

A method to optimise compressed air supply pressure to hydropower mine refuge bays

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ABSTRACT

Title: A method to optimise compressed air supply pressure to hydropower mine refuge bays

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Keywords: Compressed air, demand side, supply side, hydropower, simulation, refuge bays.

The cost of electricity is rapidly increasing in South Africa. This leads to high operational costs for deep-level mines, which furthermore reduces production. As companies mine deeper, temperatures generally increase partly due to the higher virgin rock temperature. The mine is responsible for making life sustainable underground and therefore services are provided underground. These services include compressed air, drinking water, ventilation, cooling, pumping, and hoisting.

Compressed air consumes up to 20% of the mine's electrical energy. In the case of deep-level hydropower mines, high-pressure water is used to drill and extract ore from the gold reef. The primary, continuous compressed air users on the demand-side of deep-level hydropower mines are refuge bays. Refuge bays are a safe and secure go-to gathering area for mining personnel in case of an emergency. Refuge bays are prone to being oversupplied with compressed air due to inefficiencies such as leaks and misuses. Therefore, an opportunity exists to reduce the compressed air consumption in deep-level hydropower mines.

Existing energy-saving methods include a combination of demand- or supply-side management techniques. On the demand-side, energy-saving strategies include leak auditing techniques or the identification of inefficiencies. Supply-side management focuses on the improvement of compressed air supply by using methods such as adjusting guide vane angles and pressure setpoint control.

The objective of this study is to construct an analytical method based on the law of conservation of energy to determine the minimum gauge pressure that each refuge bay

should receive, based on its size and occupancy, while still adhering to regulations. In the case study that was investigated, it was found that the refuge bay with the highest pressure requirement, according to the method developed, requires roughly 87 kPa supply pressure while currently receiving 238 kPa.

Thereafter, a simulation model was constructed within the boundary of the case study. The simulation was verified, yielding an error of 5%. In addition, the simulation was validated by manual measurements, achieving an error of 3%. The simulation model was implemented by reducing the compressed air setpoint. It was found that the setpoint can be reduced by 35 kPa throughout a typical 24-hour period. This reduction in pressure setpoint resulted in an annual cost saving of over R 50 000.

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NOMENCLATURE

Symbol	Unit	Description
K	Kelvin	Kelvin is a unit of measurement for temperature in the International System of Units (SI).
kJ	kilojoule	A kilojoule is a unit of measurement for energy in the SI.
kPa	kilopascal	A kilopascal is the fundamental unit of pressure in the SI, defined as 1000 Pa.
kW	kilowatt	A kilowatt is a unit of power in the SI.
kWh	kilowatt-hour	A kilowatt-hour is a unit of energy commonly used to measure electrical consumption. It represents the amount of energy expended or consumed when one kilowatt of power is used for one hour.
m	meter	A meter is the fundamental unit of length in the SI.
mm	millimetre	A metre is the fundamental unit of length in the SI.
Pa	Pascal	The SI unit of pressure is defined as one newton per square meter, representing the amount of force applied per unit area.
Re	Reynolds number	The Reynolds number is a dimensionless number used in fluid dynamics to predict the flow characteristics of a fluid inside a pipe.

ABBREVIATIONS

BAC	Bulk air cooler
CA	Compressed air
ESKOM	Electricity supply commission
HVAC	Heat, ventilation, and air conditioning
MAE	Mean absolute error
PGM	Platinum group metals
PPM	Parts per million
PTB	Process Toolbox
SCADA	Supervisory control and data acquisition
SPG	Standard procedure guideline
TOU	Time of use

1. INTRODUCTION

1.1. Overview of South Africa's mining industry

1.1.1. Value of mining in South Africa

South Africa is very rich in mineral resources, such as gold, platinum, diamonds, as well as coal. Half of the world's gold deposits are found in South Africa [1]. These minerals have played a vital role in the economy of South Africa, aiding with employment, economic growth, and international exchange. According to the Mineral Council of South Africa, the mining sector contributed R494 billion to the South African gross domestic product in 2022 [2].

The mining industry attracts substantial domestic and foreign investments, leading to higher employment rates, the development of infrastructure, and the advancement of technology in the country [3]. As seen in Figure 1, platinum group metals (PGM), gold, and coal have the highest employment rate in the mining industry of South Africa.

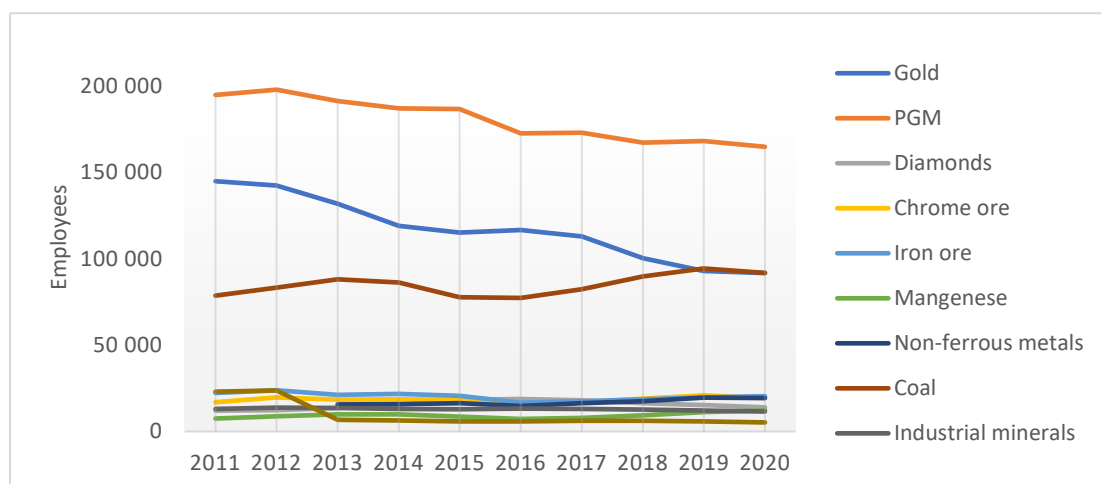


Figure 1 - Percentage employment per mineral group in the mining industry [4]

The mining industry plays an important role in employment, especially in rural areas where the unemployment rate is very high. In 2022, a total of 475 561 individuals were employed in the mining industry [2]. In addition, mining companies invest in the development of skills in the local communities by funding community-based educational programs [5].

1.1.2. South Africa's mining production

The mining trend in South Africa has decreased since the gold rush in the 1880s in the Witwatersrand area. The discovery of gold led to South Africa being the leader in the gold production industry [6]. However, the increase in gold production led to a decrease in the availability of easily accessible gold, accompanied by a decline in ore grades. This resulted in the development of deep-level mines. Mines are classified as deep-level when they are deeper than 1 300 m. This mining depth led to higher production costs due to additional cooling requirements to combat higher virgin rock temperatures [7].

Labour disputes also contributed to the increasing production cost due to the safety concerns of working underground. Safety regulations have been put into place by the Mine Health and Safety Act to ensure employees are safe while mining [8].

Due to the decline in production in the gold industry, South Africa diversified their mining industry to various other minerals such as PGMs, coal, and diamonds. Figure 2 shows that the production rate of mining in South Africa between 2019 and 20-21 has stayed fairly constant due to the diversification of the mining industry. South Africa is currently the world's leader in the mining production of PGMs [2].

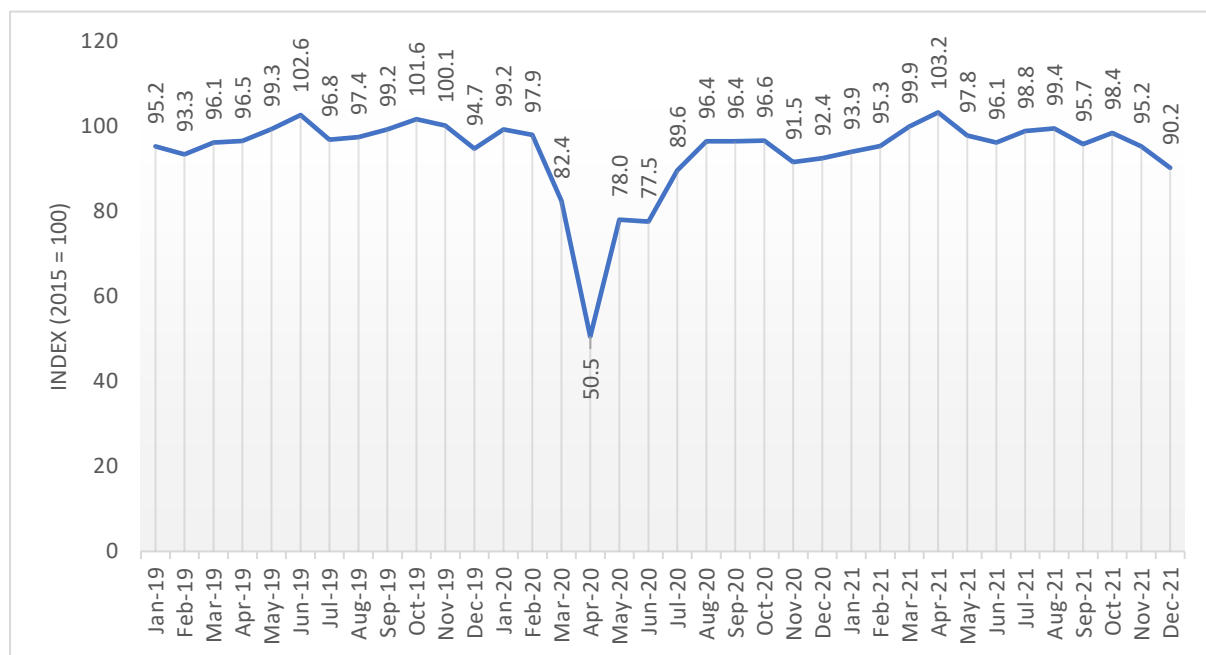


Figure 2 - Index of seasonally adjusted mining production [4]

1.1.3. Challenges faced in South African mines

Mines in South Africa face various challenges, of which Eskom tariffs stand as a pivotal concern. This section discusses the issues regarding the Electricity Supply Commission (ESKOM) pricing policies and the impact of these policies on the mining industry of South Africa.

Eskom tariffs:

One of the main challenges faced in deep-level gold mines is the increase in electricity costs. The continuous increase in electricity cost by ESKOM, has contributed to an increase in mining expenses and reduced profitability [9]. The National Energy Regulator of South Africa (NERSA) approved an electricity cost increase of 18.65% in the 2023/2024 financial year. This increase, with the additional 12.4% forecasted increase for the next year, will result in a 33% increase in electricity costs by the end of 2024. This amounts to an increase of electricity cost of R13.5 billion for the mining industry per annum [4]. Figure 3 shows the cost increase of the average kilowatt hour (kWh) for electricity from 2003 to 2021/2022.

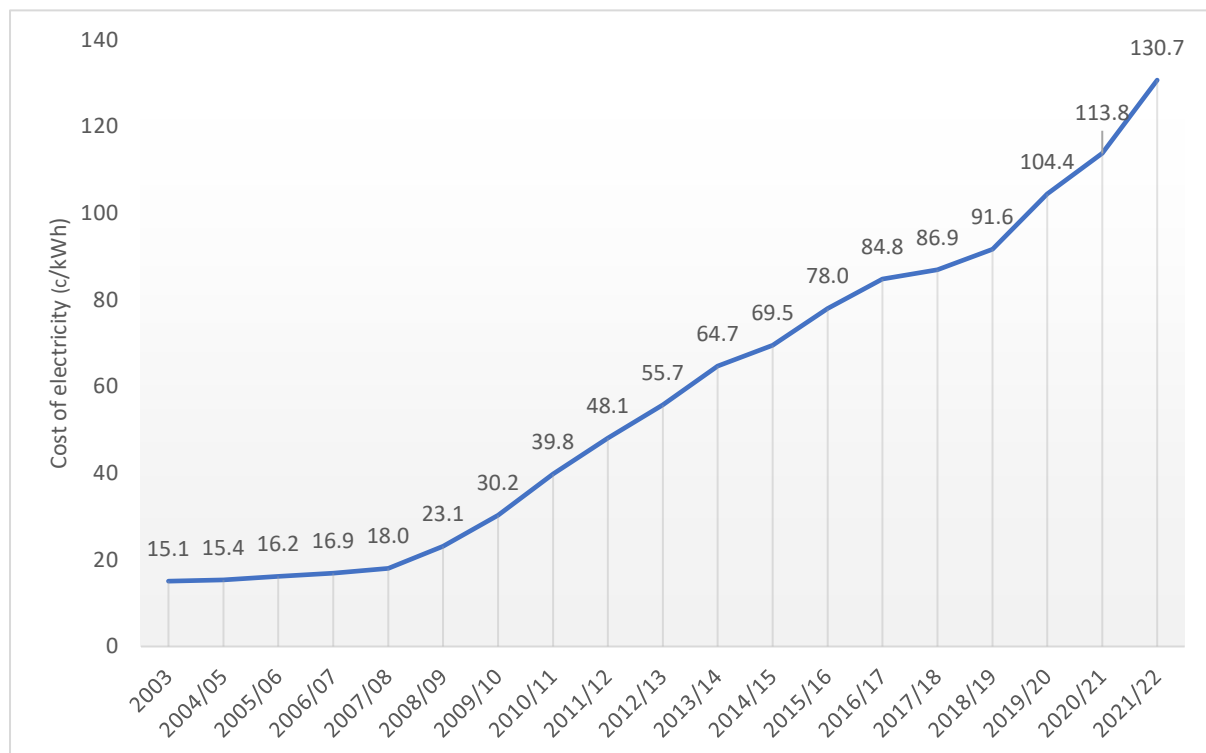


Figure 3 - Eskom's average electricity price trend for mining in South Africa [10]

In addition to the increase in electricity cost, the effect of load shedding also takes its toll on the mining industry. Load curtailment is implemented by ESKOM by forcing large energy consumers to reduce their demand. Load curtailment involves four stages, where companies must reduce their energy consumption by 10% during Stages 1 and 2, while Stage 3 requires a 15% reduction, and Stage 4 a 20% reduction.[11].

1.2. Electricity as an operational expense in deep-level mines

In deep-level mines, electricity as an operational expense is used to cover crucial operations such as ventilation, refrigeration, pumping, surface winders, compressed air and mining processes. This section gives insight into the electricity cost for the operations mentioned above.

1.2.1. Overview of operational expense

Figure 4 shows the typical electricity consumption among various consumers in deep-level mines, represented as percentages of the total consumption. Mining processes are the leading electricity consumer, contributing 29% of the total energy consumed in a deep-level mine.

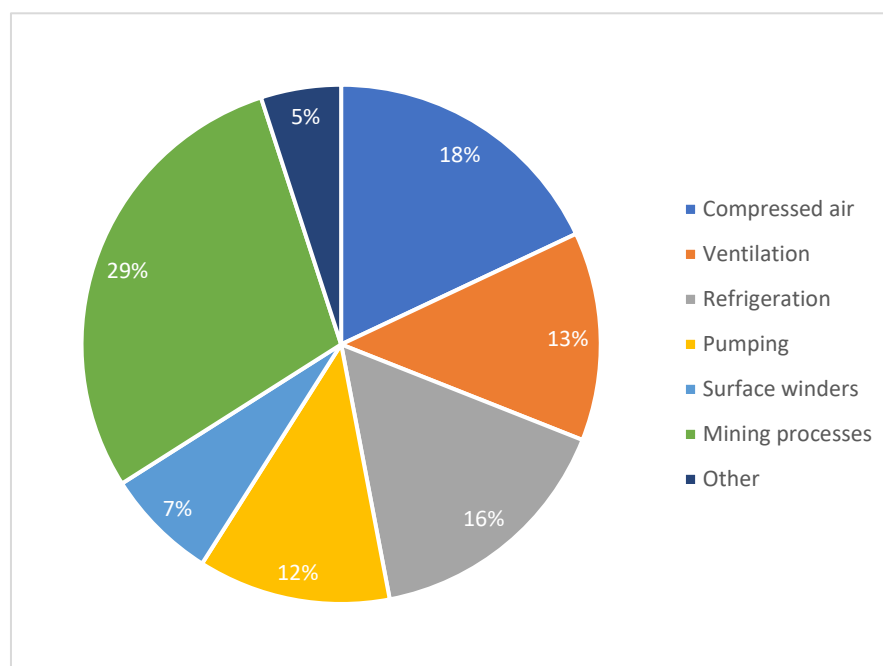


Figure 4 - Typical electricity consumption of a deep-level mine [12]

Compressed air generally consumes 18% of electricity in deep-level mines [12]. In a typical deep-level gold mine, compressed air is generated by compressors and sent to underground levels via an intricate network [9, 13].

Pumping has a significant impact on the energy consumed in deep-level gold mines, consuming typically 12% of the total electricity usage [12]. Service water is sent underground through an intricate piping network for mining purposes. Drinking water is for the consumption of workers and is required for refuge bays, according to the Mine Health and Safety Act [8]. All this water needs to be pumped back to surface to prevent flooding. Fissure water is defined as water that accumulates in cracks and fractures of rock [14]. This fissure water also needs to be pumped out in addition to the service and drinking water [15].

Due to depleting ore grades, gold mines need to go deeper than ever before to extract precious minerals. However, the deeper the mine goes, the higher the virgin rock temperature [7]. For depths above 600 m natural ventilation through surface extraction fans would be sufficient. Mines exceeding depths of 600 m require additional cooling. Additional cooling comes in various forms such as BACs (bulk air coolers) or fridge plants [16]. Therefore, ventilation through surface fans and cooling through BACs consumes up to 18% of the electricity used in the mines [12].

Hoisting is the process of transporting the mined minerals up to surface. In addition, workers are transported underground by hoisting. Hoisting consumes up to 14% of the electricity [12].

1.2.2. Compressed air as an operational expense

As mentioned in the previous section, compressed air consumes up to 18% of a deep-level mine's electricity. Surface compressors generate and supply compressed air to underground levels through an intricate piping network [17]. Figure 5 indicates a typical deep-level gold mine compressed air network, where compressed air is sent to underground levels and the control valves restrict the flow into the levels based on their requirements [18].

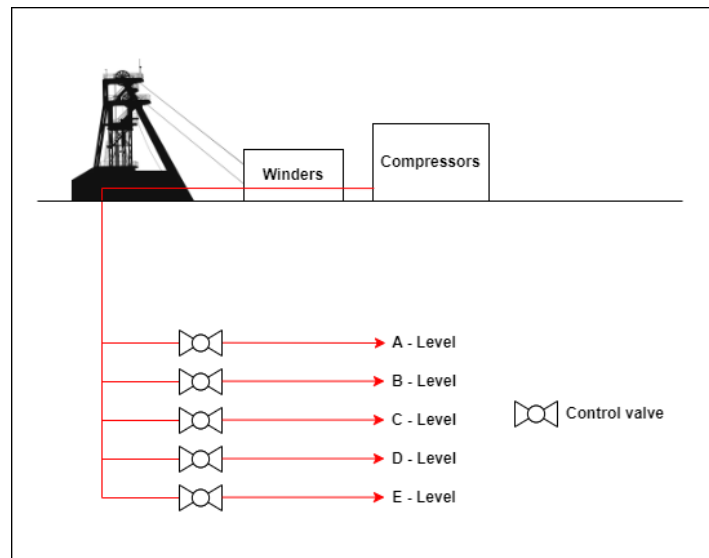


Figure 5 - Typical deep-level mine compressed air network [18]

Mining:

For a conventional mine, the main compressed air users include pneumatic rock drills, which are used to drill holes for blasting purposes. The compressed air demand varies throughout the day, which in turn requires varying pressure requirements. Figure 6 shows the typical compressed air pressure requirement throughout the day for a deep-level mine [18].

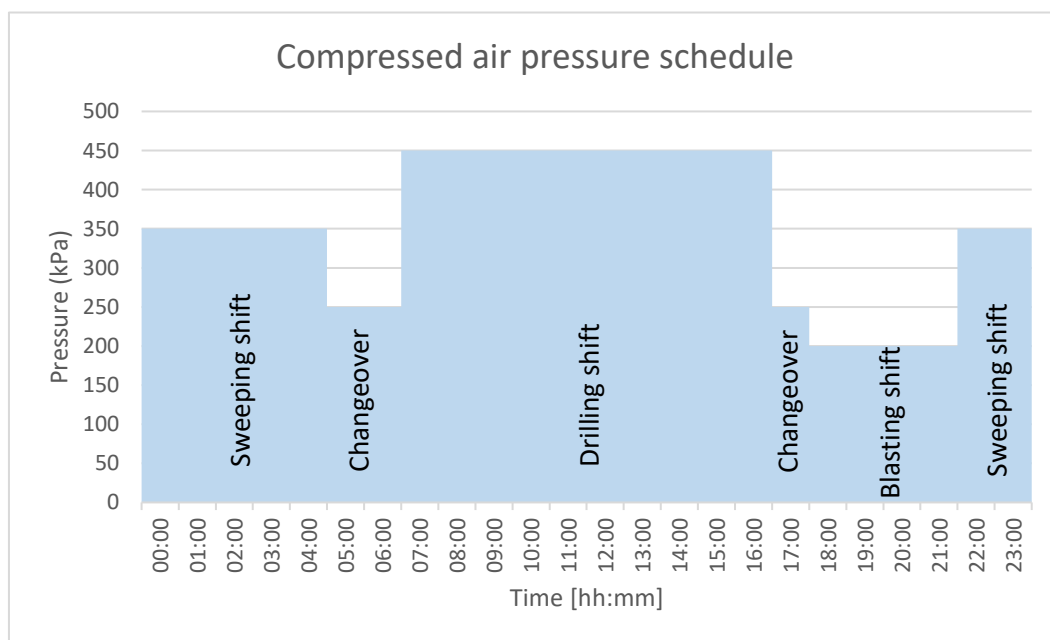


Figure 6 - Typical deep-level mine compressed air pressure schedule [18]

The drilling shift requires the highest compressed air pressure [12]. Table 1 indicates the compressed air (CA) consumption of pneumatically operated equipment at a given pressure.

Table 1 - Pneumatic equipment CA consumption and operating pressure requirement [18]

Equipment	Shift	Consumption	Operating pressure
Pneumatic rock drills	Drilling shift	190 - 320 m ³ /h	400 – 620 kPa
Pneumatic loaders	Sweeping shift	348 m ³ /h	400 – 490 kPa
Pneumatic cylinders	Sweeping shift	11 m ³ /h	400 – 500 kPa

Refuge bays:

In the case of deep-level mines, a refuge bay is a secure underground go-to gathering area for mining personnel in case of an emergency. Underground emergencies include rockfalls, fires, or high levels of toxic gasses such as methane. Refuge bays are required to be supplied with life-sustaining essentials such as ventilation, communication to surface, drinking water, and medical supplies [8, 19].

Underground refuge bays are ventilated using compressed air. The compressed air ensures a positive pressure inside the refuge bay, which means that there is a higher pressure inside the refuge bay compared to the pressure outside the refuge bay. This positive pressurisation prevents harmful gasses from entering the refuge bay [19].

According to the Mine Health and Safety Act, each refuge bay is required to be supplied with sufficient respirable air [8]. The Mine Health and Safety Inspectorate states that, where the life sustainability of a refuge bay is dependent on compressed air, the supply to the refuge bay should be tamper free, with a valve on the inside of the refuge bay [20].

The Mine Health and Safety Act does not state how much pressure should be supplied to the refuge bay. It is the responsibility of the employer to ensure that sufficient air is supplied to the refuge bay. Figure 7 shows a general layout of refuge bays found in deep-level mines.

