enough to accommodate the maximum number of persons likely to be present in the area with a minimum floor area of 0.6 m^2 per person, with seating arrangements where applicable [7], [8], [10]. Any additions to the ERS must in no way lower the integrity of the chamber or reduce the size below the minimum requirement [7], [10].

Every ERS should provide a fail-safe means of providing breathable air or at least have a backup supply inside the chamber, such as oxygen tanks, should the main supply fail that must either be fire resistant or protected from any possible fires [7]–[10]. Where compressed air is used to supply breathable air to the ERS, the supply should be tamper-free with a control valve with a 30 mm orifice to ensure constant supply situated on the inside of the chamber such that the chamber will always have a positive pressure to prevent unwanted gasses to enter. [7], [8], [10] .

This will ensure that when the miners enter the refuge chamber, they are assured that the environment is safe to breath in as usually the gasses will reach the area where the refuge chamber is located long before they have. This air is typically supplied via a 150 mm pipe located no more than 300 mm from the roof of the ERS [7] in order to eliminate the build-up of carbon dioxide and limit the reduction of oxygen within the ERS [8].

Each ERS must also be fitted with ablution facilities that must be tested before commissioning and at regular intervals [7], [8], [10]. The entire refuge chamber should be inspected at regular intervals.

All ERSs should not be further away than the maximum range of the self-contained self-rescuers from working areas on the normal route followed by workers [7], [8], [10]. This is usually around 660 m to 750 m from the working area [7], [8]. The ERS should be positioned away from any combustible material and adverse travelling conditions [8], [10]. The ERS should be situated in the fresh air side of air ways and may not be situated in a return airway.

Brick walls should be used in construction that can withstand the effects of any nearby explosions and coated in two coats of oil-based paint to avoid gas leakage [7]–[10]. The ERS should be sealed using a single, weighted steel door that opens to the outside to maintain a positive pressure within the chamber and prevent air leakage [7]–[10]. The installed door should also be able to withstand the effects of any possible nearby explosions [7], [10].

Notices should be present on the walls of the ERS to offer simple directions on how to treat electric shock, drowning, heat exhaustion, heatstroke and gassing. [7] Smoking is prohibited throughout the entire underground section. [8]–[10].

Additionally, the outside of the ERS must be fireproof and have emergency lighting that can operate even during power failures as well as a way to reduce the internal temperatures to avoid heat-related conditions afflicting the occupants [9], [10].

It is very important to adhered to these safety guidelines as failure to do so can result in the unnecessary loss of life. One example of such an event is the 2018 Palabora copper mine fire [11]. On 15 July 2018, a fire broke out at a conveyer belt. Mine workers rushed to the nearest refuge chamber, but the pipe supplying compressed air to the chamber were located above the conveyer belt and were damaged in the blaze.

No secondary oxygen source was available inside the chamber and due to the loss of compressed air supply a positive pressure could no longer be maintained within the chamber. The carbon dioxide and carbon monoxide levels inside the chamber thus raised to dangerously high levels and the temperature inside the chamber reached 70°C. Therefore, due to the loss of a sealable door, no back-up oxygen supply, gas detection or air-conditioning 3 miners lost their lives within the chamber.

Other issues with refuge chambers in deep level mines is that they are constantly relocated as the working areas move further away due to normal mining activities without confirming if the air supply will still be acceptable. As the compressed air supply is rarely measured to confirm that it is of sufficient quantity and pressure.

1.3 Safety requirements for air supply to refuge chambers

Several studies have revealed that there are two main requirements namely, positive pressure in the refuge chamber as well as the quality and quantity of breathable air. The consensus is that maintaining a positive pressure within the refuge chamber will ensure that no toxic gases or fumes can enter the refuge bay. A gauge pressure of 200 Pa to 300 Pa is recognised as a positive pressure, but the absolute pressure inside the refuge chamber will be determined by the environmental conditions surrounding the refuge chamber [9].

Kielblock *et al.* [12] simulated the effect of people entering a refuge chamber on the rise of toxic gases inside the chamber. They simulated 30 people entering the chamber, each time breaking the seal for five seconds as they opened the door and entered the chamber. The results showed that if a positive pressure was maintained within the chamber the increase in toxic levels was negligible when opening the door.

When it comes to the breathable air requirement, it should be understood what normal breathable air is and what the limitations of the human body are. Normal dry air at the standard conditions of 101.325 kPa and 0 °C has a volumetric distribution of 20.95% oxygen, 78.08% nitrogen, 0.0314% carbon dioxide, 0.93% argon and trace amounts of 14 other gases.

An average person who is at complete rest will inhale about 7.5 litres of air a minute and exhale air with a quality of 17% oxygen and 3.2% CO_2. [9] This results in an oxygen consumption of 0.3 L/min and a CO_2 production of 0.24 L/min, but a miner trapped underground in a confined space cannot be considered an average person at rest. In 1999, Venter *et al.* [13] found that using an oxygen consumption of 0.5 L/min would be a more conservative estimate for use in refuge chamber designs. This equates to a fresh air consumption of 12.5 litres per person.

In 2015, Yang *et al.* [14] did experiments to determine the minimum pressure difference required to create a positive pressure system within a mine refuge chamber. The study focussed on creating a positive pressure barrier that would prevent air leakage to military-grade proportions and to limit the build-up of carbon monoxide, methane and carbon dioxide from external factors. They found that, at a pressure differential of between 200 Pa and 1 000 Pa, the air leakage within the chamber was less than 0.05 m^3/min which is the military-grade requirement for airtight sealed containers. At differential pressures between 200 Pa and 800 Pa the methane concentration did not increase at all, even after three hours of exposure. However, it was found that if the differential pressure decreased below 500 Pa the carbon monoxide levels within the chamber would equalise at a dangerous level.

It was then concluded that, to create a safe environment within the refuge chamber using a positive pressure barrier, the pressure within the chamber must remain over 500 Pa higher than the pressure outside of the refuge chamber.

Yang *et al.* [15][2] also did a manned test with 50 miners in an actual refuge chamber located on level 150 of the Guilaizhuang mine. They observed the oxygen uptake and carbon dioxide generation during a 48-hour period while doing various activities that would not be uncommon during an emergency and awaiting evacuation. The maximum oxygen consumption observed was 0.362 L/min per person and the maximum carbon dioxide production observed was 0.312 L/min per person.

According to Hartman *et al.* [16], the oxygen limit within a mine should never drop below 19% by volume. At 18% workers will start to have difficulty breathing. At 14% workers will lose coordination abilities and start making irregular mistakes along with emotional outbursts. At 12% major health issues and vomiting can occur and at 10% unconsciousness and death are inevitable. It is thus recommended to keep the oxygen levels within a refuge chamber above 19%.

In 2018, Yong *et al.* [17][2] did a study where they exposed 32 subjects to high temperature, relative humidity and carbon dioxide concentrations in an underground refuge chamber and measured the effects of these conditions on the human body. They found that at the high temperatures and relative humidity that is common in most mines, most workers started complaining about severe headaches and the quality of the air when the carbon dioxide concentrations went above 0.5%. Therefore, it is recommended that the carbon dioxide concentration be maintained under 0.5%.

Figure 3 shows the changes in the oxygen and carbon dioxide concentrations if a single miner was to be left in a refuge chamber that contains one cubic metre of air and no compressed air ventilation. The blue line represents the oxygen concentration within the chamber, with the grey line representing the lower safe limit and the orange line represents the carbon dioxide concentration within the chamber, with the yellow line being the upper safe limit.

[2] The author of this dissertation does not endorse similar research which makes use of human test subjects.

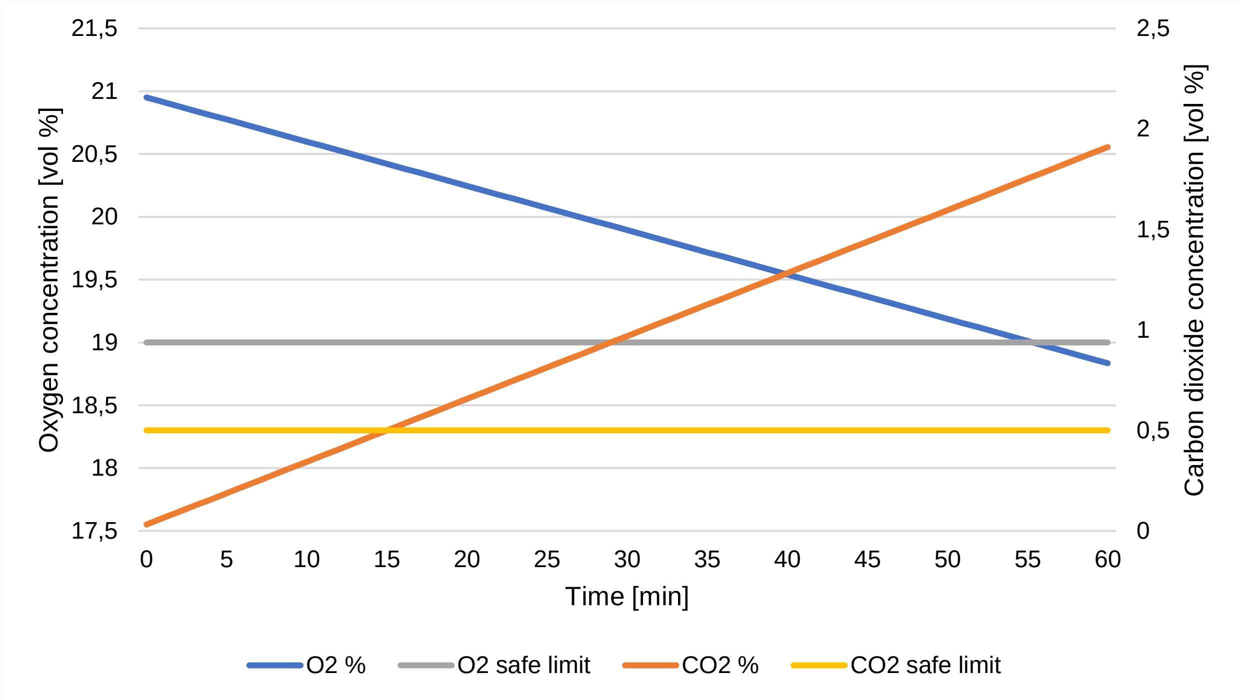


Figure 3: Changes in O_2 and CO_2 concentration due to one miner in a cubic metre of air [13], [16], [17]

It is evident from the graph that the oxygen safety limit is reached after 56 minutes and the carbon dioxide safety limit is reached after only 16 minutes. Thus, it is concluded that limiting the carbon dioxide build-up is the defining factor in compressed air delivery requirements.

In 2015, Yang *et al.* proposed a simple equation for calculating the required compressed airflow to a refuge chamber [15] . The equation is as follows:

$$M = \frac{U_{CO_2}}{Z_{CO_2} - C_{ICO_2}} \tag{1}$$

where M is the flow requirements per person in L/min, U_{CO_2} is the carbon dioxide production per person in L/min, Z_{CO_2} is the upper safety concentration for carbon dioxide and C_{ICO_2} is the concentration of carbon dioxide in the compressed air supply.

If the values mentioned earlier are substituted, it will result in a minimum required airflow of 66.58 L/min per person, which is the exact same value that Yang *et al.* [15] found.

In 2016, Shao *et al.* [18] created a theoretical model for calculating the carbon dioxide and oxygen concentration within a refuge chamber as a function of time. Two assumptions were made in the development of this model namely, that the pressure and temperature within the chamber remain constant so that the inlet airflow is equal to the outlet airflow and that the gases inside the chamber are evenly mixed such that the outlet oxygen and carbon dioxide concentrations are equal to the concentration within the chamber.

The model for the carbon dioxide concentration is as follows [18]:

$$\frac{dC_{OCO_2}}{dt} = -\frac{M}{V}C_{OCO_2} + \frac{MC_{ICO_2} + U_{CO_2}}{V} \tag{2}$$

where C_{OCO_2} is the concentration of carbon dioxide in the chamber, t is time in minutes and V is the total volume of the chamber in litres.

Solving Equation 2 yields:

$$C_{OCO_2} = X_0 e^{\left(-\frac{Mt}{V}\right)} + \left(\frac{U_{CO_2}}{M} + C_{ICO_2}\right)\left(1 - e^{\left(-\frac{Mt}{V}\right)}\right) \tag{3}$$

where X_0 is the initial concentration of carbon dioxide in the chamber.

The model for the oxygen concentration is as follows [18]:

$$\frac{dC_{OO_2}}{dt} = -\frac{M}{V}C_{OO_2} + \frac{MC_{IO_2} - U_{O_2}}{V} \tag{4}$$

where C_{OO_2} is the concentration of oxygen in the chamber, C_{IO_2} is the concentration of oxygen in the air being fed to the refuge chamber and U_{O_2} is the rate of oxygen consumption in L/min.
Solving Equation 4 yields:

$$C_{OO_2} = Y_0 e^{\left(-\frac{Mt}{V}\right)} + \left(+C_{IO_2} - \frac{U_{O_2}}{M}\right)\left(1 - e^{\left(-\frac{Mt}{V}\right)}\right) \tag{5}$$

where Y_0 is the initial concentration of oxygen in the chamber.

When assuming a refuge chamber with a volume of 15.2 m^3 is housing five miners and is filled with normal air Equation 3 and 5 are used to calculate the oxygen and carbon dioxide concentrations inside the chamber when supplied with the minimum compressed air, as stipulated by Yang *et al.* Figure 4 shows the results of this example. The blue line shows the change in carbon dioxide concentration in the chamber and the orange line shows the change in oxygen concentration in the chamber.

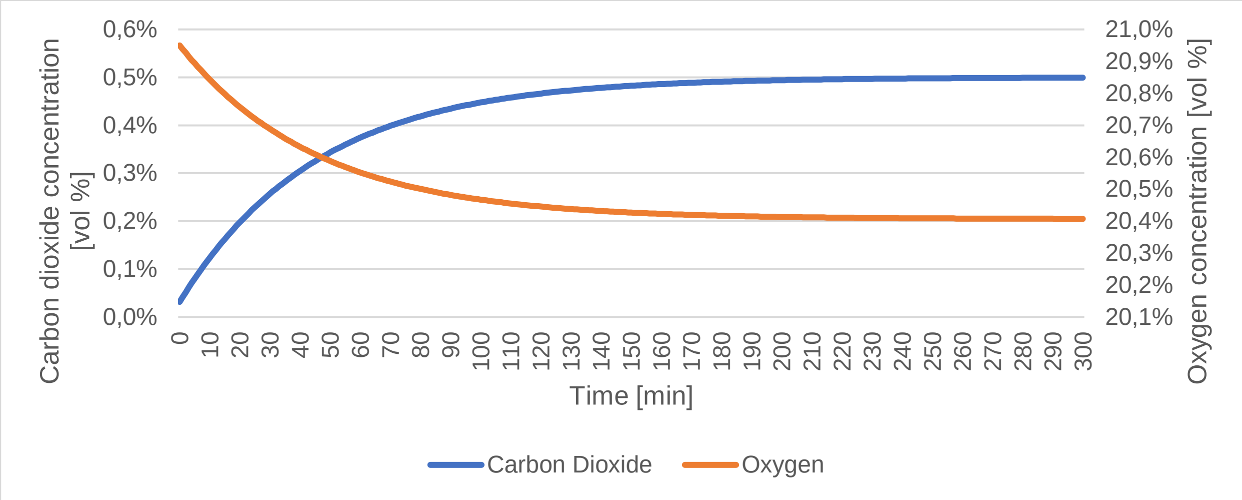


Figure 4: Changes in CO_2 and O_2 concentrations in an ERS with minimum supply [15], [18]

As seen in this figure the oxygen concentration initially lowers and then stabilises at 20.4%, which is well above the minimum requirement of 19%. The carbon dioxide concentration increases initially and then stabilises at 0.5% which is the upper safety limit. Thus, we can safely say that Yang *et al.*'s formula can be used to estimate the minimum compressed air requirement for a refuge chamber.

The aim of these studies was purely to establish what the air requirements in a single refuge chamber should be and the results provided valuable information for further studies. This information can now be used to extend to the supply of compressed air to multiple refuge chambers within a mining network as well as other compressed air users to ensure that the correct airflow and pressure is delivered to all.

1.4 Mining compressed air networks

A typical mining complex has several compressed air users both on the surface (Table 1) and underground (Table 2) [9], [15], [19]–[21]. Each of these users requires compressed air at a different pressure and flow rate, these requirements can vary significantly from mine to mine.

Table 1: Surface compressed air user requirements

Compressed air user	Description	Requirement
Ore processing plant	Extracts precious minerals from mined ore Uses agitation and instrumentation air	0.08–0.7 m^3/s 420–500 kPa
Workshops	Servicing and maintenance of existing equipment as well as the construction of new equipment	0.028 m^3/s 250 kPa
Ore hoisting	Pneumatic cylinders on the skips and stations	0.071 m^3/s 420–500 kPa
Surface control valves and guide vanes	Actuators on control valves, guide vanes on compressors and ventilation fans	Very low flow rates 350–600 kPa

Table 2: Underground compressed air user requirements

Compressed Air User	Description	Requirement
Agitation	Agitation of water dams and pre-processing of ore in leaching tanks	0.47 m^3/s 200–300 kPa
Workshops	Servicing and maintenance of existing equipment as well as the construction of new equipment	0.0094–0.028 m^3/s 250 kPa
Ore loaders	Underground hoppers are used to load the locomotives that transport the ore	0.28 m^3/s 350–860 kPa
Refuge chambers	Supply of breathable air during emergencies and to provide a constant positive pressure within the chamber	0.0094 m^3/s or 0.0011 m^3/s per person 150–300 kPa
Sweeping	Cleaning of areas after blasting (stopes) or drilling (development)	0.47–0.71 m^3/s 250 kPa
Ore transport	Trams are used to transport ore from loading boxes to the shaft to be hoisted	0.23 m^3/s >350 kPa
Drilling	Used in stopes to drill holes for explosives and in the development of new mining areas	0.085–0.42 m^3/s 350–620 kPa
Loading boxes	Used to load mined ore onto skips to be hoisted up the shaft to the surface	0.024 m^3/s 350–600 kPa
Ventilation	Used to cool down certain mining areas	0.019–0.35 m^3/s 350–620 kPa
Raise borers	Used to create vertical connections between different mining levels	0.28–0.42 m^3/s 450 kPa
Other pneumatic equipment	Pneumatic doors, shotcrete machines, motors, welders, lifts, fans, light and valve actuators	0.019–0.35 m^3/s 420–500 kPa

One additional user which is not mentioned above is that of leaks. Even though leaks are not a user in the traditional sense they do this pose one of the biggest challenges faced with underground compressed air networks. One method of assuming the amount of compressed air lost to leaks present in an area would be to determine and then subtract all the flow rates from that of the total supply to the section or level and then assigning the difference to the category of leaks.

Mines make use of large multi-stage centrifugal compressors to supply the required compressed air at the required pressure to all these different users. These compressors are preferred over positive displacement compressors due to [22]:

- Supplying a higher flow rate for the same size
- Being more energy-efficient
- More controllable pressure delivery due to guide vane control
- Less moving parts, thus requiring less maintenance

Figure 5 shows the typical components found in an industrial compressed air system [18]. Mining compressed air systems are much larger than that of an industrial system, but they do share many of the same parts and thus an industrial representation can be used to explain some of the basic components.

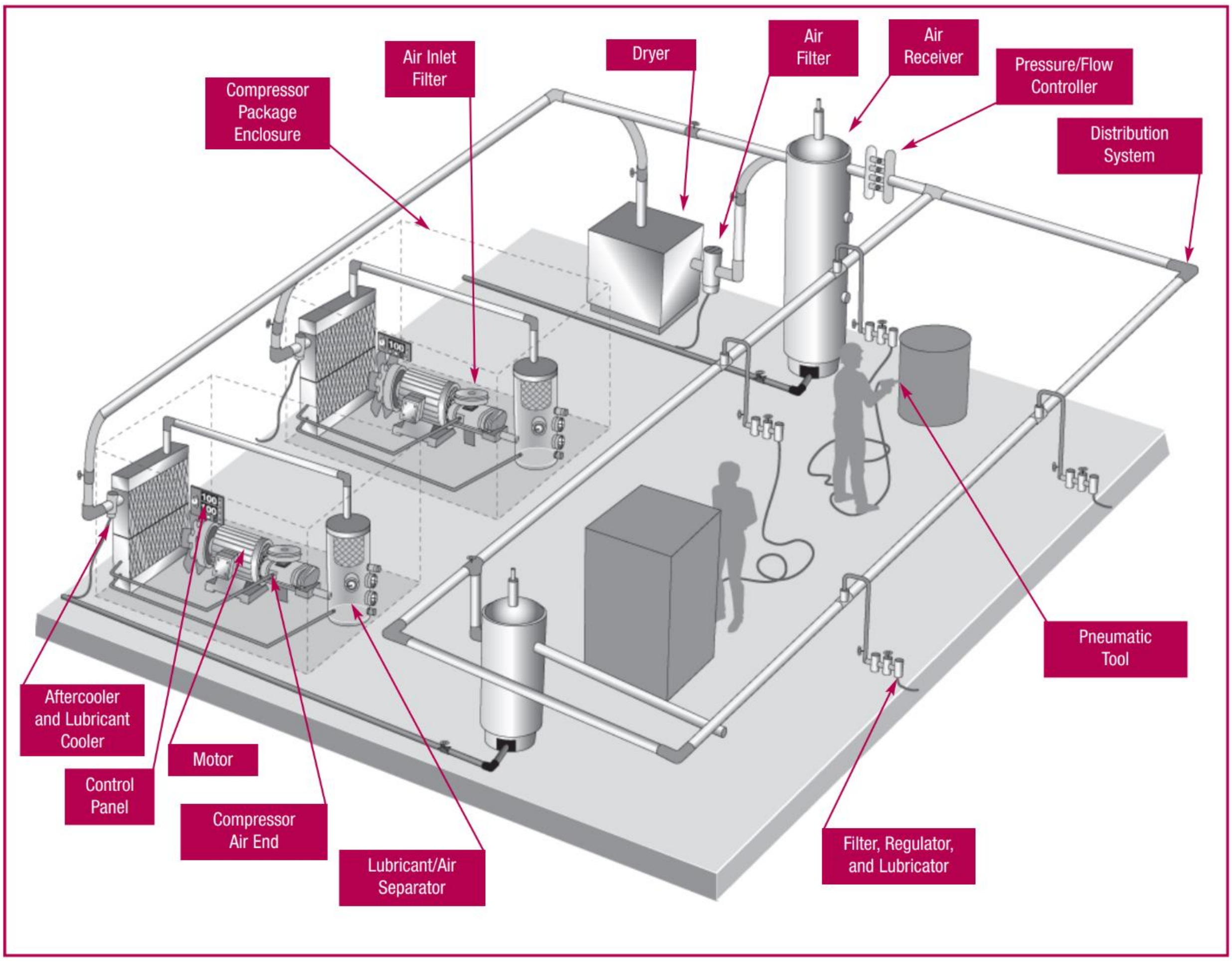


Figure 5: Components of a typical industrial compressed air system [23]

Some of the main components to take note of are [23]:

- **Intake air filter:** The air being sucked into the compressor needs to be filtered to remove dust that can cause a lot of friction within the compressor causing wear-and-tear damage over time.
- **Motor:** Converts electrical energy into mechanical energy, which is then used to compress the air to increase the pressure.
- **Inter-stage cooler:** Decreases the temperature of the air between compressor stages to increase the efficiency of the compressor by reducing the energy required to compress the air further.
- **After-cooler:** Used to decrease the temperature of the air leaving the compressor in order to remove the moisture from the air.

Compressors used in mining are much larger than illustrated in Figure 5. These compressors also have guide vanes at the air intake after the air filters to control the amount of air entering the compressor. The distribution system in mine compressed air networks is also much larger, often spanning over several kilometres with various users connected to the network.

The fact that the network in so large and that it is located underground poses the following challenges:

- The network is difficult to maintain thus the network is subject to leaks and potentially faulty equipment
- The large quantity and location of all the air users make it difficult to physically identify all of them, not to mention measuring the applicable flows and pressures.
- Changes to the network can have significant impact on the various users, because of the interconnectivity and complex nature of the network.

All mine compressed air networks can be characterised into one of two groups [22]:

- Stand-alone networks
- Ring feed networks

In a stand-alone network, one compressor house would supply compressed air to one shaft and in some cases also a processing plant. As can be seen in Figure 6 this is a very basic network.

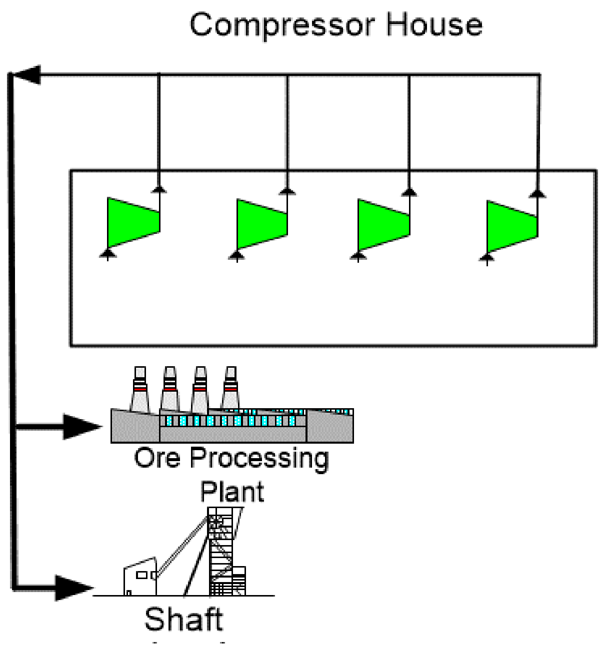


Figure 6: Stand-alone network

In the case of a ring feed network there can be several compressor houses supplying compressed air to numerous shafts and ore processing plants. As can be seen in Figure 7, this can be a very complex system with connections both above ground and below ground. It should be noted that a single compressor can supply a ring feed network as well. If the supply line creates a closed loop in such a way that air can be supplied from multiple sides, it is classified as a ring feed. For instance, if a user is connected to a ring feed and a pipe needs to be closed for whatever reason, the user is still supplied from another leg on the network.

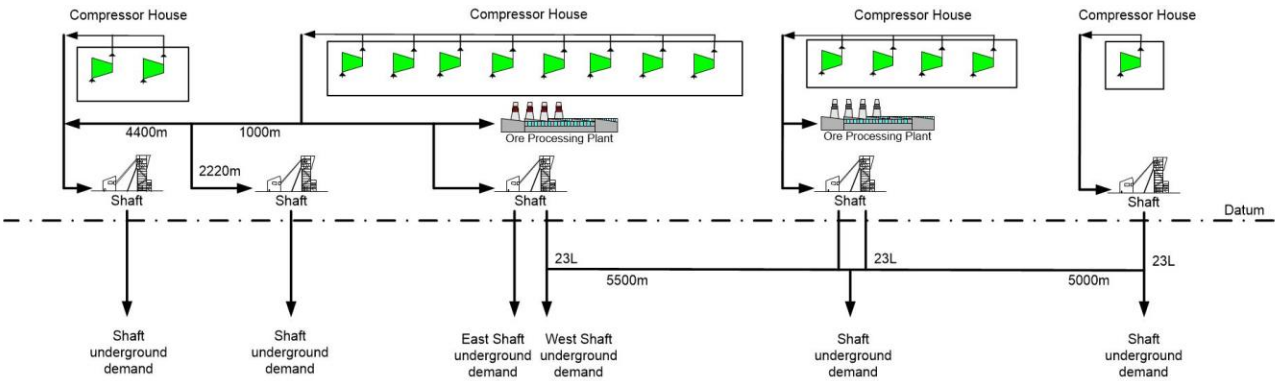


Figure 7: Ring feed network

Some advantages of a ring feed system are that the compressed air flow is decentralised so that it is possible to switch off certain compressors for maintenance and still be able to provide compressed air to all users [22]. Another advantage of a ring feed system is that work on the piping network can be done whilst still supplying the users on the ring feed section with compressed air. Finally ring feed systems assist in reducing pressure fluctuations when multiple users are active at the same time.

Due to the large size of the network, high-pressure drops can occur from the compressor house to the users. This is not advantageous as different users on the system require compressed air at different pressures and thus the pressures within the ring can vary a lot between different locations [22].

This means that it is very difficult to predict what the changes in the network will be if any changes are introduced, such as a compressor being switched off for maintenance. The use of process simulations, however, may provide a means to predict the effect of changes to a compressed air network.

1.5 Compressed air simulation software

Process simulations have various benefits and, owing to developments in the computer industry, have become a tool that is widely used by various industries not only to investigate the future but to constantly optimise daily operations [24].

Some of the advantages of using process simulations are [24]:

- Simulations allow for smarter decision-making, by allowing the test of designs before any capital expenditure has taken place.
- By compressing or expanding time, simulations make it possible to view several days of activity within a few minutes or deeply analyse the activities of one minute over several hours.
- Simulations make it possible to see what the effects of any small changes are to an entire complex system.
- Simulations allow for the investigation of different scenarios without the need to disrupt the actual system.
- Simulations simplify the process of understanding complex systems and how they interact with one another.

