

Evaluating the feasibility of integrating mine compressed air systems for energy savings

FJL Matthee



[orcid.org/ 0000-0002-0781-140X](https://orcid.org/0000-0002-0781-140X)

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Supervisor: Dr. J. Marais

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Abstract

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Author : F. J. L. Matthee

Study leader : Dr. J. Marais

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The South African metals and mining industry is under pressure to increase their production output. While South Africa's production trend has been decreasing, even though it is the third largest gold reserve, the global trend has been increasing. The rising cost to produce has forced these production rates to decrease. The rising production cost is coupled with the high electricity cost, which Eskom has been increasing steadily over the last few decades.

As one of the industry's highest expenditures, namely energy, increased, so has the importance of energy efficiency projects. The South African gold mining industry consumes approximately 15% of the total electricity generated by Eskom. The largest consumer of electricity on a mine is compressed air production. Compressed air production consumes 20% to 50% of a typical mine's energy usage.

Previous studies have investigated methods to reduce compressor energy consumption by reducing compressed air wastage on the supply and demand side. This included implementing pressure control schedules, auditing networks, and repairing leaks to minimise wastage. Experimenting with different compressor combinations also assisted in reducing the supply load. In some cases, compressors were found to have been over-specified for their networks, resulting in excess air being discharged into the atmosphere. To prevent compressors from blowing off, investigations into increasing network size through integration have been launched.

These studies were based on mines with a wide range of compressors to choose from but with control philosophies limited to surface operations. The studies on integration that were based on simulations were those studies where factors such as infrastructure and pressure control prevented implementation.

This research focuses on finding a cost-effective method to reduce compressor energy usage by integrating compressed air networks without impacting the flow or pressure negatively. Simulations will be used to verify the credibility of the methods before moving on to physical testing and implementation.

The case study focused on two deep-level gold mine shafts and a processing plant supplied by two compressor houses and three compressors. The demand was reduced firstly by implementing proper control schedules, underground audits, and decreasing wastage. The compressor houses were then re-evaluated due to over-supply. Simulations were created to test the feasibility of integrating the two networks and were calibrated for an accuracy of 99.5%. The simulations proved that, with the proper control, only two compressors were required to provide both shafts with compressed air.

The simulation was implemented on the network and resulted in a daily average power reduction of 1 160 kW. The total reduction was 1 450 kW when including the effect of the control schedules and underground audits, which equates to an approximate cost saving of R 7.37 million and R 11.19 million per annum, respectively. Thus, the study proved that it was possible to reduce compressor energy by integrating two compressed air systems; therefore, the set out objectives were met.

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List of abbreviations

Amperes	A
Cent per kilowatt	c/kWh
Demand Side Management	DSM
Dynamic Compressor Controller	DCC
Gold processing plant	GP
Kilogram per hour	kg/h
Kilogram per second	kg/s
Kilometre	km
Kilopascal	kPa
Kilotonnes	kt
Kilowatt	kW
Level	##L
Mega Volt Amperes	MVA
Megawatt-Hour	MWh
Megawatt	MW
Millimetre	mm
Minute	min
Process Toolbox	PTB®
Rand	R
Supervisory Control and Data Acquisition	SCADA
Time-of-use	TOU
Tonnes	t
Variable Speed Drive	VSD
Programmable Logic Controller	PLC

Chapter 1: Introduction

1.1 The gold mining industry in South Africa

1.1.1 The history of gold

Gold was originally used as a form of currency. Later, the “gold standard” was implemented. This means that the value of a country’s currency was directly associated with gold. To this day, gold can still be used as security to protect a country’s currency. This is possible because the value of gold does not diminish over time¹. Although, globally, gold was first discovered thousands of years ago, the first recorded sighting in South Africa was in 1884 in what is now Johannesburg². The high potential of mining opportunities gave rise to the South African metals and mining industry [1].

1.1.2 The gold production trends in South Africa

The South African metals and mining industry is divided into categories of coal, aluminium, iron-steel, base metals, and precious metals. A volume increase of 3.6% to reach 250 kt annually is expected for the period between 2016 and 2021 [2].