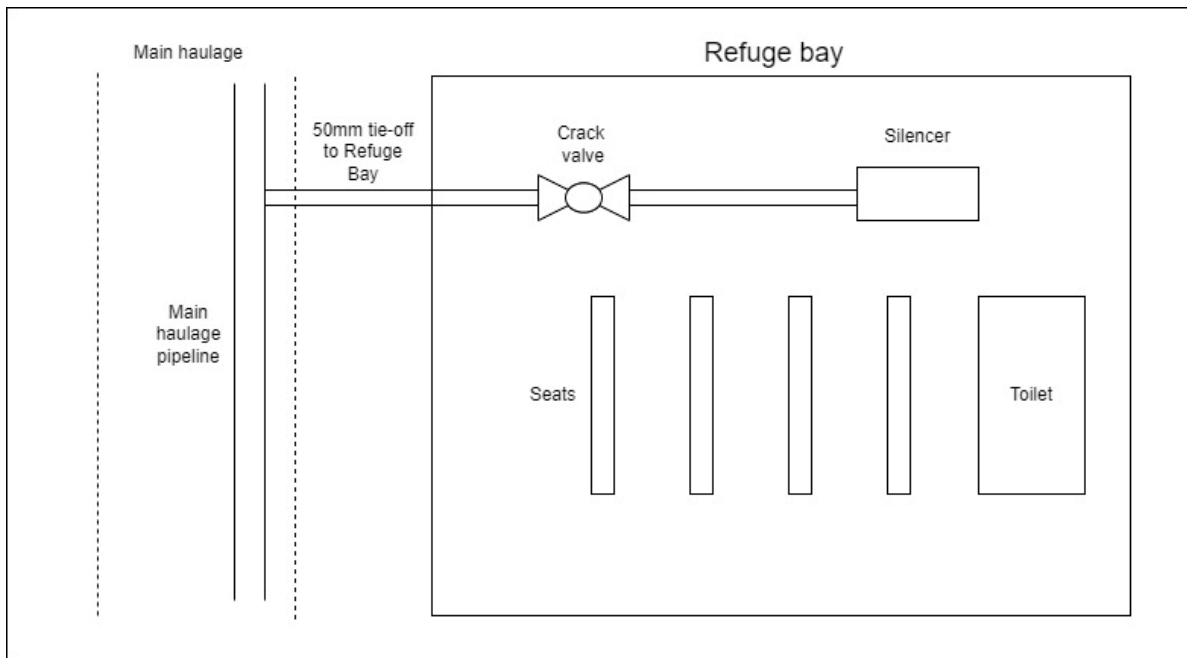


Figure 7 - General layout of refuge bays in deep-level mines [19]

Simulation of compressed air networks:

Compressed air networks are an easy way to convey energy in deep-level mines, but their complexity and unpredictability can pose significant challenges. These networks include various components such as compressors, pipes, valves, and regulators, which interact in complex ways. Factors including varying demand, changing ambient conditions, and system wear and tear make it difficult to predict how the system will behave over time[21, 22].

Simulation plays a pivotal role in overcoming this complexity. By developing virtual simulation models that accurately replicates the real-life scenarios of compressed air systems, engineers and operators can run specific scenarios to analyse the compressed air network behaviour under different conditions [23].

Simulation also allows for the identification of potential issues, optimising performance, and prevent costly downtime, thus ensuring a more efficient and reliable compressed air supply. Simulation not only helps us understand the intricacies of these networks, but also provides a valuable tool for managing their intricacies with confidence [22, 23].

1.3. Problem statement and study objectives

1.3.1. Problem statement

Multiple compressed air demand- and supply-side management techniques exist. On the demand-side, energy-saving strategies include leak auditing techniques or the identification of inefficiencies. Supply-side management focuses on the improvement of compressed air supply by using methods such as adjusting guide vane angles and pressure setpoint control.

However, none of these techniques focusses on improving compressed air usage in deep-level hydropower mines. In deep-level hydropower mines, the refuge bays are the main continuous compressed air user. These refuge bays are prone to being oversupplied with compressed air due to leaks and misuse, which result in wasted cost and energy consumption [26].

1.3.2. Aim & Objectives

The aim of this study is to develop a method to determine the minimum supply pressure that a refuge bay on a hydropower mine needs while still adhering to regulations.

To achieve the aim, the following objectives need to be satisfied:

1. Develop a new method to determine the minimum supply pressure needed for each refuge bay on a given mine, based on their size and maximum number of occupants present.
2. Develop and verify a simulation model of the mine's compressed air network.
3. Assess the feasibility of reducing the compressed air setpoint based on the minimum requirements.
4. Evaluate the cost-savings of the setpoint reduction.

1.3.3. Research approach

The research approach used to develop this method is the case study methodology [27]. The general purpose of the case study methodology is to describe the individual situation, identify issues, analyse the problem with relevant theoretical concepts from literature, and

recommending a solution for the particular problem identified in the case study. Figure 8 shows the flow diagram of the case study methodology.

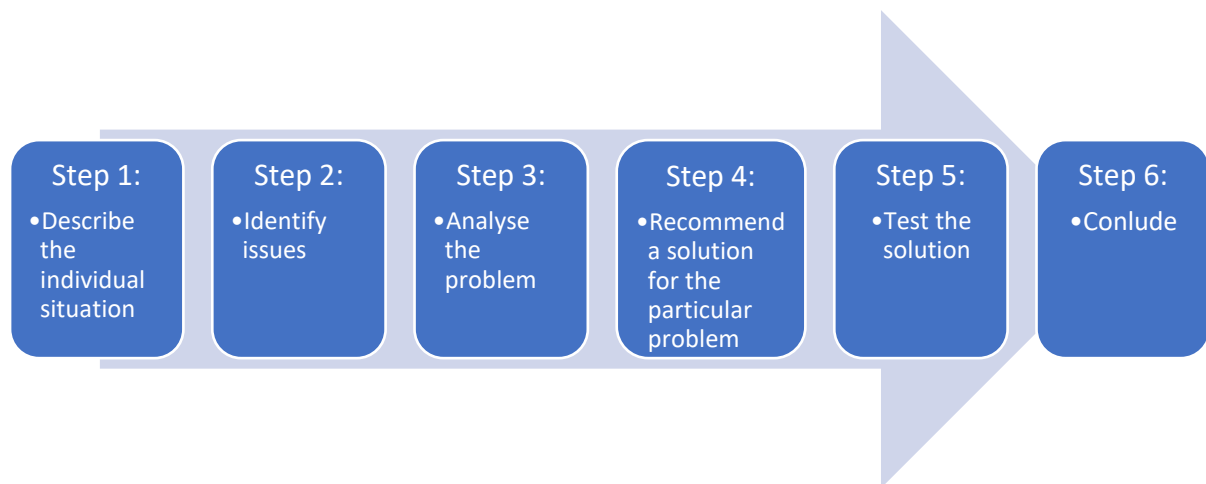


Figure 8 - Case study methodology process followed in this study [27]

1.4. Dissertation outline

Chapter 1 - Introduction: This chapter gave a description of the individual situation mentioned in Step 1 of the case study methodology. It gave a background of the study from which the problem statement, aim, and study objectives have been formulated.

Chapter 2 - Literature review: This chapter gives a brief overview of previous studies done on compressed air networks in deep-level mines. Thereafter, issues are identified, and the problem is analysed using theoretical concepts as mentioned in Steps 2 and 3 of the case study methodology.

Chapter 3 - Methodology: This chapter aligns with Step 4 in the case study methodology and a solution is recommended for the particular problem identified in the previous chapter.

Chapter 4 - Implementation and results: This chapter describes how the recommended solution was tested on a case study mine as mentioned in Step 5 of the case study methodology.

Chapter 5 - Conclusion: The conclusion drawn from this method are discussed, as seen in Step 6. Thereafter, recommendations are made regarding future studies.

2. LITERATURE REVIEW

2.1. Preamble

A literature study is conducted to analyse current compressed air systems in deep-level mines. This review takes a look at existing demand- and supply-side management techniques used in these mines. Thereafter, simulation packages that are used in deep-level gold mines will be investigated. Finally, the legislation surrounding refuge bay safety is investigated and existing techniques to adhere to standards set out in legislation are examined. Figure 9 shows the sections discussed in the literature review.

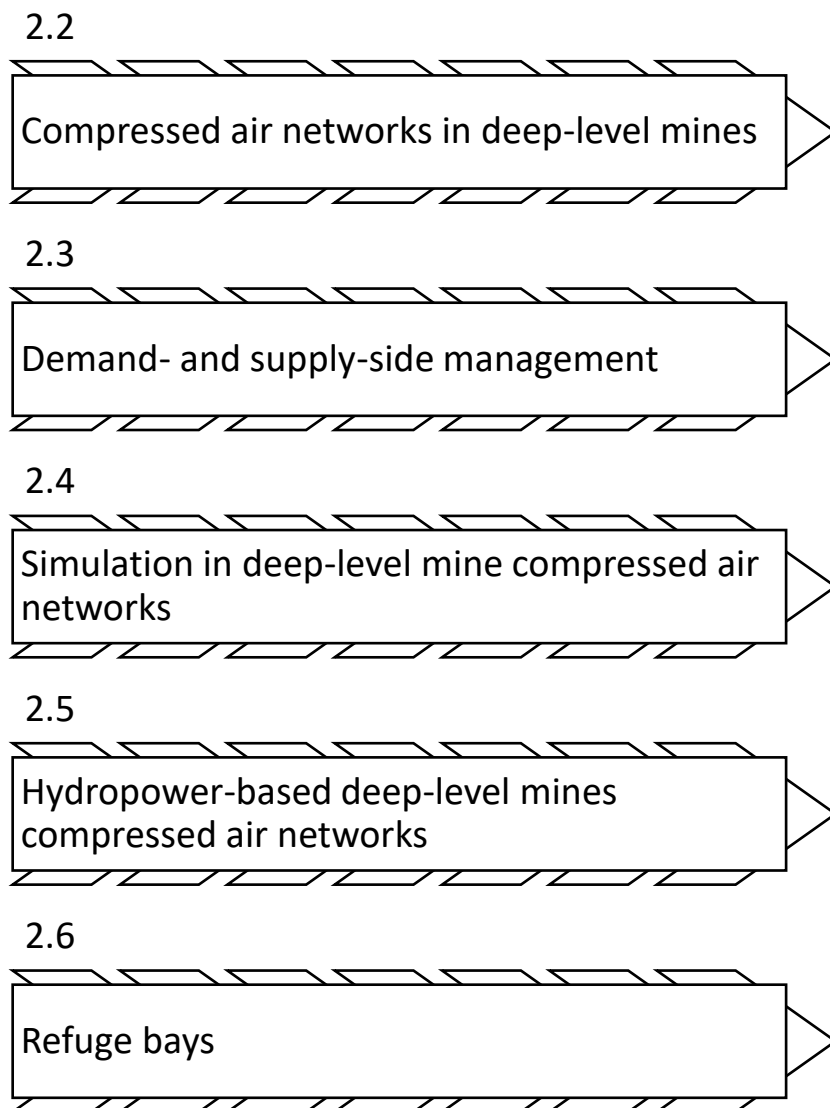


Figure 9 - Overview of literature study

2.2. Compressed air networks on deep-level mines

A gold mine's compressed air network is categorised into three main divisions, namely the supply side, reticulation side, and demand side.

Supply side

The supply side of a deep-level mine's compressed air network comprises of the equipment that is responsible for generating compressed air [28]. Typically, in deep-level mines, the supply side starts at the compressor house situated on the surface of the mine [24, 25]. The compressor house contains various compressors that establishes the connection between the supply side and the demand side through the reticulation network [31]. As the compressed air reaches underground areas, a pneumatic control valve is used to adjust the pressure based on the requirements of the demand side [27 – 29]. Figure 10 shows a standard multi-stage centrifugal compressor commonly used in deep-level mines [27, 30].



Figure 10 - Multi-stage centrifugal compressor [27, 30]

Reticulation side

The reticulation network consists of an intricate piping network that facilitates the flow of compressed air to underground working areas [35]. Pipe sections and sizing are important to note within the system due to the end-user requirement. Proper design of the reticulation network is important to minimise the effect of losses [27, 32].

Demand side

The demand side of compressed air networks in deep-level mines consist of various users. These users include pneumatic rock drills, refuge bays, and pneumatic cylinders [27, 33].

According to the Mine Health and Safety Act, all mining operations are required to have refuge bays within 500 m of each working place [8, 18, 19]. Refuge bays are a secure and go-to area for mine workers in case of an emergency. Compressed air is supplied to refuge bays to ensure a positive pressure inside the refuge bay so that no harmful gasses can enter the refuge bay [19, 34]. Refuge bays and their legislation according to the Mine Health and Safety Act are discussed in Section 2.6.

2.3. Demand- and supply-side management

In this section, current strategies for improving the demand- and supply sides of compressed air networks in deep-level mines are discussed. These strategies are discussed in terms of optimising the energy usage and operational efficiency in deep-level mines.

2.3.1. Supply-side management

Currently, supply-side management techniques include the use of control valves in underground levels. The main objective of an underground control valve is to supply the correct amount of pressure to reduce wastage [38]. This results in higher upstream pressure, which reduces the inlet guide vane angles of the compressors, which in turn reduce the power output of the compressors [18, 36].

The primary function of a control valve is to regulate and maintain a predefined downstream pressure by adjusting the valve position [22]. This control valve contains pressure transmitters to measure both upstream and downstream pressures. The downstream pressure serves as the process variable, while the desired pressure acts as the setpoint. The valve's position is regulated based on the pressure differential between the process variable and the setpoint [40].

It has been found that control valves are used to reduce pressure during the ESKOM peak time of use (TOU) periods. This is done by reducing the pressure setpoint during these periods.

This energy saving strategy serves to reduce the pressure supplied to the level during non-operational periods [41]. Figure 11 shows how the pressure is reduced during ESKOM peak periods.

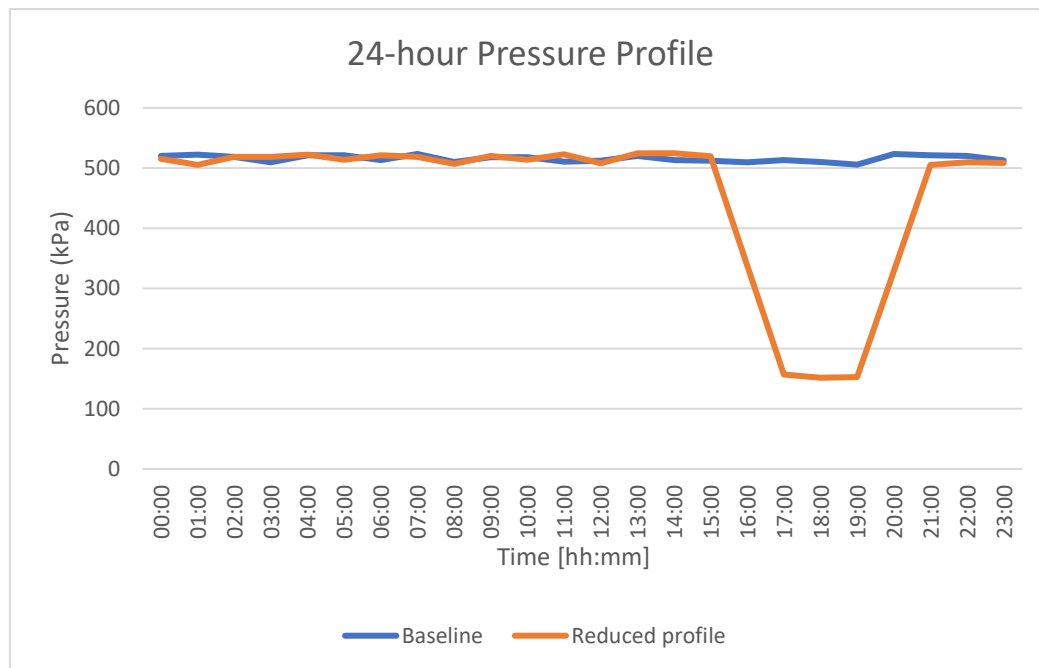


Figure 11 - Control valve pressure profile reduction [18]

2.3.2. Demand-side management

The demand-side of compressed air systems varies from mine to mine due to different mining approaches. The demand-side of the compressed air system depends on the end users. Many demand-side strategies exist to reduce compressed air usage in deep-level gold mines [39, 40].

Previous studies developed strategies to improve the efficiency of mine compressed air systems by looking at the supply- and demand sides. Typically, the initiatives to improve a mine's compressed air systems are to fix active leaks and to adjust the delivery pressure by changing the pressure setpoint of the compressed air supplied by the compressor [41, 42]. This has proven to be the most effective strategy to reduce compressed air consumption due to the expensive nature of replacing traditional pneumatic equipment [18].

The mass flow rate of compressed air leaks can be calculated using Equation 1 [18, 43]:

Equation 1 - Mass flow rate of compressed air through a leak [18, 43]

$$\dot{m}_{pipe} = C_{Discharge} \left(\frac{2}{k+1} \right)^{1/(k-1)} \frac{P_{line}}{RT_{line}} A \sqrt{kR \left(\frac{2}{k+1} \right) T_{line}} \quad (\text{kg/s})$$

where

$C_{discharge}$ is the discharge coefficient that accounts for imperfections in flow

k is the specific heat ratio of air, taken as 1.4

T_{line} is the temperature in the compressed air line (K)

P_{line} is the pressure in the compressed air line (kPa)

R is the universal gas constant for air, taken as 0.287 (kJ/kg K)

Using Equation 1, the following graph is derived to indicate the impact of different compressed air leak sizes at different line pressures.

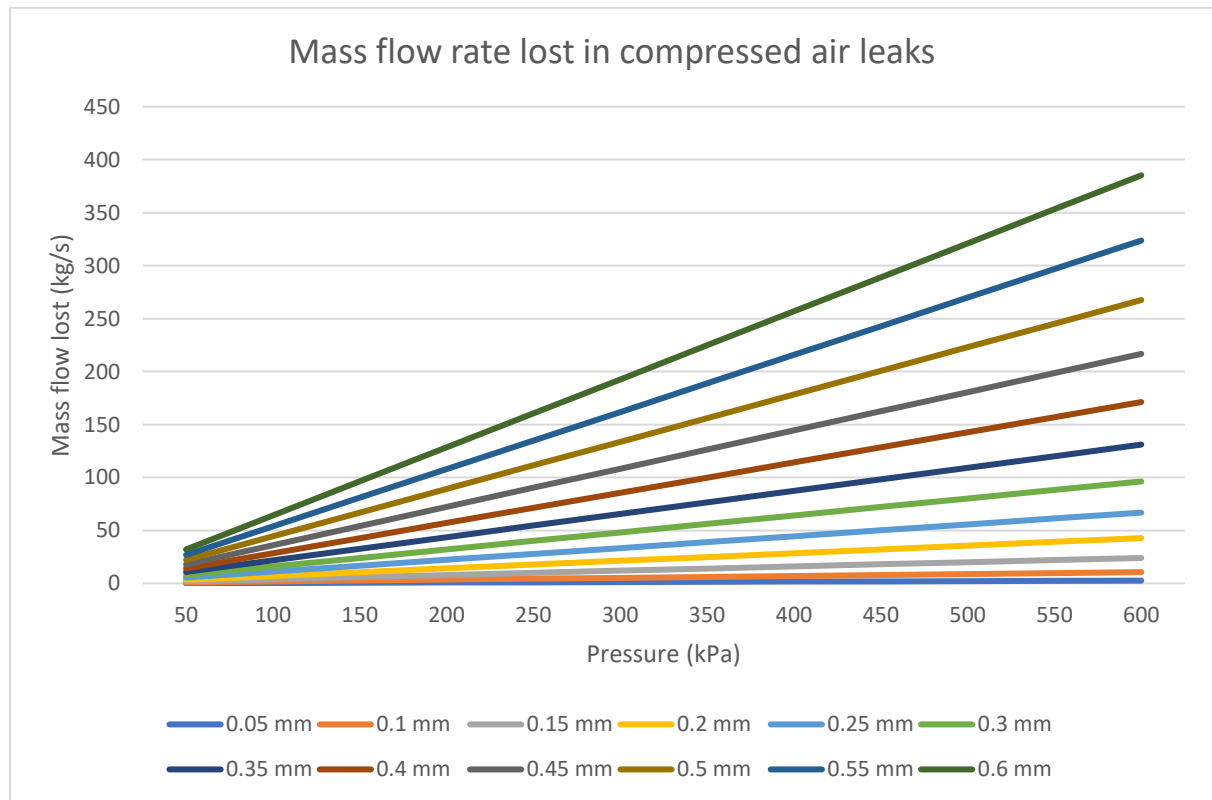


Figure 12 - Mass flow rate lost through compressed air leaks

2.4. Simulation in deep-level mine compressed air systems

Simulation is a powerful tool for improving compressed air systems in deep-level mines [32]. Simulation allows for replication of real-life scenarios in a digital environment, which in turn allows for testing of various scenarios, system configurations and optimisation strategies without disrupting real-life operations. Ultimately, simulation is a cost-effective strategy to evaluate operation improvements before large capital expenditure is spent to implement the improvements [23]. In the following section, different simulation packages are discussed.

2.4.1. Process toolbox

Process toolbox (PTB) is a versatile thermal hydraulic simulation package which is used to simulate complex mining systems. These systems include compressed air, refrigeration, ventilation, and water networks. PTB is characterised by its 3-dimensional user-friendly interface which allows for easy drag and drop features. It integrates components into one system to identify inefficiencies in the system. In addition, PTB has the capability to estimate possible energy savings through initiatives [19, 44, 45]. Figure 13 indicates an example of a simulation model done on PTB.

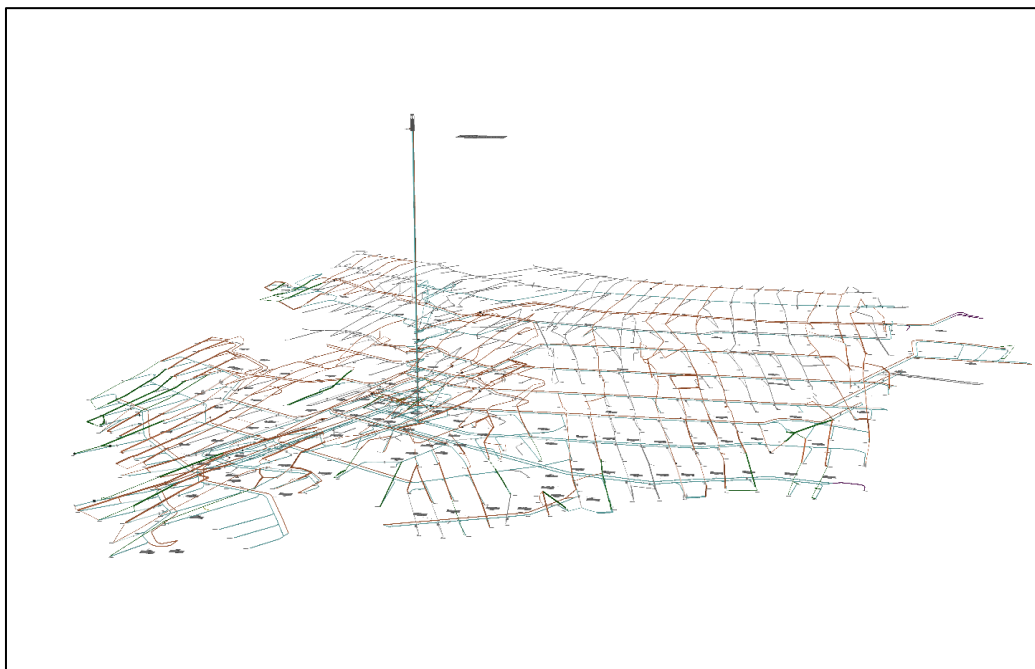


Figure 13 - Process toolbox ventilation simulation model example

2.4.2. Flownex®

Flownex® simulation is a platform that analyses real-life scenarios that are fluid driven. It is used to understand the impact of changing specific properties of single components. This capability empowers the user to explore system variations to ensure the most efficient system. This simulation package is very complex, specialising in various industries such as hydrogen, spaceflight, gas turbines, nuclear, and CO₂ cycles [19, 46].

2.4.3. KYPipe

KYPipe is simulation software that is used to model various fluid systems which include water, petroleum, and chemicals. It is used to select important components such as pipe sizes, valves, and tanks. The software also provides optimisation tools for pump selection, ensuring accurate and safe modelling [19, 47]. Figure 14 shows a KYPipe simulation model example of a compressed air system on a deep-level mine [18].

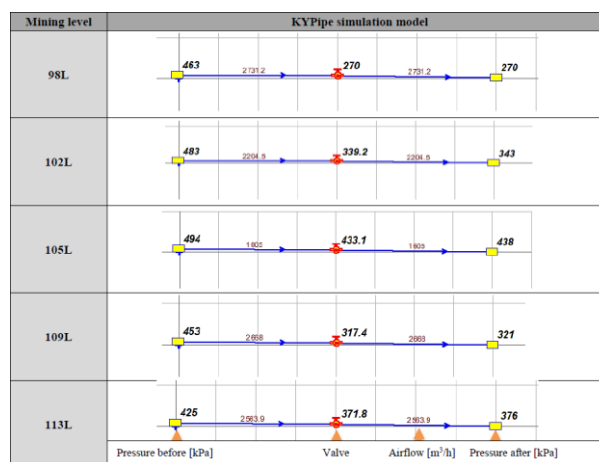


Figure 14 - KYPipe simulation model example [18]

2.4.4. AIRMaster+

AIRMaster+ is a simulation package that assists in analysing energy usage and quantifying possible saving in industrial compressed air systems. AIRMaster+ can be used to improve existing models or to simulate future operational improvements. The package uses a systematic approach to analyse compressed air systems by collecting data, analysing the data, and reporting the results [19, 48].

2.5. Hydropower-based deep-level mines

Hydropower-based deep-level mines refer to mining operations where hydraulic high-pressure water is used as the primary energy source to drive essential mining processes. Some of these processes include [50]:

- drilling equipment,
- loading cylinders,
- loading equipment, and
- dewatering pumps.