Some of the disadvantages of using process simulations are [24]:

- Simulations may be used inappropriately when an analytical solution is preferred.
- Simulations are very resource and time intensive endeavours. Applying less time and resources to a simulation than what is necessary will result is lower than required accuracy.
- Simulation results can be difficult to interpret due to the inherent randomness of a simulation model.
- Learning how to build accurate simulations in time consuming and requires special training.

With this in mind, it is clear that process simulations are the perfect tool to use to understand systems in the mining industry as they can be used to understand the workings of a large complex system such as a compressed air network and then study the effects that change to this network will have on the compressed air supply to all the users within this system.

In order to accurately model a mining compressed air network, the simulation software package used must be able to accurately simulate dynamic air compressors and the fluid dynamics of compressed air through a large integrated mining network. The simulation software package should also be able to simulate transient state scenarios as mines do not operate as steady-state systems.

One such simulation software package is Process toolbox (PTB), developed within ETA Operations. PTB is a transient thermal-hydraulic system simulation and optimisation tool that enables the user to design, analyse and optimise system performance.

PTB has the following features and capabilities:

- The systems consist of pressure nodes and pipes specifying the flow paths.
- Pressure drops are calculated in the pipes and the thermal-hydraulic properties in the pressure nodes.
- The gas flow solver is a compressible quasi-steady-state semi-implicit solver.
- The energy solver is a transient explicit solver.
- The simulation platform simulates steady-state and transient systems for any number of time periods and period size.
- The system component inputs, optimisation variables, optimisation constraints and outputs automatically expand to match the specified number of time periods.

The use of PTB therefore meets the minimum requirements for simulating mine compressed air networks. Other viable simulation packages that are available are Flownex (Figure 8) and KYPipe (Figure 9).

Flownex is a thermal-fluid software system that makes use of a node structure like PTB. Flownex can be used to do reticulation system design and pipe sizing, compressor selection, energy optimisation and heat exchanger sizing (inter- and aftercoolers of the compressors). Flownex is a very powerful simulation tool with applications that stretch far beyond the mining industry. However, it has been found by previous studies that due to the high level of quality data required by Flownex it is not always the best option to be used in RSA mining [25].

Without the required quality of data, the possible error associated with the simulation results would be too high for accepted use in decision making. In order to get the high level of quality data required one would have to do manual measurements at all compressed air users in a network. This is not only very time consuming but also not a practically viable approach to building a simulation.

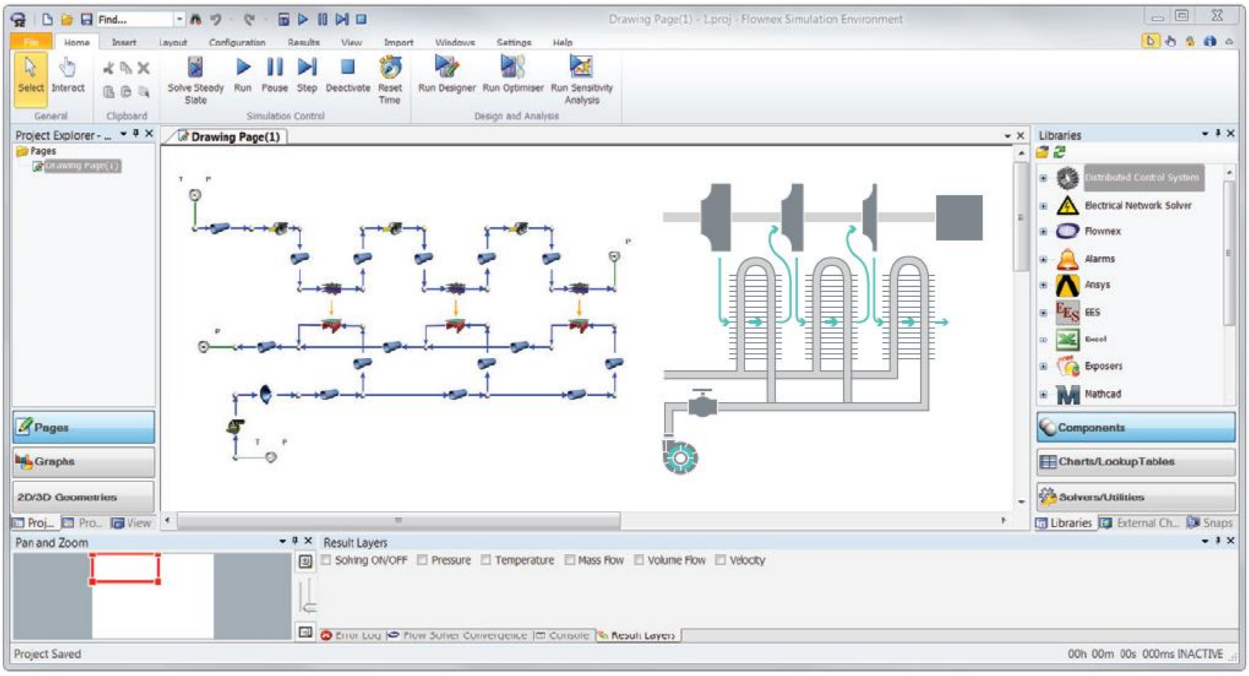


Figure 8: Flownex simulation software environment[3]

KYPipe is a steady-state, one-dimensional, isothermal flow simulation package used with ideal and non-ideal variable density gases applications. It makes use of the Darcy Weisbach equations and ideal gas law to describe the pressure-temperature-density relationships of gases. Due to KYPipe being limited to only steady-state conditions it was deemed to not be suitable for creating high accuracy mine compressed air simulations [26].

[3] "Flownex Simulation Environment – Precise 1D Simulation." Internet: *https://flownex.com/*, [2020/11/09]

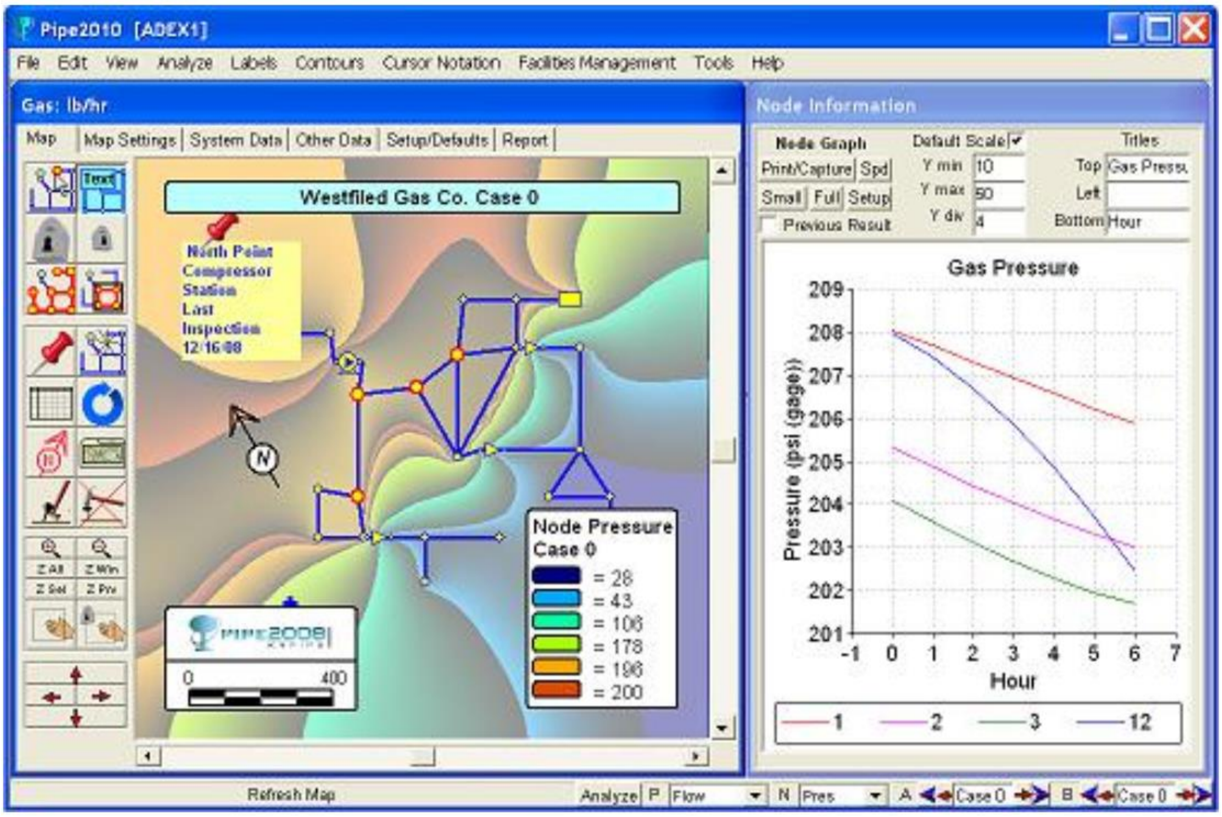


Figure 9: KYPipe Pipe2020 (GAS)[4]

Many studies have been done on the simulation and/or optimisation of mining and compressed air systems. Some of these studies are discussed in the following section.

1.6 Literature on mining compressed air simulations

In this section, several studies are reviewed to emphasise their contributions to the current understanding of mining and compressed air simulations.

In 2014, Kriel [27] made use of simulations to modernise the approach of compressed air demand-side management projects to reduce operational costs on RSA mines. Kriel used simulations as a tool to provide an accurate representation of the benefits of energy savings projects.

Kriel identified that the main data required to create the simulation are as follows:

- Surface supply pressure
- Supply pressure for each level

[4] “Pipe2020: KYPipe Hydraulic Modelling Software (Steady-State).” Internet: *https://kypipe.com/gas/*, [2020/11/09]

- Mass flow of each level
- Shaft mass flow
- Power consumption of compressors

Three months' worth of data were obtained and used to create a typical daily profile for each data set that were used to create the simulation using KYPipe as the simulation software package. Each mining level was then investigated to identify the scope for reducing the pressure requirement of the level. The KYPipe simulation was then used to calculate the expected mass flow on each level.

The required surface pressure was then calculated using the following equation [28], [29]:

$$\Delta P_{Total} = \rho g \left(h - f \frac{Lv^2}{d2g} \right) \tag{6}$$

where ΔP_{Total} is the increase in air pressure in kPa at a vertical distance h in metres from the surface, ρ is the density of air in kg/m^3, g is gravitational acceleration in m/s^2, f is the friction factor of the pipes, L is the length of vertical pipe in metres, v is the flow velocity in the pipe and d is the inner diameter of the pipe.

With the new surface pressure requirement, the improved power usage of the compressors can be calculated using the following equation [30]:

$$W_e = \left[\dot{m} C_p T_{in} \left(\frac{P_{out}}{P_{in}}^{\left(\frac{k-1}{k}\right)} - 1 \right) \right] \frac{1}{\eta_c \eta_m} \tag{7}$$

Here W_e is the electrical power required by the motor powering the compressor in kW, $\dot{m}$ is the mass flow of air in kg/s, C_p is the specific heat of the air in kJ/(kg·K), T_{in} is the inlet air temperature in K, P_{out} is the compressor outlet pressure in kPa, P_{in} is the compressor inlet pressure in kPa, k is the polytropic coefficient (unitless), η_c is the efficiency of the compressor, and η_m is the efficiency of the motor.

This can then be used to quantify the effect of the energy-saving initiative. The KYPipe simulation an error percentage of 10% and therefore the actual savings achieved in the study was 10% less than that predicted by the simulation, but this still resulted in an annual cost saving of R4.17 million.

Kriel's study only focussed on changing the operational setpoints of the compressors and did not consider changes in the compressed air network. Bredenkamp [21], however, did use simulations to quantify the effect of changes to a compressed air network on cost savings. In this study, Bredenkamp simulated two scenarios: one where two compressed air networks would be connected and one where a compressor was relocated from an abandoned shaft to an active shaft. KYPipe was also used as the simulation software package.

Through the study, it was shown through simulations that by relocating the compressor an increase in compressed air pressure could be realised while decreasing the compressor power required. This resulted in a continual daily power saving of 2 100 kW. In the second scenario, one compressed air network was oversupplying its users. It was thus proposed to connect this network with another network by means of a new pipeline.

This reconfiguration of the compressed air network resulted in a daily power saving of 1 700 kW. This study showed that simulations can be used accurately to estimate major changes to a compressed air network. It may therefore be possible to use simulations for scenarios other than for the purpose of energy savings.

In 2015, Zahlan and Asfour [31] posed the question that if it was possible to lower the energy usage of a compressed air system by moving the location of the compressors, how would one determine the most efficient location for said compressors? They developed a mathematical model using MATLAB that could accurately determine the optimal location for a compressor within a manufacturing plant.

Their model also considered the possibility of placing a compressor in a certain location. As the location may be blocked by unmovable equipment or in an important walkway, it was critical to consider this factor. They referred to it as the personal preference factor.

They divided the factory floor into several zones of equal size and then evaluated the energy output for the compressor when placed in each of these zones. As can be seen in Figure 10, each zone in the factory would deliver a different energy output with Zone 85 deemed to be the most energy optimal.

Unfortunately, this location is not a feasible location as it would have placed the compressor in the middle of a production line. Zone 145 was selected as it had the best energy output to personal preference factor ratio. This resulted in a power-saving of 1.71 kW or 6.2%.

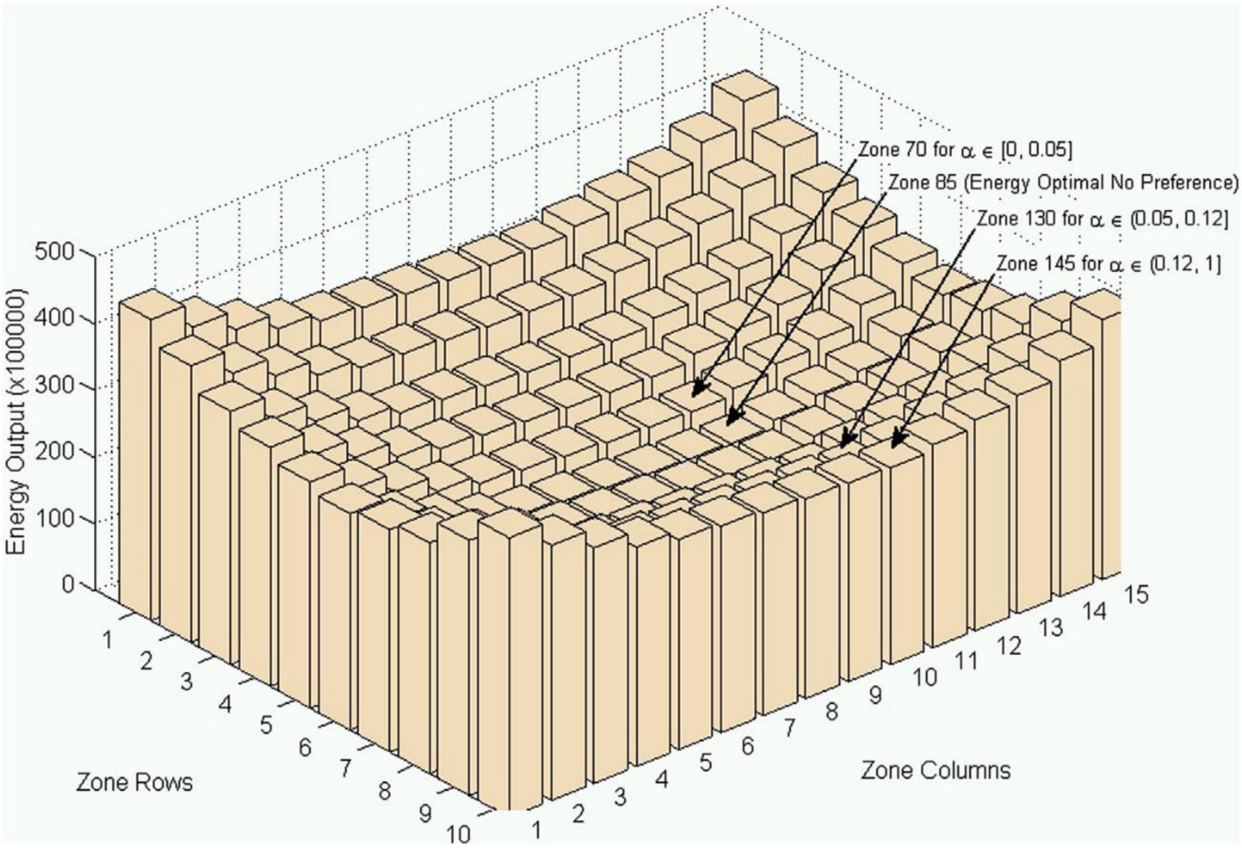


Figure 10: 3D representation of the energy output for each zone, sourced from [31]

Unfortunately, mine compressed air systems are too large for this kind of application, but this study did prove that simple changes to an existing network can have an impact on the entire system.

In 2016, Slaughter and Tien [32] combined a simulation of a mine's ventilation system with simulations regarding the spread of fires and were able to simulate the effects that fires have on mine ventilation systems. Figure 11 provides a visual representation of their simulation, which shows that after only 30 minutes the airflow in the parallel airway got reversed due to the fire. This causes dangerously high levels of carbon monoxide (> 1 200 ppm) to accumulate in the parallel airway.

Figure 11: The effects of a fire on a mine ventilation network, sourced from [32]

Slaughter and Tien concluded that this type of visual simulation could be used to educate miners on the dangers of underground fires. By implementing this data into evacuation training drills, miners can be educated on which escape ways to use and when to rather retreat to a refuge chamber during a fire situation, therefore saving lives. While this study did not focus on compressed air, it did prove how simulations can be used to improve the health and safety conditions of a mine.

Simulations of compressed air can also be used for training, the drafting of procedures and risk assessments and the updating of evacuation plans. Various failure scenarios can be simulated, for example, a break in the supply pipe to certain refuge chambers and breakdowns on several compressors. All of which is not always easy to physically test as it poses significant risks and can be costly exercises if proto teams need to be called in to conduct the tests. However, by using simulations the required data can be obtained quickly, safely and cost effectively.

In 2018, Friedenstein [33] had set out to create a simulation methodology that could be used to create high accuracy simulations. By applying this methodology to three case studies, Friedenstein was able to create simulations using PTB with accuracies between 1.36% and 3.0%. A graphical representation of the methodology can be seen in Figure 12.

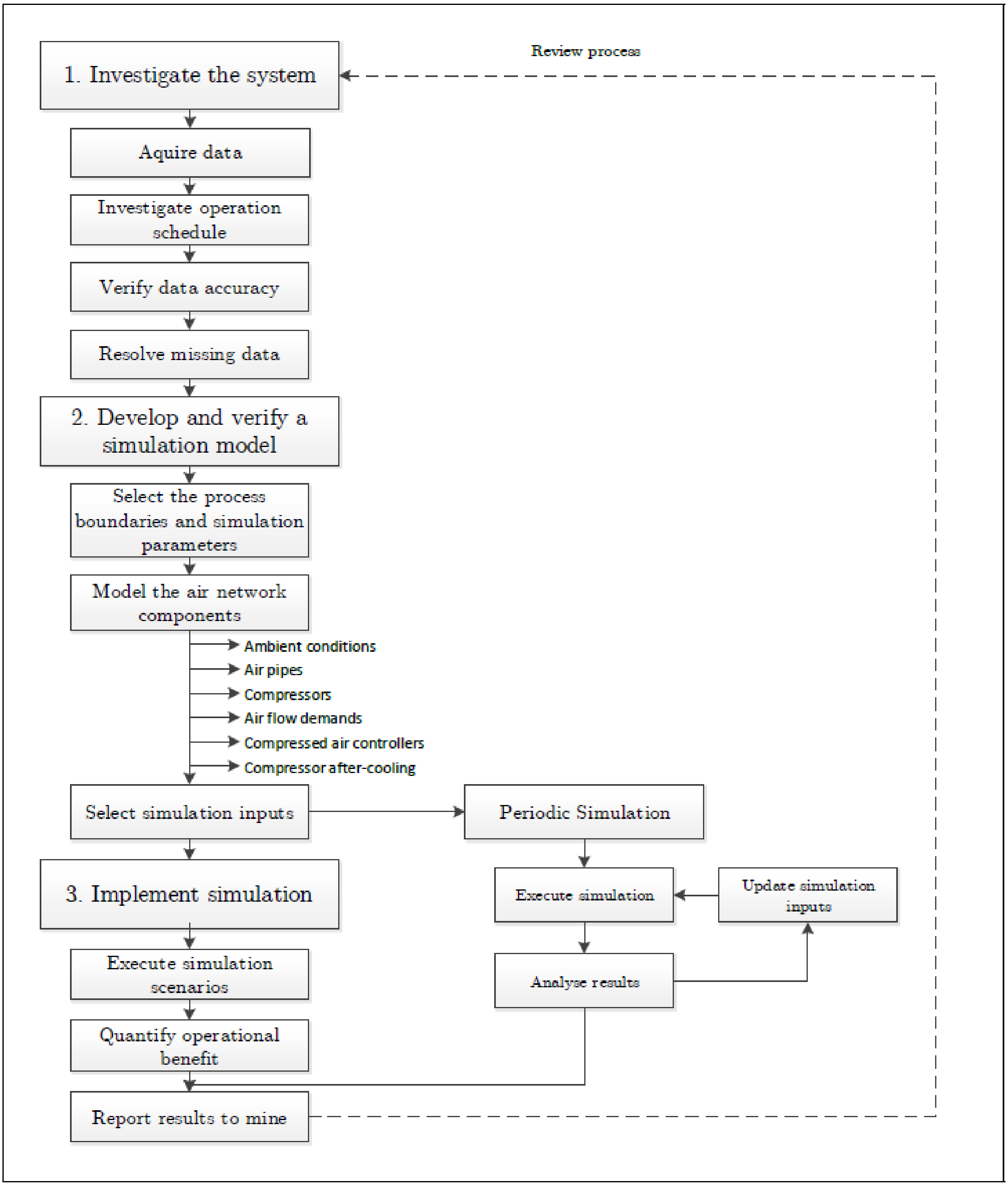


Figure 12: Simulation methodology proposed by Friedenstein [33]

In this study, Friedenstein was able to simulate a compressed air network down to the demand of each individual refuge chamber. This made it possible to assess the effect of a reduction in compressed air use at individual users on the total power usage of the network. The study also showed that it was possible to detect faulty equipment using simulations with periodic simulation. By repeatedly using the simulation to replicate daily data, a large difference was detected between the simulated power values and the actual values. The discrepancy was investigated, and it was found that one of the power meters was faulty.

This study showed that PTB was more than capable of simulating very complex compressed air networks with high accuracy. It also demonstrated that simulations can be used for more than just identifying energy-saving initiatives. This study, however, did not consider the health and safety regulations surrounding refuge chambers when lowering the compressed air supply to the chambers.

Friedenstein also pointed out that, to create such high accuracy simulations, a lot of accurate data are required. This information is not always readily available and sometimes it may be necessary to decrease the complexity of a simulation to compensate for the quality of data available for the simulation.

Watkins [34] compared simulation accuracy by decreasing the complexity of the simulation. Watkins created three surface compressed air simulations of varying complexities on a single mine compressed air ring. This ring had seven compressor houses consisting of 19 compressors in total which fed 12 different shafts. The simulation software used was AFT Arrow[5] to characterise the compressors and PTB to build the simulation model.

For the most complex simulation, Watkins simulated each individual compressor and each pipe was characterised individually. The shaft demands were divided into each individual level's demand. The second simulation assumed an average pipe specification and totalled all the level demands into a single shaft demand. The simplest simulation simulated each compressor house as an individual compressor.

The simulation accuracies for the three simulations from most complex to most simplistic were 2.88%, 4.50% and 4.87%, respectively. This showed that when all the data required for a complex simulation are not available it is possible to simplify the simulation without having a noteworthy effect on the accuracy of the simulation. However, it should be noted that these simulations focussed only on the surface compressed air network and did not take into consideration the complexities associated with the underground section of the network and can therefore not be used to accurately predict the compressed air supply to refuge chambers.

In 2019, De Villiers [35] did a study on reducing the airflow to refuge chambers to reduce the energy costs of a mine. Specialised valves were installed on all refuge chambers to limit the

[5] "AFT Arrow | Fluid Dynamic Simulation Tool." Internet: *https://www.aft.com/products/arrow*, [2020/11/09]

flow of compressed air into the chambers so that only the minimum as required by health and safety regulations were to enter these chambers.

A PTB simulation was used as a tool to help convince mining personnel of the benefit of the project and what effect it would have on the energy consumption of the compressors. In the end, a power reduction of 840 kW was realised by installing these valves in 42 refuge chambers.

A PTB simulation was again proven capable of accurately simulating the compressed air delivery to a refuge chamber. However, there was no indication given whether the supplied compressed air was at a high enough pressure to be able to ensure a positive pressure within the chamber. This study also did not consider what effects a change in the compressed air network would have on the supply to the chambers.

1.7 Literature summary and need for the study

During this chapter, several studies were researched to understand the background of the regulations in relation to the health and safety of mine personnel with special regard to the regulations surrounding refuge chambers and why they are important. The main regulations that were focussed on were the supply of breathable air and the maintenance of a positive pressure. Both regulations are governed by the supply of compressed air to the refuge chamber.

This compressed air is supplied to the refuge chamber using compressors on the surface that need to provide compressed air to various users on the compressed air network. These compressed air networks can become very complex and are therefore not easily understood.

Process simulations provide a means to understand the effects that changes to the network will have on the supply to all users on the network, but it was also seen that the simulations provide little value unless they can be verified using real world data and scenarios.

The literature studies discussed in the previous section were found to contribute to one or more of the following topics:

- Health and safety
- Refuge chambers
- Complete mine simulation
- Compressed air network changes

- Verification

Table 3 provides a visual representation of the most relevant studies and whether they addressed all the topics mentioned in this chapter. Green blocks show that the study did cover the topic and red blocks show that the study did not cover the topic sufficiently.

Table 3: State of the art matrix

Source	Health & safety	Refuge chambers	Complete mine simulation	Compressed air network change	Verified
[14]					
[15]					
[17]					
[18]					
[21]					
[27]					
[31]					
[32]					
[33]					
[34]					
[35]					

From the table, it can be seen that there is a clear gap in the literature when it comes to combining the health and safety requirements for refuge chambers with process simulations while also addressing what effect changes to a compressed air network will have on the supply of compressed air to the refuge chambers.

From this, it was seen that a need exists to know what effect changes to a compressed air network will have on the compressed air supply to all refuge chambers and to ensure that they still meet the minimum safety requirements.

The objectives of this study are thus:

- Develop a simulation-based methodology to investigate various configurations of a mine's compressed air network.
- Calibrate the simulation using data from a mining case study.
- Use the method to quantify the effect of different configurations on the compressed air supply to refuge chambers in the case study.
- Verify the methodology using real world scenarios to validate its degree of accuracy.

1.8 Dissertation overview

This dissertation consists of four chapters:

Chapter 1 introduces the reader to the background environment of the study and provide relevant literature regarding refuge bays, mining compressed air networks and process simulations. Relevant studies are highlighted after which their shortfalls are highlighted and used to develop the need for this study and its objectives.

Chapter 2 provides the methodology followed to develop the solution for the identified need. This methodology is written in such a way that future researchers will be able to replicate the process to draw their own conclusions.

Chapter 3 presents the results of the study and discussions on the findings.

Chapter 4 concludes the study and review whether the need was adequately addressed while achieving the objectives. There are also recommendations for future studies based on challenges encountered within this study.

Additional information is provided in the appendices at the end of the dissertation.

CHAPTER 2 METHODOLOGY

In the previous chapter the need for the study was clearly defined. From the literature study a hypothesis was proposed that simulations could be used to solve the problem statement. In order to test the hypothesis, a case study methodology was used. A process was created that would allow for simulations to be produced that will be able to answer the question of how changes to the compressed air network would affect the supply to refuge chambers. If the simulation can accurately predict the effects of changes to a network in a case study, then the hypothesis will have been proven and the method validated.

This chapter will further discuss the specifics surrounding the process that was created in order to test the hypothesis. Figure 13 depicts a simplified flow chart of the process. Firstly, the system to be simulated must be investigated by gathering information regarding the physical system and all relevant data. After this, a baseline simulation is to be constructed, calibrated and then verified against real data.

As soon as the baseline simulation has been verified the desired scenario can be identified and this scenario simulation can be created, by making the proposed changes to the baseline simulation. The scenario simulation should then be checked to ensure that the outcomes satisfy the minimum safety requirements while still delivering the required compressed air supply to all other users to ensure production continues. If not, the scenario should be deemed not feasible or the simulation can be used to identify which configurations would represent the desired scenario the closest while adhering to all the relevant minimum requirements.

The scenario can then be implemented on the real world system. When confirmed that the proposed solution is working the baseline simulation should be updated to reflect the new real world system.