According to Nell *et al.* [24], hydropower pumped energy sources have a 18% higher overall efficiency than compressed air. Table 2 shows the comparison of energy delivery efficiency for different drilling methods [50].

Table 2 - Comparing the energy delivery efficiency for different drilling methods [50]

Drilling: Energy delivered to face	Efficiency of compressor or pump (%)		Reticulation pressure or voltage drop (%)		Energy left after leaks (%)		Efficiency of drill (%)	Overall Efficiency (%)	
Compressed air	58	x	75	x	18	x	24	=	2
Oil electro-hydraulic	80	x	80	x	100	x	36	=	23
Hydropower-pumped	85	x	80	x	95	x	31	=	20
Hydropower-gravity	96	x	89	x	90	x	31	=	24
Electric drill	100	x	90	x	100	x	35	=	31

Frazer [50] stated that it would be possible to replace all compressed air equipment in deep-level mines with localised hydropower systems. Their study states that mines using existing piping networks to supply compressed air for refuge bays can replace compressors with a low-pressure ‘blower’ on surface. This will only require pressurising the piping network to a low pressure, for example, 30 to 80 kPa gauge pressure.

2.6. Refuge bays in deep-level mines

2.6.1. Legislation

A refuge bay is a designated, secure go-to area within the underground environment where workers can gather during an emergency while awaiting rescue. These areas are equipped with life-sustaining resources such as compressed air and water. Legislation is established in the form of the Mine Health and Safety Act to ensure proper design. The Mine Health and Safety Act, summarised according to Regulation 16.6, states the following regarding refuge bays [8]:

1. *The employer of any underground mine should ensure that:*
 - a) *Readily accessible refuge bays are supplied underground;*
 - b) *Refuge bays should be positioned within the range of coverage of the self-contained self-rescuers used within the mine. Refer to regulation 16.2.*
2. *Considering the anticipated occupancy, each refuge bay should adhere to the following criteria as dictated by the employer:*
 - a) *The refuge bay must be of sufficient size;*
 - b) *Should be supplied with sufficient respirable air;*
 - c) *Should be supplied with sufficient potable water;*
 - d) *Should be equipped with ablution facilities;*
 - e) *Should be equipped with sufficient lighting;*
 - f) *Should be equipped with first aid equipment;*
 - g) *Should be equipped with communication devices to communicate with surface;*
 - h) *Should be in a practical location, where the area is not used for storage of combustible materials;*
 - i) *Should be constructed so that toxic gasses cannot enter the refuge bay;*
 - j) *Should be equipped with an escape route plan indicating the position of the refuge bay and its relation to the shaft or any other escape route;*
 - k) *Should be equipped with a sign indicating emergency procedure to be followed and containing emergency phone numbers;*
 - l) *Should be equipped with a clear indication sign on the outside of the refuge bay indicating where the refuge bay is. Should be visible in poor visibility.*

As seen in the Mine Health and Safety Act above, no regulation has been given regarding the supply pressure of compressed air to refuge bays. However, the following additional information is contained in the Mine Health and Safety Inspectorate regarding the construction of refuge bays [20]:

- 1. Refuge bay dimensions should reflect the highest expected occupancy, with a minimum floor area of 0.6 m^2 per person;*
- 2. A refuge bay must be sealed to establish positive pressure, preventing harmful smoke, fumes, or gasses to enter;*
- 3. In mines where a refuge bay's life support relies on compressed air, the supply must remain tamper-proof, with a valve ensuring regulated flow.*

As seen in the additional information provided by the Mine Health and Safety Inspectorate, no specifications regarding the pressurisation of refuge bays or the gauge pressure of the pipe supplying the refuge bay with compressed air has been given. Therefore, this has led to the investigation of the refuge bay compressed air requirement of the case study that is being investigated.

To ensure safety, each mine has a standard procedure guideline (SPG) to ensure that the requirements from the Mine Health and Safety Act are met. A typical SPG for fire prevention in refuge bays, will state the minimum requirements for refuge bays to be life sustaining, including [51]:

- 1. Should be equipped to supply sufficient respirable air;*
- 2. Ensure sufficient flow for pressurisation of the refuge bay while fully opening the compressed air valve, maintaining a positive pressure difference of $x \text{ Pa}$ within the refuge bay after y minutes.*

2.6.2. Refuge bay pressurisation

Underground refuge bays are pressurised to ensure a positive pressure in comparison to the outside conditions. The following equation is used to calculate the pressurisation of a room [52]:

1. The original air volume of the room is calculated by:

Equation 2 - Room volume calculation

$$V_{Refuge\ bay} = L \times W \times H \quad (m^3)$$

where

L is the length of the room (m)

W is the width of the room (m)

H is the height of the room (m)

2. The air volume of the pressurised room is calculated by:

Equation 3 - Pressurised room air volume

$$V_{pressurised} = \frac{P_{atm} + \Delta P}{P_{atm}} \times V_{Refuge\ bay} \quad (m^3)$$

where

P_{atm} is the atmospheric pressure (kPa)

ΔP is the increase in pressure (0.02 kPa)

$V_{Refuge\ bay}$ is the refuge bay volume (m^3)

3. The additional air volumes supplied to the room are calculated by subtracting the room's original air volume from the pressurised volume:

Equation 4 - Additional air volumes supplied to pressurise room

$$V_{additional} = V_{pressurised} - V_{Refuge\ bay} \quad (m^3)$$

The time to pressurise the room is selected according to regulation. In the case study that is being investigated, 15 minutes are required, which are equivalent to 900 seconds. The density of air is drawn from a psychometric chart using the atmospheric pressure in conjunction with

the wet and dry bulb temperatures [53]. Therefore, the mass flow rate to supply the additional air volumes is calculated as follows:

Equation 5 - Mass flow rate required to pressurise room

$$\dot{m}_{pressurise} = \frac{V_{additional}}{T} \times \rho \quad (\text{kg/s})$$

where

T is the time to pressurise the room (s)

ρ is the density of air (kg/m³)

2.6.3. Door leakage

In any heating, ventilation, and air conditioning (HVAC) system, leakage is an important factor to consider. Door leakage is a critical factor influencing the integrity of closed environments. It directly impacts pressure differentials and air quality, potentially allowing harmful gasses to enter. Taking door leakage into account ensures a controlled atmosphere, crucial for maintaining safe environments in closed spaces [54].

A method for detecting door leakage is the blower door test. This method includes the pressurising and depressurising of a room. Equation 6 shows the empirical power-law equation, which uses the flow through an orifice to characterise the leakage through door gaps [55]:

Equation 6 - Door leakage calculation

$$\dot{m}_{doors} = \rho C A (\Delta P)^n \quad (\text{kg/s})$$

where

ρ is the density of air (kg/m³)

n is the leakage coefficient

A is the area of leakage (m^2)

C is the flow factor

ΔP is the difference in pressure between inside and outside of room (Pa)

The density of air is drawn from a psychrometric chart using the atmospheric pressure in conjunction with the wet and dry bulb temperatures [53]. The leakage coefficient n varies from 0.5 to 1, where 0.5 corresponds to a higher Reynolds number (Re) and 1 corresponds to a lower Re . Door leakage in the form of gaps is relevant, with the coefficient n equal to 0.5 [55]. Figure 15 below shows a psychrometric chart [56].

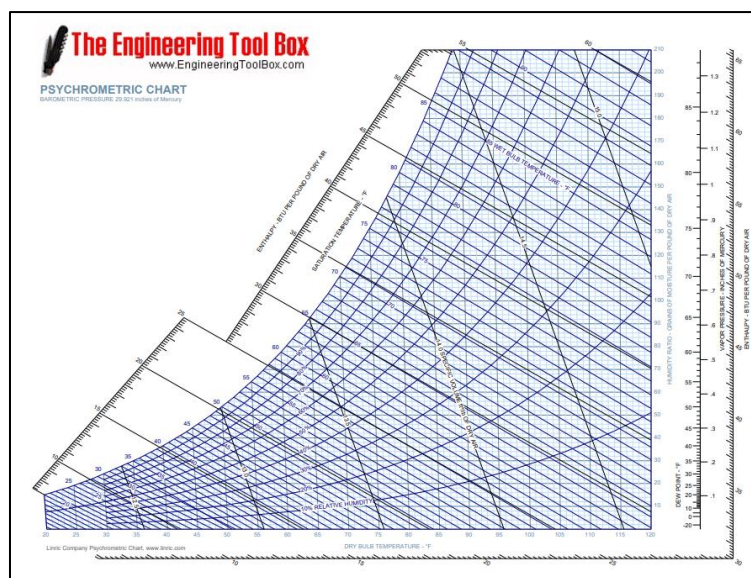


Figure 15 - Psychrometric chart example¹

2.6.4. Human air consumption

Human air consumption is an important factor to consider when understanding the air consumption within a refuge bay. Under standard pressure and temperature conditions (101.325 kPa and 25 °C), typical dry air is composed of approximately 21% oxygen, 78% nitrogen, 0.035% carbon dioxide, 0.92% argon, and trace quantities of various other gases [53].

¹ The Engineering Tool Box – Psychrometric chart

In human metabolism, there are two primary sources of energy, namely glycogen and fatty acids [57]. Glycogen, also commonly referred to as carbohydrates, serves as the main fuel source for muscles, especially during increased workload [58]. Glycogen has a respiratory quotient of 1. The respiratory quotient is a measure of the stable ratio between the volume of oxygen consumed and the volume of carbon dioxide produced during metabolism [59].

Fatty acids serve as the secondary metabolic fuel, primarily utilised during periods of rest, and have a respiratory quotient of 0.7 [60]. In situations of rest, such as those encountered in entrapment conditions, the respiratory quotient typically hovers around 0.8 [61]. The respiratory quotient can be used for calculating the ratio of oxygen consumed to carbon dioxide produced.

In a completely restful state, a person weighing 70 kg will inhale air at a rate of 7.5 L/min, with exhaled air containing approximately 17% oxygen and 3.2% carbon dioxide [62]. This results in an intake of 0.3 L/min of oxygen and an output of 0.24 L/min of carbon dioxide. It is important to note that breathing rate is predominantly influenced by the concentration of carbon dioxide in the atmosphere, with higher carbon dioxide levels leading to increased respiration rates.

Furthermore, even a small increase in activity or body weight can lead to a notable rise in metabolic rates, subsequently resulting in elevated oxygen consumption and increased carbon dioxide exhalation [63, 64]. According to the research conducted by Venter *et al.* [65] the average oxygen consumption for a group of 12 individuals is approximately 0.44 L/min.

Carbon Dioxide

Carbon dioxide has a higher solubility in blood compared to oxygen, with a ratio of 20:1. An increase in carbon dioxide levels results in an increase in breathing rate [66]. The concentration of carbon dioxide in normal air is roughly 300 parts per million (PPM). The time-weighted average exposure limit for carbon dioxide is set at 500 PPM [67]. At 10 000 PPM, headaches occur and breathing rate starts to increase. The temporary exposure limit is 30 000 PPM, which results in roughly double the breathing rate than normal [68]. However, intoxication occurs at 50 000 PPM and unconsciousness occurs at 100 000 PPM [69]. These findings apply for normal oxygen content [64].

Oxygen

A reduction in oxygen content surprisingly results in only a marginal elevation in respiration rate. This is an effect governed by the aforementioned carbon dioxide concentration in inspired air. The normal lower oxygen limit is 19% and slight increased breathing effort is observed at 18% [70]. When the oxygen concentration drops to 16%, a lamp flame will extinguish, but this decreased concentration typically leads to only a minor increase in heart- and respiratory rates. Emotional instability, compromised decision-making, and coordination challenges start to manifest at an oxygen concentration of 14%. Substantial consequences follow at 12%, including cardiac damage and vomiting. A critical threshold of 10% results in unconsciousness, progressing to fatality [64].

Compressed air

As mentioned previously, many mine uses compressed air to pressurise refuge bays. However, it is important to consider how much compressed air a single refuge bay occupant require to prevent exceeding the oxygen and carbon dioxide limits mentioned above. Brake *et al.* [64] mentioned that a compressed air supply of 85 L/min per person would be sufficient to keep the carbon dioxide levels below the time-weighted average exposure limit of 500 PPM. This flow rate will also ensure a 'steady state' oxygen content of roughly 20.3 %.

2.6.5. Mass balances

The conservation of mass is a key principle in the law of physics. It states that mass can neither be created nor destroyed but can be transferred from one form to another. The mass of an object can be calculated as the product of the object's volume and its density. In the case of gases, the shape, volume, and density of the object can vary over time, allowing mass to be transferred within a system. The general equation for the law of conservation of mass is shown in Equation 7 [71]:

Equation 7 - Law of conservation of mass

$$\dot{m}_{in} = \dot{m}_{out} \quad (\text{kg/s})$$

From this equation, it is evident that everything moving into the system is equal to what is moving out of the system.

2.7. Critical analysis of previous studies

A systematic keyword-based search approach was used to identify studies for review. The keywords used included compressed air, supply side, demand side, hydropower, and refuge bays. When considering refuge bays, two key factors were evaluated: whether the study incorporated supply pressure from existing literature, or whether it conducted an analytical calculation to establish supply pressure to refuge bays based on its size and the number of occupants present.

The search was conducted across various academic platforms, which included Google Scholar, the NWU electronic library, Elsevier Springer, and more, ensuring a comprehensive and diverse collection of relevant research materials for the study. The most relevant studies identified throughout the review are discussed below.

Study 1, De Villiers [19]

Title: Reducing deep-level mine refuge bay compressed air consumption

The study had the objective of enhancing the efficiency of compressed air consumption in deep-level gold mines, particularly within refuge bays that have minimal infrastructure. It involved evaluating current compressed air supply designs in the refuge bays and suggested new configurations to reduce wastage.

The study adapted a rapid re-engineering method for deep-level gold mines. The existing practice of partially opening refuge bay compressed air valves to 25% during non-emergencies was addressed by installing crack valves. The term “crack valve” are a colloquially used for a ball valve which has a hole drilled through which reduces airflow while maintaining pressurisation. The solution was implemented and verified through simulation. The success, impact, and sustainability of the project was measured and reported.

The solution was implemented on 42 refuge bays. The implementation of the solution led to a baseload power reduction of 962 kW, which equates to an estimated saving of R 5.25 million annually.

There are multiple similarities between the current study and De Villiers' [19] study. Both studies look at improving compressed air efficiency in deep-level mines. However, De Villiers looked at improving compressed air consumption of refuge bays by installing crack valves, while the current study investigated the supply pressure to these refuge bays while ensuring that they are not oversupplied with compressed air.

The study [19] had limiting factors such as assumptions made based on occupant consumption, line pressures, etc. It did not calculate each individual refuge bay requirement based on size or occupant consumption.

Study 2, Brake *et al.* [64]

Title: Criteria for the design of emergency refuge stations for an underground metal mine

The objective of the study was to provide guidelines for both fixed- and relocatable refuge bays in terms of location and specifications. Brake *et al.* looked at literature in terms of human air consumption to determine general specifications and guidelines for refuge bays. They looked at human respiratory rates, carbon dioxide limits and oxygen limits to determine these specifications.

The study [64] stated that, taking oxygen- and carbon dioxide limits into account, a fresh air supply of 85 L/min should be supplied per person in an emergency refuge bay. This is equivalent to 1.4 L/s. The study contributed to this study by investigating refuge bay requirements where occupants are present. It provides valuable insight regarding the human air consumption rates and respiratory rates.

The study extensively investigated occupant air consumption, but has certain limitations. It neither delves into the aspect of refuge bay door leakage, nor does it look at pressurisation requirements based on the refuge bay size. Furthermore, the study did not provide a supply line pressure of the compressed air pipe entering the refuge bay to ensure positive pressurisation.

Study 3, Nell [24]

Title: Optimising production through improving the efficiency of mine compressed air networks with limited infrastructure

The study aimed to improve the compressed air network by addressing inefficiencies such as incorrect pipe sizes and restrictions within the pipeline and developed a procedure for optimising the compressed air networks using limited infrastructure. After implementation, the objective was to quantify the optimised compressed air network in terms of production.

The root-cause analysis methodology was used to find the area of concern. Firstly, different measurement points were identified. Thereafter, a scoring system (0-Low, 10-High) was developed to prioritise inefficiencies such as pressure losses or pipe sizes between two measurement points. The same was done for the repair time and cost. The solution strategy to repair these inefficiencies was simulated to verify its priority and quantify its impact.

The inefficiencies with the highest score and lowest fixing cost were repaired first. The simulation proved to be 97% accurate, ensuring the accuracy of the scoring system. After implementation, the pressure difference across the measurement points was, on average, 25 kPa, compared to 87 kPa before implementation.

There are multiple similarities between this study and the study conducted by Nell. Both these studies looked at improving the demand-side of the compressed air system. In addition, Nell quantified the mass flow rate of compressed air through a leak by using Equation 1. In the current study, the compressed air supplied to the refuge bay was considered as a leak and was quantified using Equation 1.

Although Nell mentioned the operating consumption of refuge bays, there are multiple limitations to the study including the optimisation of refuge bays.

Study 4, Vermeulen *et al.* [9]

Title: Simplified high-level investigation methodology for energy saving initiatives on deep-level mine compressed air systems

Vermeulen *et al.* [9] developed a new benchmarking method to reduce compressed air consumption in deep-level mines. This method is less resource intensive than existing approaches. The new method only requires power consumption data as input parameter on a mine's compressed air system. Typically, this data is readily available on mine compressed air systems. In addition, the method reduces the cost and time spent to quantify cost savings.

The method includes quantifying the power consumption difference between the peak drilling shift and the peak blasting shift. Typically, the blasting shift requires less compressed air than the drilling shift. However, compressed air was being oversupplied during the blasting shift. Therefore, the method quantifies the cost saving of reducing the supply during the blasting shift based on the requirements.

The study did not look at individual components such as refuge bays. However, the study can be used to quantify the cost savings of reducing the compressed air pressure setpoint after implementation.

Study 5, Zietsman [12]

Title: Novel solutions for compressed air demand management on deep-level mines

Zietsman [12] created a benchmarking model that prioritises shafts according to their potential for reducing underground demand. The study adapted leak auditing techniques from the potable water industry and applied it on mine compressed air networks. When this method was implemented, it proved to reduce underground auditing time by roughly 65%.

The methods created in the study were combined into one method to reduce underground leaks and achieve electricity cost savings on the compressed air system. Zietsman used Equation 1 to quantify the effects of leaks. However, the study did not quantify the pressure that needs to be supplied to each refuge bay and gave a supply pressure and flow from literature.

Study 6, Fouche [18]

Title: Improving efficiency of a mine compressed air system

Fouche [18] developed a leak auditing technique. The study focussed on control valves and their control philosophies during the morning change period. The study discusses the effect of fixing leaks on the compressed air system. The positive effect was then used to adjust the compressed air system's supply to reach cost savings. Additionally, the study examined the supply side of the compressed air system, improving it by replacing compressors, selecting the most efficient compressors to operate, replacing compressor inlet air filters, and off-loading compressors.

To adjust the supply pressure of the compressed air systems, the study had to consider refuge bays due to their continuous compressed air supply requirement as per the Mine Health and Safety Act. However, the supply pressure for refuge bays lacked a thorough in-depth analysis and was obtained from literature.

Study 7, Hernandez-Herrera *et al.* [72]

Title: Energy saving measures in compressed air systems

This article analysed the main efficiency measures in compressed air systems, implementation cost, and return rate. These efficiency measures included identifying incorrect compressed air usage, such as personnel cooling; assessing the location and extent of leaks; designing appropriate storage capacity to minimise compressor cycling; analysing the system's pressure drop; assessing compressor intake air temperatures, and heat recovery; as well as discussing the energy performance index and benchmarking techniques in compressed air systems.

The study explored various methods to improve the compressed air system's efficiency. However, it excluded an energy-saving technique that involves reducing compressed air supply to refuge bays according to their specific demand requirements.

Study 8, Taljaard [25]

Title: Practical low-cost method to sustain mine compressed air savings

Taljaard [25] developed a method that identifies cost-saving initiatives to reduce compressed air network inefficiencies. The method includes setpoint control, the most efficient compressor selection and predicting compressed air behaviour. This method was incorporated into an existing energy management system and was developed to be implemented without any additional infrastructure cost. The solution strategy was implemented on a case study and it was proven to have no negative impact on the production of the mine. This led to an annual cost saving of R1.1 million per annum.

As mentioned in Fouche's [18] study, if the compressed air setpoint is changed, an in-depth analysis of the end users is required. However, the study by Taljaard lacks an in-depth analysis of refuge bays and states that a supply pressure of 200 – 300 kPa would be sufficient according to literature.

Study 9, Friedenstein *et al.* [23]

Title: Simulating operational improvements on mine compressed air systems

The study developed a simulation methodology to simulate compressed air systems in deep-level gold mines. The methodology started off with investigating the system. When investigating the system, data were acquired and compressed air operational schedules were defined. However, it was important to verify the data's accuracy and resolve any missing data. Thereafter, the simulation model was developed and verified. Using the verified simulation model, scenarios were executed and the results were analysed.

The current study adapted the methodology of Friedenstein *et al.* to construct a simulation model of a compressed air system on a level within a deep-level hydropower mine. This simulation model was verified, whereafter it was implemented by running scenarios.

Study 10, Shaw *et al.* [31]

Title: Using specific energy as a metric to characterise compressor system performance

Shaw *et al.* [31] developed a method to determine the performance of a compressed air system by using specific energy relative to the compressor supply and energy consumption. However, the study only looked at the compressed air system as a whole, and did not include refuge bays, hydropower mines or simulation.

Study 11, Frazer [50]

Title: Saving energy by replacing compressed air with localised hydropower systems: a ‘half level’ model approach

Due to the high operational cost to generate compressed air, Frazer looked at replacing all compressed air equipment with localised hydropower systems. The study stated that hydropower is 18% more efficient than compressed air. In terms of refuge bays, the study stated that mines using existing piping networks to supply compressed air for refuge bays can replace compressors with a low-pressure ‘blower’ on surface. This would only require pressurising the piping network to a low pressure, for example, 30 to 80 kPa.

However, due to cost implications and existing compressed air piping networks, this is not a feasible solution.

Study 12, Trčka *et al.* [73]

Title: Overview of HVAC system simulation

This article gives an overview of HVAC system modelling and simulation. The following approaches, which were used for modelling, are discussed: HVAC components, HVAC control, and HVAC systems in general.

This article gives a general guideline of how an HVAC system should be modelled in order to pressurise. This modelling approach was used in this study [73] to perform calculations to pressurise refuge bays. Basically, a mass balance of air that enters and exits the refuge bay was considered. The net mass flow into the refuge bay causes the refuge bay to pressurise.

Study 13, Min-Hwi *et al.* [54]

Title: Feasibility of building envelope air leakage measurement using combination of air-handler and blower door

In the study, an air-handler and a blower door test was proposed and verified by performing pressurisation tests in an office building. To calculate the amount of air leaking out of the door, Equation 6 was used. It was found that the results of this blower door test were accurate for quantifying leakage in a building.

Although this calculation is typically used to quantify door leakage within a building, it is applicable to refuge bays. The study contributes to the current study by quantifying how much a refuge bay's door will leak at a given pressure differential.

2.7.1. Summary of literature

From the literature review, it is evident that various studies have been conducted on compressed air systems in deep-level mines. These studies often looked at demand- or supply-side management techniques, while some incorporated both into their study. However, in most of these studies, the main demand-side user was drilling operations.

In addition, simulation is a powerful tool which can aid in optimising the supply- or demand side of compressed air systems in deep-level mines. Many studies used simulation in conjunction with both demand- and supply-side management techniques in their optimisation strategies. Studies have been found that focused on replacing compressed air systems with localised hydropower systems. However, none of these studies looked at the optimisation of compressed air systems in deep-level hydropower mines.

The Mine Health and Safety Act does not state any regulation of the compressed air supply pressure to refuge bays. As legislation does not provide the answer to compressed air supply pressure, the mines SPG had to be looked at. These SPG's typically stated that refuge bays should maintain a positive pressurise differential of x Pa within y minutes. Many studies have been found indicating the supply pressure to refuge bays according to literature. However, no studies did an analytical or simulation-based investigation of the air requirements in terms

of air leaking out of the refuge bay and air consumption by occupants. Therefore, there is no method from literature to provide a minimum supply pressure to individual refuge bays based on their size and occupancy.

For the method to be successful, some criteria need to be addressed based on the literature discussed above. The method must be able to:

- consider the compressed air network;
- consider demand- and supply-side users;
- use simulation modelling as a tool;
- be applicable to hydropower mines; and
- consider refuge bay pressure requirements;

In Table 3 , the red blocks indicate the specific criteria that have not yet been covered in Studies 1 – 13 above. The green blocks indicate that the study did in fact cover the criteria mentioned. It is evident from Table 3 that an analytical/simulation-based approach is missing from literature to determine the compressed air supply pressure to refuge bays in deep-level hydropower mines.