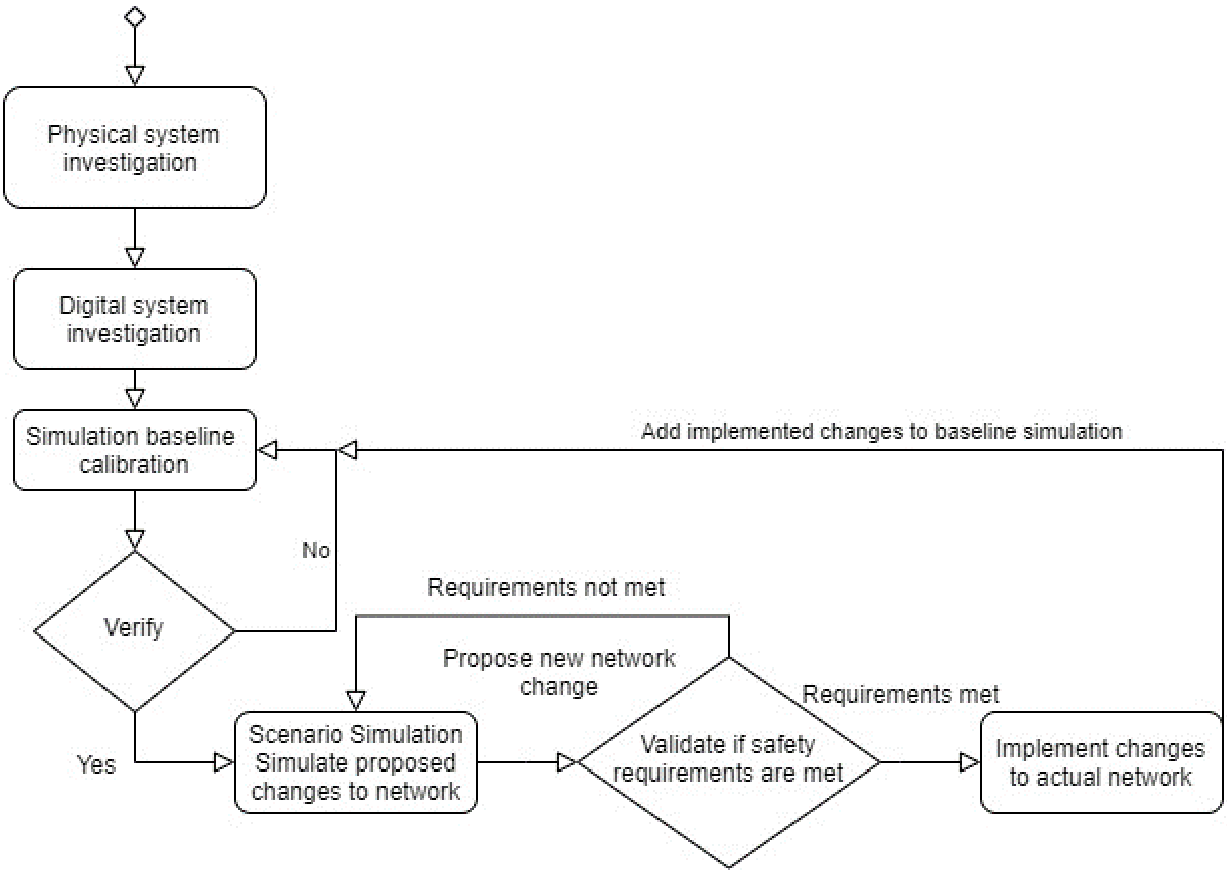


Figure 13: Flowchart depicting a summary of the process used in this study

2.1 System investigation

Before any system can be simulated there must first exist a detailed understanding of the system in question. In this case, the mine compressed air network must first be thoroughly investigated to gain the necessary insight to create an accurate digital representation. The investigations that need to be performed can be grouped into two main categories namely physical and digital investigations.

2.1.1 Physical investigation

The physical investigation is the first step as seen in Figure 13. During this step, the actual layout of the compressed air network is to be investigated. This can further be grouped into surface and underground investigations.

In surface investigations, the number, sizes, locations and compressor curves (if available) of all compressors on the ring are acquired as well as the number, location and demand profile of all users such as shafts and/or gold plants. Each of these users will have their own compressed air requirements. Details regarding the surface piping network and ambient conditions will also be required. All this information can be obtained by consulting the original equipment manufacturers, conducting audits and consulting documentation in the planning office of the mine.

During underground investigations layouts of the underground piping can be used to determine the number and location of underground users such as refuge bays and active crosscuts[6]. It should be noted that the drawings can sometimes be outdated and therefore, it is good practice to perform a physical verification to ensure the information is accurate.

It is important to get the exact sizes and vertical elevations of all piping involved along with the locations of valves and whether they are in a permanently open or closed position as this determines the amount of compressed air that can be supplied through the pipe to the users. The maximum capacity for all refuge chambers must be known as this can be used in conjunction with Equation 1 to calculate the minimum required compressed air. Mining personnel must also be consulted to ascertain type and amount of equipment required in the working areas and then specification sheets can be consulted to establish the air supply requirements.

In some cases, the required information may not be regularly known by the mining personnel. Therefore, audits must be carried out both on the surface and underground to verify any collected data and to gain any here to yet unknown data that is required before the simulation can be built.

Commonly found equipment along with their individual air supply requirements have been listed in Table 2. If the type and quantity of equipment in a working area is known the minimum required compressed air can be calculated. When the compressed air requirements of all working areas on a level is known the total compressed air requirement for that level can be calculated. In order to calculate the size of the leaks present on the level the minimum required air flow can be subtracted from the actual airflow in order to estimate the leaks present on that level.

2.1.2 Digital investigation

The next step is the digital investigation (see Figure 13). The simulation will require digital data that will be used to calibrate the simulation. Most mines have a SCADA[7] system which is used

[6] Areas where active mining or haulage development is taking place.
[7] Supervisory control and data acquisition

to log and monitor all measurement data on the mine. Historical measured data can significantly increase the accuracy of a simulation.

The important data points to gather are as follows:

For compressors:

- Compressor outlet flow
- Compressor outlet pressure
- Compressor power
- Blow-off valve position
- Guide vane angle
- Compressor outlet temperature
- Ambient temperature

For compressed air users:

- Compressed airflow
- Compressed air pressure

If for whatever reason, the required data are not available, the missing data can be simulated to ensure the accuracy of the simulation. These data points can be used to calculate the characteristics of a compressor when the corresponding compressor curve is unavailable. When the data for a specific compressor are not available the characteristics of a compressor of similar size and age can be used to model the compressor in question.

It should be noted that not all compressed air users on a network are monitored with the flow- and pressure meters. Typically, the individual users on a single level will not have dedicated meters. Instead, the main inlet to the level will have a flow- and pressure meter to indicate the flow and pressure of that level.

All required data will not always be collected by automated systems and will sometimes require manual measurements. It can also occur that the accuracy of an installed meter may come into question deeming it necessary to perform manual measurements and then to confirm these measurements with those measured by the installed meters.

Therefore, it is important to ensure that the quality of data acquired is of a high standard to avoid the “garbage in, garbage out” principle of simulating. There are several factors that contribute to the quality of the data:

- Abnormal data readings [36]
- Damaged measuring equipment delivering false or inaccurate measurements [36]
- Unit conversions of measurements [37]
- The data collection and storage methods used [38]
- The traceability of measurement sources [39]

As a result, all data should be checked before being used for simulation purposes. Here are some guidelines to use when checking data quality:

- There could be areas of data loss. This can be due to the measuring device being removed, the connection between the device and the server being lost or there being a power outage.
- The data can have unrealistically high or low values which are common with measuring errors.
- If the data values are constant for long periods of time it may be that the measuring device has encountered some error and is displaying a default value.
- Compare related data sets. For instance, a compressor that is not using any power cannot be supplying a flow of compressed air.
- Conduct mass balances to determine if there are any unmeasured compressed air users on a network or if there is an error in the measuring devices. Always conduct an audit if any discrepancies occur.

Once the acquired data are deemed to be of a high enough quality, average daily trends can be constructed to create simulation inputs for the baseline simulation. Figure 14 is an example of what the daily pressure profile of an active mining level can look like. It should be noted that some mines do not use compressed air for drilling and therefore will not see an increase in pressure and flow demand during the drilling shift.

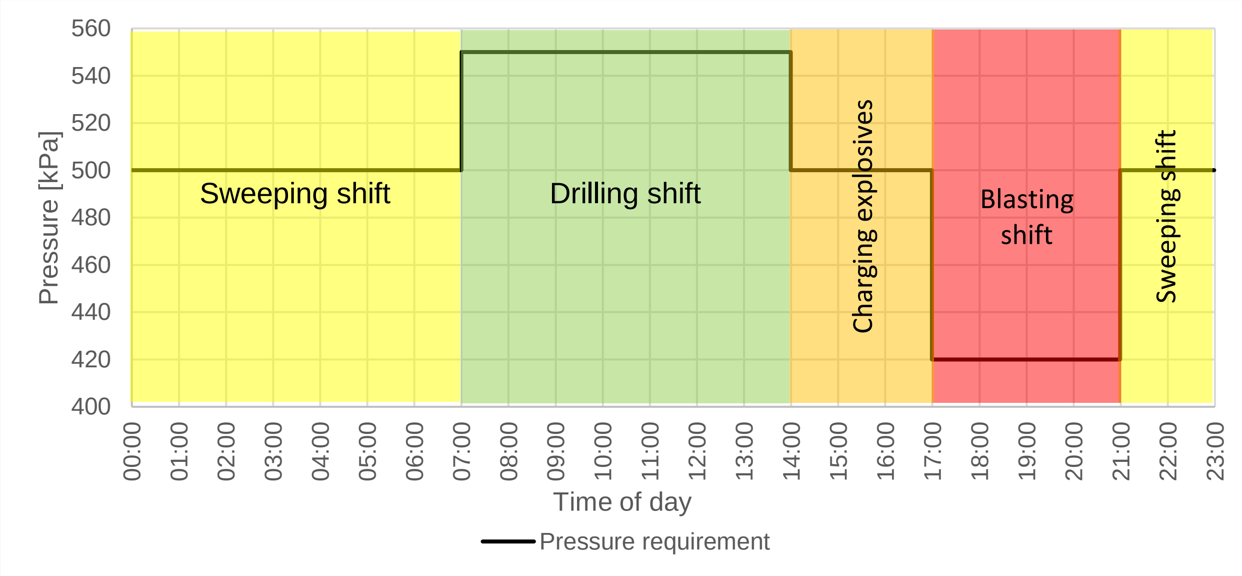


Figure 14: A typical representation of the daily pressure demand of a deep-level mine [40]

After gathering all the necessary information, a refuge chamber supply benchmark can be set up, which will then be used during the scenario simulation step to compare the scenario results to the baseline.

For the refuge chamber benchmark, the current compressed air supply flow and pressure for each refuge chamber needs to be measured. This is done by fully opening the valve inside the refuge chamber while ensuring that the door is closed. A flow meter is used to measure the flow of compressed air into the chamber and a pressure meter is used to measure the pressure in the pipe. If no pressure measuring point exists within the chamber (which is usually the case) the nearest pressure measuring point before the refuge chamber can be used as a fair estimation of the compressed air pressure being delivered to the chamber.

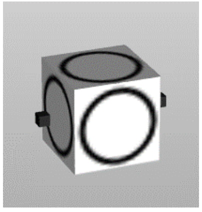
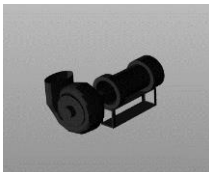
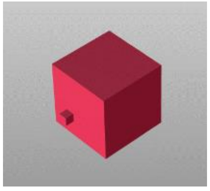
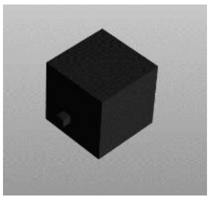
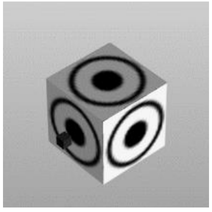
These values must then be compared to the minimum requirements for the specific refuge chamber in order to determine the refuge chamber benchmark. The minimum flow is calculated using Equation 1 from Chapter 1 and requires the maximum capacity of the refuge chamber. The minimum pressure must be at least 500 Pa higher than the ambient pressure as stipulated by Yang *et al.* [14].

2.2 Baseline simulation

After the investigation phase, the next step is to construct a baseline simulation. The baseline simulation will serve as the control by representing the compressed air network before any changes are implemented. This simulation should therefore be able to accurately represent an average day's operation.

In this study, PTB is used as the simulation software package, but any simulation software that can accurately model compressors and the flow of compressed air through piping can be used in future studies. Table 4 lists the various components used in PTB. These components will be discussed in more detail in the next section.

Table 4: PTB simulation components

Graphical representation of component	Component name
	Air pressure node
	Air dynamic compressor
	PI control
	Air demand
	Air pressure boundary

2.2.1 Building the simulation using PTB

The various components that make up a PTB simulation are discussed next and how they are used when building a compressed air simulation.

PTB makes use of pressure nodes and pipes to link different components within the simulation environment. Pressure nodes are required in the flow network where the user requires system condition outputs, where flow paths split or come together, and where there is a change of elevation. Table 4 shows the graphical representation of an air pressure node. Air nodes are used to calculate all properties of the network such as the pressure, temperature and density at certain points.

Figure 15 shows the graphical user interface for an air node. On the left-hand side is the input screen showing all the possible inputs that can be used as starting conditions for the simulation. On the right-hand side is the outputs that the air node gives after the simulation is complete. These outputs can be in either the form of a table or a graph as can be seen in Figure 16. Air nodes assume that 100% occurs with no stratification, the air has a constant specific heat of 1.006 kJ/kg.°C and that the ideal gas law applies.

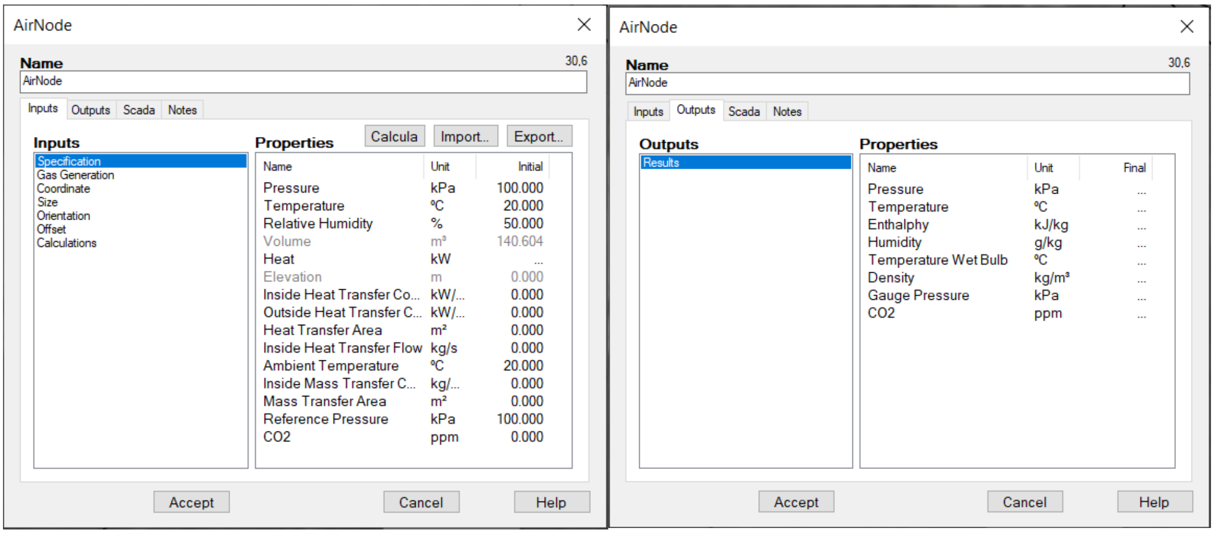


Figure 15: Input and output interface of an air pressure node

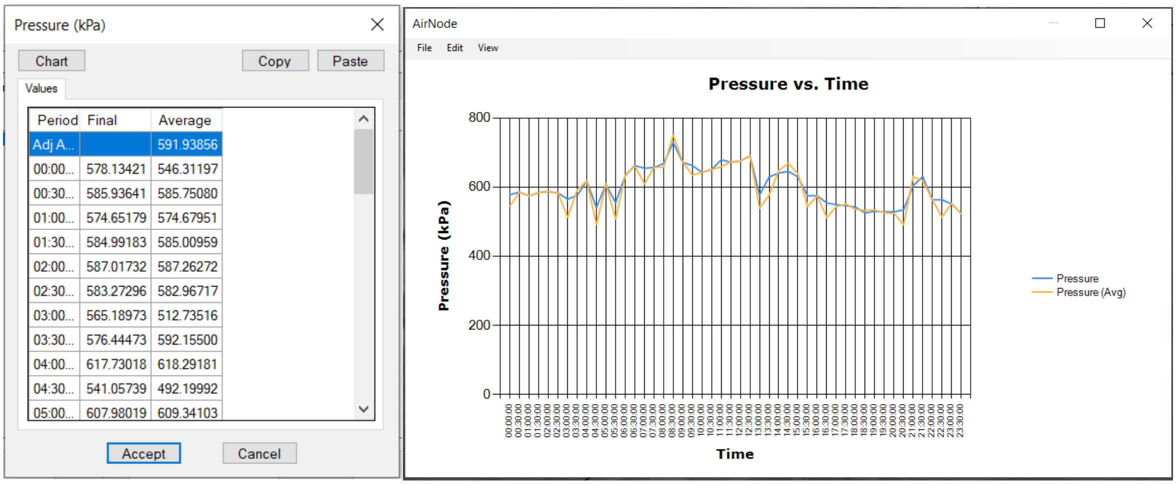


Figure 16: Table and graphical outputs of an air pressure node

Pipes are used to connect nodes (as is visible in Figure 17). Within these components, the pressure losses of the network are calculated along with the heat generated by auto compression. These components also have a variable valve fraction to simulate pressure control or to decrease the flow through a section of the network. Figure 18 shows the available inputs for the pipe component. The most important inputs are the pipe hydraulic diameter and the pipe flow area. These values should match the diameter and flow area of the real world pipe that is being simulated. The length of the pipe is determined by the distance between the two nodes that are being connected by the pipe.

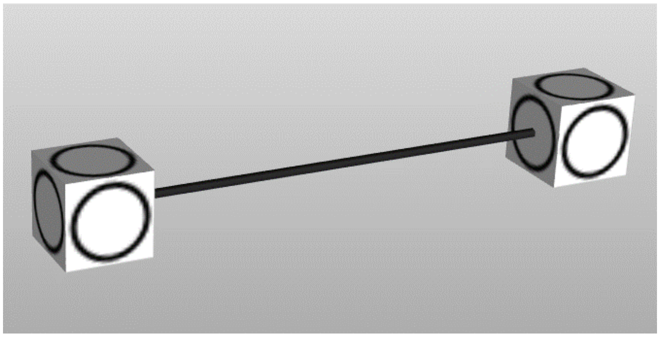


Figure 17: Graphical representation of a pipe component connecting two nodes

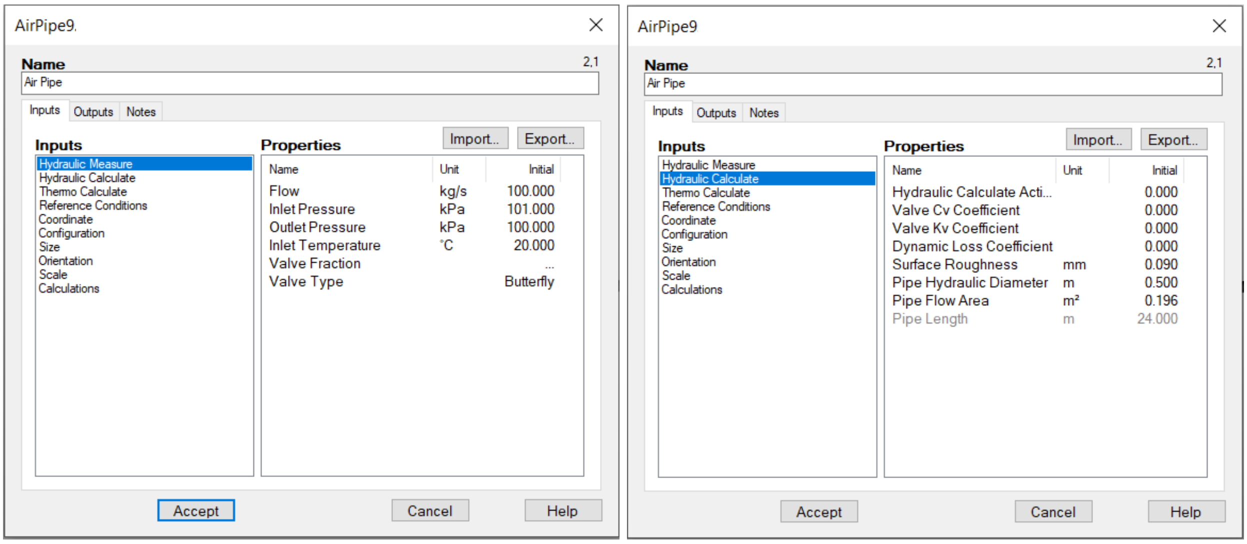


Figure 18: Input interface of an air pipe

These pipes can also be set as valves (visible in Figure 19), which have their own unique valve Cv and Kv coefficients. The valve's Cv and Kv coefficients can be changed to the required values of the valve being simulated. Any changes to a pipeline such as a bend, T-off or reduction in pipe size is simulated using air nodes. Air nodes are placed between pipe sections were the geometry (such as direction or size) of the pipe changes. One air node can have multiple pipes leading to and from it in order to simulated splits in pipes such as T-sections.

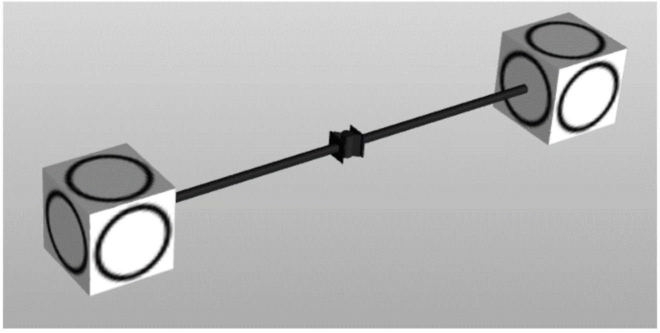


Figure 19: A pipe component representing a butterfly valve

Figure 20 shows the output interface for a pipe. Normalized volume flow refers to volumetric flow under standard temperature and pressure conditions. These outputs are also available in table and graphical form such as with the air node. During the calculations, the pipe component assumes that the thermal dynamic conditions remain constant within the length of the pipe and that the ideal gas law applies.

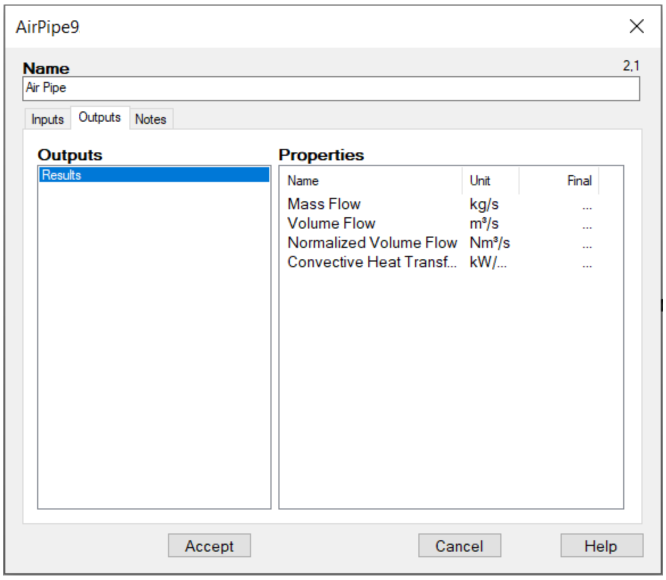


Figure 20: The output interface of an air pipe

The next component is the air dynamic compressor (as seen in Table 4) which will be used to simulate the operation of the compressors. This component generates a pressure difference in the network to induce airflow through the network. The airflow that is created is a function of the pressure difference over the compressor. The component also generates heat in the airflow due to polytropic compression and inefficiencies.

The air dynamic compressor component requires a lot of inputs as shown in Figure 21. Most of these inputs can be acquired from the compressor curve. If the fan curve is unavailable, then the following equations can be used to estimate the parameters using historic data acquired during the investigation phase:

$$Pr = \frac{P_o}{P_i} \tag{8}$$

$$Q = (a_2 Pr^2 + a_1 Pr + a_0)F^2 \tag{9}$$

$$m = \frac{Q}{(T_i + 273.15)^{0.5}\left(\frac{P_i}{100}\right)} \tag{10}$$

$$\eta_c = \frac{(b_2 Q^2 + b_1 Q + b_0)}{F} \tag{11}$$

$$T_o = (T_i + 273.15)\left(1 + \left[\frac{Pr^{\frac{k-1}{k}} - 1}{\eta_c}\right]\right) - 273.15 \quad (12)$$

$$W_e = \frac{0.287([273.15 + T_i] - [273.15 + T_o])}{\frac{(1-k)mk}{\eta_m}} \quad (13)$$

Here:

Here:	m	= Air mass flow rate (kg/s)
	P_i	= Air inlet pressure (kPa)
	P_o	= Air outlet pressure (kPa)
	a	= Fan pressure curve coefficients
	b	= Fan efficiency curve coefficients
	F	= Part load fraction
	k	= Polytropic coefficient
	T_i	= Air inlet temperature (°C)
	T_o	= Air outlet temperature (°C)
	W_e	= Compressor motor electrical power (kW)
	Q	= Corrected mass flow rate (kg·K$^{0.5}$/(s·bar))
	η_c	= Compressor efficiency
	η_m	= Motor efficiency
	Pr	= Compressor pressure ratio

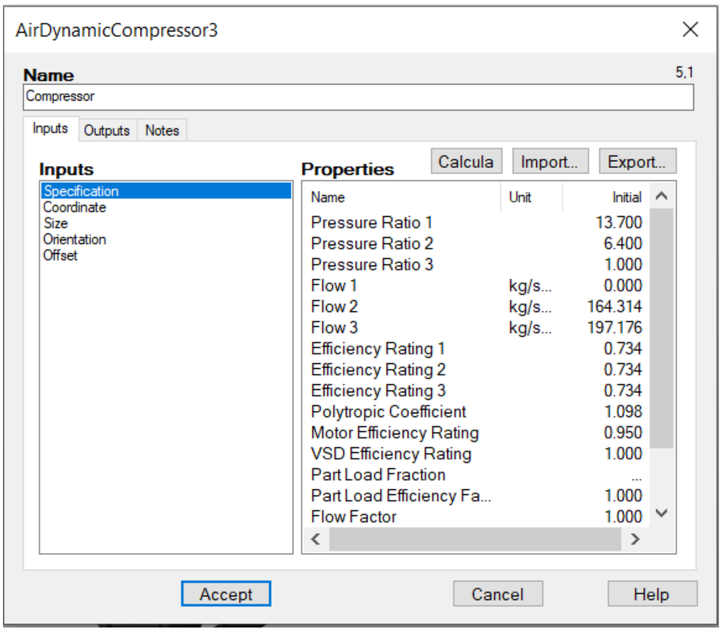


Figure 21: Input interface of an air dynamic compressor

Figure 22 shows the outputs available from the dynamic compressor components. These outputs are also available in table or graphical form. The dynamic compressor assumes that the compressor motor efficiency remains constant at full and partial load operations and that the polytropic coefficient is not a function of the air or cooling fluid temperature. This component acts as a specialised pipe component and can therefore serve as a connection between two nodes.

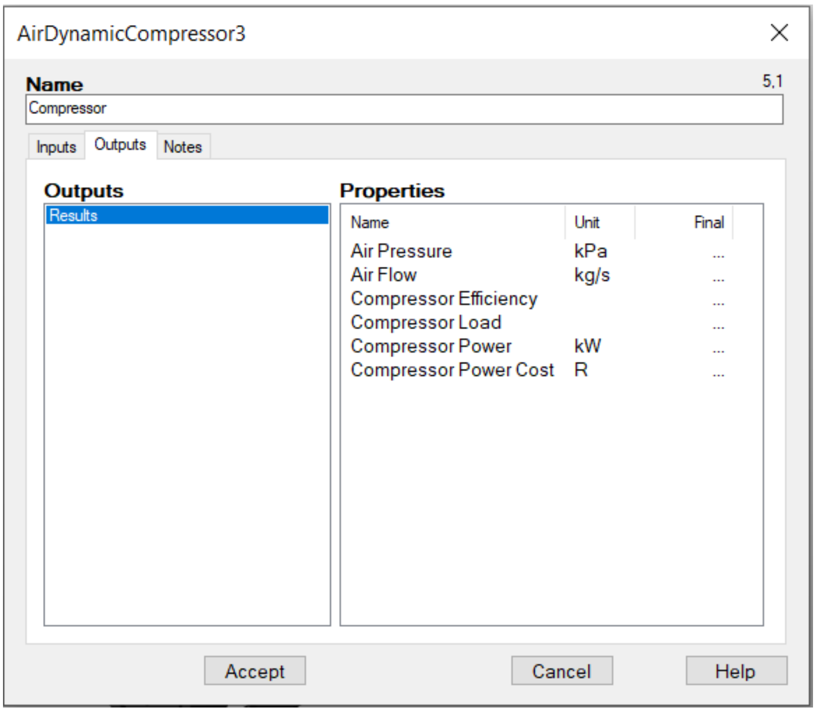


Figure 22: The output interface of an air dynamic compressor

The guide vanes of the compressor component are controlled using a proportional-integral (PI) control component. The graphical display of a PI control component can be seen in Table 4. This component is a proportional and integral controller that delivers an output signal of between 0 and 1. The input and output interface of the controller can be seen in Figure 23.

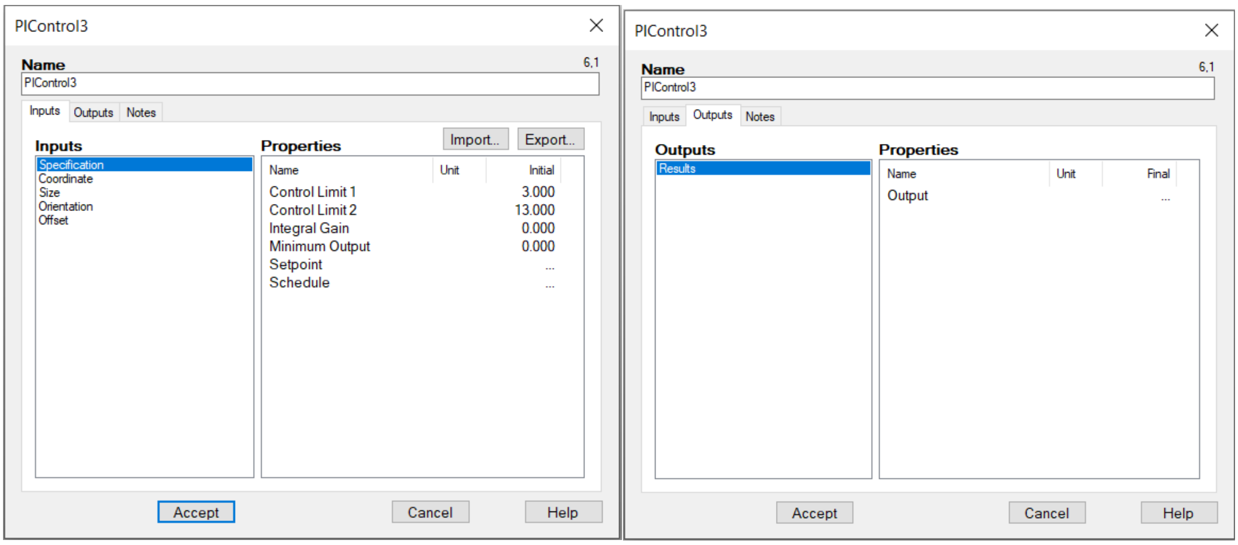


Figure 23: The input and output interface of a PI control

When connected in the manner displayed in Figure 24 the PI control changes the guide vane angle of the compressor to change the outlet pressure to the desired setpoint. When the PI control is also given a schedule, it can turn the compressor on and off during certain times of the day. The PI control can also be used to change a pipe component into a pressure control valve when connected as displayed in Figure 25. In this instance, the PI control will change the valve fraction of the pipe component to meet the pressure setpoint.

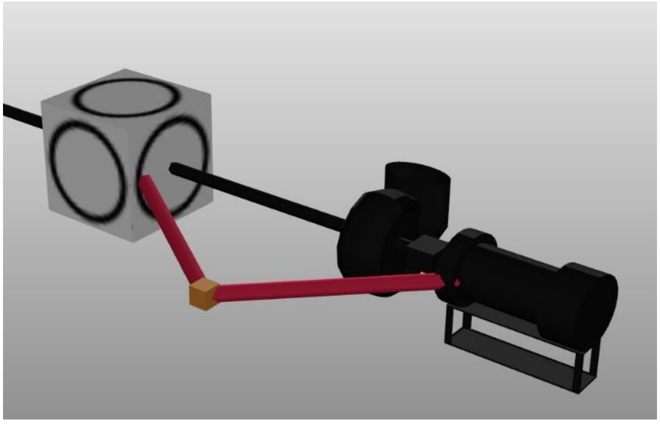


Figure 24: PI control used to control the compressor outlet pressure

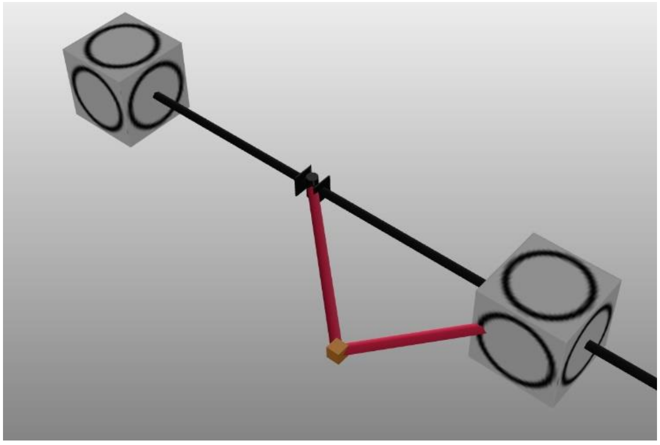


Figure 25: PI control used to create a pressure control valve

All compressed air users in the network are modelled using an air demand component (Table 4). This component functions in much the same way as a pipe component with the difference being that as an input it requires a flow and a pressure profile (Figure 26). This is where the daily profiles discovered during the investigation phase will be entered into the simulation. When the simulation is running, the software will try to match the compressed air flow and pressure demand much like when a user starts using a piece of equipment that requires a certain compressed air flow at a certain pressure.

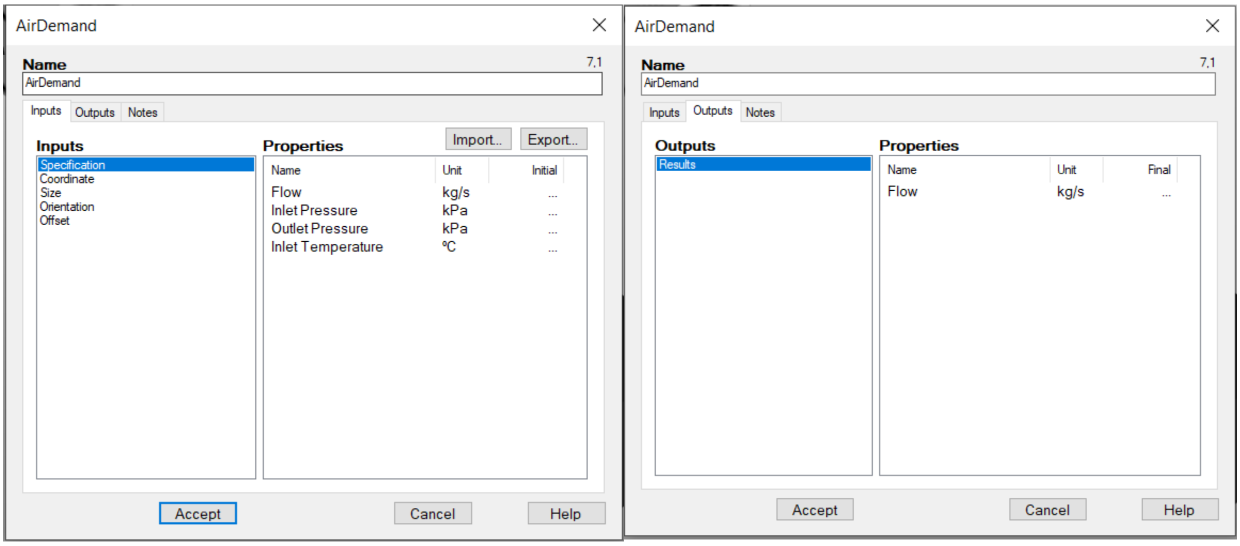


Figure 26: Input and output interface of an air demand

The final component to discuss is the air pressure boundary (Table 4). This component represents the boundary/ambient conditions of the network. It has constant user-specified pressure, temperature and humidity profiles (Figure 27) that represent the conditions present where the boundaries of the simulation are drawn. Such as the ambient air being drawn into the compressor or the conditions after a compressed air user or where the network connects with a different system that is beyond the scope/boundary of the simulation.

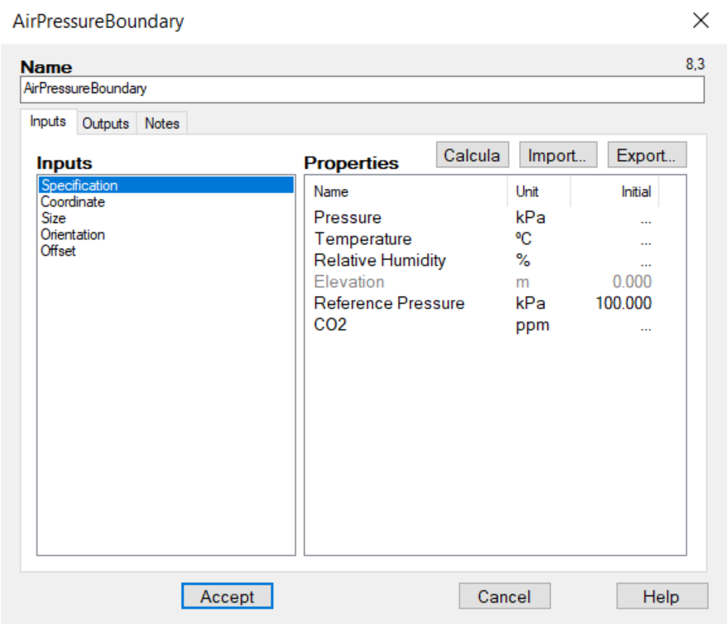


Figure 27: Input interface of an air pressure boundary

All these components are used together to form the compressed air simulation. Figure 28 shows how a compressed air user is modelled in PTB. An air demand is used to specify the compressed air flow and pressure required by the user and a node and pipe are used to connect the user to the supply. The air demand is then connected to an air pressure boundary to specify the ambient conditions of the user.

Leaks can be simulated two different ways. If the exact location and size of a leak is known, then the leak is simulated using an air pipe set to the size of the leak leading to an air pressure boundary. If the leak is only known as an estimate of the total leaks on a level the leak is simulated the same as any normal compressed air user on the network.

In Figure 29 a compressor house is modelled using dynamic compressors, which get their ambient air from air pressure boundaries. These compressors' outlet pressures are controlled using PI controllers. A blow-off valve is added to each compressor which is also controlled using a PI controller. Each blow-off valve is then connected back to the atmosphere using air pressure boundaries. Nodes and pipe components are then used to connect the compressors to the rest of the network.

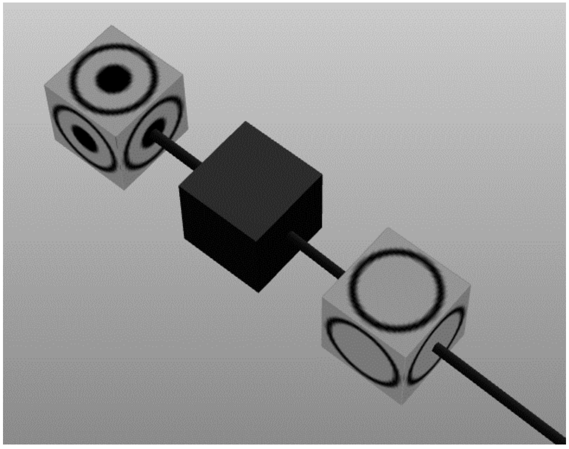


Figure 28: Compressed air user simulation

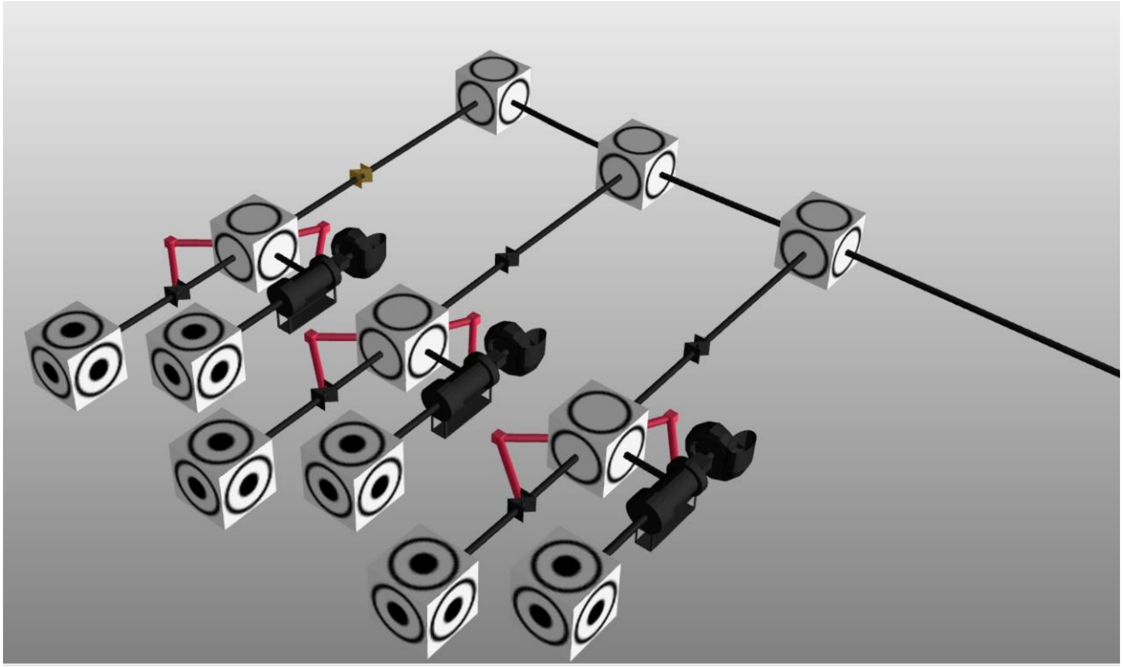


Figure 29: Compressor house simulation

It should also be mentioned that the simulation time can be adjusted. The default simulation time is an hourly 24-hour profile, but this can be adjusted to suit any need. In this study, the profile will be set to a half-hourly 24-hour profile. Figure 30 shows the properties available for the simulation. The number of time periods are the largest time intervals to be used in the simulation. In this case, there are 24 one-hour periods. These are the values that will be given in the outputs of the components. Each time period consists of several time steps, in this case, 60 minutes in each hour. The size of each time period is thus 3600 seconds. In order to change this to a half-hourly 24-hour period one would change the time periods to 48 half-hours, the time steps to 30 minutes and the size to 1800 seconds.

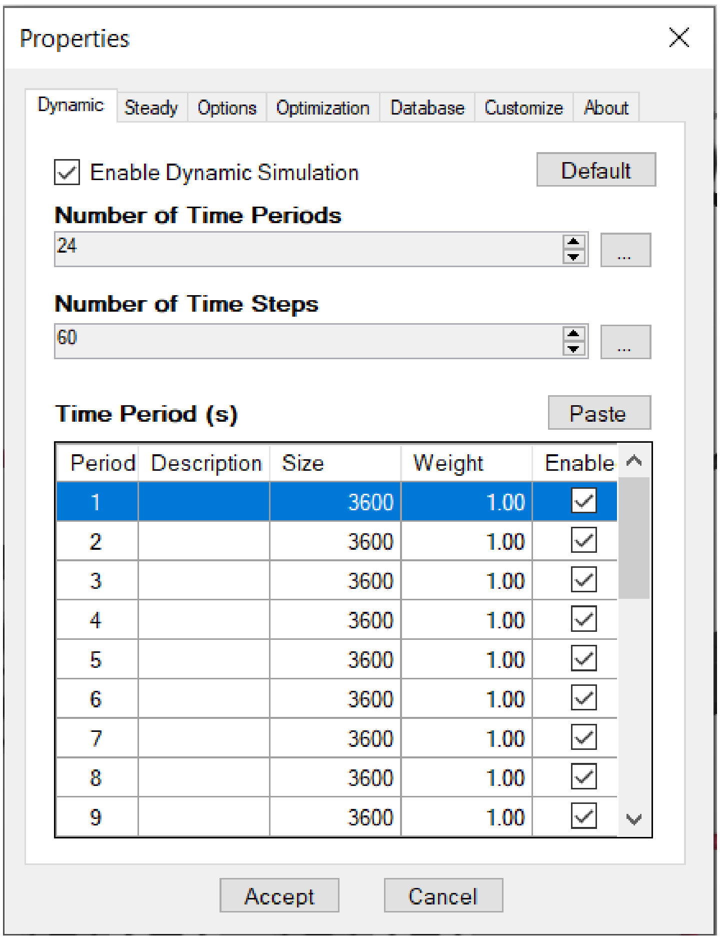


Figure 30: Simulation properties

2.2.2 Simulation calibration

After the simulation model has been built it must then be calibrated using real world data acquired during the digital investigation. This is done to minimise the error of the simulation output. This is an iterative process as outlined in Figure 13 as the simulation must be verified with actual data before the process can continue. The calibration method used has been adapted from the method used by Friedenstein [33].

Firstly, an average production day's data are chosen as input to the simulation. This should be a day where no extraordinary situations occurred and where there is no data loss present in the data.

These compressed air flow and pressure profiles should then be entered into their respective compressed air demands as stated in the previous section. Different compressors would have been operated during different times of the day. These compressor schedules will be entered in the PI control component associated with the compressor.

After this, the PI Controls will be used to calibrate the pressure of the system. PI Controls should be present on all compressors and level inlet valves. If the pressure and flow data are correct the flow output will automatically be calibrated as soon as the pressure output is calibrated.

Initially, the inputs for the PI Controls will be guessed or estimated. After running the simulation with the initial configuration, the error of the output conditions must be calculated. The inputs for the PI Controls, where the error is above the minimum requirement, should then be adjusted to minimise the error. This process will be repeated until the simulation error for the baseline is satisfactory.

Some helpful tips for calibrating the simulation include:

If the output has a lot of oscillations as seen in Figure 31. This is possibly due to the integral gain of the PI control being too high. Reducing the integral gain should fix this.

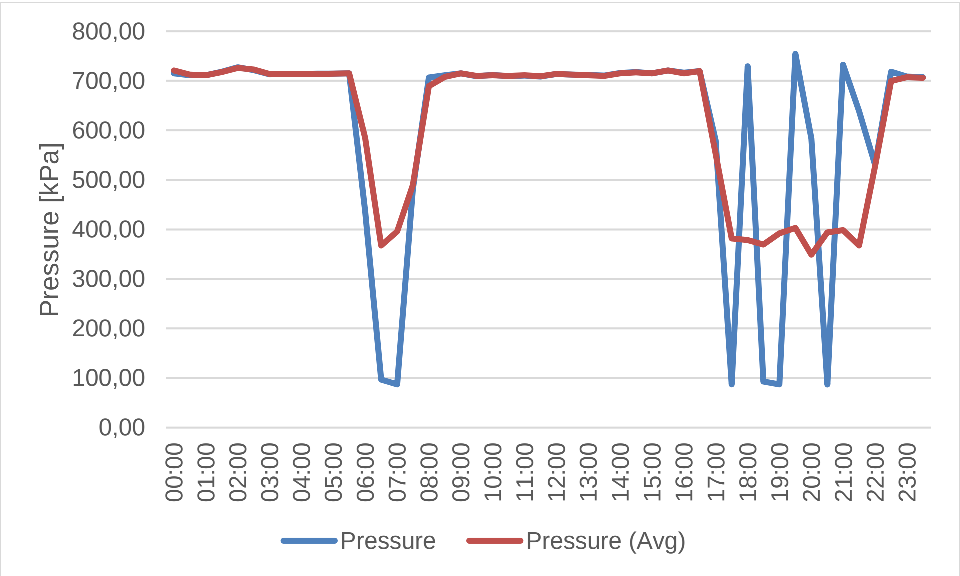


Figure 31: Pressure output with too many oscillations

On the other hand, if the integral gain of the PI control is too low it may cause the outputs of the PI control to appear “sluggish” to react to changes in the system. Figure 32 is the same PI control as seen in Figure 31, but with a low integral gain. This can be rectified by increasing the integral gain.

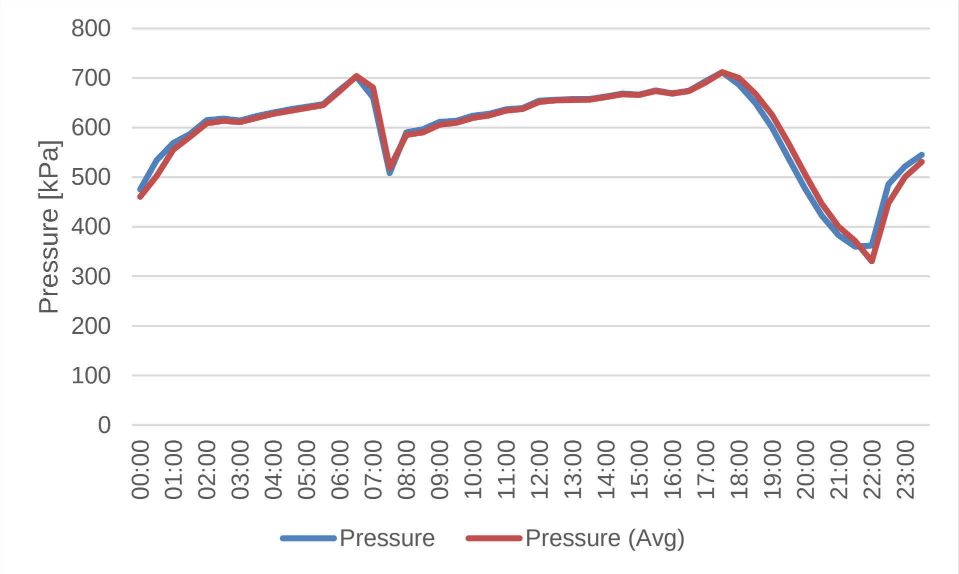


Figure 32: Output of a PI control with a "sluggish" reaction

2.2.3 Simulation verification

After the simulation has been constructed, calibrated and run using the baseline profiles developed in the investigation phase, the simulation must then be verified with the actual profiles. Three widely accepted verification methods were used in this study to verify the simulation results, namely the mean absolute error (MAE) method, the mean square error (MSE) error and the coefficient of determination.

The formula for the MAE method is as follows [41]:

$$Err_{\%} = \frac{1}{N}\sum_{n=1}^{N}\left|\frac{A_n - S_n}{A_n}\right| \times 100\% \tag{14}$$

Here: A = Actual value at timestamp

S = Simulated value at timestamp

n = Timestamp

N = Total number of timestamps in simulation period

The MSE method is calculated as follows [42]:

$$MSE = \frac{1}{N}\sum_{n=1}^{N}(A_n - S_n)^2 \tag{15}$$

And the coefficient of determination (r^2) is calculated as follows [43]:

$$r^2 = \left(\frac{\sum_{n=1}^{N} [A_n - \bar{A}][S_n - \bar{S}]}{\sqrt{\sum_{n=1}^{N} [A_n - \bar{A}]^2 \sum_{n=1}^{N} [S_n - \bar{S}]^2}} \right)^2 \quad (16)$$

As can be seen in Table 5, each of these methods has an upper error limit to ensure that the simulation can be deemed accurate [41], [42], [44], [45]:

Table 5: Error limits as found in literature

Verification method	Error limit
MAE	$Err_{\%} < 5\%$
MSE	$MSE < 1.7e^{-3}$
Coefficient of determination	$r^2 > 0.95$

These verification methods will be applied to the flow and pressure profiles where applicable to indicate the accuracy of the baseline simulation model.

2.3 Scenario simulation

After the baseline simulation has been built and verified, the next step as seen in Figure 13 is to implement the proposed changes to the compressed air network in the baseline simulation to create a scenario simulation.

2.3.1 Simulation of changes

Before any changes are made to the simulation a detailed understanding must exist of the need for the proposed changes. Possible changes that can be implemented are:

- Expansion of an existing underground network.
- Moving of a compressor from one location to another.
- The opening of previously closed valves.
- The construction of a new pipeline.
- The addition of new users to the network.

Any changes that are being proposed must be implemented in the simulation when building the scenario simulation.

2.3.2 Validation of results

After the scenario simulation has been constructed the results of the simulation must be validated to ascertain whether the proposed change to the network will still meet the health and safety guidelines.

In order to check this, the compressed air flow and pressure supply to each refuge chamber must be compared to the benchmark that was established during the digital investigation. It should be noted that there may be other systems on the network that require a minimum supply of compressed air to function properly. These systems should also be checked that they receive the required supply before the proposed changes can be accepted. If any of these requirements are not met, then the proposed changes must be rejected, and new changes can be proposed as seen in Figure 13. These new proposed changes must then once again be tested by means of a different scenario simulation.

2.3.3 Implementation of changes

After the proposed changes have been proven to adhere to safety guidelines and still meet all other criteria, the changes can be implemented on the actual network. After implementation, the scenario simulation needs to be verified.

When the changes to the network have been implemented the compressed air pressures and flows that are being measured will change. These changes must then be compared with what the scenario simulation predicted these changes would be. Also taking care to ensure that the safety minimums as defined in the digital investigation are being adhered to.

The process for determining the accuracy of the scenario simulation after implementation is the same as when determining the accuracy of the baseline simulation. By making use of the MAE, MSE and coefficient of determination the simulation will be evaluated to ensure that a high degree of accuracy was maintained after the implementation of changes to the compressed air network.

By verifying the scenario simulation, the method can be demonstrated to be a useful tool that can then be applied to any new proposed changes to any compressed air network. Therefore, fulfilling the study objective to develop a simulation-based methodology to investigate various configurations of a mine’s compressed air network.

The scenario simulation must now be repurposed as the new baseline simulation to be used when any new changes are to be implemented as illustrated by Figure 13. In order to ensure that when any future changes are required on the compressed air network there would be no need to recreate a new baseline simulation.

CHAPTER 3 RESULTS AND DISCUSSION

3.1 Introduction

The methodology developed in Chapter 2 was implemented on a South African deep-level gold mine. The shafts mentioned in this dissertation have been given new names to protect the privacy of the mine. This chapter consists of two main sections, namely the baseline simulation, where the initial building of the simulation along with any challenges encountered are discussed and the scenario simulation, where the different scenarios that were tested and implemented are discussed.

3.2 Baseline simulation

3.2.1 Physical investigation

As was discussed in Figure 13 of Chapter 2 the first step is always the physical investigation. The gold mine that was investigated in this study has three compressed air networks. These networks are referred to as the 1# network, the 5# network and the 2, 3, 4# network. A schematic layout of these compressed air networks can be seen in

Figure 33.

The 1# network and the 5# network are stand-alone networks with the 1# network having one compressor supplying one shaft and the 5# network having one compressor house, with four compressors, supplying one shaft and one gold plant (GP2). The 2, 3, 4# network is a ring feed network, with two compressor houses, one with two compressors and one with eight compressors, supplying three shafts and a gold plant (GP1).

As can be seen in Figure 33 these networks can be linked using an underground connection on Level 23. These connections were put in place back when 1# shaft was still a conventional pneumatic powered shaft. Later 1# shaft was turned into a hydropower shaft and it was decided to close the connections and decommission all but one of the compressors at 1# shaft. These connections, however, have not been used in a very long time and it is thus unknown what effect it would have on the networks when these connections are established.

Surface audits were conducted to determine the number and size of the compressors in each compressor house as well as the available instrumentation installed on these machines. As can be seen in the figure at the 2# compressor house the VK50_1, VK50_3 and VK32_1 have no pressure or flow meters installed and the VK32_2's pressure and flow meters are not operational. The Sulzer and Centac at the 3# compressor house, the Centac, GEC_1, GEC_2 and VK50_2 at the 2# compressor house and the Sulzer_2 at the 5# compressor house have non-operational flow meters. The flow meter at the 1# shaft may not be operational, but due to 1# compressor house only having one compressor the flow meter at the compressor can be used to determine the flow at the 1# shaft.