Table 3 - Summary of literature review

	Compressed air	Demand side	Supply side	Simulation	Hydropower	Refuge bays pressure requirement	
						Literature	Analytical/ Simulation
[9]							
[12]							
[24]							
[18]							
[72]							
[36]							
[23]							
[31]							
[50]							
[52]							
[54]							

Table 4 - Legend for the summary of literature table

	Study considered the criteria
	Study did not consider the criteria

3. DEVELOPMENT OF A METHOD TO OPTIMISE COMPRESSED AIR SUPPLY PRESSURE TO HYDROPOWER MINE REFUGE BAYS

3.1. Preamble

This study used the case study methodology to develop a compressed air model to ensure that refuge bays are pressurised according to regulations. The data obtained from this case study was used to calibrate the model. Different equations from literature were integrated and implemented to solve the problem identified in this study. The steps of the methodology were determined to achieve the study objectives. The methodology consists of six stages, starting with system investigation and ending with model validation. Each stage has substages and is discussed in detail in the following sections. Figure 16 shows a typical refuge bay found in deep-level mines.



Figure 16 - Typical refuge bay found in deep-level mines²

² Z Victor, Personal photograph, Theunissen, 2023

3.1.1.1. Proposed method to optimise compressed air supply pressure to hydropower mine refuge bays

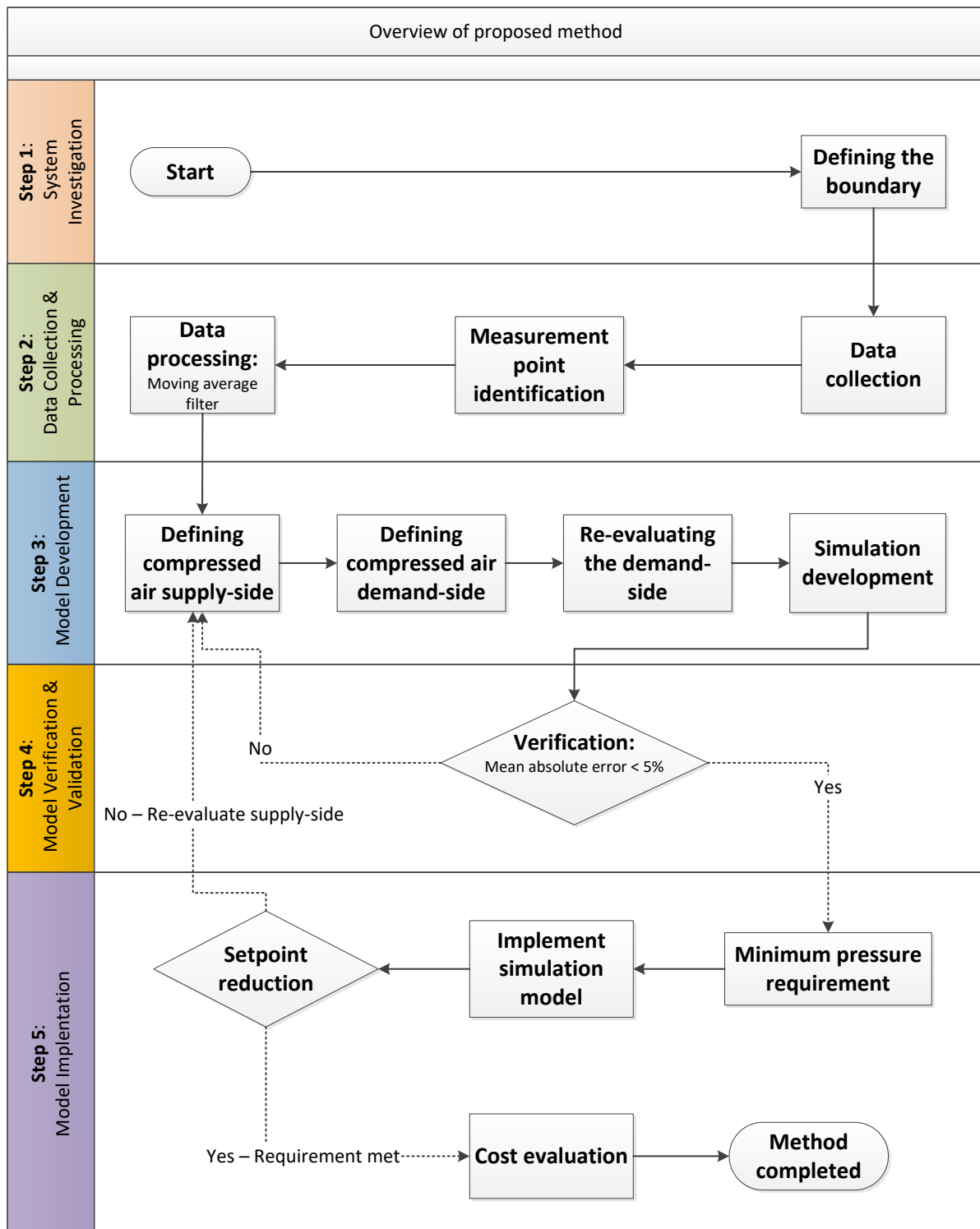


Figure 17 - Overview of proposed method to optimise compressed air supply pressure to hydropower mine refuge bays

3.1.2. Method guidance

Table 3 listed various studies that have been conducted on deep-level mine compressed air systems. These studies often looked at a combination of demand- and supply-side management techniques including leak auditing techniques and the identification of inefficiencies. Most of these studies looked at conventional mines where compressed air is used as drilling medium.

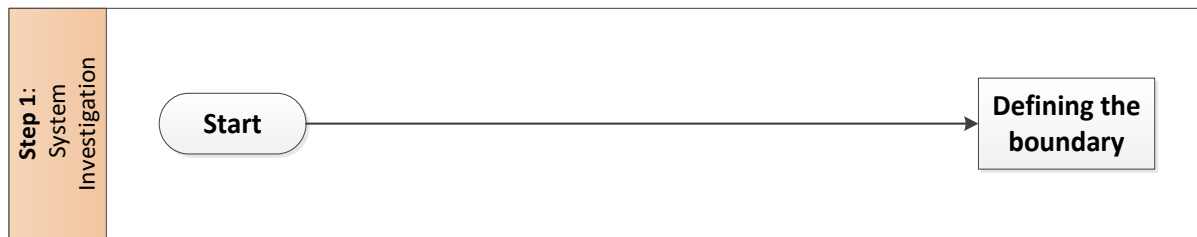
From Table 3, we can see that only one study [50] looked at compressed air systems in hydropower mines. However, the study specifically looked at replacing an entire compressed air system with localised hydropower systems. Therefore, no studies have been found that looked at improving the demand side of a hydropower mine compressed air system. This led to the investigation of hydropower mine compressed air systems, which focussed on identifying the main compressed air user, which is refuge bays. However, from previous studies, it has been suspected that these refuge bays are oversupplied with compressed air. This led to the investigation of the regulation of refuge bays in deep-level mines.

The Mine Health and Safety Act does not give guidance on the compressed air supply pressure to a refuge bay, which led to the investigation of the mine SPG for refuge bays. The mine SPG states that a refuge bay should maintain a positive pressure differential of x kPa within y minutes. Studies on compressed air systems have included refuge bays, but they obtained their refuge bay requirements from literature, which led to the development of a model to determine the minimum compressed air supply pressure in order for refuge bays to pressurise accordingly. The model could also indicate whether refuge bays are, in fact, oversupplied with compressed air.

From multiple studies in Table 3, it is evident that energy savings can be achieved by reducing the compressed air pressure setpoint. However, the compressed air setpoint on hydropower mines can only be reduced if the refuge bays are being oversupplied with compressed air. This reduction in setpoint needs to be simulated to ensure that it would not have a negative effect on the refuge bay pressurisation. As seen in Table 3, many studies have used simulation in conjunction with demand- and supply-side management techniques. Therefore, simulation is used as a validation tool.

3.2. Step 1: System investigation

3.2.1. Defining the boundary



In this section, the boundary of the compressed air system that is studied is defined. The three main boundaries in a compressed air system are:

- compressed air demand side,
- compressed air supply side, and
- compressed air reticulation side.

It is important to note that the above-mentioned boundaries are interlinked. Therefore, by changing one component in a single boundary, the other boundaries might be affected and should be considered [24].

Compressed air demand side:

The demand side of the compressed air system consists of all the end users such as refuge bays, drills, loading boxes. To define the boundary of the demand-side of the compressed air network, the following information is important [12, 19, 27]:

- Number of shafts and metallurgical plants dependent on compressed air.
- Operations dependent on compressed air such as drilling and refuge bays.
- Compressed air flow and pressure requirements per shaft.
- Compressed air demand shift dependent or a constant baseline.

Compressed air supply side

The compressed air supply side involves the components that are responsible for generating compressed air. Compressed air is generated using compressors on surface and is then supplied to the underground levels. The following information is important when defining the supply-side of the compressed air network [36]:

- Number of compressor houses
- Number and type of compressors located in these compressor houses
- The power, flow, and pressure ratings of each compressor
- Availability of historical data regarding these compressor ratings (flow, pressure, power data)
- The pressure setpoint of each compressor and its control system to maintain these setpoints
- Any control valve on the compressed air network

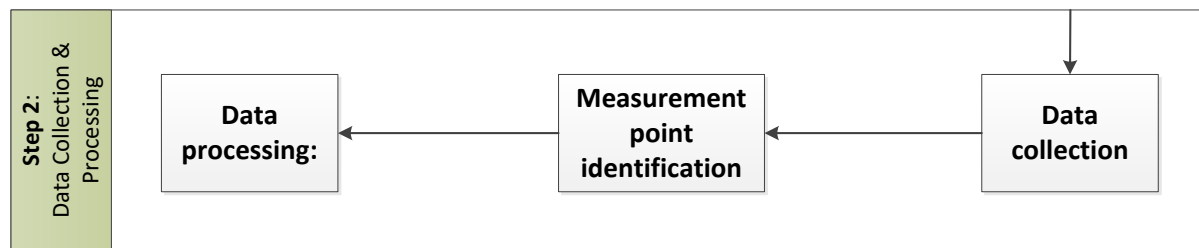
By processing the information regarding the supply side of the reticulation network, a general understanding of the overall system is obtained. The supply side of the compressed air system tends to be static and predictable.

Compressed air reticulation side

The reticulation side is a link between the supply- and demand sides of a compressed air network. The reticulation side acts as a transportation medium from the supply side to the demand side. In deep-level mines, pipes are used as transportation medium from the supply side to the demand side. The following information is critical when defining the reticulation side of the compressed air network [19]:

- The entire underground layout of the compressed air network
- The length and pipe sizes of the reticulation network
- Condition of the reticulation network, such as the presence of leaks

3.3. Step 2: Data collection



Data need to be acquired to develop the method mentioned in Figure 17 above. Three sets of data need to be obtained:

1. Refuge bay data. This includes refuge bay sizes, atmospheric pressures, door sizes, door gaps, and dry and wet bulb temperatures. The refuge bay and door size can be measured with a laser distance meter while the door gap is measured with a vernier. The atmospheric pressure can be measured with a barometer while the wet- and dry bulb temperatures are measures with a whirling hygrometer. These data are used to determine the minimum supply pressure to each refuge bay based on their size and occupant consumption.
2. The compressed air flow and pressure data are acquired through the mine's supervisory control and data acquisition (SCADA) system. The SCADA system receives its data from a pressure and flow transmitter. These data are used to verify the simulation model to be developed.
3. The compressed air pressure inside each individual refuge bay is needed to further verify the accuracy of the simulation model to be developed.

3.3.1. Measurement points identification

Measurement points are identified to verify the data acquired in the previous section.

1. To acquire refuge bay data, all refuge bays within the system are identified.
2. Measurement points just after the control valve are identified to verify the data obtained from the mine's SCADA system. This can be done by focussing on the supply column.

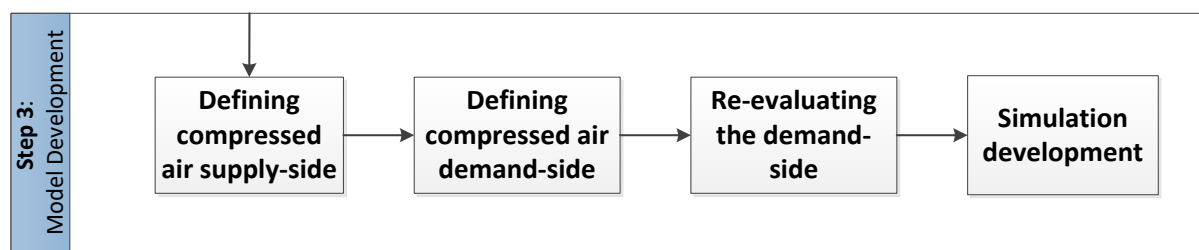
3. Measurement points are identified inside the refuge bay to measure the gauge pressure. This is done for verification purposes.

3.3.2. Data processing

The data obtained from the mine's SCADA system and from the manual measurements need to be processed. The raw data by itself often have significant outliers. The data are processed to reduce the effect of outliers. After these data have been processed, they can be used to identify patterns and trends of the compressed air consumption.

The data processing method involves obtaining a month's worth of compressed air flow and pressure data from the mine's SCADA system. The first step is to identify and remove any data gaps; if there is a gap, the data are not considered for further analysis. Next, the standard deviation of the data range is calculated. Subsequently, the average of the data is determined. An "if" function is then implemented, specifying that if a value falls within two standard deviations of the average value, it is considered an outlier and should be disregarded [74].

3.4. Step 3: Model development



3.4.1. Defining the compressed air supply side

The supply side of the compressed air model starts at the control valve, which serves as a critical component in the operation of the compressed air system. The control valve supplies compressed air flow and pressure profiles over time, which helps with identifying potential inefficiencies, peak usage periods and areas for optimisation. Figure 18 shows a expected operational flow and pressure baseline obtained from the mine's SCADA system and processed into a 24-hour profile.

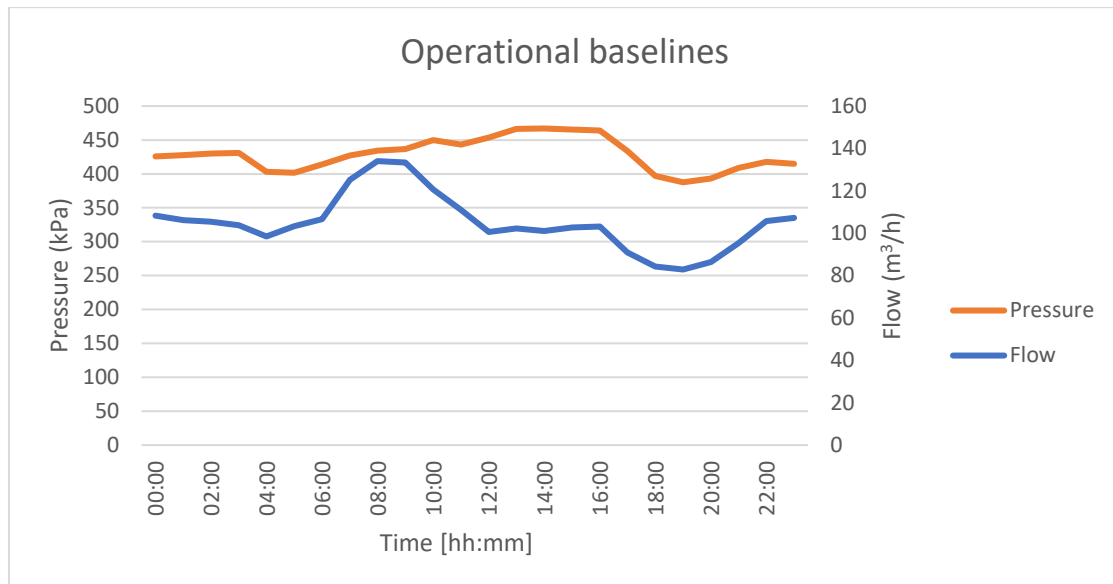


Figure 18 - Expected operational baselines

3.4.2. Defining the compressed air demand side

This model is developed for deep-level gold mines where hydropower is used as drilling medium and the main continuous compressed air user on the demand side of the network is refuge bays. Therefore, the compressed air requirement for deep-level hydropower mines only revolves around refuge bays. The model is adapted according to the specific mine's regulation.

3.4.3. Re-evaluating the demand side

The demand side is re-evaluated according to the regulation of a specific mine, as discussed in Chapter 2.6.1., according to the differential pressure that should be maintained after a given time. In this section, a steady-state mass balance of air entering and exiting the refuge bay is conducted.

Equation 8 - Mass balance to ensure that the refuge bay pressurises

$$\dot{m}_{pipe} - \dot{m}_{doors} - \dot{m}_{consumed} \geq \dot{m}_{pressurise} \quad (\text{kg/s})$$

The four main terms of the mass balance are shown below:

1. the flow required to pressurise the refuge bay ($\dot{m}_{pressurise}$);
2. the flow that is being provided to the refuge bay by means of the reticulation network ($\dot{m}_{pipe}$);
3. the flow that exits the refuge bay through door leakage ($\dot{m}_{doors}$); and
4. occupant consumption.

1. The air flow rate required to pressurise the refuge bay

The flow required to pressurise the refuge bay depends on the following factors:

- refuge bay size and
- atmospheric pressure inside the refuge bay.

The refuge bay sizes are obtained from the mine's ventilation department. However, if this information is not available, the refuge bay sizes and atmospheric pressure can be obtained through underground audits by using a laser distance meter and a barometer, respectively. In order to pressurise according to regulations, the following calculations need to be done.

Firstly, the air volumes of the pressurised refuge bay are calculated using Equation 3:

$$V_{pressurised} = \frac{P_{atm} + \Delta P}{P_{atm}} \times V_{Refuge\ bay} \quad (m^3)$$

where

P_{atm} is the atmospheric pressure (kPa)

ΔP is the increase in pressure (kPa)

$V_{Refuge\ bay}$ is the refuge bay volume (m^3)

$V_{pressurised}$ are the air volumes of pressurised refuge bay (m^3)

Therefore, the additional air volumes can be calculated using Equation 4:

$$V_{additional} = V_{pressurised} - V_{Refuge\ bay} \quad (m^3)$$

The time to pressurise the refuge bay is used to calculate the flow rate required to pressurise the room within a given time period. Thereafter, the flow rate is multiplied by density to determine the mass flow rate required to supply the additional air volumes using Equation 5:

$$\dot{m}_{pressurise} = \frac{V_{additional}}{T} \times \rho \quad (\text{kg/s})$$

where

T is the time to pressurise the room (s)

ρ is the density of air (kg/m³)

2. The air flow rate to the refuge bay

The mass flow rate provided to the refuge bay is calculated using Equation 1:

$$\dot{m}_{pipe} = C_{Discharge} \left(\frac{2}{k+1} \right)^{1/(k-1)} \frac{P_{line}}{RT_{line}} A \sqrt{kR \left(\frac{2}{k+1} \right) T_{line}} \quad (\text{kg/s})$$

where

$C_{discharge}$ is the discharge coefficient that accounts for imperfections in flow, which is taken as 0.97 for a well-rounded edge such as an open-end pipe

k is the specific heat ratio of air, taken as 1.4

T_{line} is the temperature in the compressed air line (K)

P_{line} is the pressure in the compressed air line (kPa)

R is the universal gas constant for air, taken as 0.287 (kJ/kg K)

3. The flow rate of air that exits the refuge bay through door leakage

In all HVAC systems, air leaks through small gaps and openings. The same happens in refuge bays. The doors of refuge bays leak air, and the magnitude of these leaks influences the

pressurisation period of the refuge bay. Therefore, it is essential to calculate the door leakage of a refuge bay. The data obtained in Chapter 3.3 is used to calculate the area of the leakage by multiplying the door perimeter with the door gap. The flow that exits out of the refuge bay through door leakage can be calculated using Equation 6:

$$\dot{m}_{doors} = \rho C A (\Delta P)^n \quad (\text{kg/s})$$

where

ρ is the density of air (kg/m^3)

n is the leakage coefficient

C is the flow factor taken as 0.84

A is the area of the leakage (m^2)

ΔP is the difference in pressure between inside and outside of refuge bay (Pa)

4. Occupant consumption

Next it is important to consider the air being consumed by occupants during 100% occupancy. The first step is to determine the number of occupants present during 100% occupancy. As mentioned in Section 2.6.1, the Mine Health and Safety Inspectorate states that a single refuge bay occupant requires 0.6 m^2 space [20]. Using the refuge bay size, the number of occupants in a refuge bay can be determined.

Equation 9 - Refuge bay occupant calculation

$$\text{Refuge bay occupants} = \frac{\text{Floor area (m}^2\text{)}}{0.6}$$

It is important to consider that some of the supplied air in the refuge bay is consumed by the occupants. Hence, it is necessary to calculate the flow rate required for human consumption to ensure sufficient air supply and prevent carbon dioxide poisoning within the refuge bay.

Looking at Section 2.6.4 an air consumption rate of 85 L/min will be sufficient to ensure that the carbon dioxide limit is not reached. Therefore, 85 L/min will be used in the design configuration, ensuring a prudent and comprehensive assessment of refuge bay air requirements.

Equation 10 - Air consumed by refuge bay occupants

$$Air_{consumed} = Refuge\ bay\ occupants \times Air_{consumption} \times \rho \quad \left(\frac{kg}{s}\right)$$

Conclusions from re-evaluating the demand side

1. Considering the air mass balance, if the flow from the pipe, accounting for losses and occupant consumption, is greater than the flow required to pressurise the refuge bay, the refuge bay will pressurise.
2. The minimum flow to the refuge bay is known, therefore any algorithm tool can be utilised to solve for the lowest supply pressure in the pipe using Equation 1. This study used Microsoft Excel's *solver* function to solve for the lowest supply pressure. This *solver* function uses a generalised reduced gradient (GRG) algorithm to solve nonlinear programs of general structure.
3. The next step is to build a simulation model of the intricate compressed air network to replicate real-life scenarios. Once the simulation is calibrated, the pressure at the location of the refuge bay can be identified.

3.4.4. Simulation development

Simulation tool selection

De Villiers [19] successfully used Process Toolbox (PTB) to simulate compressed air systems in deep-level mines. In their study, PTB was used to simulate the impact of crack valves in refuge bays. Through simulation, the study found a power reduction of 840 kW to be possible.

Nell [24] developed a methodology to identify large compressed air inefficiencies in deep-level mines. In their study, PTB was used to simulate the effect of fixing these inefficiencies.

The solution was implemented and PTB was used as a validation tool. Validating the results with the predictions resulted in an error of less than 2%.

Taljaard [25] developed a method to reduce compressed air network inefficiencies. The method used setpoint control, the selection of the most efficient compressor, and the prediction of compressed air usage. In their study, PTB was used as verification tool for the method developed. The verification proved to be within an error range of 4.68%.

For this study, PTB was used due to the software's success in simulating compressed air systems. In addition to the success of PTB, it has a user-friendly interface in conjunction with capabilities of simulating 24-hour periods of mine compressed air systems. This is crucial due to the fact that control valves use a 24-hour pressure profile for the compressed air supply to working levels.

Component modelling

During the component modelling phase, each component is looked at individually. The purpose of the component and its role within the larger simulation are discussed in the following sections. Figure 19 is a visual representation of the components used to develop a compressed air model in PTB.

Component	Air pressure Boundary	Air pipes	Air nodes
Visual representation			

Figure 19 - PTB Component representation

Air pressure boundaries

The air pressure boundary has a constant user-specified pressure. This is technically the starting point of the simulations and provides air at the specified pressure to the rest of the compressed air network.

Air pipes

Air pipes are used to model the intricate compressed air network from the control valve into the levels. Frictional losses in pipes cause pressure drops. Due to the large distances that compressed air travels in pipes, it is an important aspect to consider when simulating a piping network. The Darcy-Weisbach equation is used to account for pressure drops in pipes due to friction and is shown in Equation 11 [75]. The size of the air pipes is determined by examining the intricate compressed air network through underground audits.

Equation 11 - Pressure drop in air pipes [23]

$$\Delta P = \frac{fL\rho V^2}{2D} \quad (\text{kPa})$$

Air nodes

An air node specifies a specific volume of air. This includes air height; in other words, it calculates the auto compression of air if a pipe is changing elevation. Various properties, such as pressure and density, are calculated at an air node. An air node is used to connect multiple pipes in a network.

Visual representation of PTB

In Figure 20 is a general representation of a simulation done in Process Toolbox. Figure 19 serves as legends for the symbols represented.