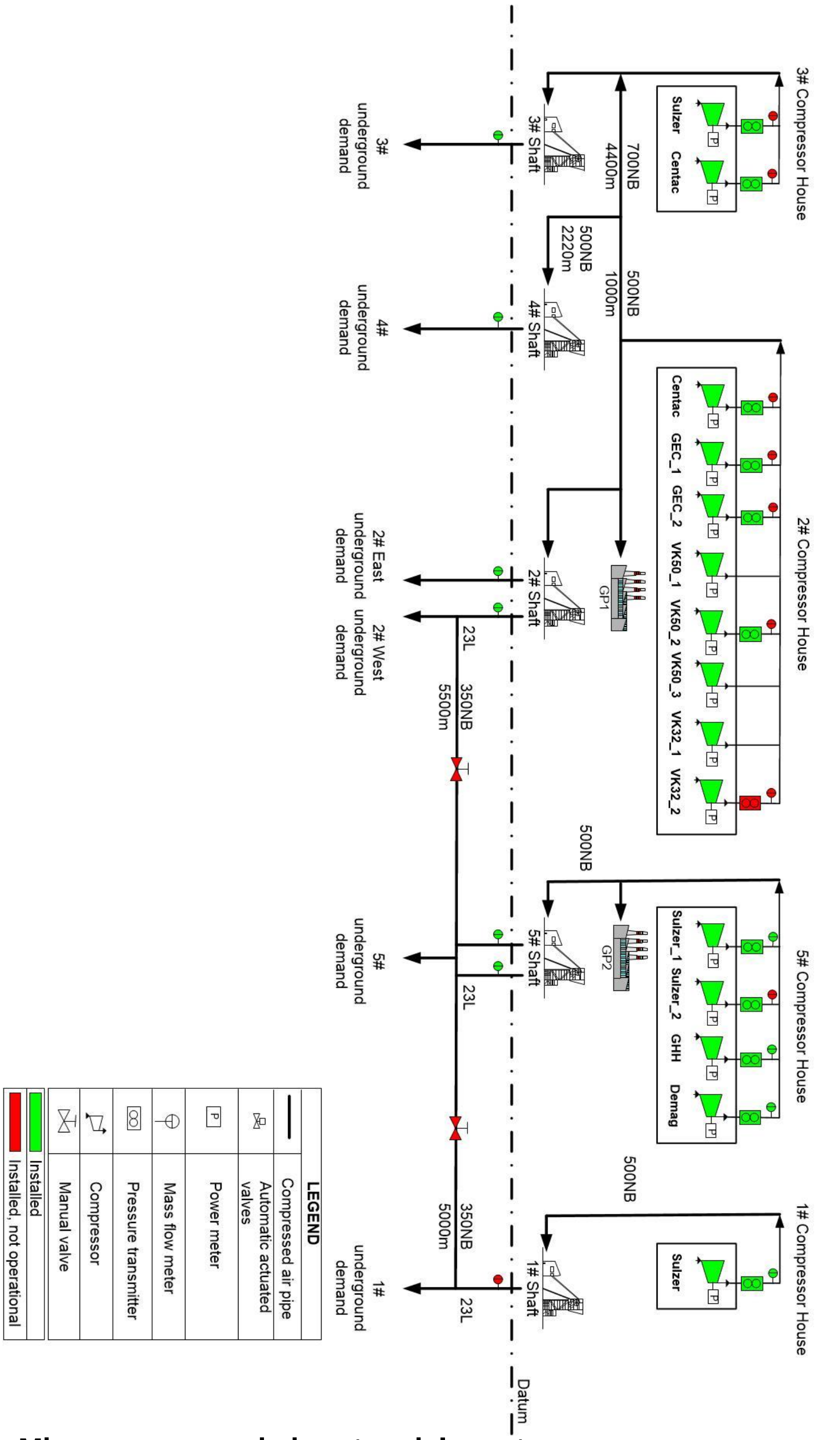


Figure 33: Mine compressed air network layout

According to mining personnel, no compressor curves were available, and thus historical data were used to determine the compressor parameters. Due to the age of the compressors and the lack of maintenance, determining the current compressor curves from historic data proved more accurate than using the old manufacturer curves. For the compressors where historical data were not available, due to pressure- and flow meters not being installed or operational, the flow was approximated by using the compressor power and the pressure was assumed to be equal to the pressure output of the compressor house. All estimated compressor curves can be found in Appendix A.

Underground piping layouts were acquired from mining personnel and where any uncertainty remained underground audits were conducted to determine the piping layouts and locations of all underground compressed air users. To protect the confidentiality of the mine in question it was chosen to omit details regarding the exact number and nature of the underground compressed air users.

All active levels on all the shafts have flow- and pressure meters installed at the inlet of the levels, but not further into the levels at the actual users. At 4# shaft, there were no flow meters installed underground and thus the flow had to be approximated using the pressure on the levels by making use of equation 6.

3.2.2 Digital investigation

All historical and current compressed air data were acquired from the mine's SCADA system. A common trend that was found while analysing the data was that underground flow and pressure meters break down on a regular basis and are not fixed in a timely manner.

Mine personnel also confirmed that many of the underground flow meters delivered very unreliable measurements due to inadequate maintenance. The 4# shaft surface flowmeter also regularly provided faulty readings. Figure 34 shows an example of the faulty measurements observed. The flow down a shaft can never be a negative value and therefore these data points cannot be used when calibrating the baseline simulation.

Another common problem with the data were areas of data loss. These events usually occur when there is a power failure at the shaft or when power to the meter in question was lost. Figure 35 shows an example of data loss as observed by the 1# shaft 45L flowmeter.

These challenges, along with the lack of installed instrumentation caused the accuracy of the simulation to decrease, as many assumptions had to be made to acquire all the information necessary to build the baseline simulation.

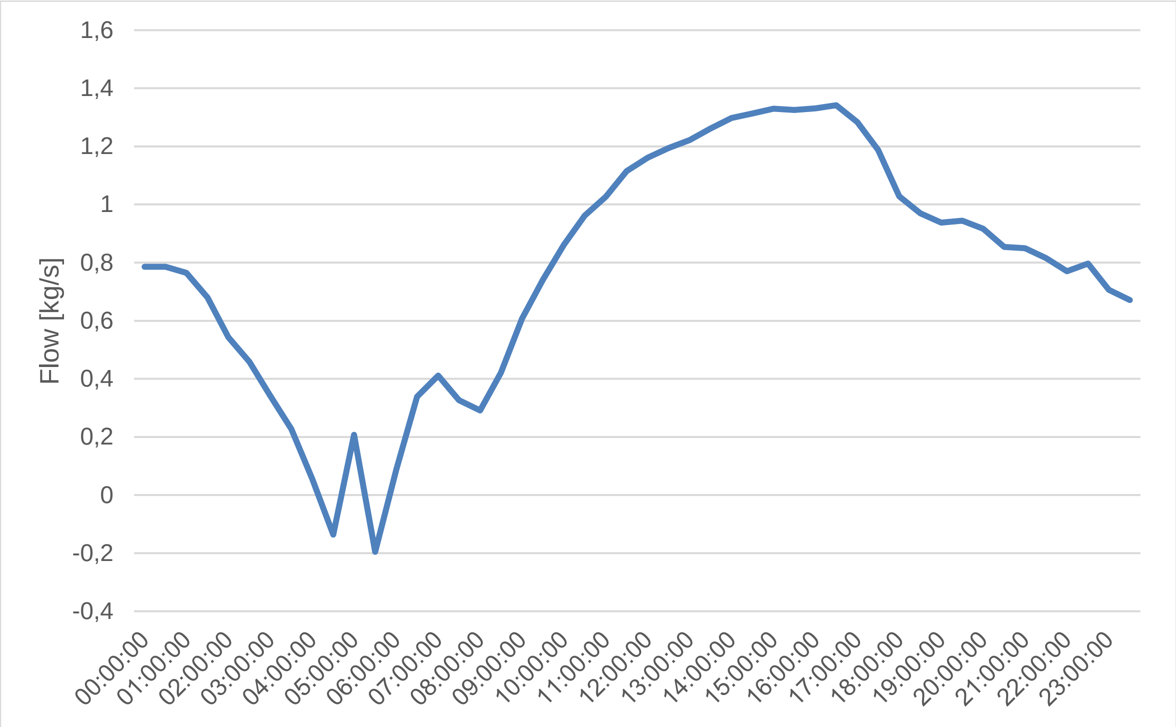


Figure 34: Example of faulty measurements by the 4# shaft flowmeter

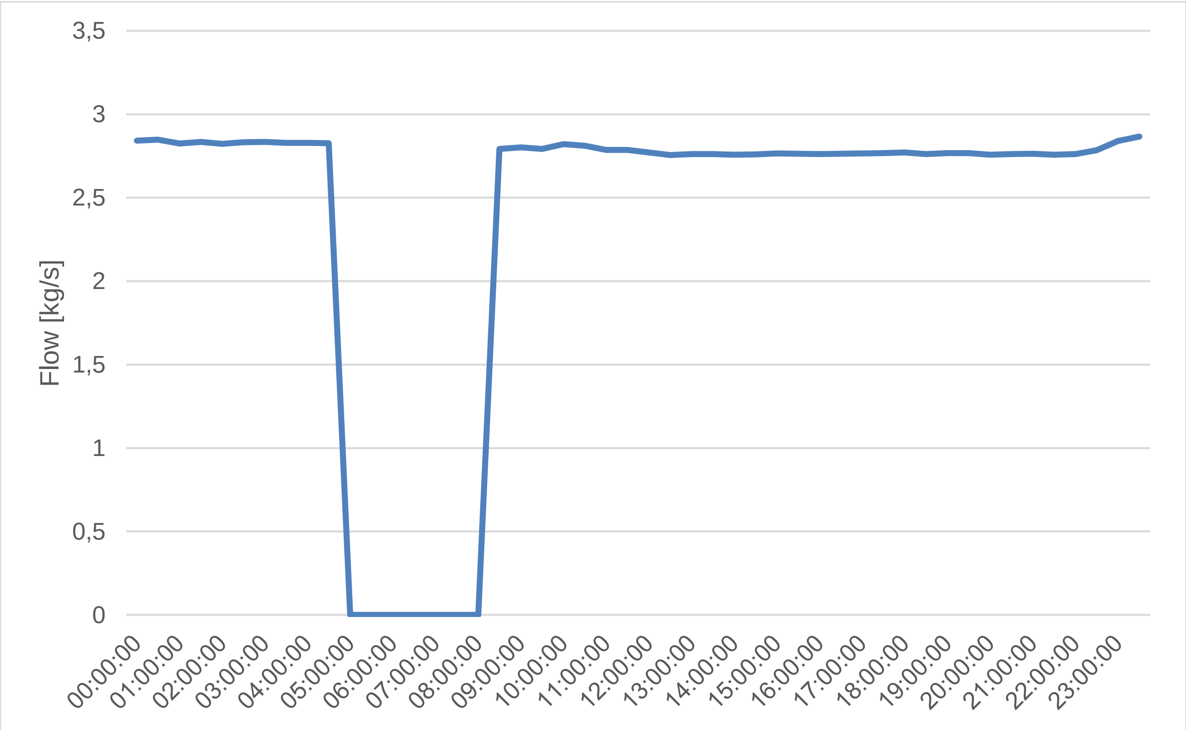


Figure 35: Example of data loss by the 1# shaft 45L flowmeter

Figure 36 and Figure 37 are examples of accurate daily profile data that can be used to calibrate the baseline simulation. In this example, the pressure (Figure 36) and flow (Figure 37) profiles for the 2# shaft is displayed. In the pressure profile you can clearly see the same demand profile as previously highlighted in Figure 14, with:

- the sweeping shift taking place between 22:30 and 07:30 at a pressure of around 450 kPa,
- the drilling shift taking place between 08:00 and 12:30 with a pressure of around 500 kPa,
- the charging of explosives taking place between 13:00 and 18:30 at a pressure of around 400 kPa and
- the blasting shift taking place between 19:00 and 22:00 at a pressure around 325 kPa.

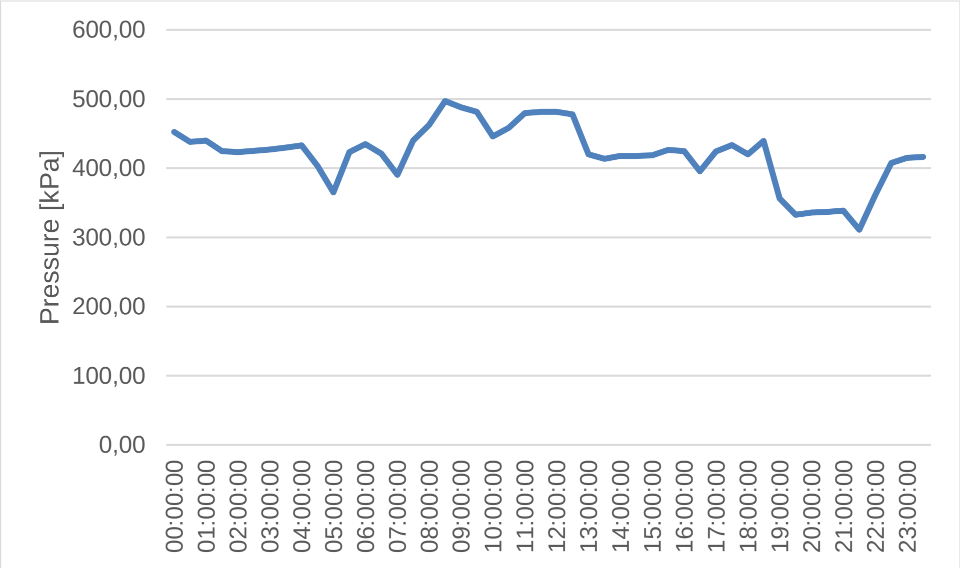


Figure 36: 2# shaft surface pressure profile

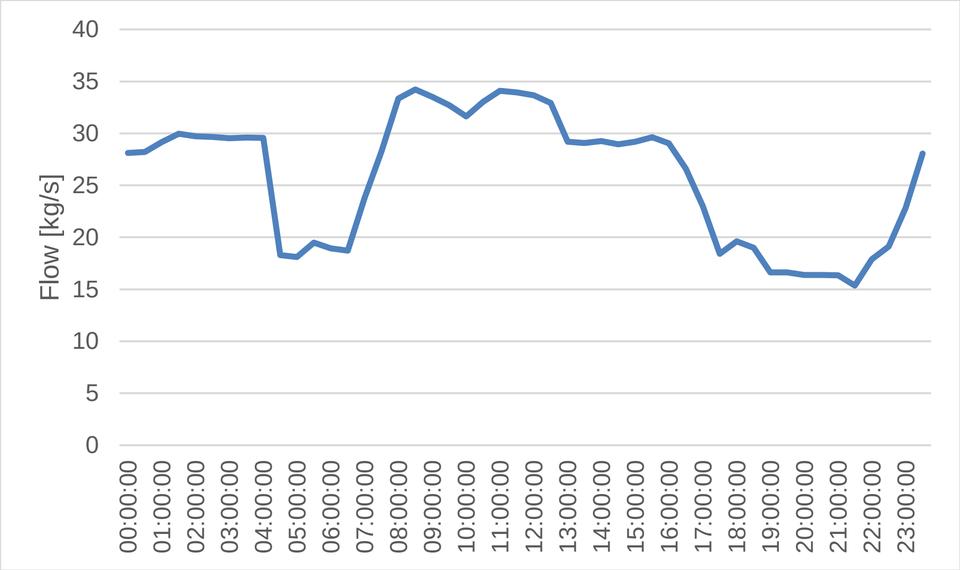


Figure 37: 2# shaft surface flow profile

A day was chosen that displayed no faulty measurement readings or data loss and that was considered as a normal operation day to be used to calibrate the baseline simulation. This was done so that the study objective to calibrate the simulation using data from a mining case study could be satisfied.

For this study, the focus was on the refuge chambers of 1# shaft. The reason for this is explained in more detail during the scenario simulation step. 1# shaft has five active levels with a total of 22 refuge chambers. The minimum flow requirement for each refuge chamber was calculated from the maximum capacity using Equation 1.

From Yang *et al.*'s study [14] it is known that, to preserve the positive pressure barrier inside the refuge chamber, the pressure should be at least 500 Pa higher than the ambient pressure. By request of the mine, a safety factor of 50 kPa was added to this value to ensure that the refuge chamber would be able to maintain its positive pressure barrier even during extreme pressure changes. This higher pressure will also ensure faster pressurisation of the chamber when the valve is open. The minimum requirements for these refuge chambers are available in Table 6.

Table 6: Minimum requirements for 1# shaft refuge chambers

Refuge chamber	Maximum capacity [# of persons]	Minimum flow requirement [kg/s]	Minimum flow requirement [L/min]	Ambient pressure [kPa]	Adjusted minimum pressure requirement [kPa]
39L RC 1	120	0.17	7 889.24	115	165
41L RC 1	270	0.39	18 098.80	117	167
41L RC 2	73	0.10	4 640.73	117	167
41L RC 3	55	0.08	3 712.58	117	167
41L RC 4	122	0.18	8 353.31	117	167
41L RC 5	270	0.39	18 098.80	117	167
41L RC 6	108	0.15	6 961.10	117	167
41L RC 7	95	0.14	6 497.02	117	167
41L RC 8	137	0.20	9 281.46	117	167
41L RC 9	137	0.20	9 281.46	117	167
42L RC 1	73	0.10	4 640.73	118	168
42L RC 2	117	0.17	7 889.24	118	168
42L RC 3	42	0.06	2 784.44	118	168
43L RC 1	215	0.31	14 386.30	119	169
43L RC 2	45	0.06	2 784.44	119	169
43L RC 3	47	0.07	3 248.51	119	169
43L RC 4	43	0.06	2 784.44	119	169
45L RC 1	137	0.20	9 281.46	121	171
45L RC 2	85	0.12	5 568.88	121	171
45L RC 3	77	0.11	5 104.80	121	171
45L RC 4	90	0.13	6 032.95	121	171
45L RC 5	78	0.11	5 104.80	121	171

3.2.3 Baseline simulation

All the information acquired during the physical and digital investigations were used to build the baseline simulation in PTB. All the surface and underground piping can be clearly seen in Figure 38. Also note the underground connection on Level 23 between 1#, 2# and 5#. This connection is closed in all directions during the baseline conditions but can be opened to connect the different networks.

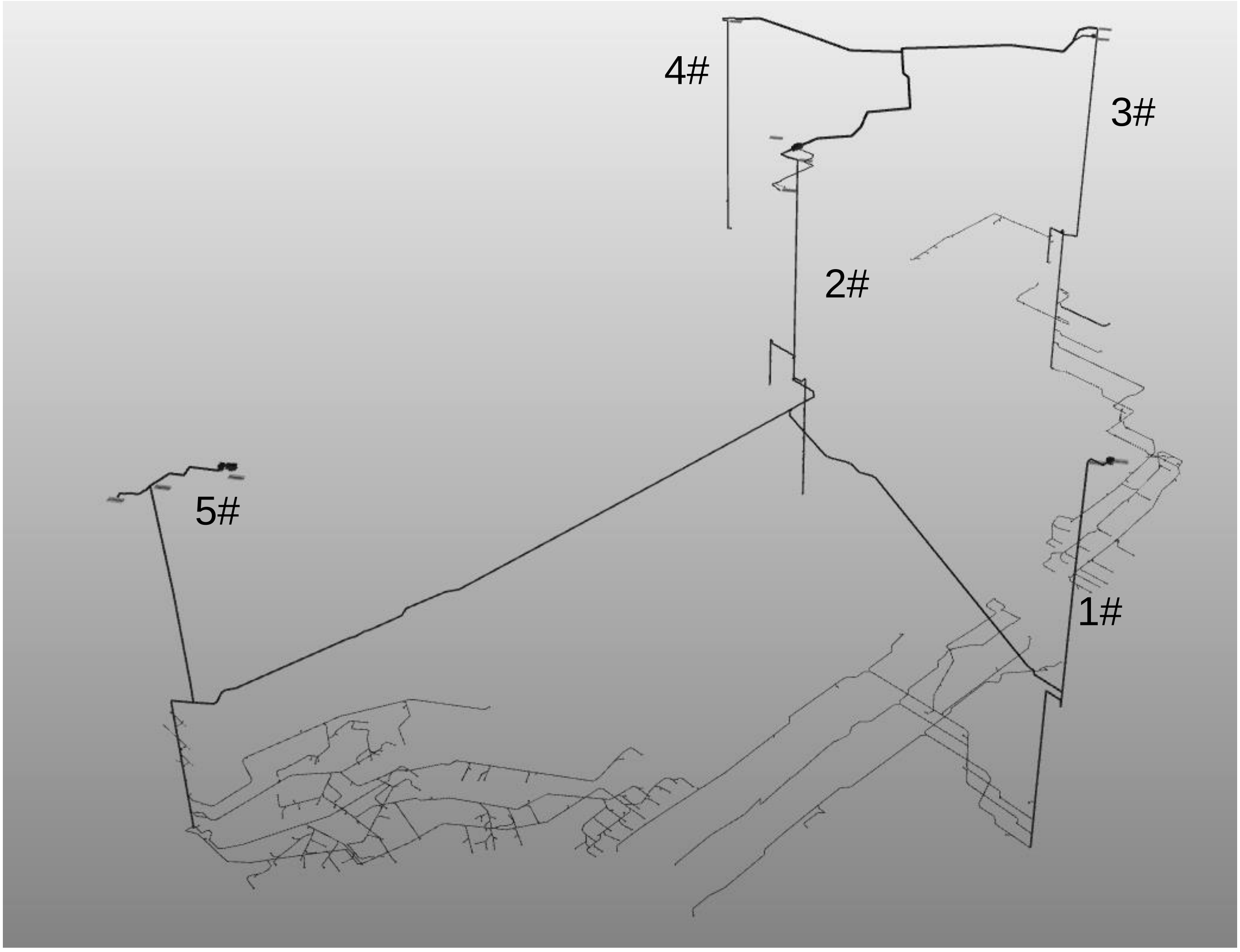


Figure 38: Baseline PTB simulation showing all surface and underground piping

Figure 39 shows the 1# Sulzer compressor as it is represented in the simulation. The simulation was built to accurately represent the real world piping layouts and sizes of the compressor houses with larger air nodes being used to represent the after-air coolers and air pressure boundaries being used to represent the inlet air filters and blow-off exhausts. The compressor was input was entered as the compressor curve available in Appendix A. PI controllers were used to control the heat reduction in the after-air coolers and the guide vanes of the compressors to ensure the pressure set point of the compressor is kept. Figures of all the other compressor houses are available in Appendix B.

Figure 39: 1# compressor house

Figure 40 and Figure 41 display the current baseline flow and pressure supplies to the refuge chambers at 1# shaft when compared to the minimum requirements. As can be seen the pressure at the chambers is more than enough to provide the required positive pressure barrier. However, the flow to some of the chambers on 39L and 41L do not meet the minimum safety requirement, whereas the flow to the chambers on 42L, 43L and 45L is more than enough. Simulations showed that this could be remedied by throttling the valves on 42L, 43L and 45L to make more air available for 39L and 41L.

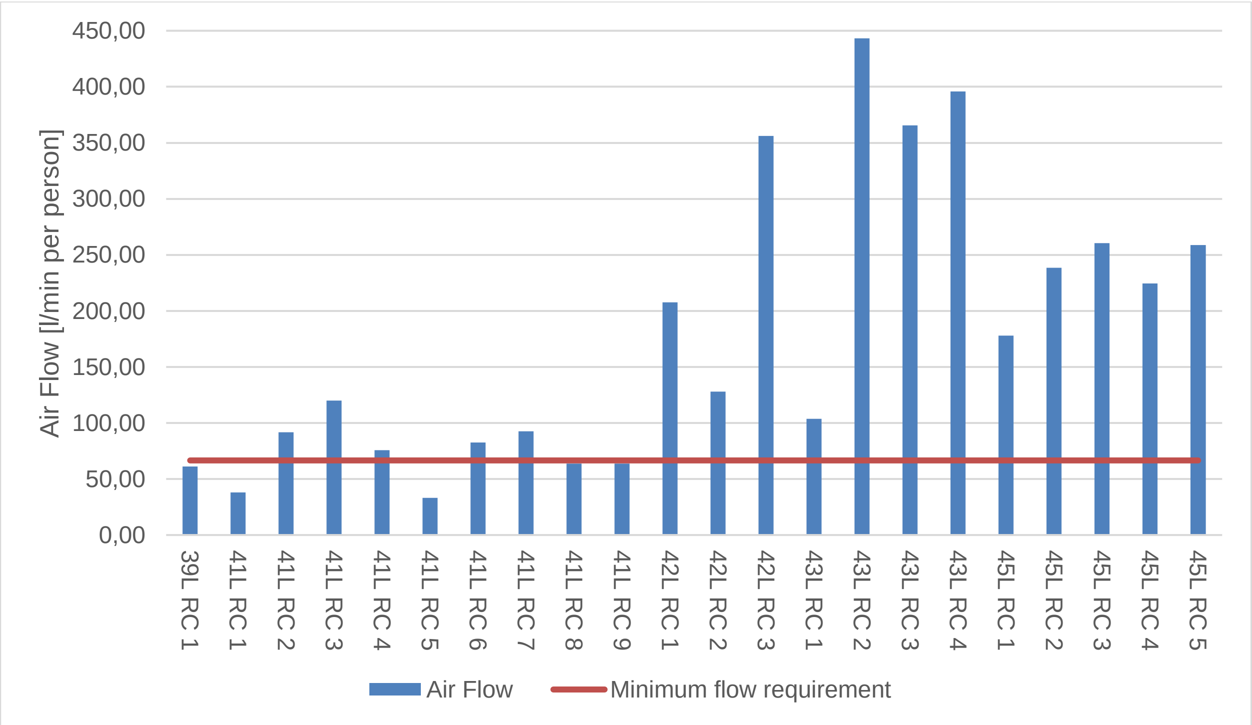


Figure 40: Refuge chamber baseline flow versus the minimum requirement

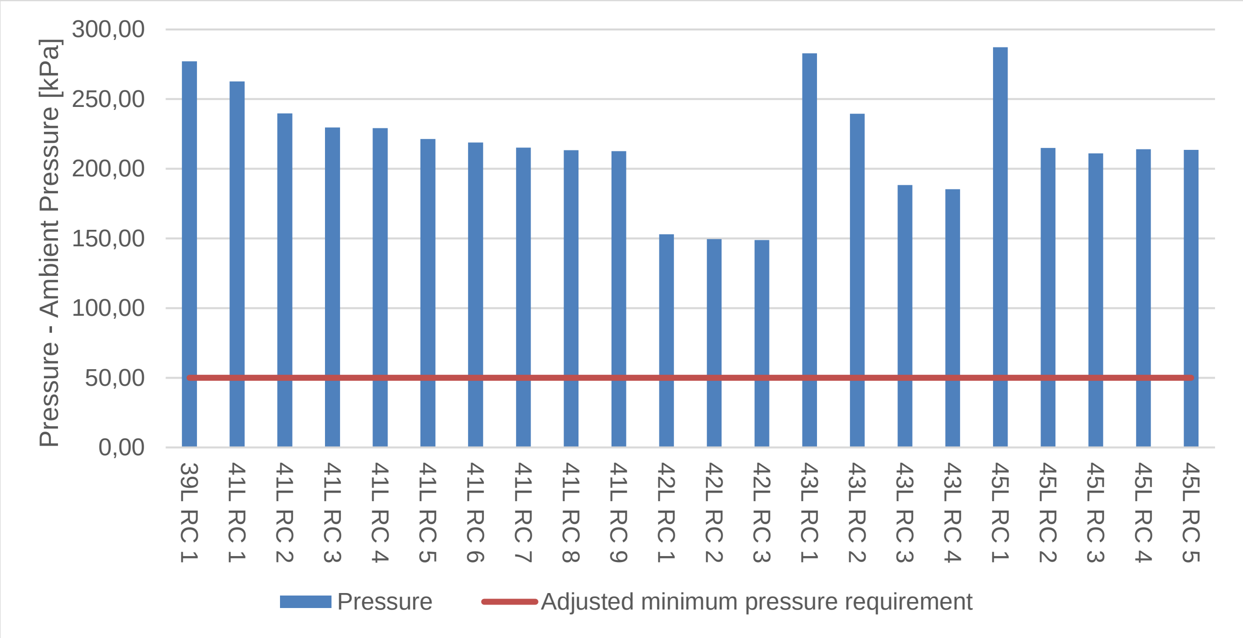


Figure 41: Refuge chamber baseline pressure versus the adjusted minimum requirement

This analysis of the refuge chamber supply was used to compare to the results of the scenario simulations to quantify the effect of different configurations on the compressed air supply to the refuge chambers in the case study.

3.2.4 Simulation calibration and verification

In order to verify the accuracy of the simulation, it was used to replicate a normal operation day on the mine that was selected during the digital investigation. The same compressors that were running on the specifically chosen day were used in the simulation and the demands and control valve setpoints were set to the same values as witnessed on that day.

The simulation results were then compared to the actual values. Because compressed airflow and pressure are only measured at the inlet for the level, these values from the simulation were compared to the actual measurements. From literature it is known that the MAE method performs better when the datapoints being compared are of a large numerical value and was used to determine the accuracy of the level pressure whereas the MSE method performs better when the data points being compared are of a small numerical value and was therefore used to determine the accuracy of the level flow. The coefficient of determination method was also applied to both these variables.

Table 7 indicates the error values for the initial run of the simulation before any calibration was done. As can be seen the uncalibrated simulation has very low accuracy and is thus not usable for the simulating of different scenarios. This highlights the importance of the calibration step.

Table 7: Summary of baseline simulation accuracy before calibration

Shafts	**Pressure**		**Flow**	
	MAE	**r^2**	**MSE**	**r^2**
1#	13.34%	0.23	0.29 kg^2/s^2	-0.15
2#	20.26%	0.53	1.11 kg^2/s^2	0.38
3#	11.69%	0.77	2.12 kg^2/s^2	0.26
4#	6.31%	0.45	1.98 kg^2/s^2	0.38
5#	38.98%	0.23	15.22 kg^2/s^2	0.25
All Shafts	21.23%	0.44	4.75 kg^2/s^2	0.26

The simulation was then calibrated using the method described in Chapter 2. Calibration is necessary to enhance the accuracy of the simulation before continuing to the next step as seen in Figure 13. Table 8 shows a summary of the final simulation errors for each shaft and the total simulation after the completion of the simulation calibration.

Because of the many challenges faced with acquiring enough high-quality data when creating this simulation, it was decided to relax the minimum error requirements. Due to the poor quality of flow data an r^2 value of more than 0.9 was deemed to be adequate and an MSE value of less than 1.0 kg^2/s^2. Therefore, there are thus two areas where the simulation did not meet the minimum requirements. These were the r^2 value of the 4# shaft pressures and the 3# shaft MSE.

Table 8: Summary of baseline simulation accuracy after calibration

Shafts	**Pressure**		**Flow**	
	MAE	**r^2**	**MSE**	**r^2**
1#	0.05%	1.00	0.20 kg^2/s^2	0.89
2#	1.14%	0.90	0.01 kg^2/s^2	0.99
3#	1.88%	0.99	1.70 kg^2/s^2	0.97
4#	0.41%	0.61	0.00 kg^2/s^2	0.97
5#	1.38%	0.97	0.40 kg^2/s^2	0.98
All Shafts	1.32%	0.93	0.54 kg^2/s^2	0.97

4# shaft was experiencing a significant lack of instrumentation. There is only one flow meter on the surface and a pressure transmitter on only two of the levels. Therefore, the flow to the levels had to be calculated using equation 6 and are thus only an approximation of the actual flow to the levels of 4#. This contributed to a reduction in the overall accuracy of the simulation of this shaft.

3# shaft's flow meters are the least reliable flow meters on the mine. The values change erratically across different days and are not always trusted even by mining personnel. This is clearly seen as the simulation struggled to replicate the values resulting in the higher-than-expected MSE value.

Overall, the simulation accuracy met the revised minimum requirements and can therefore accurately replicate conditions at the level inlet and because all the simulation inputs were for the different end-users on the network, it can be assumed that the simulation can also accurately represent the conditions at these end-users.

3.3 Scenario simulation

With the baseline simulation calibrated and proven to be of a high enough accuracy, a scenario simulation can be created from the baseline to observe what the effects of any different configurations in the compressed air network will be on the different users on the compressed air network.

For this case study the problem that needed solving was the following:

1# shaft is a hydropower shaft, meaning that only water is used for drilling and not compressed air. Compressed air is therefore only used to keep the refuge bays pressurised and supplied with breathable air. 1# shaft also only has one compressor and since refuge bays must always be supplied, this compressor is never switched off. However, this compressor requires critical maintenance and therefore changes must be made to the existing compressed air network to ensure the safety of all personnel at 1# shaft. Two possible solutions were presented:

3.3.1 Scenario 1

The first proposed solution was to open the Level 23 connection between 1# shaft and 2# shaft. This would mean that the 1# Sulzer can be switched off as compressed air would be supplied from 2# shaft. Figure 42 is a graphical representation of the proposed configuration.

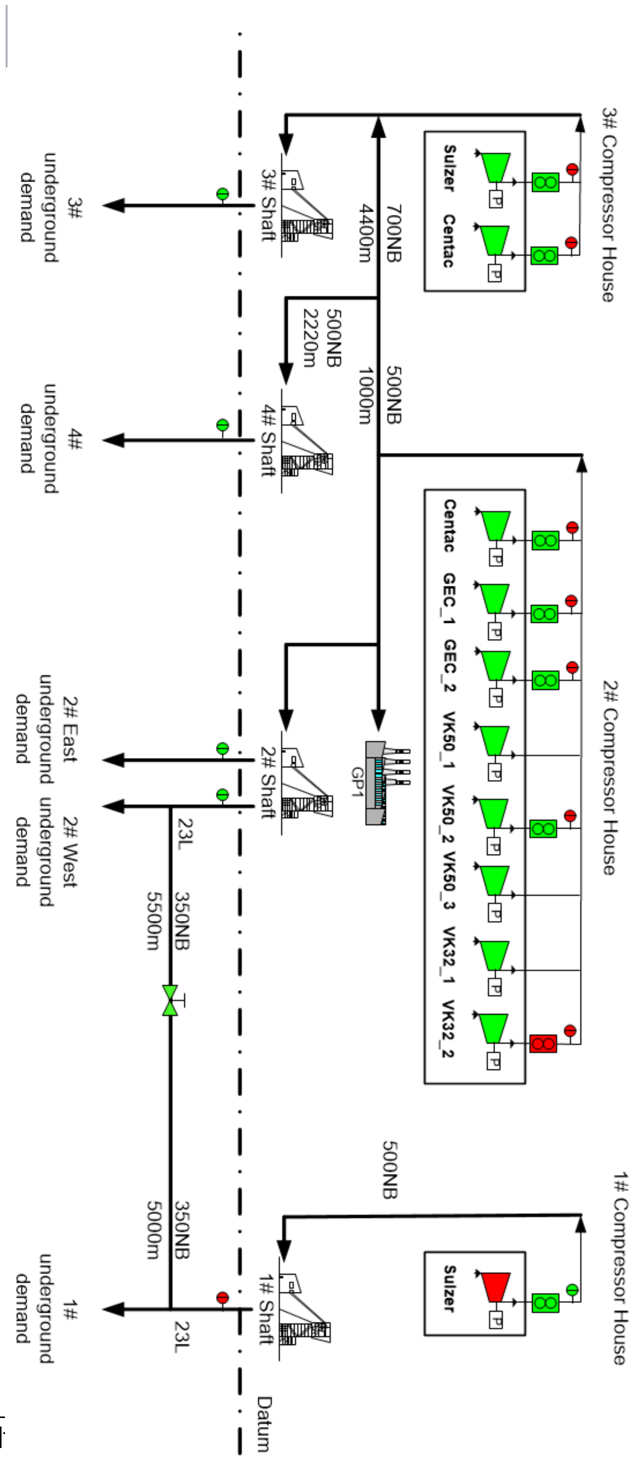


Figure 42: Schematic of proposed operation for Scenario 1

For this configuration to be accepted and the process outlined in Figure 13 to continue the following prerequisites needed to be met:

- Minimum pressure and flow requirements at 1# shaft refuge chambers must be met.
- The actuator pressure supply to GP1 should remain above 400 kPa.
- The agitator pressure supply to GP1 should remain above 250 kPa.
- The air flow required by GP1 is very small when compared to the rest of the network and is thus not included in the minimum requirements.
- Normal supply at 2# shaft, 3# shaft, and 4# shaft must still be met.

In order to account for the additional demand on the compressed air network, the current compressor operation at the 2# and 3# compressor houses must be changed. The standard compressor operation can be seen in Figure 43.

In order to meet the new additional demand, it was proposed to operate an additional compressor in order to accommodate the extra demand on the network. Numerus simulations were run in order to find the most efficient compressor combination to operate. The new proposed compressor operation is available in Figure 44.

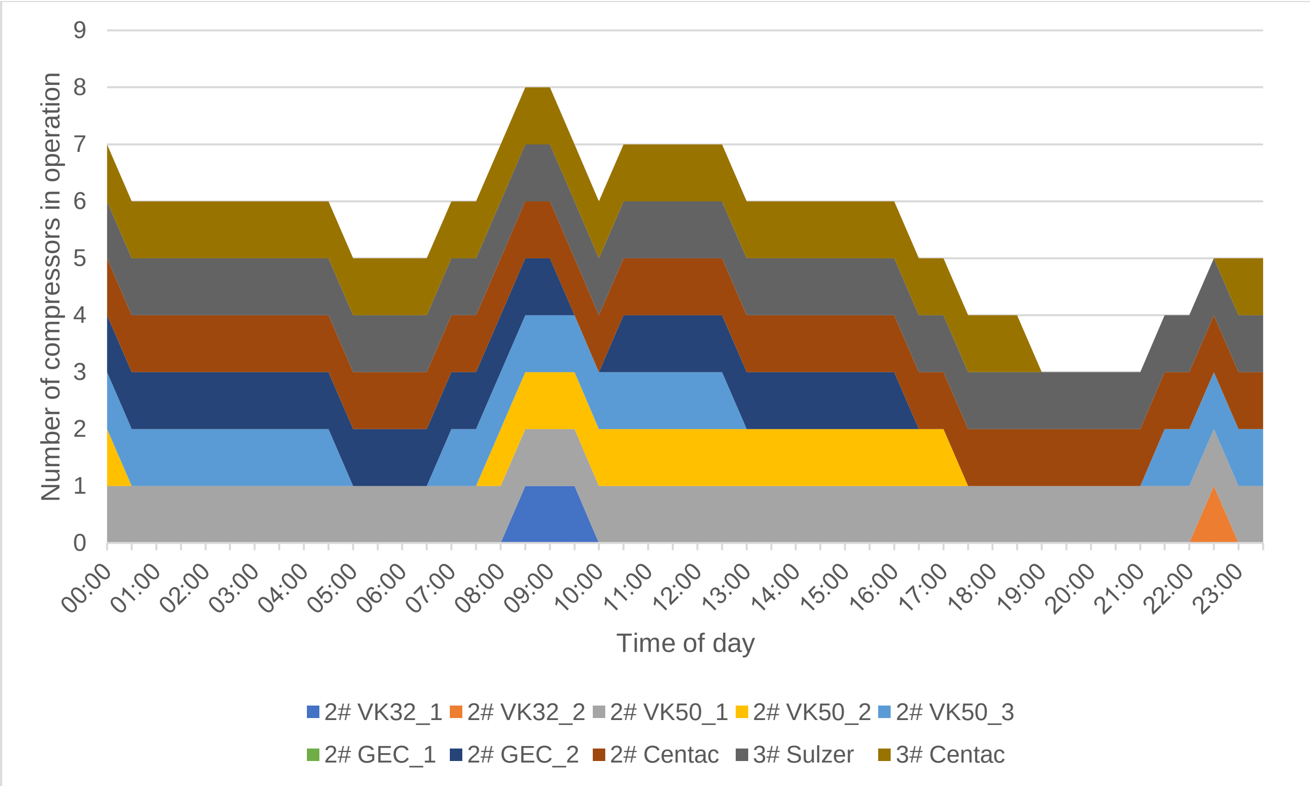


Figure 43: Standard 2, 3, 4# network compressor operation

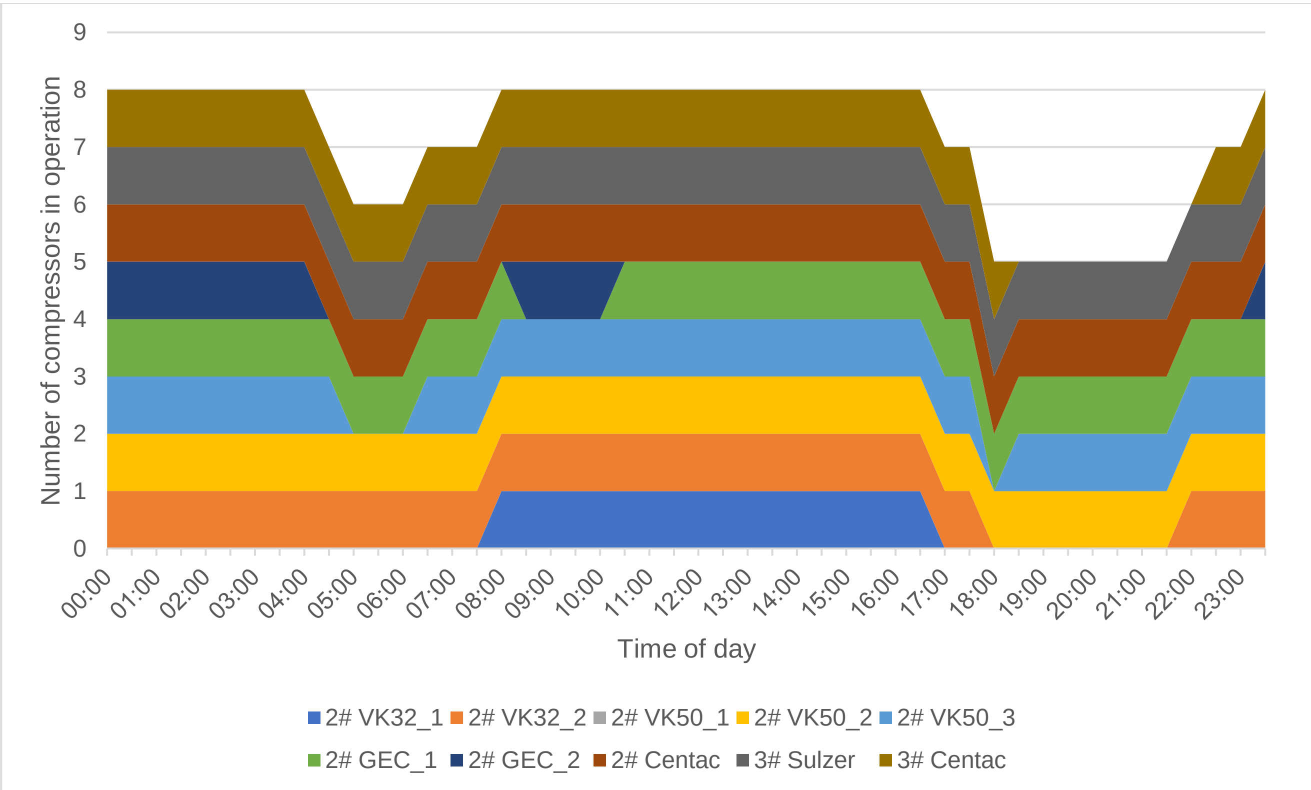


Figure 44: Proposed new 2, 3, 4# network compressor operation

Figure 45 and Figure 46 indicate the expected airflow and air pressure at the refuge chambers where Scenario 1 was implemented. As can be seen, all but two of the refuge chambers meet the minimum flow requirement. Only 41L RC 2 and 41L RC 6 do not meet the requirements, but the margin is so small that by decreasing the maximum capacity of the chamber to ensure that the minimum flow requirement is safely met would ensure that no complications with air supply will occur. By reducing the airflow to the refuge chambers on the lower levels there is now more air available for the higher levels. With both measures implemented all the refuge chambers would easily meet the adjusted minimum pressure requirement and thus the configuration was approved to move on to the final step as outlined in Figure 13.

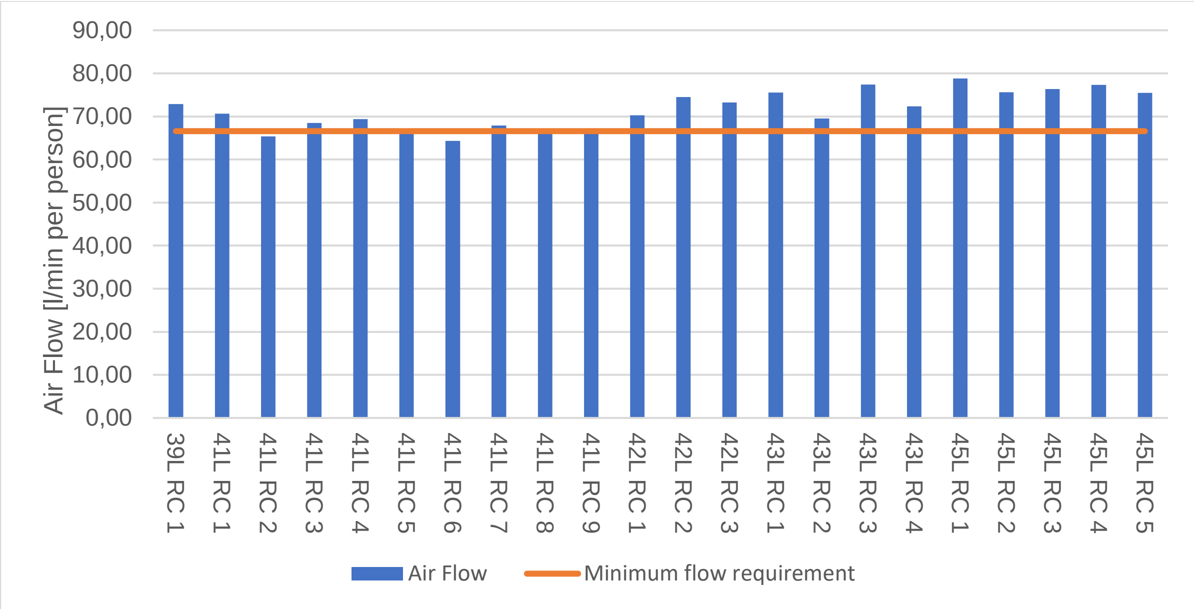


Figure 45: Simulation prediction of airflow to refuge chambers during Scenario 1

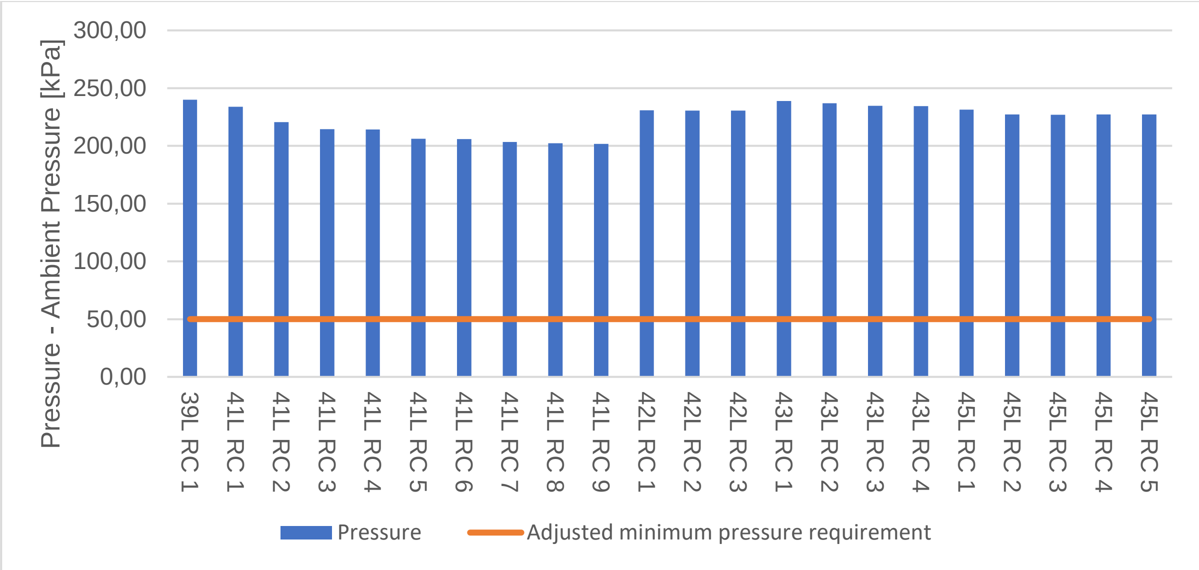


Figure 46: Simulation prediction of air pressure at refuge chambers during Scenario 1

Scenario 1 was implemented by the mine and thus the results of the simulation can be compared with the actual data before the change and after the change. Figure 47 to Figure 50 display the flow and pressure changes on all active levels of 1# Shaft. As can be seen, there is no figure for Level 42 as this level does not have any instrumentation and gets its compressed air from Level 43.

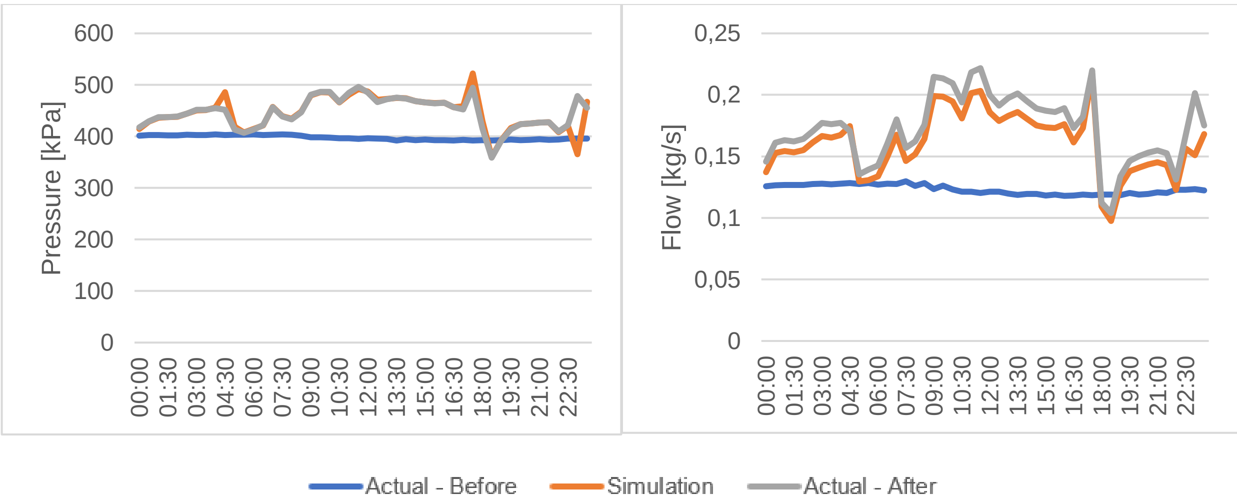


Figure 47: 1# Shaft Level 39 pressure and flow

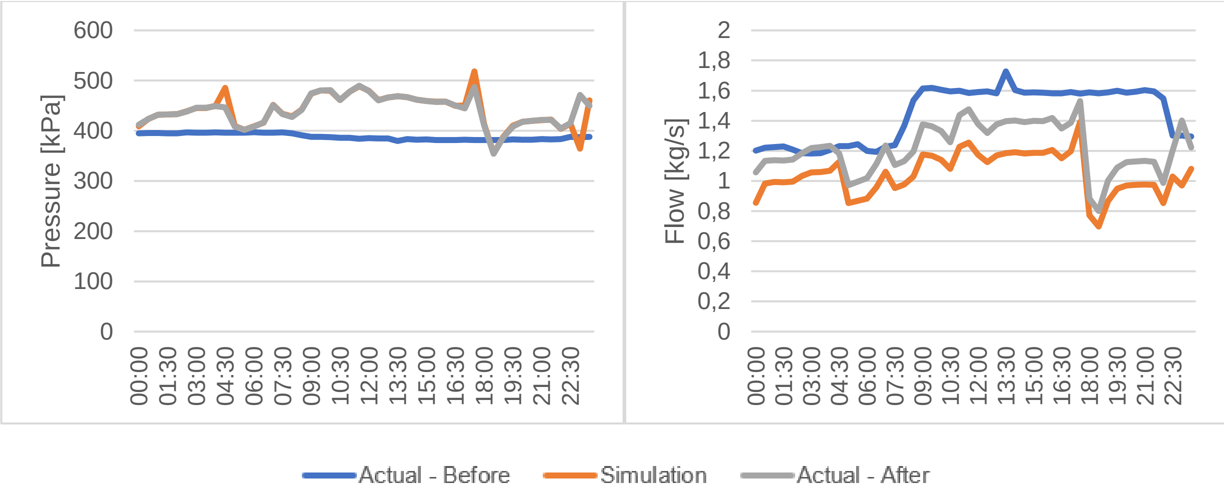


Figure 48: 1# Shaft Level 41 pressure and flow

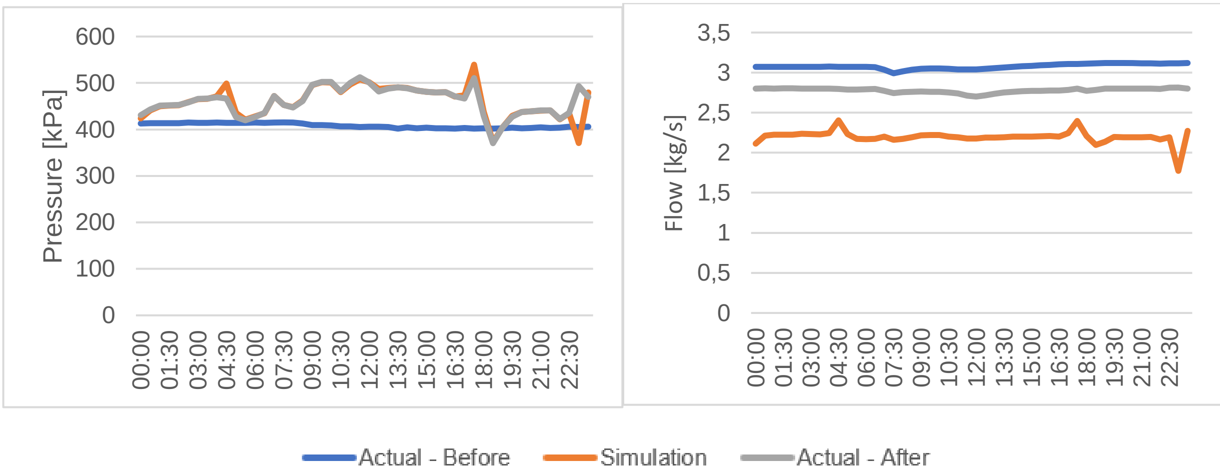


Figure 49: 1# Shaft Level 43 pressure and flow

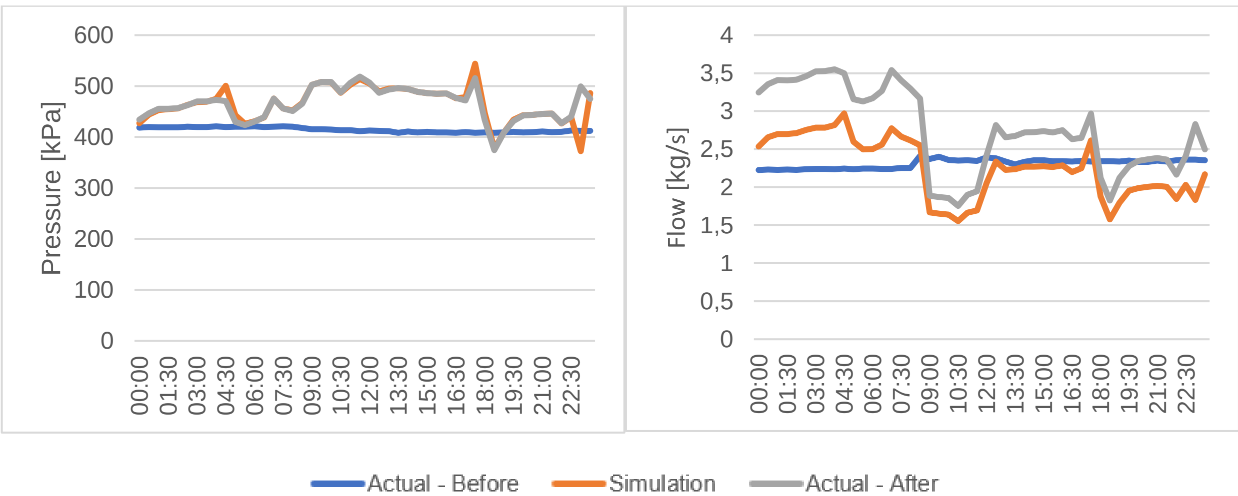


Figure 50: 1# Shaft Level 45 pressure and flow

From the graphs, the high accuracy of the simulation in terms of the pressure predictions can clearly be seen. The accuracy of the simulation regarding the flow is unfortunately not as high. The simulation constantly predicted a lower flow than that which was observed prior to the implementation of Scenario 1. This is, however, not detrimental as the flow needs to be above a minimum amount to be feasible. As a result, it can be said that if the simulation is feasible the real world application will be feasible.

From Figure 51 it is observed that the pressure supply to the gold plant remained relatively unchanged and therefore met the prerequisite for the Scenario.

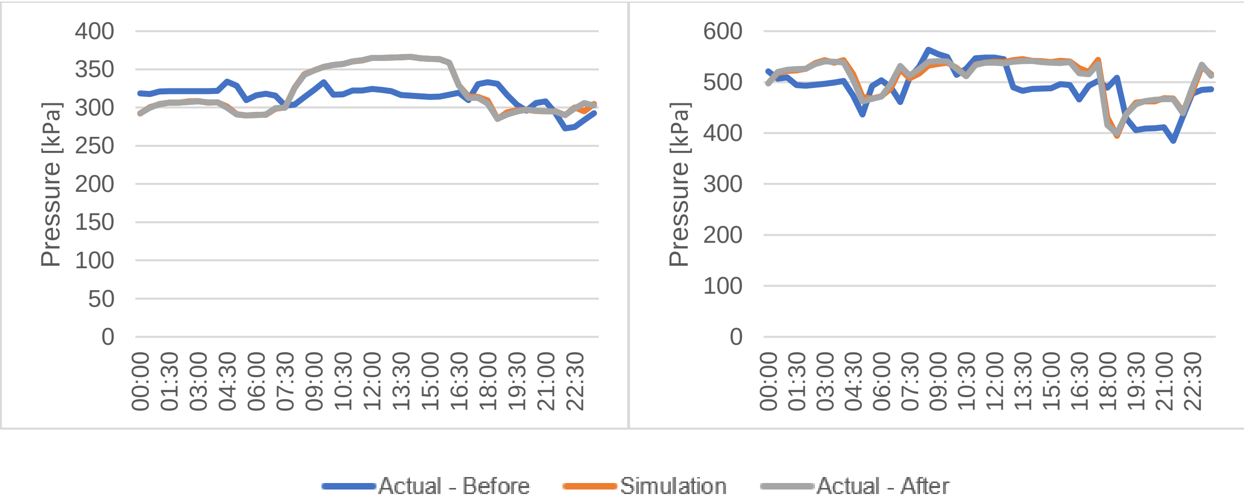


Figure 51: GP1 pressures – Agitation (left) and Actuation (right)

Figure 52 details the changes observed on the surface at 2# Shaft along with the simulation predictions. The pressure remained relatively the same while the flow down the shaft increased. This is due to the increased demand as 2# Shaft is now also supplying 1# Shaft with compressed air. Once again, the simulation accurately predicted the change in pressure but underestimated the change in flow. This is not a large issue as the simulation still correctly predicted that an increase in compressed air flow would occur.