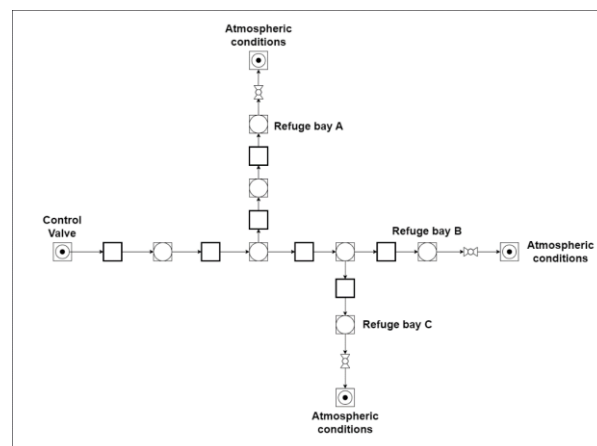
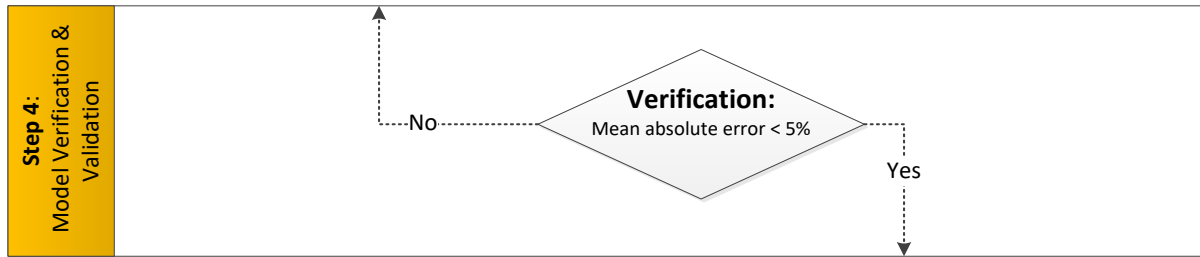


Figure 20 - Process Toolbox simulation representation

3.5. Step 4: Model verification and validation



Verifying and validating the simulation model is crucial to ensure its accuracy. This is done by calibrating the simulation to match real-life scenarios. To verify this simulation model, a 24-hour monthly average of flow data, obtained by averaging half-hourly values from the mine's SCADA system, is used. It was found that the mean absolute error (MAE) shown in Equation 12 is the most effective method to verify the accuracy of the model [23]. This method compares the actual flow data from the mines SCADA system with the flow data from the simulation model.

Equation 12 - Mean absolute error method [23]

$$MAE = \frac{\sum_{i=1}^n |y_i - x_i|}{n}$$

where

y is the actual SCADA value

x is the simulated value

n is the total measurements

The verification constraints were selected to be an error of less than 5% [23]. Figure 21 shows an example of the 24-hour flow profiles obtained from both the mine's SCADA system (orange) and the simulation (blue) are indicated. The direct visual comparison demonstrates the alignment between the two profiles, affirming the accuracy of the model.

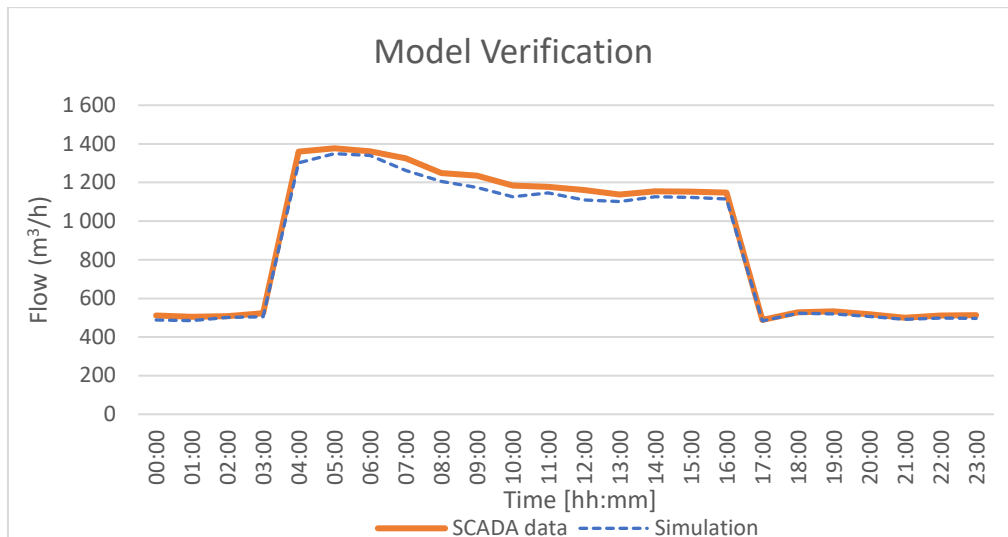


Figure 21 – Example of the expected model calibration graph

To further aid in verifying and validating the simulation model, actual pressure data are obtained from refuge bays through underground measurements. This real-world pressure data are then compared to the values predicted by the simulation model. This direct correlation between the observed measurements and simulated outcomes serves as support for verification. Overall, this improves accuracy and credibility of the simulation.

Figure 22 shows the expected alignment of the measured (blue) and simulated (orange) pressures in various refuge bays are shown. The margin of error is expected to be small, enhancing the credibility of the simulated pressures.

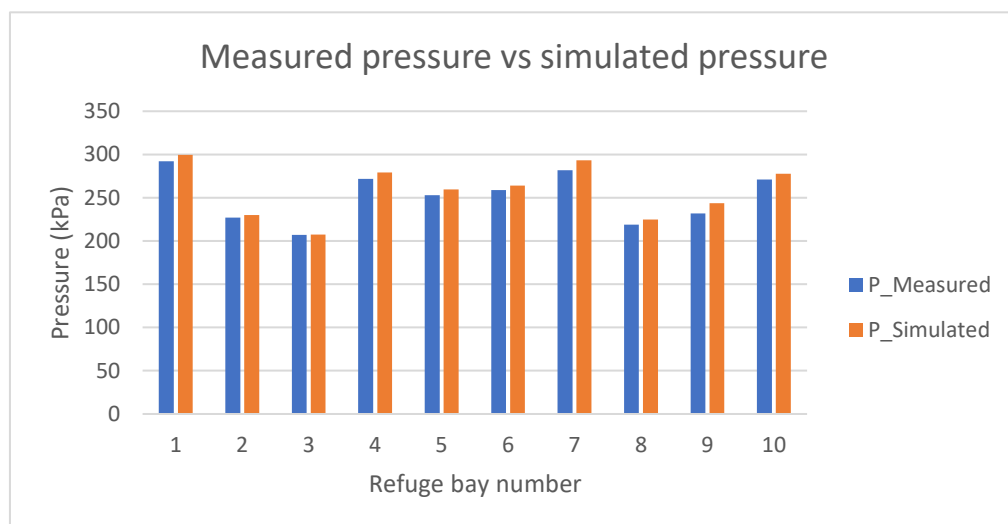
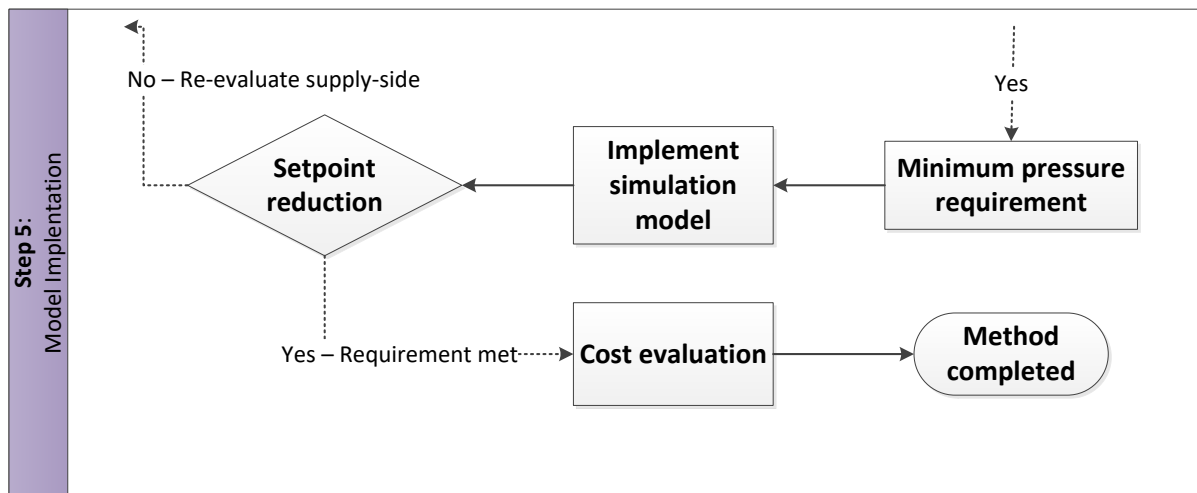


Figure 22 – Example of the expected model validation

3.6. Step 5: Model implementation



To implement the model in deep-level hydropower mines, an iterative approach is followed. The varying iterations involve adjusting the pressure setpoint at the control valve while ensuring that all refuge bays still receive sufficient pressure.

3.6.1. Minimum pressure requirement

The minimum pressure requirement for each individual refuge bay can be calculated using the law of conservation of mass. The minimum pressure requirement differs for all refuge bays due to their size and atmospheric conditions. Figure 23 in Section 3.6.2 shows an example graph of the minimum pressure requirement for each individual refuge bay is shown.

3.6.2. Implement simulation model

After the minimum pressure requirement for the refuge bays has been established, the digital twin is developed. Thereafter, simulations are run to assess the pressure at different refuge bays. If the pressure from the simulation exceeds the minimum requirement determined in the previous section, the refuge bay will pressurise according to regulation and vice versa. Figure 23 is an example graph of the expected minimum pressure (orange) requirements and the actual pressure (blue) that is supplied.

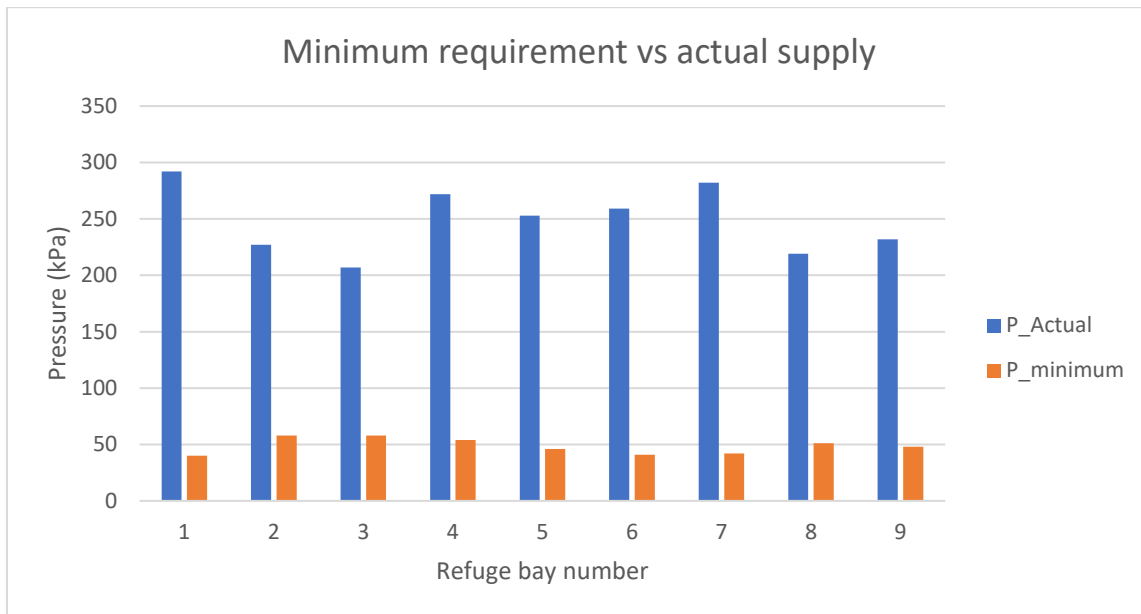


Figure 23 - Expected minimum pressure requirement vs expected supply pressure

3.6.3. Setpoint reduction

From Figure 23 it is evident that refuge bays are oversupplied with compressed air. Therefore, the pressure setpoint at the control valve can be reduced to minimise wastage. Figure 24 shows how the current setpoint (blue) is expected to be reduced to minimise the effects of wastage while ensuring that all refuge bays receive sufficient pressure.

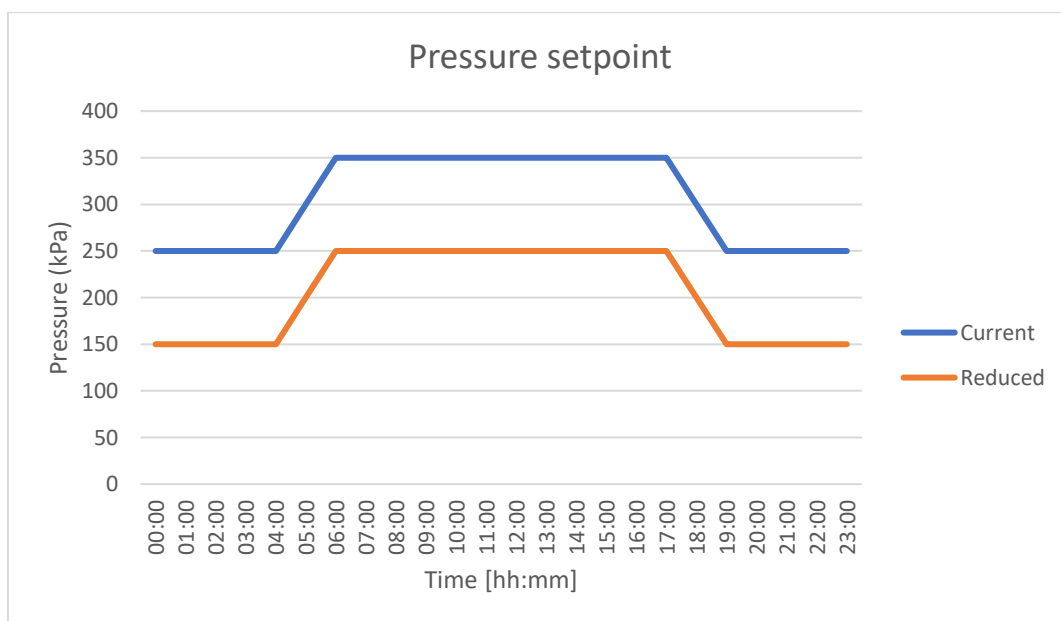


Figure 24 - Current pressure setpoint vs expected setpoint after implementation

With the calibrated simulation model, the pressure at the refuge bays can be verified to ensure that the minimum requirement is still adhered to. Figure 25 shows that the expected pressure after implementation (blue) still adheres to the minimum pressure requirement (orange).

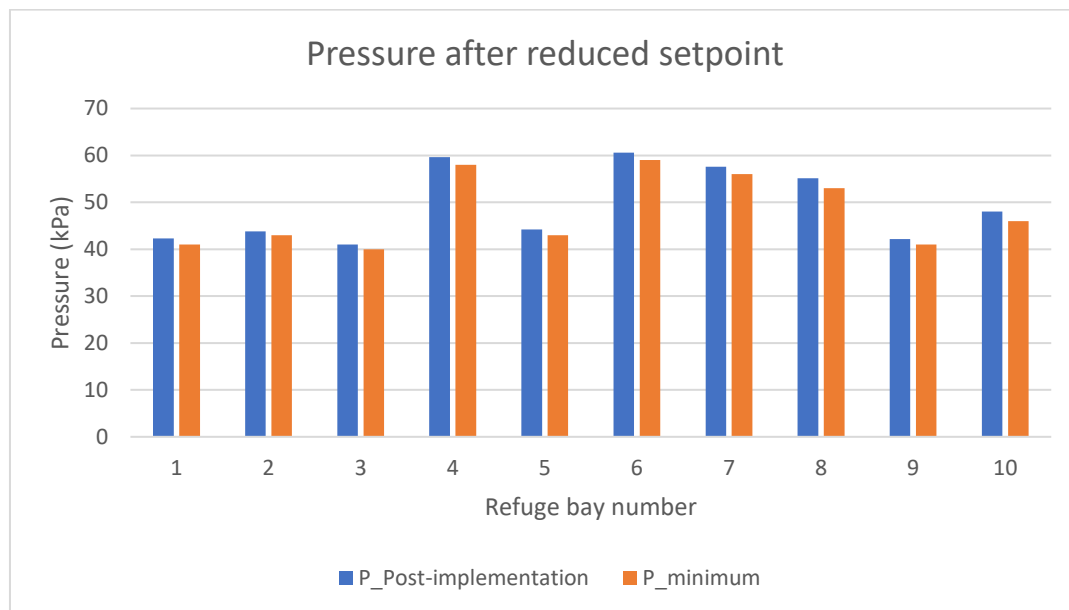


Figure 25 - Expected pressure after implementation

If the setpoint cannot be reduced, it is important to evaluate the system for potential leaks or misuses of compressed air. Addressing these issues is essential for optimising the setpoint. When repeating the method and finding that the setpoint still cannot be lowered, it indicates that the system has reached its optimized setpoint.

3.6.4. Cost evaluation

An in-depth cost analysis is conducted to determine the financial impact of reducing the setpoints. When the compressed air setpoint is reduced, the flow also reduces. Therefore, the power output of the compressors is reduced. The cost evaluation is done by quantifying the reduction in compressed air volumetric cubes sent into the level with the current and reduced setpoint. This reduction in volumetric cubes was then compared to the power required for a compressor to generate these volumetric cubes. Thereafter, the cost was evaluated by comparing the power with the ESKOM tariffs. Figure 26 shows an example graph of how the current flow profile is expected to be reduced after implementation.

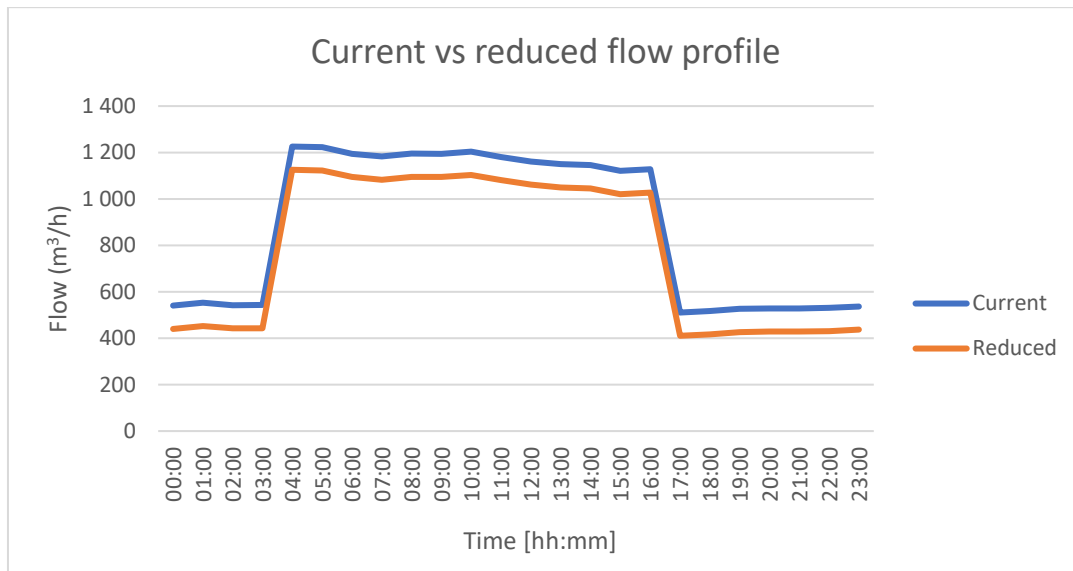


Figure 26 - Expected flow profile before and post-implementation

3.7. Method verification

As mentioned in Chapter 1, the cost of energy is rapidly rising in South Africa. Due to this increase in energy cost, operational costs have dramatically increased the cost of mining gold in deep-level mines. Compressed air is very expensive to generate and is one of the leading energy consumers in deep-level mining.

The method involves reducing the compressed air consumption in deep-level hydropower mines. In deep-level hydropower mines, refuge bays are the only continuous compressed air user. However, mines are prone to oversupply compressed air due to inefficiencies such as leaks and misuses.

The verification of the method is a crucial step in determining the credibility of the approach used to achieve the objectives of the study. This section aims to verify the chosen method, emphasising the credibility of the study outcomes. For the method to be successful, some criteria need to be addressed, based on the literature discussed in Chapter 2. The method must be able to:

- consider compressed air networks,
- consider demand- and supply-side users,
- use simulation modelling as a tool,

- be applicable to hydropower mines, and
- consider refuge bay pressure requirements.

In Section 3.2, the compressed air network is considered within the boundary of the system. This section discusses the supply- and demand sides of the compressed air network within deep-level mines, thus covering the criteria of a compressed air network and looking at the demand- and supply-side users within a hydropower mine.

In Section 3.4.3, the minimum compressed air pressure for each individual refuge bay was determined using the law of conservation of mass. It included the flow into the refuge bay by means of the reticulation network, and the flow out of the refuge bay by means of door leakage and refuge bay occupant consumption. By deducting these flows, a net flow is determined.

The flow required to pressurise a refuge bay with was determined. If the net flow exceeds this requirement, the refuge bay is pressurised. Finally, the pressure in the compressed air pipeline was optimised according to the required flow. By repeating this method, the pressure for each refuge bay is determined according to its size and number of occupants present, covering the criterion of considering refuge bay pressure requirements.

In Section 3.4.4, a compressed air simulation model was developed to replicate real-life scenarios. Thereafter, in Section 3.5, the simulation was verified using the mean absolute error method, ensuring an accuracy within 95%.

In Section 3.6, the verified simulation model was used to quantify the difference between the minimum pressure requirement determined in the previous section and the actual pressure. The calibrated simulation model was then used to determine how much the setpoint at the control valve can be reduced while still supplying adequate pressure to all the refuge bays. This covers the criterion of using simulation as a tool. Table 5 indicates which section achieved the criteria.

Table 5 - Indication of which section completes each criterion

	Compressed air	Demand side	Supply side	Simulation	Hydropower	Refuge bay pressure requirement
Section 3.2	✓				✓	
Section 3.3						
Section 3.4		✓	✓		✓	✓
Section 3.5				✓		
Section 3.6				✓		

4. IMPLEMENTATION AND RESULTS

4.1. Case study background

Due to the confidentiality of the mine, the mine in this case study will be referred to as Mine A. Mine A consists of six active levels. A summary of the levels is shown below.

- Mine A currently has Levels 19 to 26
- The only active mining levels are 20-Level, and 22-Level to 26-level.
- On 20-Level, compressed air is used as drilling medium.
- On 22-Level to 26-Level, hydropower is used as drilling medium.
- 19-Level and 21-Level are closed.

Figure 27 shows a layout of the mining levels in Mine A:

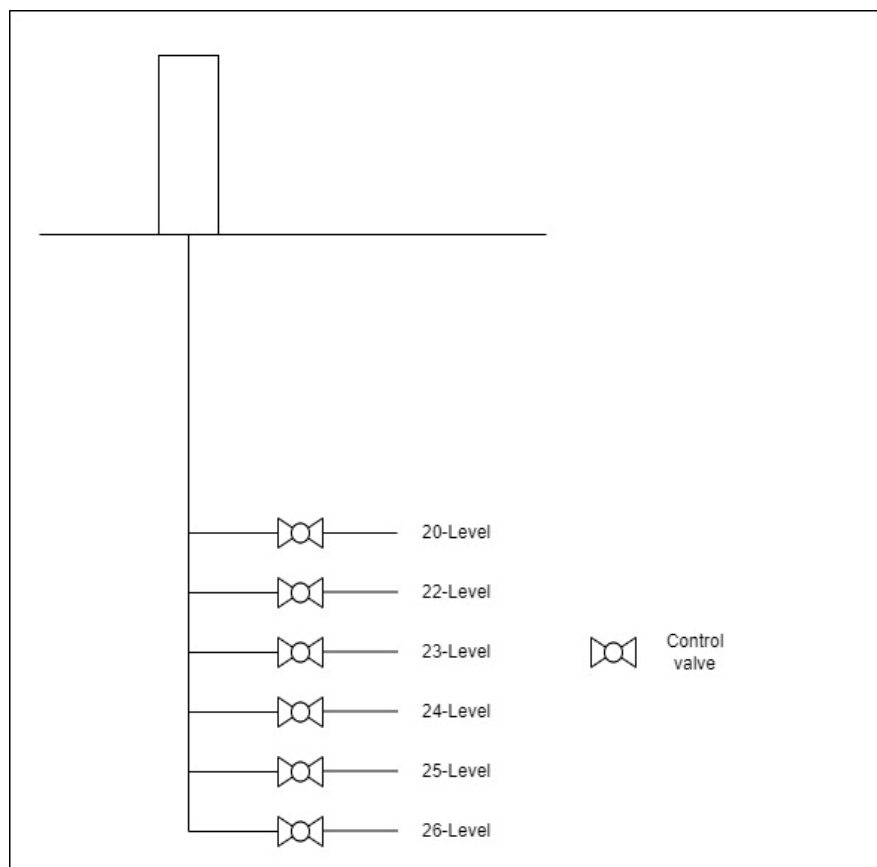
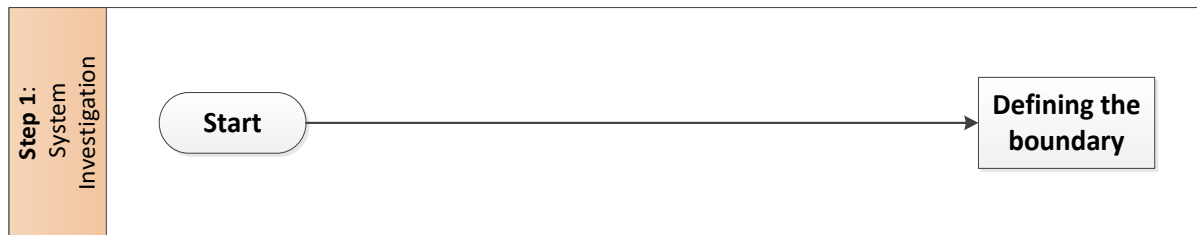


Figure 27 - Basic compressed air layout of Mine A

4.2. Step 1: System investigation



4.2.1. Defining the boundary

For the purpose of this dissertation, the boundary of the methodology was set on 23-Level. The analysis and implementation of the methodology began at the control valve situated after the tips and extended to the end users within the system. Figure 29 (Section 4.3.1) shows the location of the tips on 23-Level.

Compressed air demand side

On 23-Level, the only compressed air user is refuge bays. Therefore, the refuge bays served as the main end user within the boundary of the system. Refuge bays have 50 mm steel pipes entering the bays, whereafter a crack valve and silencer are inserted on the pipe. The purpose of these valves is to reduce the compressed air flow into the refuge bay during non-emergency conditions, while still ventilating the refuge bay. The silencer is inserted onto the end of the 50 mm steel pipe to reduce noise when the valve is fully opened during emergencies.

Compressed air supply side

The compressed air supply side starts at the control valve. On 23-Level, the control valve is situated after the tips shown in Figure 29 (Section 4.3.1). The control valve has a pneumatic actuator controlling the compressed air flow to the level by means of a compressed air pressure setpoint. The pressure setpoint varies throughout a 24-hour day. The 24-hour pressure profile of 23-Level is shown in Figure 28 below. From this it is evident that the pressure profile changes from 4:30 to 17:30 this is due to mining personnel that enters the level during blasting shift and misuses compressed air for cooling. Therefore, a higher pressure is required to compensate for these misuses.

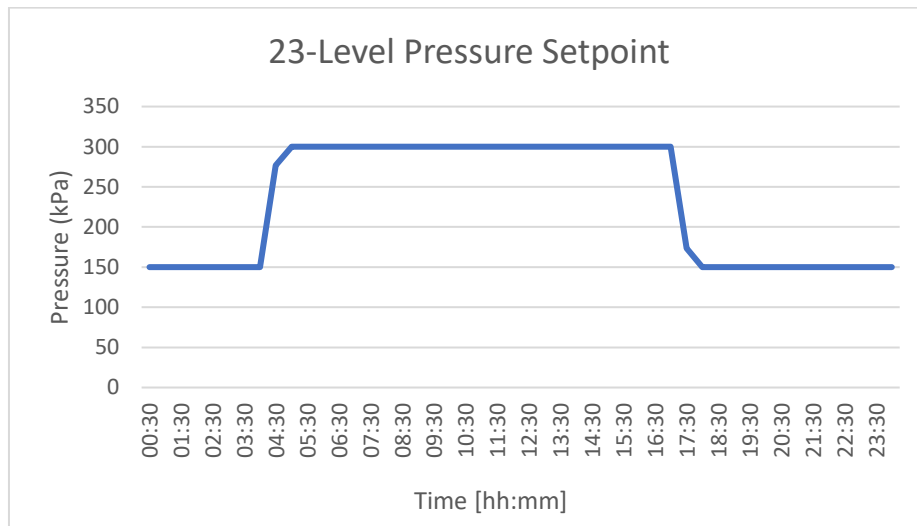
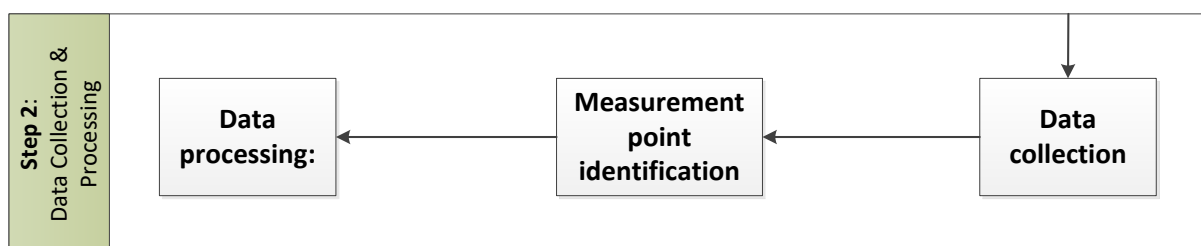


Figure 28 - 23-Level compressed air pressure setpoint

Compressed air reticulation side

The reticulation side of the compressed air network connects the supply side to the demand side. At 23-Level, the compressed air travels through a piping network, consisting of steel pipes, to reach the refuge bays. The piping network begins with 100 mm pipes at the control valve and continues throughout the level. At each refuge bay, a 50 mm pipe branches off from the main column, delivering compressed air to the refuge bay. The pipe sizes and increments within this network was obtained through underground audits, ensuring an accurate model development. Figure 30 (Section 4.3.1) shows where the 50 mm pipe ties off from the 100 mm pipe to a refuge bay. In addition, Appendix A shows the level layout of 23-Level and the refuge bay positions.

4.3. Step 2: Data collection



The data that needed to be acquired, as mentioned in Section 3.3 were obtained as follows.

1. The data regarding refuge bay sizes, atmospheric pressures, door sizes, door gaps, and dry and wet bulb temperatures were obtained from the refuge bays on 23-Level.
2. A months' worth of half-hourly averaged flow and pressure data of 23-Level were obtained from the mine's SCADA system;
3. The measured gauge pressure inside the refuge bays on 23-Level were obtained through underground audits.

4.3.1. Measurement point identification

Measurement points were identified to obtain the data mentioned in the previous section.

1. The refuge bays identified on 23-Level are shown in Appendix A.
2. The control valve identified just after the tips records the flow and pressure supplied to 23-Level. A measurement point was identified just after the control valve. Figure 29 indicates the position of the control valve and the measurement point identified on 23-Level.

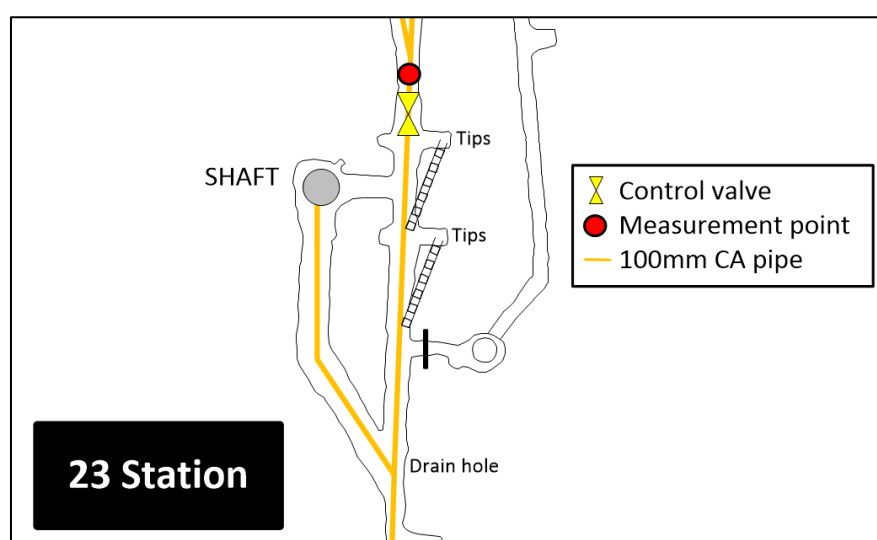


Figure 29 - Measurement point identified and location of the tips on 23-Level

3. A measurement point was identified in each refuge bay to measure the compressed air gauge pressure. Figure 30 shows the measurement point identified (red dot) inside a refuge bay where compressed air supply pressure can be measured.

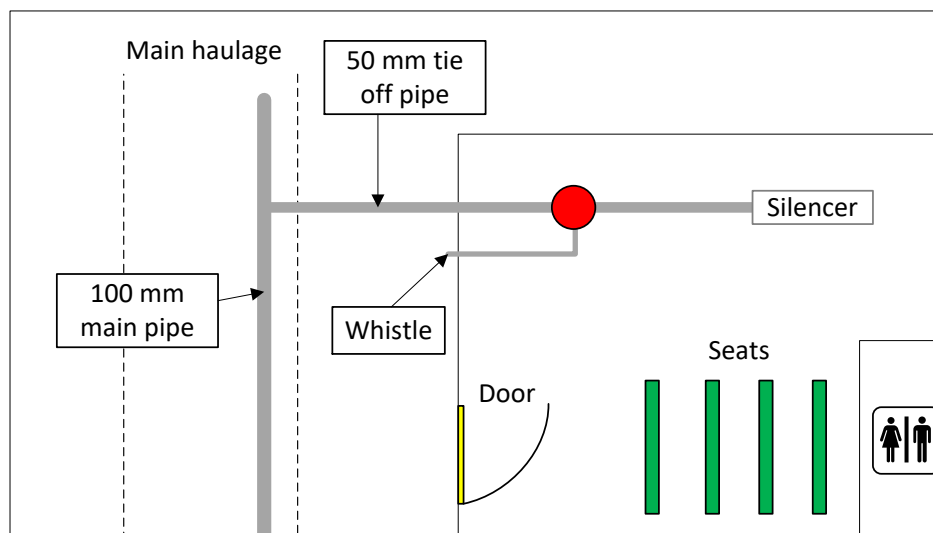


Figure 30 - Measurement point identified to measure gauge pressure inside refuge bays on 23-Level.

4.3.2. Data processing

The pressure and flow data obtained in the previous step needed to be processed. Initially, data gaps were identified and excluded from further analysis. Subsequently, the standard deviation of the data range was calculated, and the average value was determined. To identify outliers, an "if" function was implemented, considering values falling outside 2 standard deviations of the average as outliers, which were then disregarded. The processed data are shown in Figure 31 :

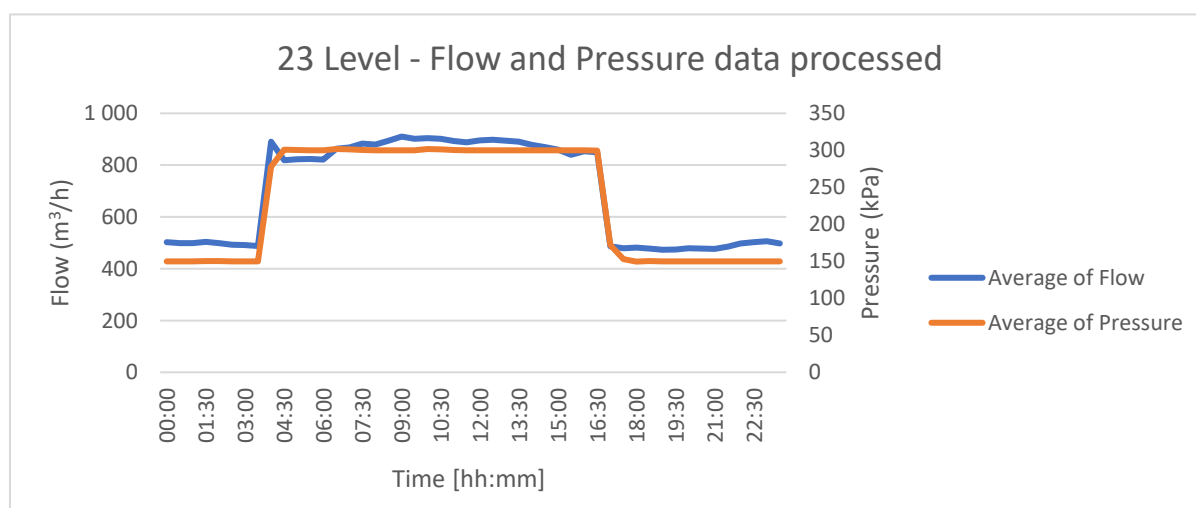
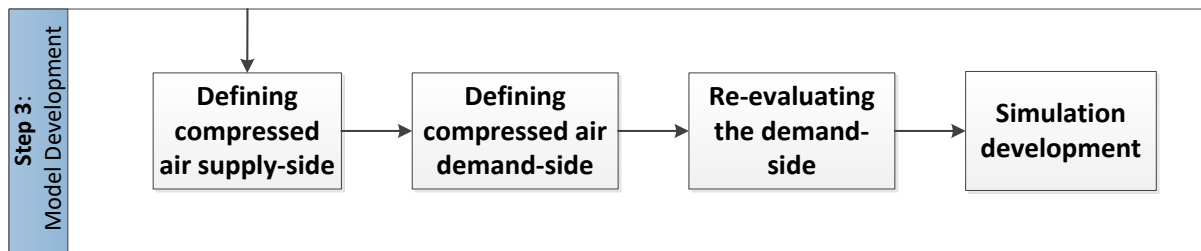


Figure 31 - Processed flow and pressure data from 23-Level

4.4. Step 3: Model development



4.4.1. Defining the compressed air supply side

The data processed in the previous section served as the supply side of the compressed air system. As the supply side starts from the control valve, the obtained pressure and flow profiles represent the key parameters that influence the supply to the level. These profiles were used in the simulation model to calibrate the model to ensure accuracy.

4.4.2. Defining the compressed air demand side

On the demand side of the compressed air system on 23-Level, refuge bays are the main continuous compressed air user. All the refuge bays on 23-Level have a 50 mm compressed air pipe entering the refuge bay. A general layout of a refuge bay like the ones identified on 23-Level is shown in Figure 30 (Section 4.3.1).

4.4.3. Re-evaluating the demand side

For the re-evaluation of the demand side, the first step was to conduct an air mass balance as described in Section 3.4.3. Focus was placed on refuge bays on 23-Level. The air entering and exiting the refuge bay was calculated in conjunction with the minimum supply pressure according to regulations. Table 6 indicates the refuge bays found on 23-Level. The table indicates manual measurements of each refuge bay, giving the number, size, temperatures and atmospheric pressures.

Table 6 - 23-Level refuge bay specifications

Refuge Bay #	Atmospheric pressure (kPa)	Wet bulb (°C)	Dry bulb (°C)	Refuge bay height (m)	Refuge bay area (m ²)	Refuge bay volume (m ³)
12	96.96	26.00	29.00	3.94	60.30	237.58
13	96.99	23.00	32.50	2.97	31.30	92.96
14	97.96	21.00	25.50	3.87	45.20	174.92
15	98.76	24.50	29.50	3.42	46.00	157.32
16	98.39	26.00	31.50	4.10	38.50	157.85
17	98.36	24.00	32.50	3.50	37.40	130.90
18	98.29	27.00	33.50	3.69	39.20	144.65
36	97.18	25.50	30.50	3.45	29.10	100.40
47	97.49	20.00	25.00	3.45	25.10	86.60
66	97.24	27.00	29.50	3.05	58.00	176.90
74	98.21	24.50	33.50	3.18	43.80	139.28
79	97.24	22.00	30.00	3.26	84.10	274.17

Following this, the information in Table 6 was used to calculate the mass air flow required to pressurise the refuge bay according to regulations. To determine air density, the atmospheric pressure and the wet- and dry bulb temperatures are used in conjunction with the psychrometric chart seen in Figure 15 (Section 2.6.3). Table 7 indicates the air density inside each individual refuge bay.

Table 7 - 23-Level air density per refuge bay

Refuge Bay	Air density (kg/m ³)
12	1.10
13	1.10
14	1.13
15	1.12
16	1.11
17	1.11
18	1.10
36	1.10
47	1.13
66	1.10
72	1.10
74	1.11
79	1.09

1. The air flow rate required to pressurise the refuge bay

As mentioned in Chapter 2.6.1, each mine has a standard procedure guideline (SPG) that shows the minimum requirements for refuge bays to be life sustainable. For the case study that is being investigated, the SPG states that refuge bays are required to maintain a positive pressurise difference of 20 Pa after 15 minutes. To accomplish this, Equation 3 , Equation 4, and Equation 5 (Section 2.6.2) were used. Figure 32 indicates the compressed air mass flow rate required to pressurise each refuge bay identified on 23-Level.

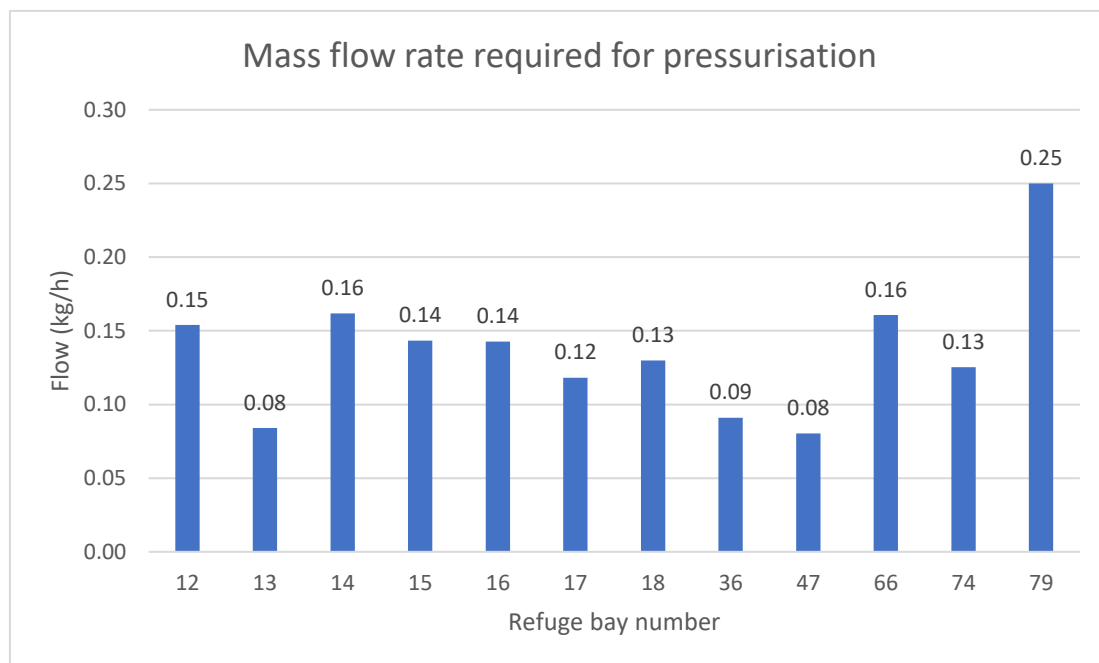


Figure 32 - Mass flow rate required to pressurise each refuge bay on 23-Level

2. The air flow rate to the refuge bay

The compressed air entering the refuge bay needed to be calculated. This was done using Equation 1. A guess value was taken for the line pressure. Therefore, the flow to all refuge bays was the same because all refuge bays are supplied with the same pipe size. Thereafter, a mass balance was performed and the pressure in the line was optimised. Microsoft excels *solver* function was used to optimise the line pressures. This *solver* function uses a generalised reduced gradient (GRG) algorithm to solve nonlinear programs of general structure. Table 8 shows the flow from a 50mm pipe.

Table 8 - Flow from 50 mm pipe entering refuge bays on 23-Level

Flow from Pipe		
$C_{\text{Discharge}}$ (well-rounded edge)	0.97	Open-end
K_{air}	1.4	
P_{line}	50	kPa
$P_{\text{Abs line}}$	147.6	kPa
T_{line}	293.15	K
R_{air}	0.287	
Area	0.00196	m ²
Mass flow from Pipe	0.224	kg/s

3. The flow rate of air that exits the refuge bay through door leakage

During underground audits, the size of the gaps was measured to determine the leakage area. Table 9 shows each refuge bay, their door height, door width, and the door gap identified during underground audits. The door height and width are used to calculate the door perimeter.

Table 9 - 23-Level refuge bay door specifications

Refuge Bay	Door height (m)	Door width (m)	area (m ²)	Gap (m)	Perimeter (m)
12	1.70	0.70	1.19	0.005	4.80
13	1.70	0.70	1.19	0.006	4.80
14	1.70	0.70	1.19	0.003	4.80
15	1.70	0.70	1.19	0.009	4.80
16	1.70	0.70	1.19	0.003	4.80
17	1.70	0.70	1.19	0.004	4.80
18	1.70	0.70	1.19	0.009	4.80
36	1.70	0.70	1.19	0.004	4.80
47	1.70	0.70	1.19	0.007	4.80
66	1.70	0.70	1.19	0.010	4.80
74	1.70	0.70	1.19	0.006	4.80
79	1.70	0.70	1.19	0.010	4.80

The leakage area was calculated by multiplying the door perimeter with the door gap. The flow exiting the refuge bays by means of door leakage was calculated using Equation 6 (Section 2.6.3). Figure 33 shows the mass flow rate of the door leakage of the refuge bays found on 23-Level.

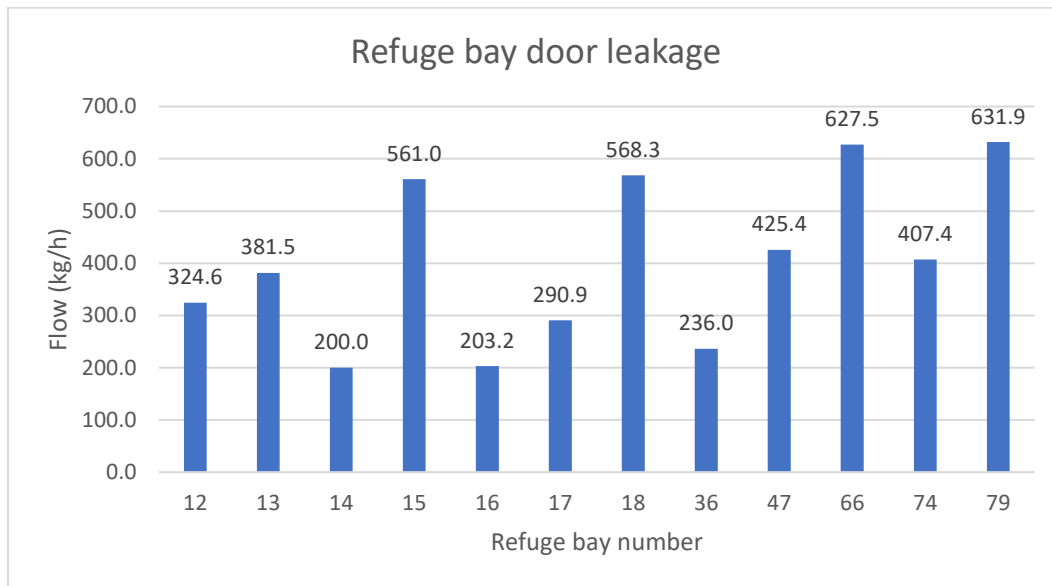


Figure 33 - 23-Level refuge bay door leakage

4. Occupant consumption

According to the Mine Health and Safety Inspectorate, each refuge bay occupant should have 0.6 m² floor area [20]. From the data obtained earlier in this method, the maximum number of occupants was calculated. It is important to note that a single refuge bay occupant requires roughly 85 L/min of compressed air. Table 10 below indicates the number of occupants during 100% occupancy and the total refuge bay air requirement.

Table 10 - Total occupants per refuge bay

Refuge Bay	Area (m ²)	Total people	Air requirement (kg/s)
12	60.3	100	0.129342
13	31.3	52	0.081380
14	45.2	75	0.117851
15	46.0	76	0.118923
16	38.5	64	0.100934
17	37.4	62	0.096419
18	39.2	65	0.101702
36	29.1	48	0.074657
47	25.1	41	0.063649
66	58.0	96	0.150540
74	43.8	73	0.114470
79	84.1	140	0.219537

After the values of compressed air flow requirement were known, an algorithm tool was used in conjunction with Equation 1 to obtain the minimum line pressure to ensure that the compressed air supplied is greater than the air consumed and leaked out through the door. Figure 34 indicates the minimum supply pressure to each refuge bay in order for the refuge bay to pressurise according to regulations.