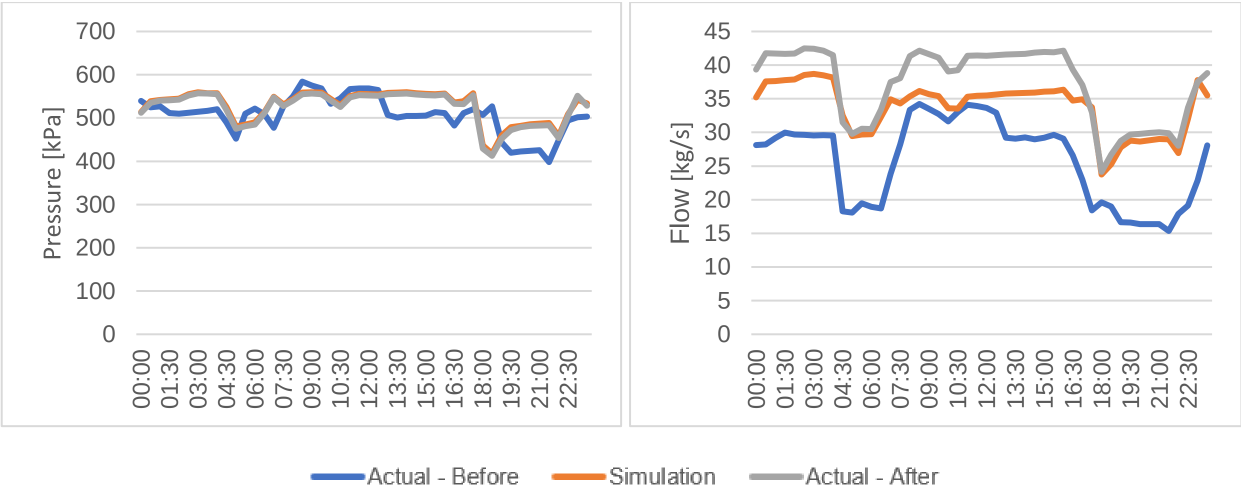


Figure 52: 2# Shaft surface pressure and flow

Figure 53 details the changes observed on the surface at 3# Shaft along with the simulation predictions. Here the simulation predicted an increase in pressure at 3# Shaft, but this was not realised as the pressure remained relatively constant after the change. However, there is a large decrease in compressed airflow with the simulation predicting an even larger flow decrease. It is unclear whether such a large decrease in compressed air flow really did occur or whether this was only due to faulty measuring devices. 3# Shaft is known for having many faulty readings and this could explain the simulation's extreme lack of accuracy with regard to this shaft.

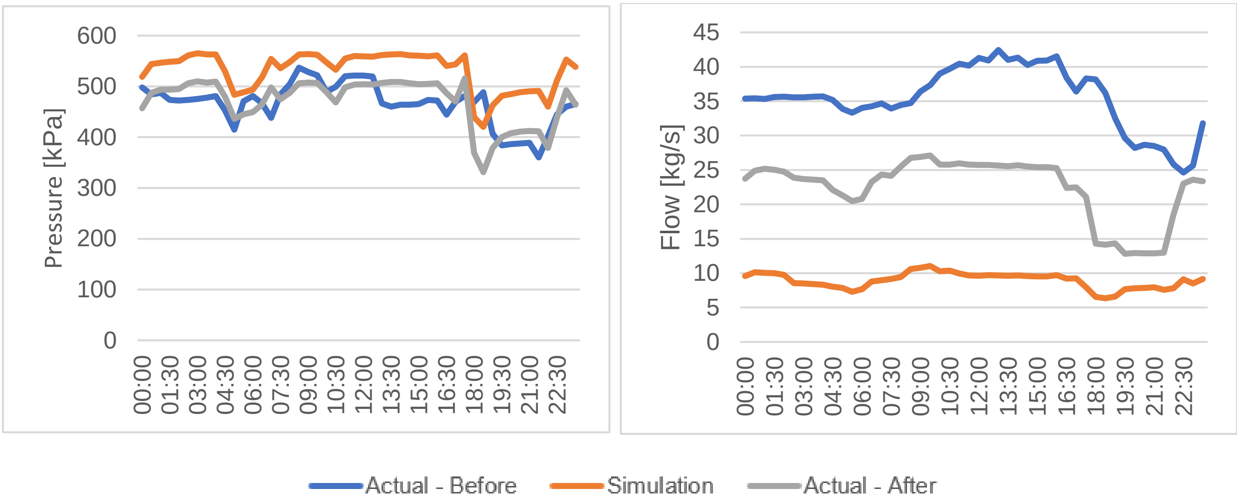


Figure 53: 3# Shaft surface pressure and flow

Figure 54 details the changes observed on the surface at 4# shaft along with the simulation predictions. At 4# there is also very little change observed regarding the pressure at the shaft, however, there is an increase in compressed air going down the shaft. This could potentially account somewhat for the decrease in the compressed air flow at 3# Shaft, but 4# Shaft's flow meter is also notoriously unreliable, and it is thus unknown whether there was a true increase in flow. Once again, the inaccuracies in the simulation prediction can be attributed to unreliable flow meters and the lack of instrumentation in the underground levels of 4# Shaft.

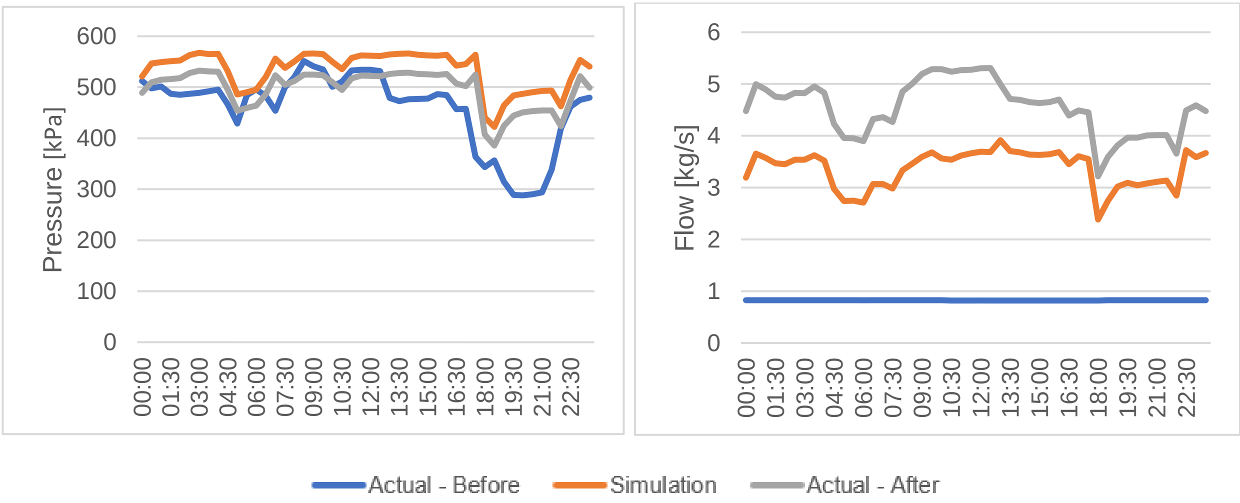


Figure 54: 4# Shaft surface pressure and flow

When observing the changes present at all the shafts after Scenario 1 was implemented it could be concluded that all operations on the shafts could continue as normal after the change was implemented as drilling with compressed air relies more on the compressed air pressure than on the flow and thus all the prerequisites for the scenario to be feasible were met.

Table 9 provides a summary of the simulation accuracy when predicting the outcomes of Scenario 1. Even though the simulation accuracy is lower than that of the baseline the overall pressure MAE error is still lower than 5% and the overall flow MSE error is still lower than 1.0 kg^2/s^2 and therefore the simulation can be deemed accurate enough to be used to predict the outcome of changes to a compressed air network.

Table 9: Summary of Scenario 1 simulation accuracy

Shaft	**Pressure**		**Flow**	
	MAE	**r^2**	**MSE**	**r^2**
1#	1.13%	0.83	0.16 kg^2/s^2	0.73
2#	8.80%	0.80	0.44 kg^2/s^2	0.90
3#	1.16%	0.98	2.17 kg^2/s^2	0.97
4#	0.38%	0.53	0.16 kg^2/s^2	0.83
All Shafts	**4.65%**	**0.84**	**0.94 kg^2/s^2**	**0.89**

3.3.2 Interpretation of the results of Scenario 1

When Scenario 1 is compared with the baseline it is evident that there was a definite improvement in the compressed air supply to the refuge chambers with much better airflow to Levels 39 and 41. There was also a pressure increase noticed on Levels 42 and 43, probably due to the decrease in flow.

The simulation had very high accuracy in terms of predicting pressure changes, but when predicting the flow changes the simulation tended to underestimate the actual flow. Which in this scenario is not a bad thing, as the simulation is being used to estimate whether the flow value will be above a certain minimum value. Thus, by use of this actual real world scenario the methodology developed in Chapter 2 has been verified.

After this scenario was implemented there were no reported complaints of a lack of compressed air supply anywhere on the mine and thus the implementation of the proposed change was a success. After the implementation of Scenario 1 the pipe that was supplying compressed air from 2# Shaft to 1# Shaft burst. It was no longer possible to supply compressed air from 1#

Shaft. Because of this incident and coupled with the fact that scenario 1 required more compressors, Scenario 2 was also proposed.

3.3.3 Scenario 2

The second proposed solution was to open the Level 23 connection between 1# Shaft and 5# Shaft, whilst having the connection between #1 shaft and #2 shaft closed. This would mean that the 1# Sulzer can be switched off as compressed air would be supplied from 5# Shaft. Figure 55 is a graphical representation of the proposed configuration.

For this configuration to be accepted and the process outlined in Figure 13 to continue the following prerequisites needed to be met:

- Minimum pressure and flow requirements at 1# Shaft refuge chambers must be met.
- The pressure supply to GP2 should remain above below 400 kPa.
- Supply to 5# shaft should not be negatively impacted.

It is a known fact that the compressors at 5# Shaft were oversupplying the shaft and thus the simulation was used to prove that, by throttling the valve that supplies air to 1# Shaft, it would be possible to supply 1# Shaft with enough compressed air without the need to start additional compressors at the 5# compressor house. Thus, no changes were proposed for the current compressor operation.

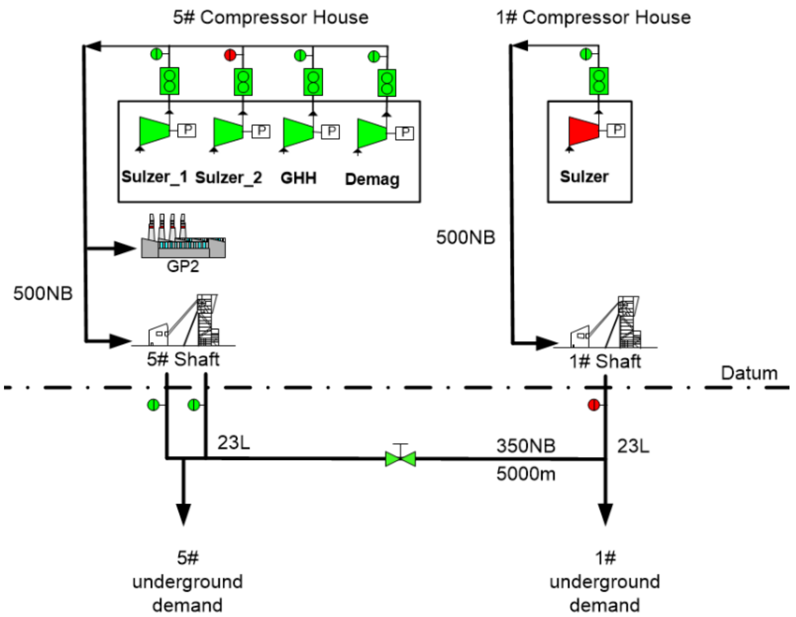


Figure 55: Schematic of proposed operation for Scenario 2

Figure 56 and Figure 57 show the expected airflow and air pressure at the refuge chambers where Scenario 2 was to be implemented. Once again all but two of the refuge chambers met the minimum airflow requirement. However, it is known from Scenario 1 that the simulation tends to underestimate the compressed air flow to the levels and thus it is likely that the airflow will be enough once implemented. In order to ensure that the minimum airflow requirements are met, the maximum capacity of those refuge chambers that are affected can be reduced. The pressures predicted at the refuge chambers are lower in Scenario 2 than they were in Scenario 1. This is due to the throttling of the supply valve to 1# Shaft. The pressures, however, are still well above the safe limit and thus the configuration was approved to move on to the final step as outlined in Figure 13.

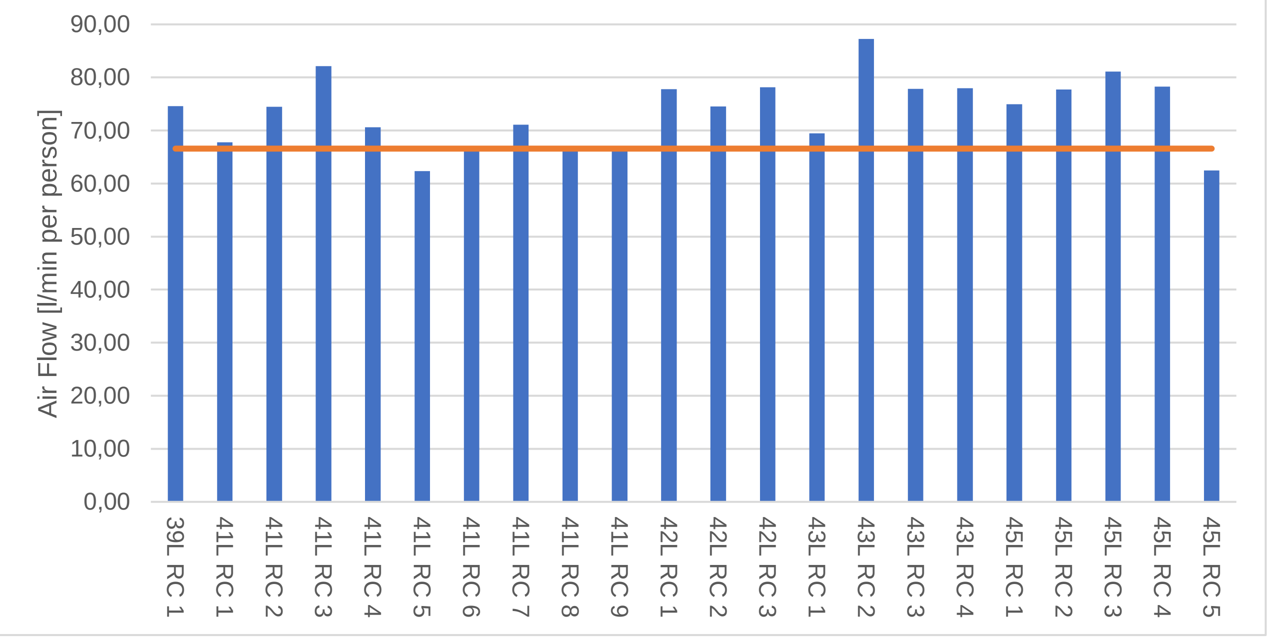


Figure 56: Simulation prediction of airflow to refuge chambers during Scenario 2

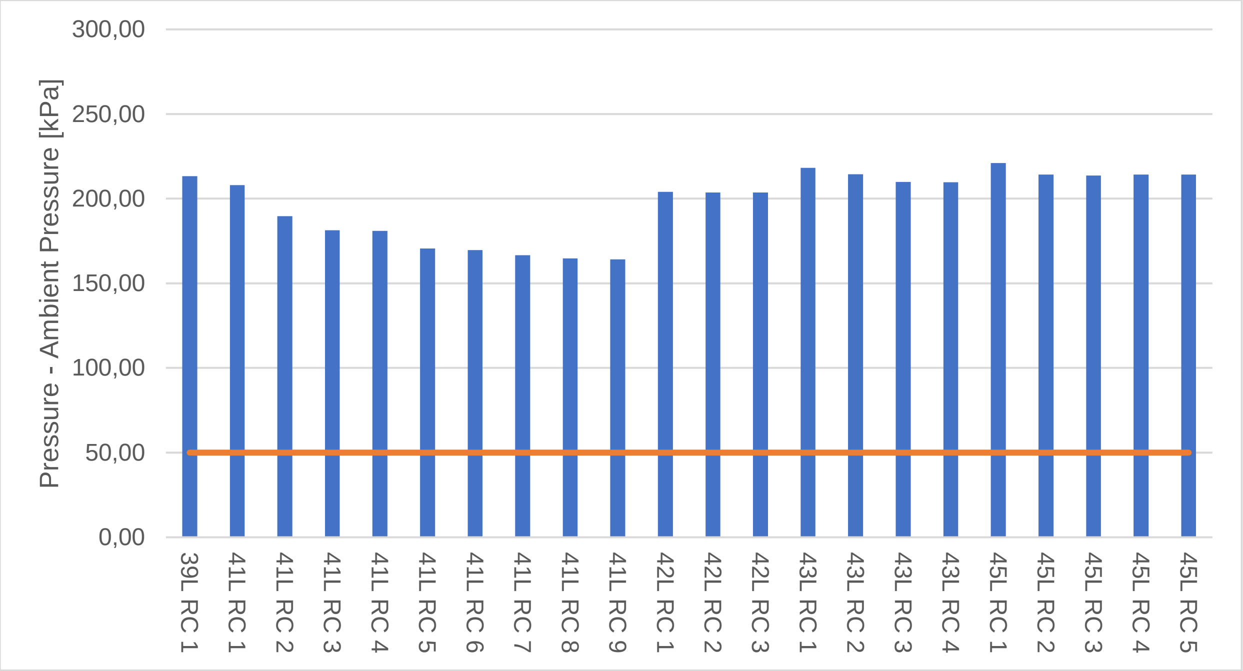


Figure 57: Simulation prediction of air pressure at refuge chambers during Scenario 2

After the incident at 2# shaft Scenario 2 was implemented. Figure 58 to Figure 61 display a comparison between the flows and pressures before and after the implementation of Scenario 2 as well as the predicted values as predicted by the simulation for Levels 39, 41, 43 and 45 of 1# Shaft.

On all the levels the simulation had a near perfect prediction of the level pressures and was reasonably close when predicting the compressed air flows. One exception being Level 43 where the simulation predicted a large decrease in compressed air flow that was not realised after implementation.

The simulation once again predicted lower-than-observed compressed air flows and therefore it can reasonably be assumed that the compressed air flow to all the refuge chambers will be above the minimum flow requirement, ultimately satisfying the requirement for this solution.

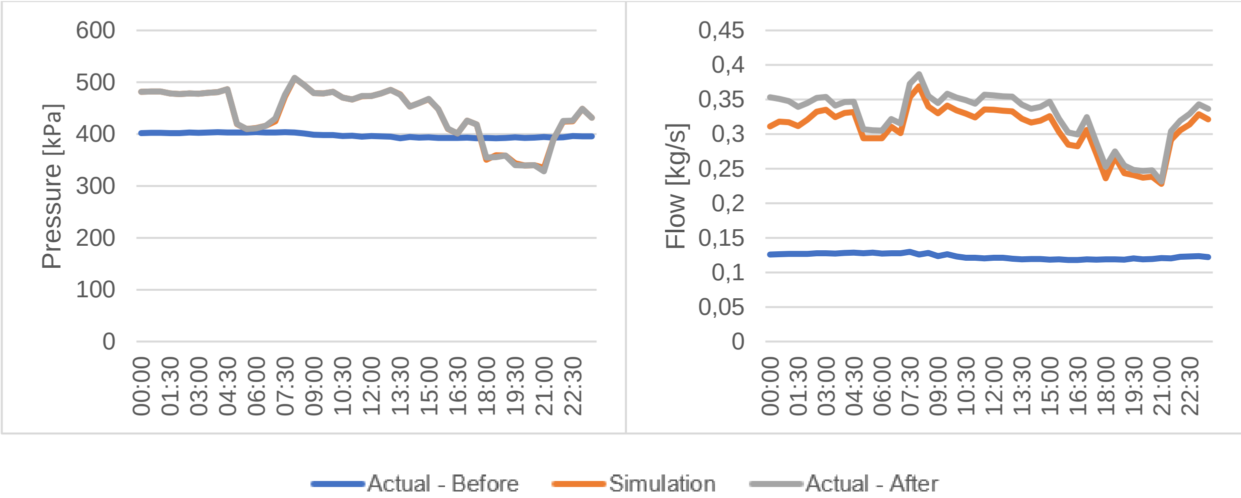


Figure 58: 1# Shaft Level 39 pressure and flow

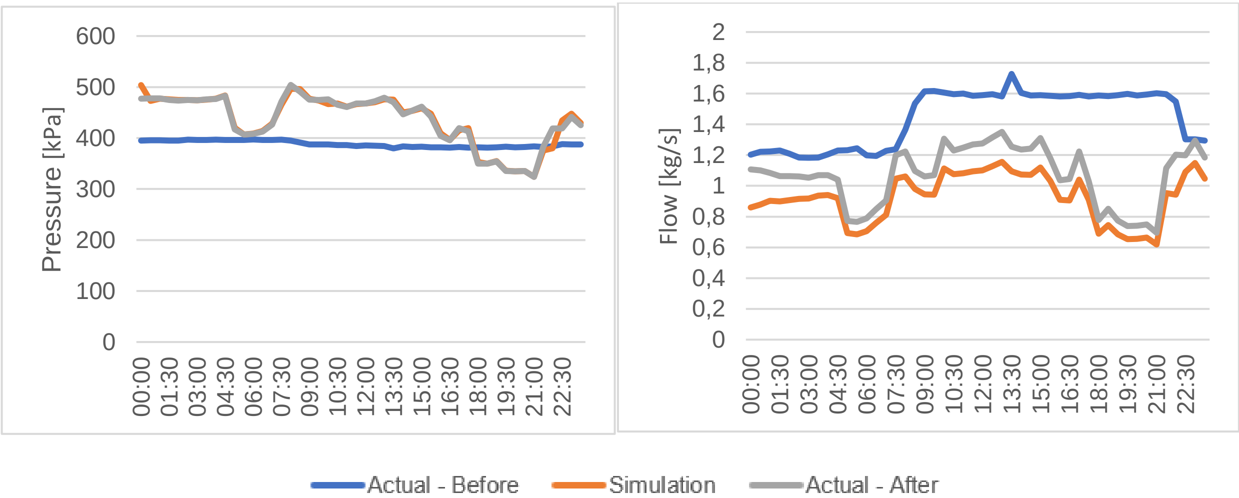


Figure 59: 1# Shaft Level 41 pressure and flow

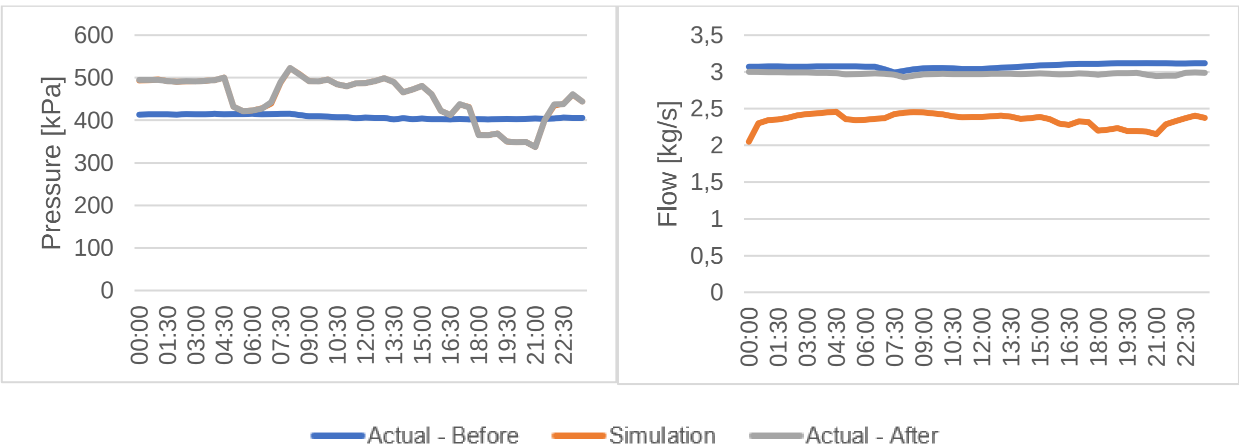


Figure 60: 1# Shaft Level 43 pressure and flow

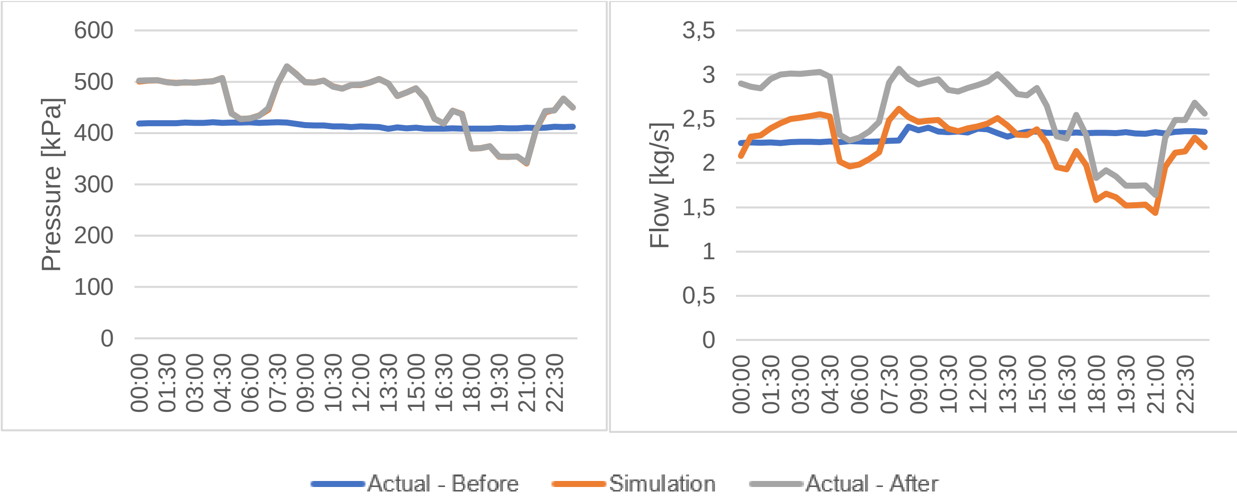


Figure 61: 1# Shaft Level 45 pressure and flow

Figure 62 details the change in pressure at the gold plant. As can be seen after implementation of Scenario 2 the pressure at the gold plant did not decrease under 400 kPa and thus met the prerequisite. The simulation also nearly perfectly predicted the change in pressure at the gold plant.

Figure 62: GP2 Pressure

Figure 63 details the changes observed on the surface at 5# Shaft along with the simulation predictions. The change in pressure at the shaft itself followed the same change in trend that was viewed at the gold plant and was once again accurately predicted by the simulation.

However, the flow at 5# Shaft did not increase as drastically as predicted by the simulation. An increase in flow was to be expected due to the additional demand coming from 1# Shaft. A possible explanation as to why the flow did not increase by such a large margin can be due to 5# implementing measures to reduce the airflow demand at 5# itself to further reduce the need to use an additional compressor along with throttling the valve leading to 1# Shaft. There were thus no drastic changes observed at 5# due to the implemented solution and thus operations could continue, as usual, meeting the last prerequisite.

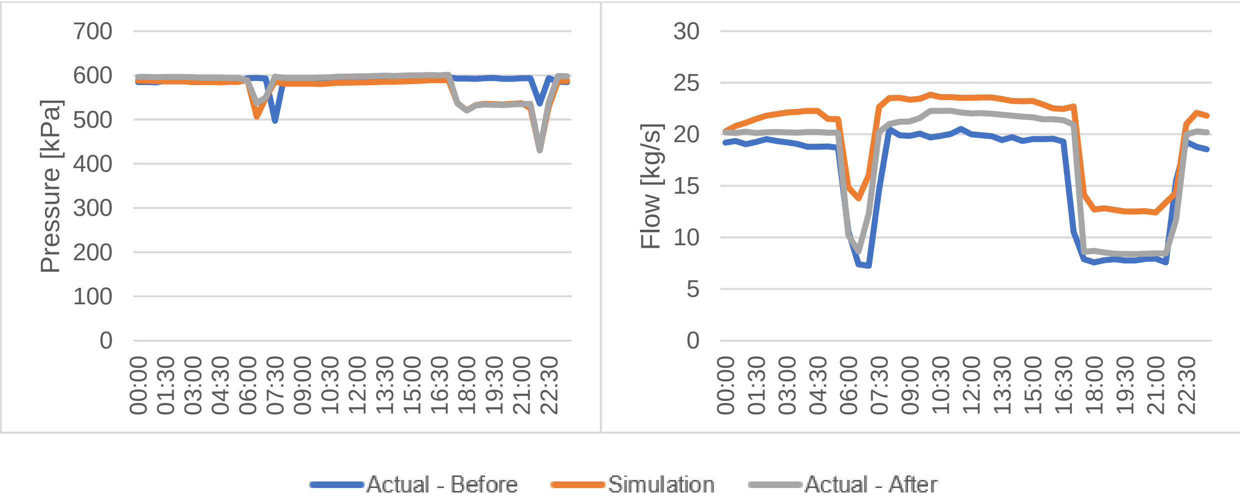


Figure 63: 5# Shaft surface pressure and flow

Table 10 provides a summary of the simulation accuracy when predicting the outcomes of Scenario 2. The simulation performed exceptionally well in predicting the outcomes of Scenario 2. This could be attributed to much more reliable measuring devices being available at 5# Shaft and the presence of adequate instrumentation at the 5# compressor house resulting in accurate determination of compressor parameters.

This configuration was selected to become the standard mode of operation at the mine due to there being fewer compressors operational across the entire mine, therefore reducing the energy costs and saving money. None of this would have been possible if not for the use of the simulation as there was a lot of uncertainty among the mining personnel surrounding what effect the opening of the previously unused connection would have on the compressed air supply to the refuge chambers of 1# Shaft.