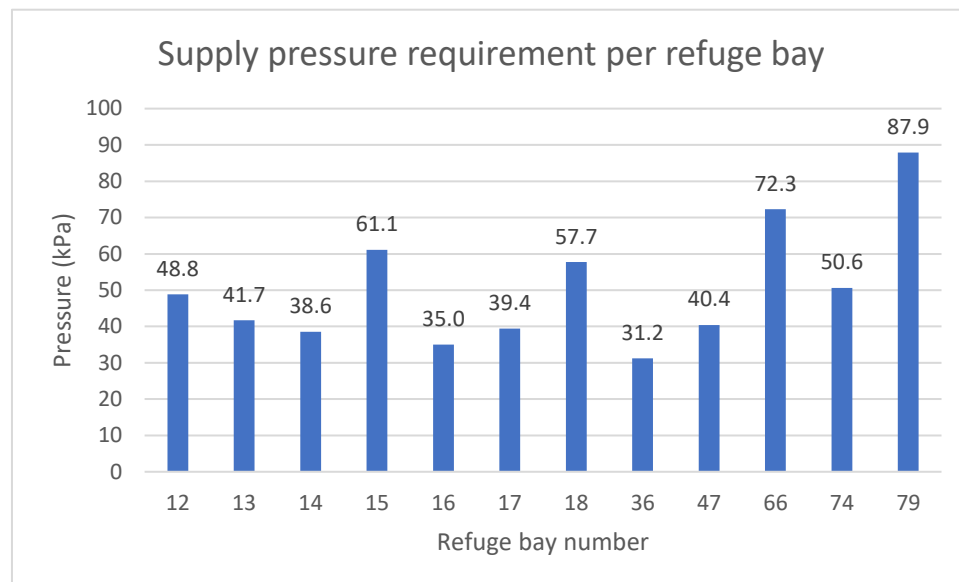


Figure 34 - 23-Level Individual refuge bay minimum pressure requirement

4.4.4. Simulation development

The simulation model was developed using PTB. The primary objective of using PTB was to gain insight into the gauge pressure in the compressed network at any specific point. The compressed air network started at the pneumatic control valve that restricts the flow into the level by means of a pressure setpoint. Thereafter, all the end users were inserted into the simulation, which in this case were the refuge bays. The refuge bay compressed air network consisted of 50 mm pipe entering the refuge bay.

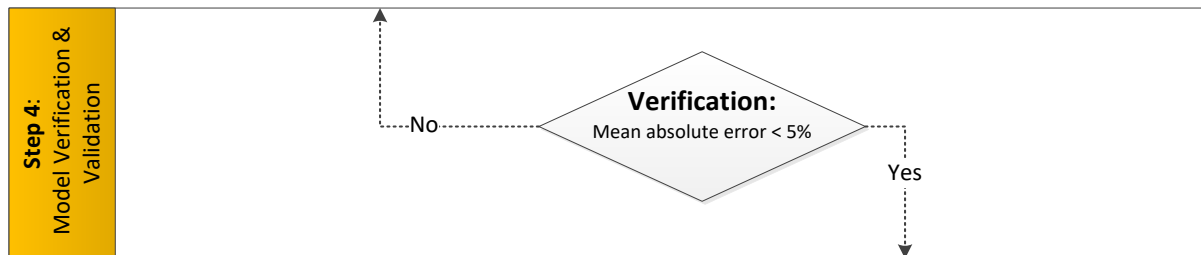
By using PTB, real-life scenarios can be matched and the pressure in the pipe that supplies compressed air to the refuge bays can be determined. Once the minimum gauge pressure before each refuge bay had been calculated by means of the analytical method, the simulation model was used to ensure that the current supply pressure was higher than the

required supply pressure. This indicated whether each refuge bay pressurises according to regulations with the current pressure setpoint.

If there is a single refuge bay that does not pressurise according to regulation, PTB enables the user to test various pressure setpoints to ensure that all refuge bays do, in fact, pressurise. Alternatively, the possibility of reducing the pressure setpoint to gain possible energy savings needs to be checked.

The methodology utilises Proportional-Integral (PI) control to account for system leaks, ensuring a more accurate simulation that mirrors real-life data from the SCADA system.

4.5. Step 4: Model verification and validation



Verifying and validating the simulation model of 23-Level was crucial to ensure its accuracy. As mentioned in Section 3.5, the mean absolute error method was used for verification purposes. This method compared the actual flow data on 23-Level from the mine SCADA system with the flow data from the simulation model by subtracting this data and dividing the answer by the total measurement points. Thereafter an average was taken over all time steps, thus ensuring:

$$MAE = \frac{\sum_{i=1}^n |y_1 - x_1|}{n} < 5\%$$

where

y is the actual SCADA value

x is the simulated value

n is the total measurements

From Figure 35 , it is evident that the simulation (orange) and the flow data from the control valve (blue) on 23-Level was within the 5% error range. Therefore, the simulation is considered accurate.

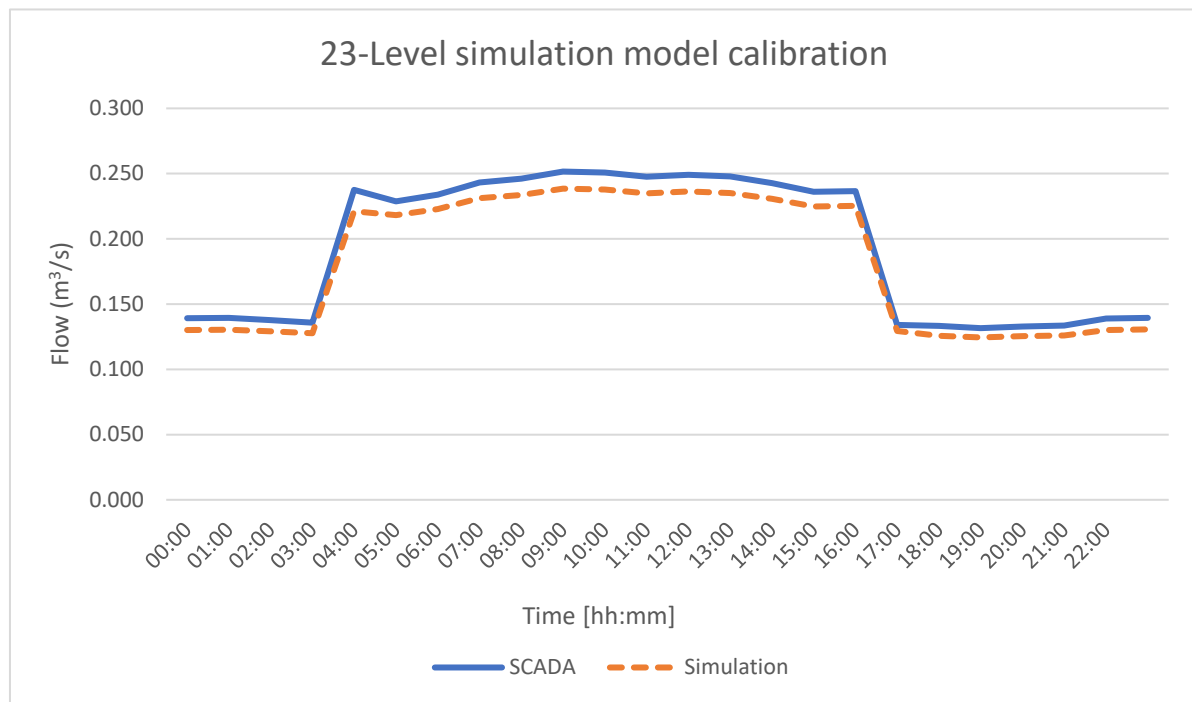


Figure 35 - 23-Level simulation model calibration

To further verify and validate the simulation model of 23-Level, actual supply pressure data were obtained from the 23-Level refuge bays through underground measurements. This real-world pressure data was then compared to the simulation model's predicted values. The direct correlation between the observed measurements and the simulated outcomes serves as support for verification. Figure 36 shows the correlation between the measured (blue) and simulated (orange) values on 23-Level, yielding an error of less than 5%.

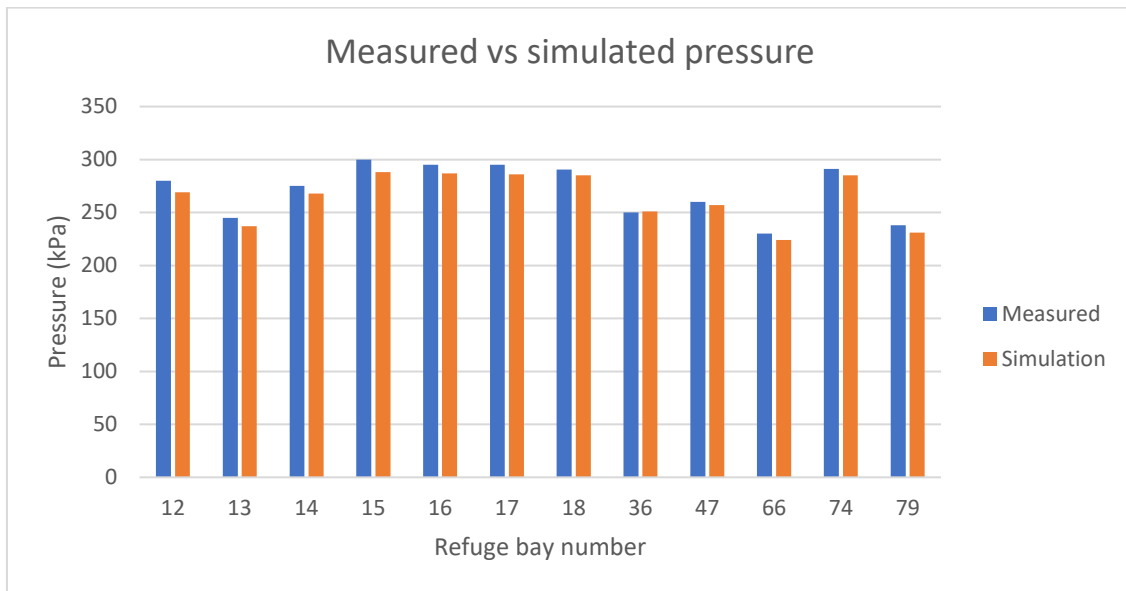
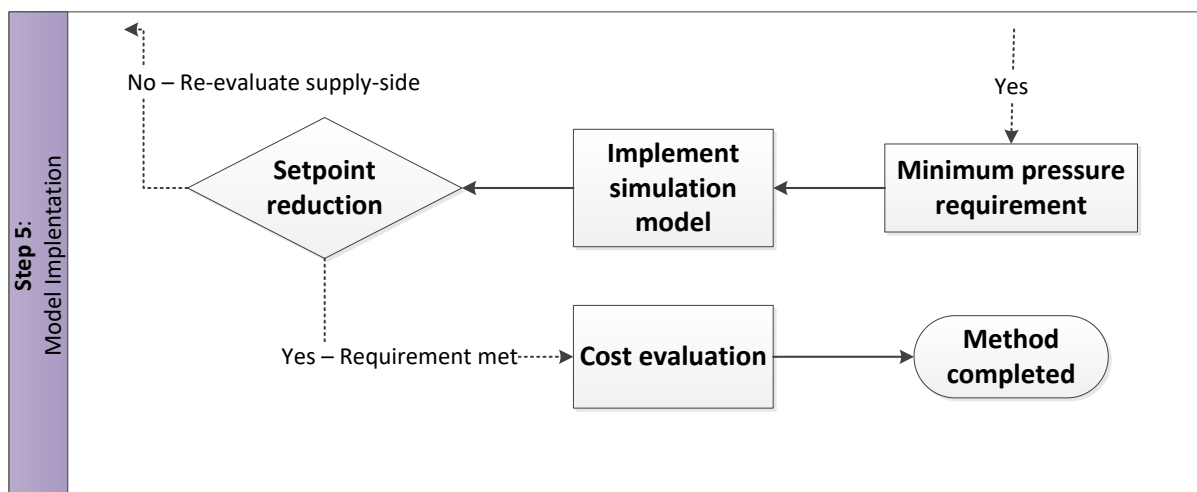


Figure 36 - 23-Level measured pressure vs simulated pressure

4.6. Step 5: Model implementation



To implement this model, an iterative approach was followed. This was done by iteratively testing various setpoints on 23-Level and ensuring that the setpoint still adhered to the minimum pressure requirements of the refuge bays.

4.6.1. Minimum pressure requirement

The minimum pressure requirement for each individual refuge bay was calculated using the analytical method described in Section 3.4.3. Figure 37 shows the minimum pressure requirements (blue) for the refuge bays found on 23-Level.

4.6.2. Implement simulation model

The minimum pressure requirement for each individual refuge bay on 23-Level was now known. Therefore, the calibrated simulation model was used to obtain the actual supply pressures to these refuge bays. As seen in Figure 37, all refuge bays on 23-Level were being oversupplied with compressed air. Therefore, the opportunity exists to reduce the compressed air setpoint in order to reduce the gap between the minimum requirement and the actual supply pressures.

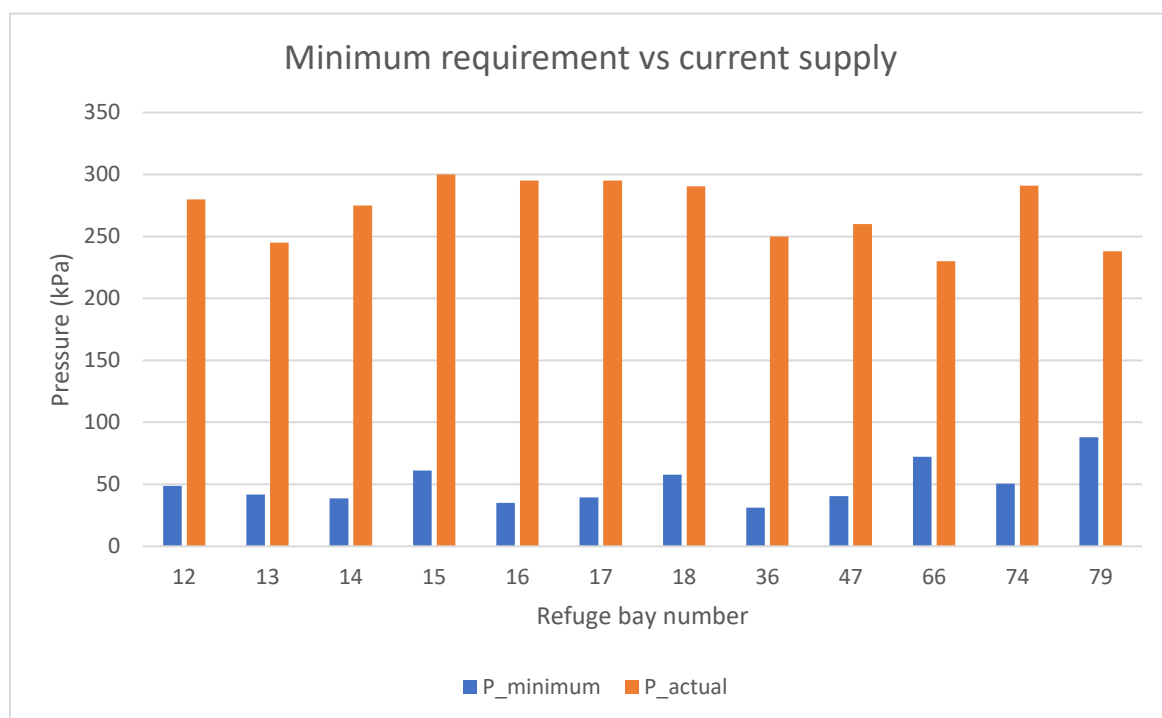


Figure 37 - 23-Level minimum pressure requirement vs actual supply pressure

4.6.3. Setpoint reduction

The calibrated simulation model was used to check the possibility of reducing the compressed air setpoint. On 23-Level, the compressed air setpoint can be reduced by 35 kPa gauge pressure throughout all shifts. In Figure 38, the current setpoint at the control valve (blue) is shown in conjunction with the reduced setpoint (orange).

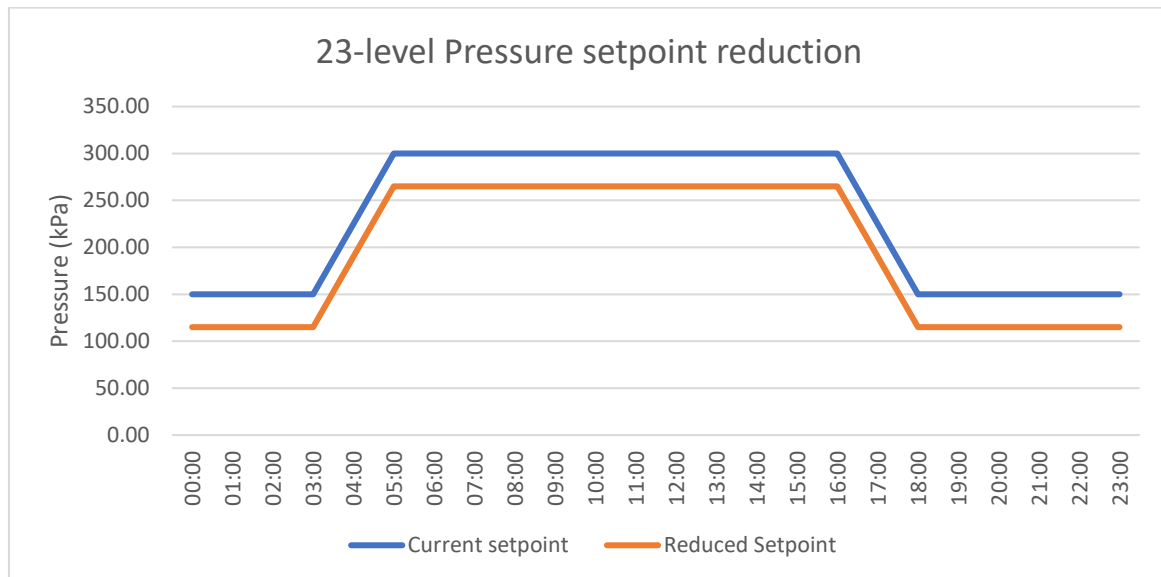


Figure 38 - 23-Level current pressure setpoint vs setpoint after implementation

However, it is important to ensure that the refuge bays still acquire sufficient pressure after the setpoint has been reduced. This is done by ensuring that the pressure at the refuge bay after the setpoint reduction is still higher than the minimum pressure requirement determined in previous steps. For this the calibrated simulation model of 23-Level was used. Based on Figure 39, it is evident that the setpoint can be reduced while still supplying sufficient pressure to the refuge bay with the highest-pressure requirement. In this case, refuge bay number 79 required the highest supply pressure.

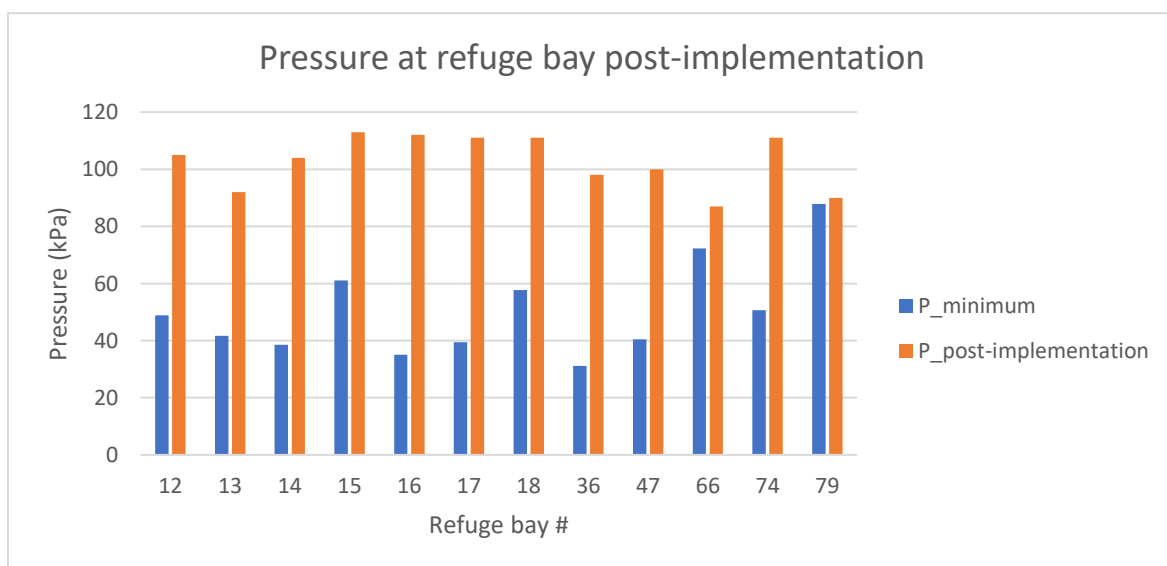


Figure 39 - 23-Level refuge bay minimum pressure vs post-implementation pressure

4.6.4. Cost evaluation

An in-depth cost analysis was conducted to determine the financial impact of reducing the setpoint on 23-Level. This was done by using the simulation model to quantify the reduction in compressed air volumetric cubes sent into the level with the current and reduced setpoint. Equation 13 shows the volumetric cubes saved when comparing the current and reduced setpoint.

Equation 13 - Flow reduced with the current and reduced setpoint

$$\text{Flow reduced (m}^3/\text{h)} = \text{Flow current setpoint} - \text{Flow reduced setpoint}$$

This reduction in volumetric cubes was then compared to the power required for a compressor to generate these volumetric cubes. Equation 14 calculates the power required for a compressor to generate a single volumetric cube.

Equation 14 - Compressor power to generate a single volumetric cube

$$\text{Power per volumetric cube } \left(\frac{\text{kW}}{\text{m}^3/\text{h}} \right) = \frac{P_{\text{Compressor}}}{\text{Comp}_{\text{Flow}}}$$

Where

$P_{\text{Compressor}}$ -The power rating for the compressor

$\text{Comp}_{\text{Flow}}$ - The flow rating of the compressor

Thereafter the power required to generate a single volumetric cube is multiplied by the flow reduction. Equation 15 shows the power saved when the setpoint is reduced.

Equation 15 - Reduction in compressor power

$$\text{Power}_{\text{reduced}} = \text{Flow reduced (m}^3/\text{h)} \times \text{Power per volumetric cube } \left(\frac{\text{kW}}{\text{m}^3/\text{h}} \right)$$

This method was used for each time step in a 24-hour period thus deriving Figure 41. Thereafter, the cost was evaluated by comparing the power with the Eskom tariffs. The Eskom tariffs differs from the low demand season to the high demand season. The low demand

season is from January to May and September to December. The high demand season is from June to August. Figure 40 shows the Eskom tariffs for the financial year 2023/24 during the low and high demand seasons.

	Low-demand Tariff			High-demand Tariff		
	Weekday	Saturday	Sunday	Weekday	Saturday	Sunday
00:00	0.9797	0.9797	0.9797	1.0978	1.0978	1.0978
01:00	0.9797	0.9797	0.9797	1.0978	1.0978	1.0978
02:00	0.9797	0.9797	0.9797	1.0978	1.0978	1.0978
03:00	0.9797	0.9797	0.9797	1.0978	1.0978	1.0978
04:00	0.9797	0.9797	0.9797	1.0978	1.0978	1.0978
05:00	0.9797	0.9797	0.9797	1.0978	1.0978	1.0978
06:00	1.4183	0.9797	0.9797	1.8372	1.0978	1.0978
07:00	1.9613	1.4183	0.9797	5.5614	1.8372	1.0978
08:00	1.9613	1.4183	0.9797	5.5614	1.8372	1.0978
09:00	1.9613	1.4183	0.9797	5.5614	1.8372	1.0978
10:00	1.4183	1.4183	0.9797	1.8372	1.8372	1.0978
11:00	1.4183	1.4183	0.9797	1.8372	1.8372	1.0978
12:00	1.4183	0.9797	0.9797	1.8372	1.0978	1.0978
13:00	1.4183	0.9797	0.9797	1.8372	1.0978	1.0978
14:00	1.4183	0.9797	0.9797	1.8372	1.0978	1.0978
15:00	1.4183	0.9797	0.9797	1.8372	1.0978	1.0978
16:00	1.4183	0.9797	0.9797	1.8372	1.0978	1.0978
17:00	1.4183	0.9797	0.9797	1.8372	1.0978	1.0978
18:00	1.9613	1.4183	0.9797	5.5614	1.8372	1.0978
19:00	1.9613	1.4183	0.9797	5.5614	1.8372	1.0978
20:00	1.4183	0.9797	0.9797	1.8372	1.0978	1.0978
21:00	1.4183	0.9797	0.9797	1.8372	1.0978	1.0978
22:00	0.9797	0.9797	0.9797	1.0978	1.0978	1.0978
23:00	0.9797	0.9797	0.9797	1.0978	1.0978	1.0978

Figure 40 - Eskom tariffs for the financial year 2023/24 in R/kWh

Figure 41 shows the compressed air flow profile while operating at the current setpoint (blue) in contrast with the flow when the setpoint was reduced (orange). This resulted in an operating cost saving of roughly R 50 000 per annum.

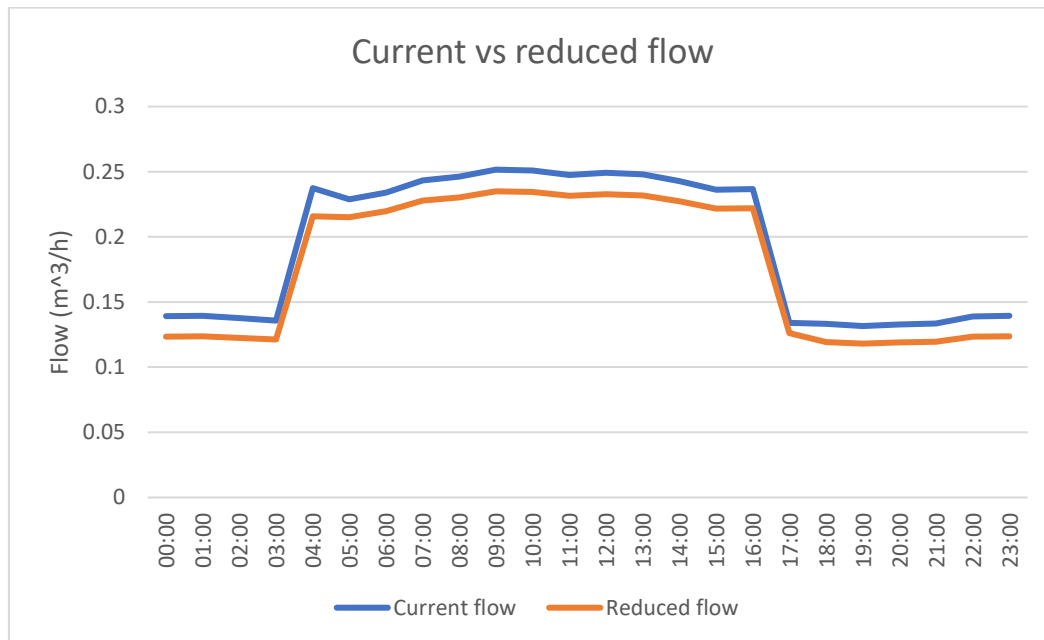


Figure 41 - 23-Level current flow profile vs reduced flow profile

4.7. Method validation

The method was validated to demonstrate the reliability and accuracy of the method used to reach the study objectives. Validating the method is a crucial step in determining the reliability and accuracy of the research findings. This section aims to validate the selected method, which highlights the trustworthy results.

The objectives of this study were:

1. Develop a new method to determine the minimum supply pressure needed for each refuge bay on a given mine, based on their size and maximum number of occupants present.
2. Develop and verify a simulation model of the mine's compressed air network.
3. Assess the feasibility of reducing the compressed air setpoint based on the minimum requirements.
4. Evaluate the cost-savings of the setpoint reduction.

The study determined the minimum compressed air pressure for each individual refuge bay using the law of conservation of mass. It included the flow into the refuge bay by means of the reticulation network, and the flow out of the refuge bay by means of door leakage and

refuge bay occupant consumption. By deducting these flows, a net flow was determined. The flow required to pressurise a refuge chamber with 20 Pascals within 15 minutes was determined. If the net flow exceeded this requirement, the refuge bay would pressurise. Finally, the pressure in the compressed air pipeline was optimised according to the required flow. By repeating this method, the pressure for each refuge bay was determined according to its size and number of occupants. This method was implemented on 23-Level and thus Objective 1, determining the minimum supply pressure, has been reached according to Section 4.6.1.

The compressed air simulation model was developed to replicate real-life scenarios. The simulation was verified using the mean absolute error method, ensuring an accuracy of within 95%. To further verify the accuracy of the simulation model, the simulation model was compared to manual supply pressure measurements. Hence, the verified simulation model can be used to quantify the difference between the minimum pressure requirement determined in the previous section and the actual pressure. Objective 2, developing and verifying a compressed air model of 23-Level, has been achieved when looking at Section 4.6.2.

The calibrated simulation model was then used to determine how much the setpoint at the control valve on 23-Level can be reduced while still supplying adequate pressure to all the refuge bays. The compressed air setpoint can be reduced by 35 kPa throughout the whole 24-hour period, according to Section 4.6.3. Therefore, Objective 3 has been achieved.

An in-depth cost evaluation was conducted to analyse the financial savings of reducing the compressed air setpoint on 23-Level. The reduction in setpoint resulted in an annual financial saving of over R 50 000 per annum. By reducing this setpoint, Study objective 4 was achieved according to Section 4.6.4.

To further validate the method, the supply pressure recommended needed to be compared to existing literature. As mentioned in Chapter 2.7 Frazer [50] stated that mines using existing piping networks to supply compressed air for refuge bays can replace compressors with a low-pressure 'blower' on surface. This would only require pressurising the piping network to a low pressure, for example, 30 to 80 kPa. As seen in Figure 34 the method proposed different pressures for refuge bays based on the refuge bay size and number of occupants present.

These pressures fall within 31.2 to 87.9 kPa which is relatively close to the pressures proposed by Frazer.

Table 11 summarises the study objectives, the sections where they were addressed, and the methods used to achieve each objective.

Table 11 - The study objectives and achievement by section

Objective	Section	How?
1	4.6.1	The study reached Objective 1 by determining a minimum supply pressure for each refuge bay based on its size and number of occupants present by doing a mass balance. This included the mass flowing into the refuge bay through the reticulation network and the mass flow exiting the refuge bay through door leakage and occupant consumption. Thereafter an algorithm tool was utilised to optimise the supply pressure. It was found that the highest supply pressure was roughly 87 kPa.
2	4.6.2	A compressed air simulation of the case study was developed and verified with the mean absolute error method, yielding an error of 5%. To further validate the simulation, the simulated predicted values were compared to manual measurements and these values showed an error of less than 3%. Therefore, study Objective 2 was reached.
3	4.6.3	The calibrated simulation model was used to investigate the possibility of reducing the compressed air setpoint while adhering to regulations. It was found that the compressed air setpoint of the case study could be reduced with 35 kPa over a 24-hour period while ensuring that all refuge bays still receive sufficient pressure, thus leading to the achievement of Objective 3.
4	4.6.4	A cost evaluation was done on the reduction of the pressure setpoint. This was done by quantifying the reduction in compressed air cubes sent into the level with the reduced setpoint. By reducing

		the pressure setpoint, an annual cost saving of over R50 000 can be achieved. This resulted in the achievement of Objective 4.
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The case study that was investigated has the potential for electricity savings within the context of hydropower mining. The case study mine has five hydropower levels and, by applying this method on all these levels, could achieve an estimated electricity cost saving exceeding R 250 000 per annum.

Reaching beyond this case, it would be worthwhile to investigate the possibility of implementing this method on other deep-level hydropower mines. A second hydropower mine, located in Gauteng province in South Africa, only requires compressed air for refuge bays. This mine has five mining levels. By applying this method to this second mine could yield an additional electricity saving amounting to roughly R 250 000. However, the variability in factors such as the number and size of refuge bays on each level, as well as the current setpoints in place, indicates the need for a thorough investigation. These estimations highlight the broader implications of this research and the potential for substantial energy efficiency improvements across mining operations, while recognising the complexity of adapting the method to different mining operations.

4.8. Reflection on results

Upon reflecting on the results, it becomes evident that the supply pressure to refuge bays is notably low. This outcome aligns with the basic principles of atmospheric pressure within an enclosed volume, wherein the supply of additional air results in an increase in atmospheric pressure. The case study's regulation required that the refuge bay should maintain a positive differential pressure of 20 Pa within 15 minutes.

The study used an air consumption of 85 L/min per refuge bay occupant because Brake *et al.* [64] stated that this air supply rate will prevent the CO₂ limit to exceed the time-weighted average exposure limit of 500 PPM. In addition, this air supply will also ensure that the oxygen concentration remains at 20.3%. Therefore, this consumption rate was used to conduct an air mass balance which predicted the supply pressures.

Brake *et al.* also stated that a 0.5 L/min oxygen consumption would be a good design figure for entrapment conditions. This leading to the investigation of an oxygen mass balance rather than an air mass balance, however there are no proof that the oxygen mass balance will ensure that the CO₂ time-weighted average exposure limit would not be reached. The supply pressures were calculated using the oxygen mass balance.

Table 12 - Supply pressure requirement based on an air and oxygen mass balance

Refuge Bay	Air mass balance Pressure requirement (kPa)	Oxygen mass balance Pressure requirement (kPa)
12	48.8	22.4
13	41.7	24.1
14	38.6	13.1
15	61.1	35.4
16	35.0	13.2
17	39.4	18.6
18	57.7	35.8
36	31.2	15
47	40.4	26.7
66	72.3	39.7
74	50.6	25.9
79	87.9	40.4

In Table 12 it is evident that the supply pressure requirement based on an air mass balance is much higher than the requirement based on an oxygen mass balance. This study used the higher-pressure requirement because literature shows that the oxygen and CO₂ limits will not be reached.

However, many mine personnel may find these low supply pressures as not suitable. Firstly, there may be a prevailing perception among personnel that higher pressure levels are required to enhance safety, and the mandated minimum positive pressure differential of 20 Pa within 15 min might be perceived as insufficient for ensuring adequate protection in emergency situations.

5. CONCLUSION AND RECOMMENDATIONS

5.1. Preamble

A brief overview of this study's background, problem statement, and the methodology followed to obtain the solution is discussed. Thereafter, the results from implementing this solution are discussed in conjunction with the objectives to see whether a viable solution was found. The limitations of this study and recommendations for future work are also identified.

5.2. Study overview

The cost of electricity has rapidly increased in South Africa. This negatively impacts large energy consumers such as deep-level gold mines. One of the leading energy consumers in deep-level gold mines is compressed air. Compressed air is very expensive to generate but existing infrastructure and ease of use makes it a viable option as energy source.

In deep-level hydropower mines, high pressure water is used as energy source for drilling operations and tramming processes. Therefore, the main continuous compressed air user on the demand side of deep-level hydropower mines is refuge bays. According to the Mine Health and Safety Act, compressed air needs to be supplied to these refuge bays. However, it does not state what the supply pressure to the refuge bay should be to pressurise accordingly. The case study that was investigated states that refuge bays should maintain a positive pressure differential of 20 Pa within 15 minutes. However, these mines are prone to oversupplying compressed air to these refuge bays to compensate for inefficiencies such as leaks and compressed air misuses.

The aim of this study was to look at individual refuge bays and to determine an optimised supply pressure which will allow these refuge bays to pressurise according to regulations. This was done by doing an air mass balance, considering the amount of air entering the refuge bay through the compressed air pipeline. In contrast, the amount of air exiting the refuge bay through door leakage and occupant consumption during 100% occupancy was also determined. By quantifying these factors, an optimal supply pressure was calculated that ensures that the regulation is adhered to. In the case study that was investigated, the refuge

bay with the highest supply pressure requirement was 87 kPa, while 238 kPa were supplied to the refuge bay, which proved the statement made that refuge bays are prone to being oversupplied with compressed air.

A simulation model of the case study was developed to replicate real-life scenarios. This was done by verifying the simulation and ensuring that the simulated flow into the level was within 95% accuracy of the mine's SCADA data. In addition, a second verification step was implemented by doing underground gauge pressure measurements in the compressed air pipeline. This secondary verification step ensured that the measured values and the simulated values were within the 5% error range, ensuring the credibility and accuracy of the simulation.

The method was implemented by running various scenarios on the calibrated simulation model. These scenarios included the reduction in the compressed air setpoint at the control valve while ensuring that the refuge bay with the highest pressure requirement still received sufficient pressure. In the case study that was investigated, the setpoint could be reduced by 35 kPa gauge pressure over the whole 24-hour period.

An in-depth cost evaluation was conducted to quantify the possible cost-savings. In the case study that was investigated, the reduction in setpoint could result in an annual cost saving of more than R 50 000.

5.3. Shortcomings

There are some shortcomings in this study, which include the following:

- The study relies on assumptions made, for example the flow rate of air consumed by a person. This is a varying factor from person to person, influenced by factors such as the persons weight and health status. Therefore, this assumption was reasonable within the scope of the research.
- The study determined a flow rate based on the case study's requirement, which is 20 Pa within 15 minutes. However, the study assumed a constant flow rate into the refuge bay, which in real-life scenarios may not be the case.

5.4. Conclusion

Compressed air generation is very cost intensive in deep-level gold mines. Many studies looked at improving compressed air networks in deep-level mines. However, none of these studies looked at hydropower mines where refuge bays are the main compressed air user. Mines are prone to oversupplying compressed air to these refuge bays.

The aim of this study was to develop a method to determine the minimum supply pressure that a refuge bay on a hydropower mine need while still adhering to regulations. To achieve this aim the study had objectives that needed to be satisfied.

The method had to determine the minimum supply pressure needed for each refuge bay on a given mine, based on its size and number of occupant present. This method successfully determined these pressures, indicating that the refuge bay with the highest-pressure requirement is 88 kPa.

A simulation model was developed and verified to replicate real-life scenarios. This simulation model was implemented through running scenarios of different compressed air setpoints while ensuring that the minimum refuge bay supply pressure requirement was adhered to. The method was developed and successfully implemented on a case study mine.

The reduction in the compressed air setpoint resulted in a substantial cost saving of roughly R 50 000 per annum per mining level. This equates to roughly R 250 000 for the case study mine.

The aim of this study was to develop a method to determine the minimum supply pressure that a refuge bay on a hydropower mine need while still adhering to regulations. This study successfully determined this method by achieving all sub objectives.

The method could be expanded to other hydropower mines, which would greatly increase overall electricity cost savings in the mining industry.

5.5. Recommendations

- For future studies it is recommended to develop a method that would provide a refuge bay pressurisation curve, in other words a method that would indicate how fast the refuge bay will pressurise at a given supply pressure.
- I would also recommend an investigation on if the compressed air supply could be controlled to each refuge bay independently.
- Additionally, an important factor to note are temperatures and noise within refuge bays. During underground audits, it was found that refuge bays are relatively hot and that the silencers on the compressed air pipes do not function properly. During emergency conditions, workers would hesitate to go to refuge bays due to these conditions. I recommend an investigation on the noise levels within refuge bays.
- Furthermore, refuge bays are a secure go-to gathering area in the case of underground fires. Deep-level mine compressed air networks consist of steel pipes that supply refuge bays with compressed air. In the case of a fire, these steel pipes would be heated up, forcing very hot compressed air into the refuge bay which may also prevent workers from going to these refuge bays. Therefore, it is recommended to investigate independent compressed air units for each individual refuge bay.

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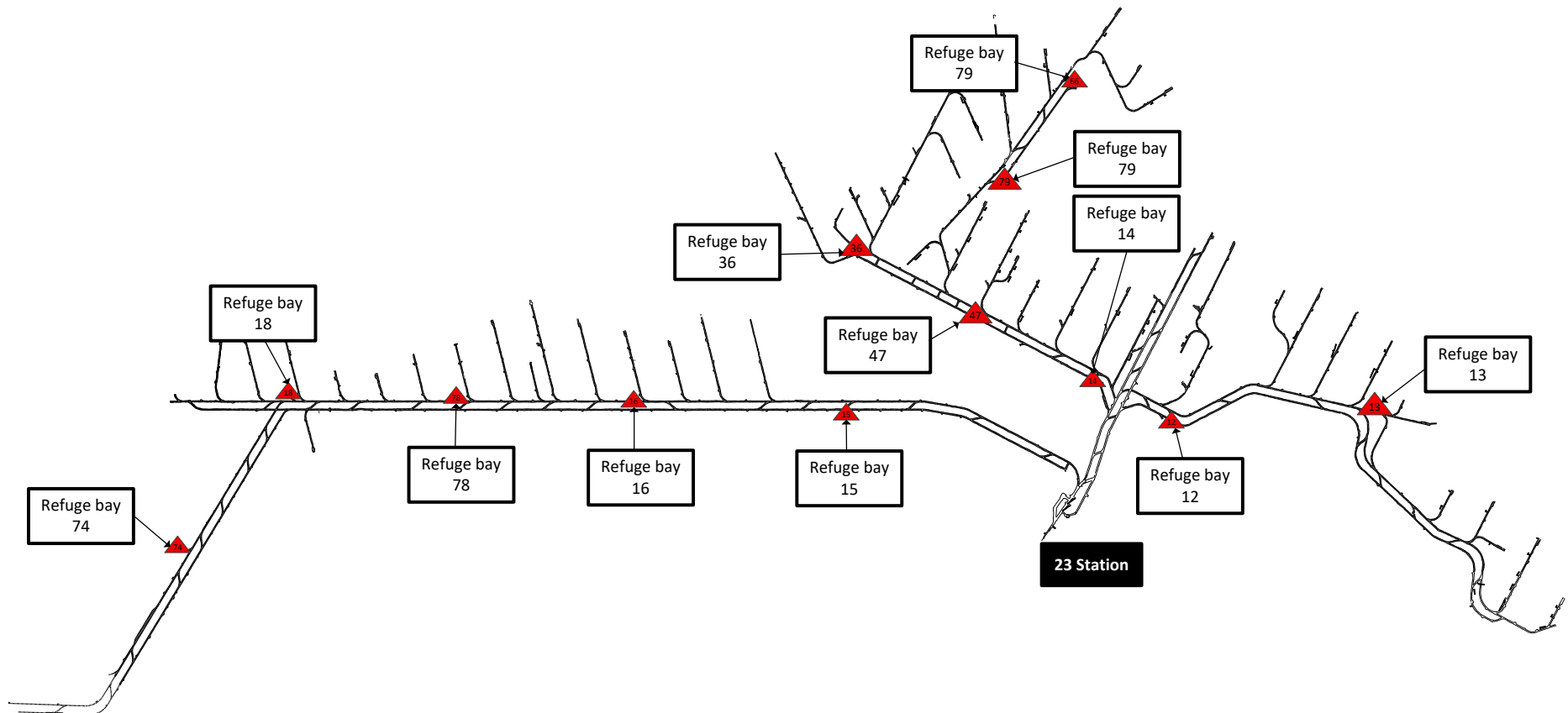
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6. APPENDICES

6.1. Appendix A



6.2. Appendix B

Appendix B serves as an example calculation, as mentioned in Chapter 3, of how a refuge bay pressurises. Consider a refuge bay pressurisation problem with the following properties:

$$L = 10 \text{ m}$$

$$W = 5 \text{ m}$$

$$H = 3.5 \text{ m}$$

$$P_{ATM} = 100 \text{ kPa}$$

$$\Delta P = 20 \text{ Pa (As per regulation of the case study)}$$

$$T_{WetBulb} = 20 \text{ }^{\circ}\text{C}$$

$$T_{DryBulb} = 25 \text{ }^{\circ}\text{C}$$

The density of air within this refuge bay can therefore be drawn from the psychrometric chart:

$$\rho = 1.1 \text{ kg/m}^3$$

1. The air flow rate required to pressurise the refuge bay

Firstly, the volume of the pressurised room is determined using Equation 3:

$$\begin{aligned} V_{pressurised} &= \frac{P_{atm} + \Delta P}{P_{atm}} \times V_{Refuge \text{ bay}} \\ V_{pressurised} &= \frac{100 + 0.02}{100} \times (10 \times 5 \times 3.5) \\ &= 175.035 \text{ m}^3 \end{aligned}$$

Thereafter, the additional air volumes that needs to be supplied to the refuge bay in order to pressurise are calculated using Equation 4:

$$V_{additional} = V_{pressurised} - V_{Refuge\ bay}$$

$$V_{additional} = 175.035 - (10 \times 5 \times 3.5)$$

$$= 0.035\ m^3$$

According to the case study's regulation, the refuge bay should pressurise with 20 Pa within 15 minutes, which is equivalent to 900 seconds. The mass flow required to supply the additional volumes is determined using Equation 4:

$$\dot{m}_{pressurise} = \frac{V_{additional}}{T} \times \rho$$

$$\dot{m}_{pressurise} = \frac{0.28}{900} \times 1.1$$

$$= 0.00004277\ kg/s$$

2. The air flow rate to the refuge bay

The next step is to determine the flow that is being provided to the refuge bay. This is done by using Equation 1 and using a line pressure with an initial guess of 100 kPa.

$$\dot{m}_{pipe} = C_{Discharge} \left(\frac{2}{k+1} \right)^{1/(k-1)} \frac{P_{line}}{RT_{line}} A \sqrt{kR \left(\frac{2}{k+1} \right) T_{line}} \quad (kg/s)$$

where

$C_{discharge}$ is the discharge coefficient that accounts for imperfections in flow which is taken as 0.97 for a well-rounded edge such as an open-end pipe

k is the specific heat ratio of air, taken as 1.4

T_{line} is the temperature in the compressed air line, taken as 298.15 K

R is the universal gas constant for air, taken as 0.287 (kJ/kg K)

A is the area of the pipe (in this case a 50 mm pipe) therefore 0.001963 m²

$\dot{m}_{pipe}$

$$= 0.97 \left(\frac{2}{1.4 + 1} \right)^{\frac{1}{1.4-1}} \frac{100}{(0.287)(298.15)} (0.001963) \sqrt{(1000)(1.4)(0.287) \left(\frac{2}{1.4 + 1} \right) (298.15)}$$
$$= 0.45 \text{ kg/s}$$

3. The flow rate of air that exits the refuge bay through door leakage

In the first step, the flow required to pressurise the refuge bay was determined with the assumption that there is no air loss. However, the air that leaks out of the refuge bay needs to be considered. The refuge bay has the following door specifications:

Door height = 1.7 m

Door width = 0.7 m

Gap = 5 mm

The door perimeter can be calculated as follows:

$$\text{Door perimeter} = 2(\text{Door height} \times \text{Door width})$$

$$\text{Door perimeter} = 2(1.7 \times 0.7)$$

$$= 4.8 \text{ m}$$

The door leakage (C) can be calculated as follows:

$$C = \text{Door perimeter} \times \text{Gap}$$

$$C = 4.8 \times 0.005$$

$$= 0.024 \text{ m}^2$$

The mass flow rate of the air leaking out of the door can be calculated using Equation 6:

$$\dot{m}_{doors} = \rho C A (\Delta P)^n \quad (\text{kg/s})$$

where

n is the leakage coefficient. Taken as 0.5

A is the area of the leakage, taken as 0.024 m²

C is the flow factor taken as 0.8.

ΔP is the difference in pressure between inside and outside of refuge bay which in this case is 20 Pa

$$\begin{aligned} \dot{m}_{doors} &= 1.1 \times 0.84 \times 0.024 \times 20^{0.5} \\ &= 0.09 \text{ kg/s} \end{aligned}$$

4. Occupant consumption

However, refuge bay occupants that consume air have not yet been considered. An air consumption of 85 L/min is taken per refuge bay occupant. When converting to m³/s, this is equivalent to 0.0014167 m³/s. According to the Mine Health and Safety Inspectorate, each refuge bay occupant requires 0.6 m² of space. Therefore, the maximum number of occupants present can be calculated using Equation 9:

$$\begin{aligned} \text{Refuge bay occupants} &= \frac{\text{Floor area (m}^2\text{)}}{0.6} \\ \text{Refuge bay occupants} &= \frac{10 \times 5}{0.6} \\ &= 83.333 \therefore 83 \text{ occupants} \end{aligned}$$

Therefore, the total rate of oxygen consumption per refuge bay becomes:

$$\begin{aligned} \text{Air}_{Consumed} &= 83 \times 0.0014167 \times 1.1 \\ &= 0.129 \text{ kg/s} \end{aligned}$$

Thereafter, an air mass balance is done using the equation below

$$\dot{m}_{pipe} - \dot{m}_{doors} - \dot{m}_{consumed} \geq \dot{m}_{pressurise}$$

$$\therefore 0.45 - 0.09 - 0.129 \geq 0.0000428$$

$$\therefore 0.231 \geq 0.0000428$$

From this we can see that the mass flow rate of air supplied to the refuge bay, accounting for door leakage and refuge bay occupant consumption, is greater than the mass flow rate required to pressurise the refuge bay. Therefore, the supply pressure can be adjusted in order to get the mass flow supplied to refuge bay as close as possible to the minimum requirement to pressurise the refuge bay. Now that the flows are known, an algorithm tool can be used in conjunction with Equation 1 to get the optimal supply pressure.

Using the algorithm tool, a supply pressure of 48.83 kPa would be sufficient to generate the flow to pressurise the refuge bay with 20 Pa within 15 minutes while accounting for losses. Therefore, at steady state conditions:

$$\dot{m}_{in} = \dot{m}_{out}$$

$$\therefore 0.0000428 = 0.000428$$