Table 10: Summary of Scenario 2 simulation accuracy

Shaft	Pressure		Flow	
	MAE	r^2	MSE	r^2
1#	0.32%	1.00	0.15 kg^2/s^2	0.72
5#	0.98%	0.99	0.51 kg^2/s^2	0.99
All Shafts	**0.78%**	**0.99**	**0.40 kg^2/s^2**	**0.91**

3.3.4 Interpretation of the results of Scenario 2

When compared with the baseline refuge chamber supply Scenario 2 performed much the same as Scenario 1. The compressed air flow supply to the refuge chambers on Levels 39 and 41 was improved while reducing the supply to the lower levels while still maintaining the minimum requirements. The pressure supply in Scenario 2 was lower than in Scenario 1, by maintaining a lower pressure, less energy was required to compress the air and thus fewer compressors were needed during this scenario, eliminating the drawback of Scenario 1.

The simulation once again performed as expected with very high accuracy regarding the pressure prediction and underestimating the flow prediction that as described during Scenario 1 is not considered a bad thing. However, the simulation did overestimate the flow to 5# Shaft, but this can be due to other energy-saving initiatives that were active at 5# during the time of this study that were aimed at reducing the amount of compressed air used by 5# Shaft.

After the implementation of the proposed solution, the mine was able to operate without any complaints of a lack of airflow to any part of the mine and thus the solution was deemed to be successful and was then accepted as the new standard operation at the mine. The changes made when creating Scenario 2 were then incorporated into the baseline simulation to form the new baseline simulation, which will then be used for all future proposed changes to the mining complex.

3.4 Validation of results

During this study, a new simulation-based methodology was developed in Chapter 2 that was then applied to a mining case study to investigate various configurations of the mine’s compressed air network.

Data were obtained from the mine and used to calibrate the simulation to create a baseline simulation that could accurately represent the current operations of the mine. This baseline simulation was then used to quantify the effect of different configurations of the mines compressed air network on the compressed air supply to the refuge chambers at 1# Shaft.

The first scenario tested involved the opening of the connection between 2# Shaft and 1# Shaft to supply compressed air from the 2#, 3#, 4# shaft ring to 1# shaft. This scenario resulted in better compressed air delivery to 1# Shaft's refuge chambers but resulted in an increase of compressors begin operated at 2# and 3# Shaft.

The second scenario tested involved opening the connection between 5# Shaft and 1# Shaft in order to supply compressed air from 5# Shaft to 1# Shaft. This scenario had the same effect on the compressed air being supplied to the 1# Shaft refuge chambers but had the added advantage of not needing to use more compressors and thus energy was being saved by the mine in total.

Due to both these scenarios being implemented at the mine it was possible to verify the methodology using actual real world data. For Scenario 1 the MAE was 4.65% and the MSE was 0.94 kg^2/s^2 and for Scenario 2 the MAE was 0.78% and the MSE was 0.40 kg^2/s^2. These values thus validate the degree of accuracy of the methodology. However, the simulation did tend to underestimate the flow to the refuge chambers, but this does not have a detrimental effect on the effectiveness of the simulation. Instead, this serves as an additional safety factor to guarantee that safety requirements are met.

Thus, it has been proven that this methodology can be used to quantify the effect that changes to a compressed air network will have on the compressed air supply to all refuge chambers and to ensure that they still meet the minimum safety requirements. This same methodology can now be used to investigate the effects of the other shafts on the compressed air network to ensure compliance with safety guidelines. The scope for this methodology can be applied to other industries that make use of compressed air for other safety equipment or fail-safes such as pneumatically operated fire and blast protection doors.

CHAPTER 4 CONCLUSION

Health and safety are considered serious topics in the South African mining sector and as a result, a lot of research needs to be done to ensure adequate safety measures are installed in all mines. One of these safety measures is refuge chambers that supply miners with fresh, breathable air during emergency situations. Compressed air is the most common delivery method of this breathable air.

Numerous studies have been done on the basic requirements inside a refuge chamber, but very little research considers the challenges faced with supplying this compressed air in complex mining networks. This study focussed on using simulations to simplify the process of quantifying the effect that changes to a compressed air network will have on the compressed air supply to all refuge chambers and to ensure that they still meet minimum safety requirements.

In Chapter 2 a methodology was developed that can be used to investigate various configurations of a mine’s compressed air network and to quantify the effects that these changes will have on the compressed air supply to all refuge chambers.

The methodology was then applied to a mining case study. The resulting baseline simulation that was created was calibrated using data gathered from the mining case study and the accuracy was defined with an MAE of 1.32% and an MSE of 0.54 kg^2/s^2. The method was then used to quantify the effect of different configurations on the compressed air supply to the refuge chambers in the case study.

Two different scenarios were tested and on both occasions the simulation predicted that not only will the safety standards at the refuge chambers be maintained, but they would also be improved when compared to the standard operations of the mine.

Because both the scenarios were implemented on the mine it was possible to verify the methodology using actual real world data and this validated its degree of accuracy. In Scenario 1 the MAE was 4.65% and the MSE was 0.94 kg^2/s^2 and in Scenario 2 the MAE was 0.78% and the MSE was 0.40 kg^2/s^2. However, the simulation did tend to underestimate the compressed air flow to the refuge chambers, but because the simulation was used to test whether the flow will be larger than a minimum specification, this would actually add an additional safety factor to the results. Further validating the usefulness of the simulation in predicting changes to the network.

This then proved that simulations can indeed be used to predict changes in compressed air pressure and flow to aid in decision-making on the mine. This further highlights the importance of simulations in aiding and maintaining mining health and safety standards. Simulations can also be used to potentially save lives by ensuring that health and safety standards on mines are always met.

Some of the challenges that were faced in this study included the lack of enough measuring devices on the mine in question, which had a large impact on the accuracy of the simulation, especially regarding the predictions of the compressed airflow.

Some recommendations for future studies include:

Research can be done to expand the scope of the simulation to include other pneumatic safety devices that may be present on a mine, or any industrial system, such as pneumatic fire-doors and pneumatic safeties that prevent ore from being dropped on mine personnel.

The methodology can also be applied to other industrial sectors other than the mining sector to observe the applicability of the method in predicting the changes in compressed air pressure and flow supply in other applications.

More research is required to better estimate values for a simulation such as this when there are not adequate measuring devices present on the system that is being investigated. Research can be done to quantify the effect that poor accuracy measuring devices have on the accuracy of a compressed air simulation.

The methodology can also be used to optimise the delivery of compressed air to other users on the compressed air network to increase productivity and/or decrease energy consumption and thus provide a financial gain to the mine.

The methodology can also be used to simulate the effects of a power failure. During a power failure a very limited supply of backup power will be available for essential systems. The methodology can be used to determine which compressors to prioritize to ensure the safety of all underground personnel.

Investigation can be done to determine the exact cause for the simulation reliably predicting a lower-than-expected flow rate.

The simulation can be used for training purposes, emergency response planning as well as for the revision of procedures and risk assessments addressing various incident scenarios.

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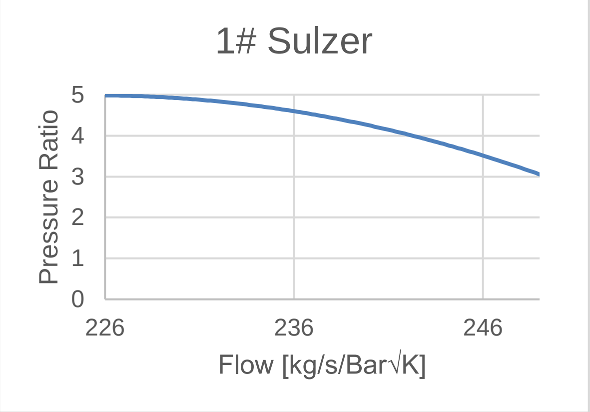
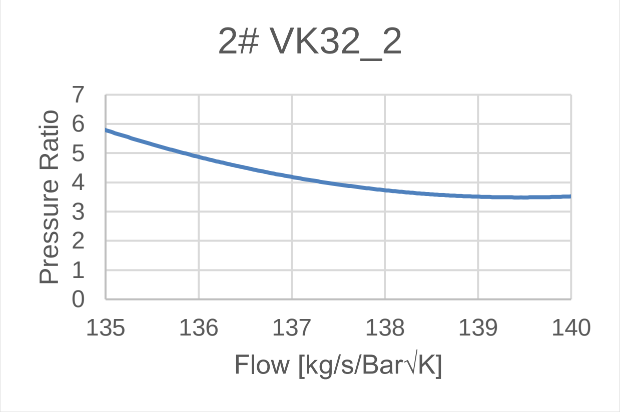
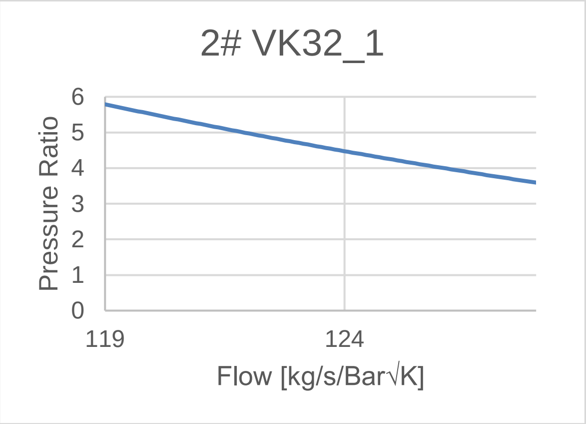
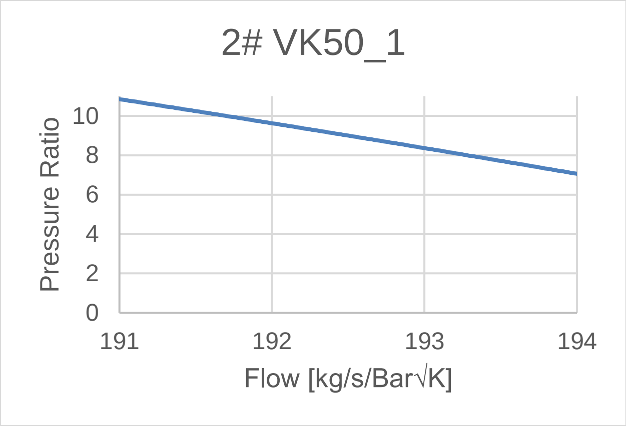
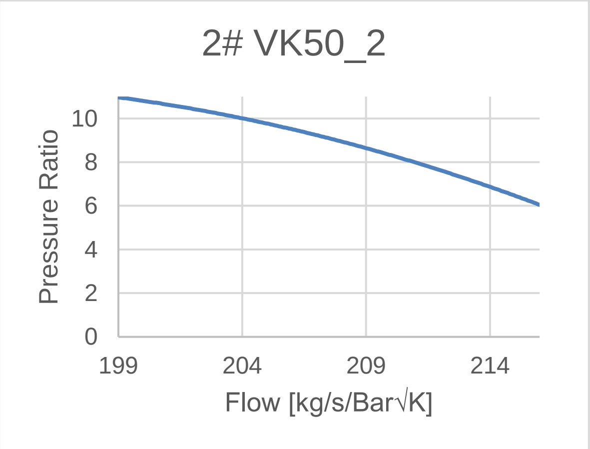
APPENDIX A – COMPRESSOR CURVES

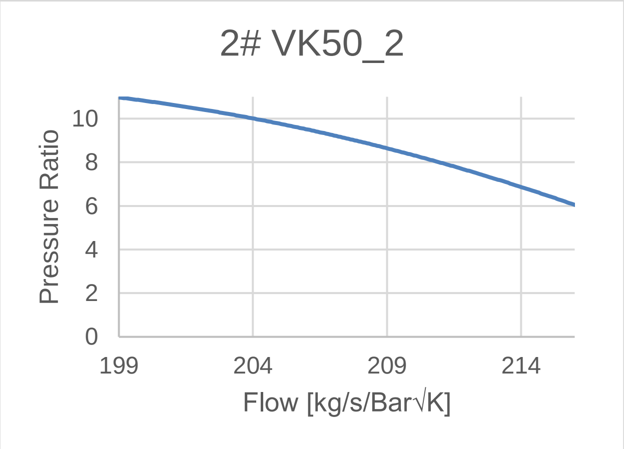


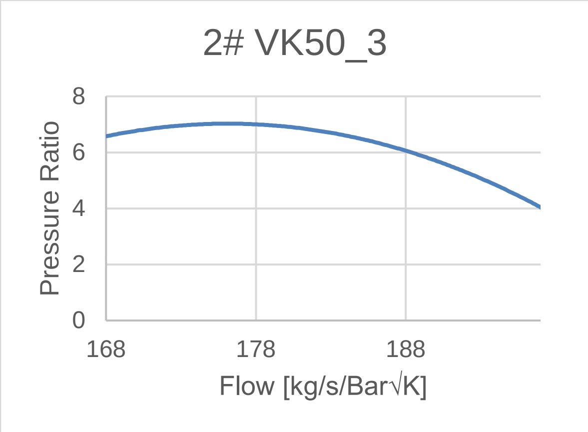


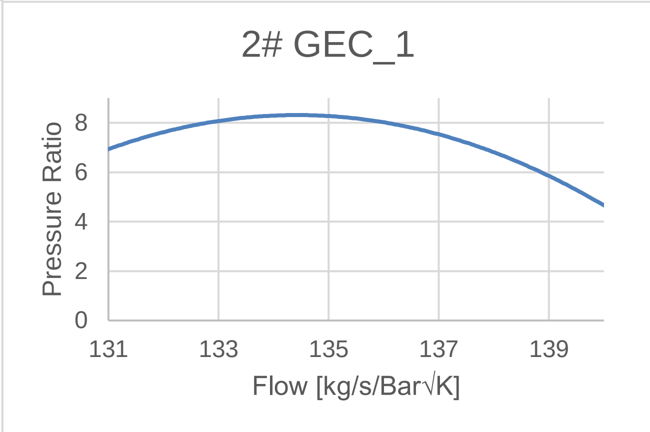


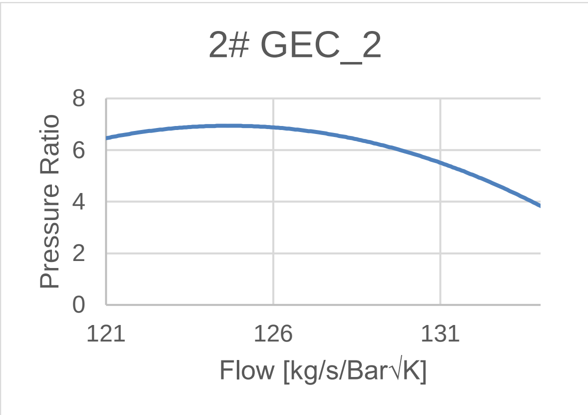


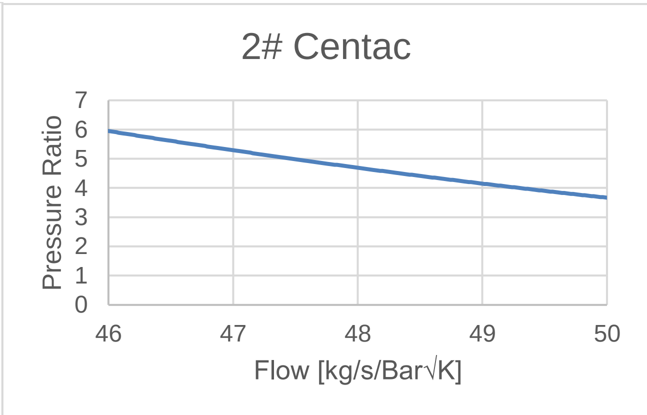


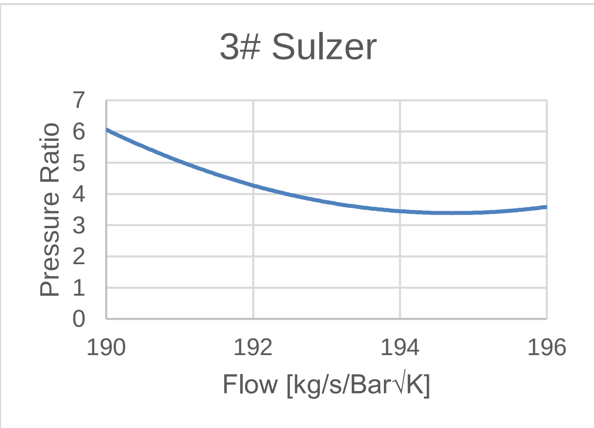


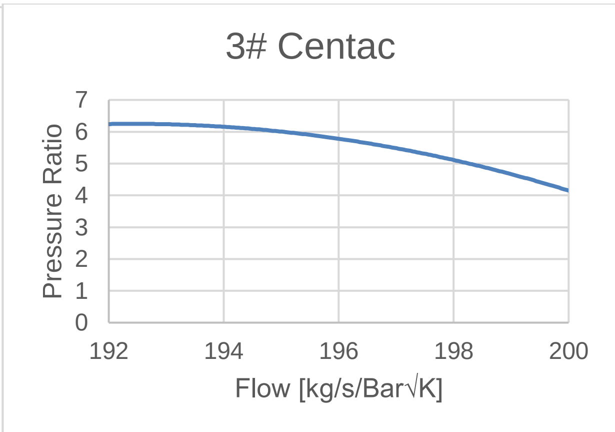

2# VK50_3
Pressure Ratio
0
2
4
6
8
168
178
188
Flow [kg/s/Bar√K]

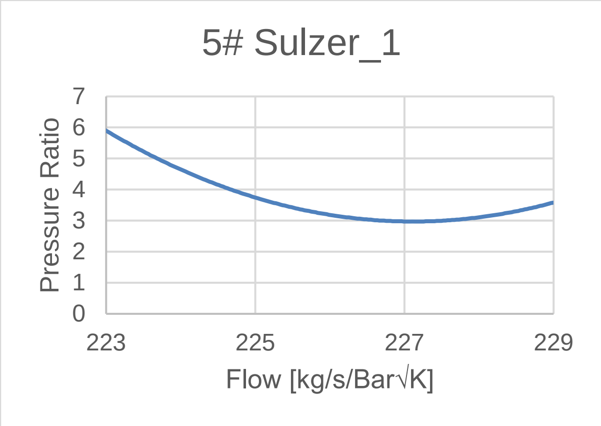

2# GEC_1
Pressure Ratio
0
2
4
6
8
131
133
135
137
139
Flow [kg/s/Bar√K]

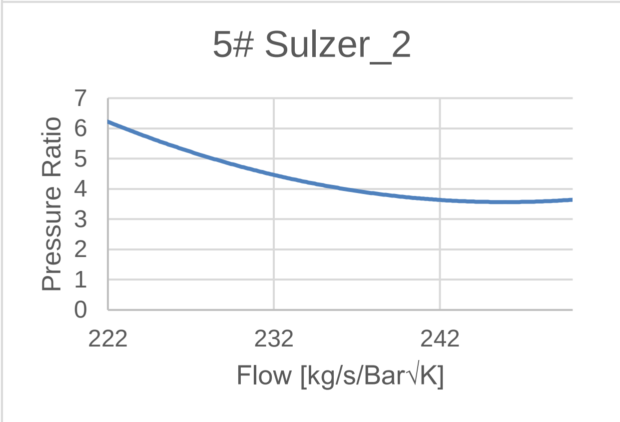

2# GEC_2
Pressure Ratio
0
2
4
6
8
121
126
131
Flow [kg/s/Bar√K]

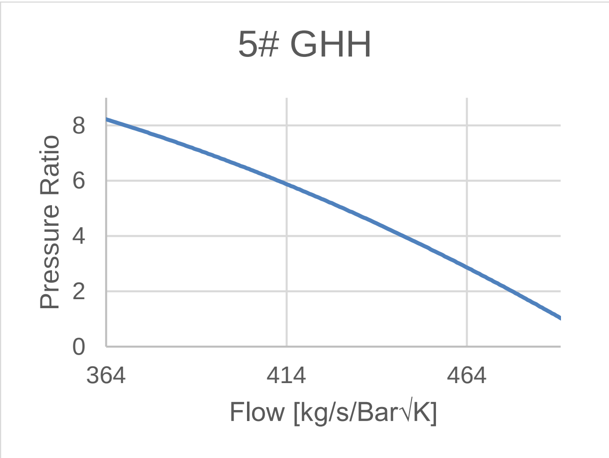

2# Centac
Pressure Ratio
0
1
2
3
4
5
6
7
46
47
48
49
50
Flow [kg/s/Bar√K]

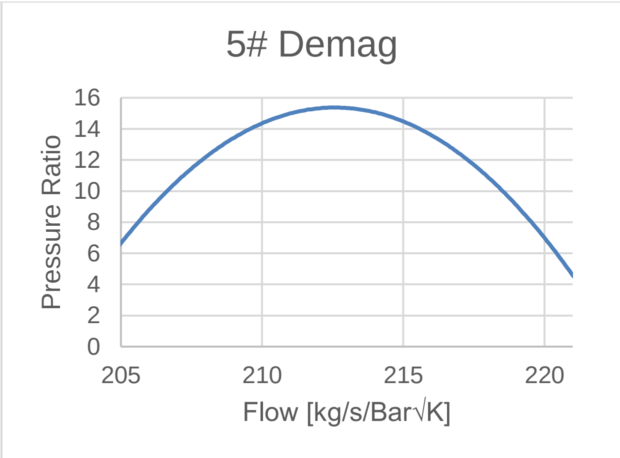

3# Sulzer
Pressure Ratio
0
1
2
3
4
5
6
7
190
192
194
196
Flow [kg/s/Bar√K]


3# Centac
Pressure Ratio
0
1
2
3
4
5
6
7
192
194
196
198
200
Flow [kg/s/Bar√K]


5# Sulzer_1
Pressure Ratio
0
1
2
3
4
5
6
7
223
225
227
229
Flow [kg/s/Bar√K]


5# Sulzer_2
Pressure Ratio
0
1
2
3
4
5
6
7
222
232
242
Flow [kg/s/Bar√K]


5# GHH
Pressure Ratio
0
2
4
6
8
364
414
464
Flow [kg/s/Bar√K]


5# Demag
Pressure Ratio
0
2
4
6
8
10
12
14
16
205
210
215
220
Flow [kg/s/Bar√K]

APPENDIX B – PTB SIMULATION - COMPRESSOR HOUSES

Figure 64: 1# compressor house

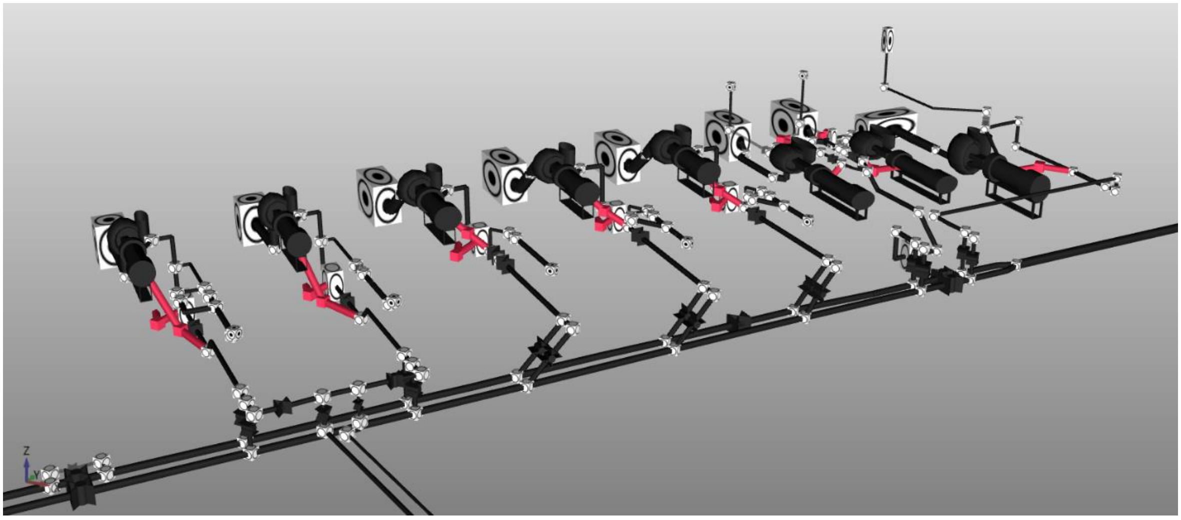


Figure 65: 2# compressor house

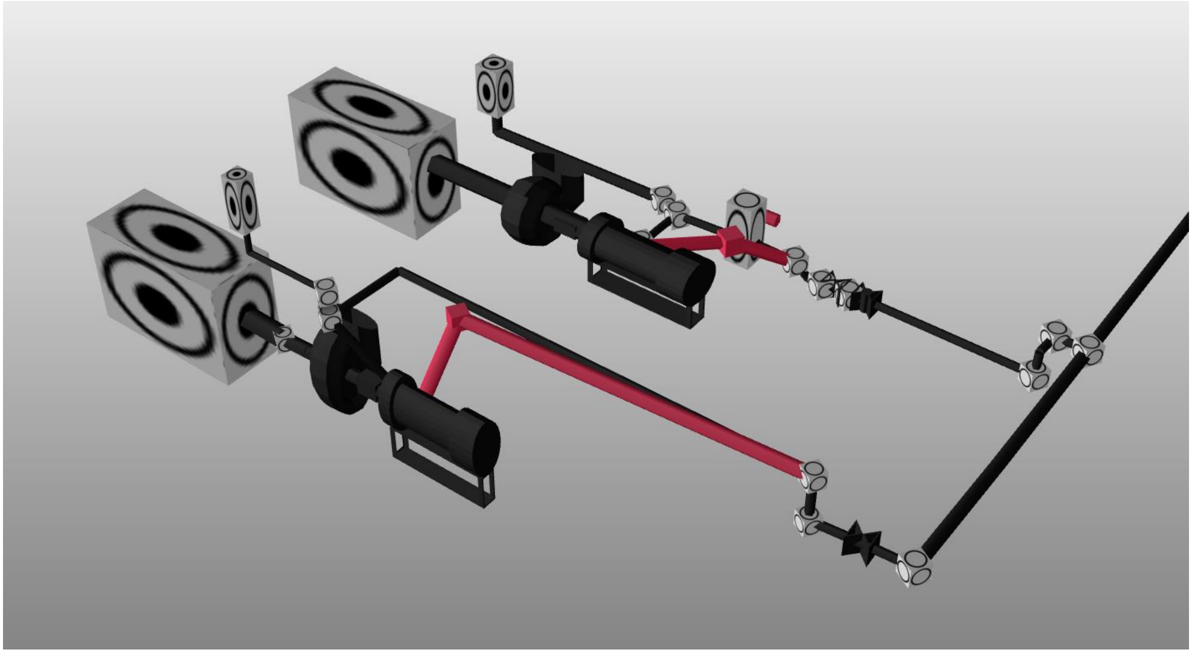


Figure 66: 3# compressor house

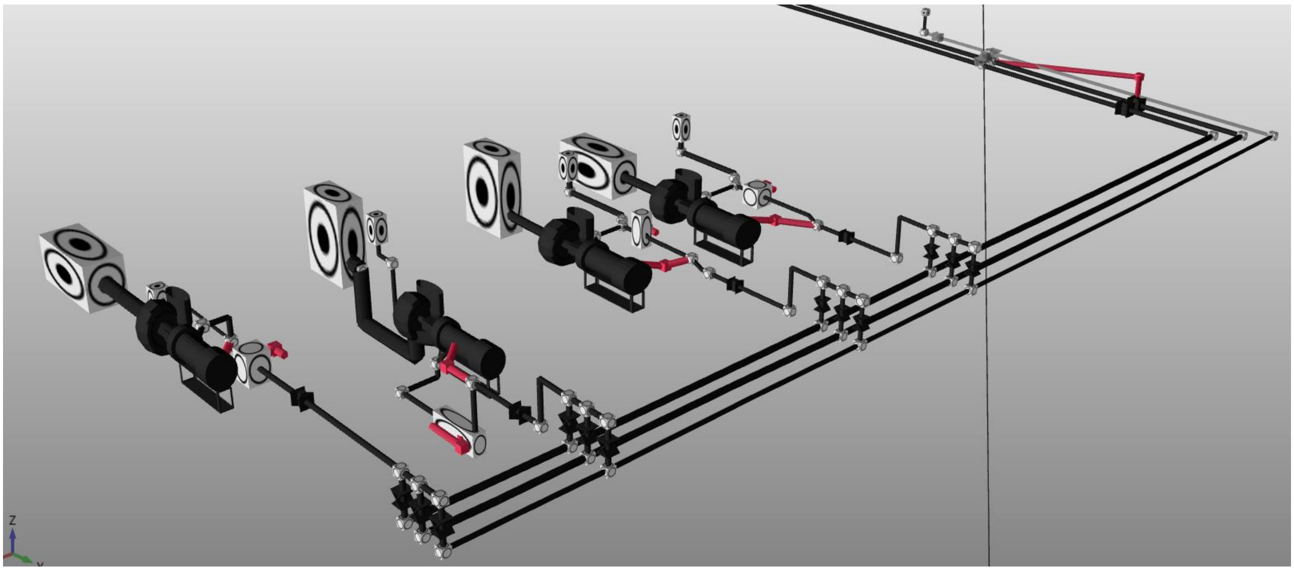


Figure 67: 5# compressor house