Despite this forecasted increase, South Africa’s gold production has been decreasing over the past years while the global production trend has been increasing [3]. Figure 1 depicts the tonnes mined in South Africa compared to the rest of the world.

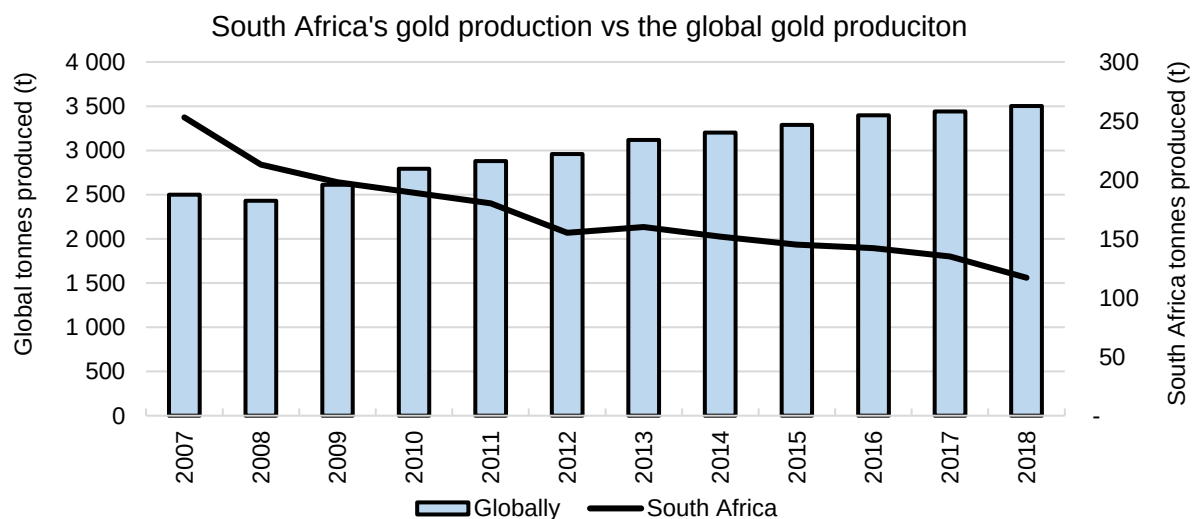


Figure 1: South Africa’s gold production vs. globally [3]

¹ N. Lioudis. “What is the Gold Standard?.” Internet: www.investopedia.com/ask/answers/09/gold-standard.asp. Sep. 24, 2020 [Aug. 18, 2020].

² SAHO. “Discovery of the Gold in 1884.” Internet: www.sahistory.org.za/article/discovery-gold-1884. Apr. 28, 2016 [Aug. 18, 2020].

This highlights the fact that South Africa is under pressure to increase its performance. These trends indicate South Africa is reducing its production unwillingly. Given that South Africa has the third-largest gold reserve, this reduced production implies that the issue cannot be a lack of availability and that other challenges must be hampering the industry [3].

1.1.3 The challenges the industry is facing

South Africa's declining production amidst increasing targets is a cause for concern, especially considering that the South African industry has been decreasing its production even as the cost of production has been increasing steadily³. The main causes of the production cost increase are electricity, labour, and maintenance cost increases [4]. Besides the pressure to increase productivity while keeping production costs to a minimum, the industry is facing additional challenges including but not limited to environmental ethics, government regulations, and access to financing [2].

Gold is the most energy-demanding precious metal to mine, responsible for 47% of the mining industry's electricity cost [5]. The gold industry consumes more electricity than any other branch of the industry, due to the ore location. Gold ore is commonly found deeper in the earth's crust; thus more energy is needed to excavate, blast, and transport from such depths⁴.

Eskom has been increasing its electricity tariffs annually. This affects the mining industry directly as the production cost is linked to the energy cost. Figure 2 depicts the annual tariffs for the mining sector's electricity [6].

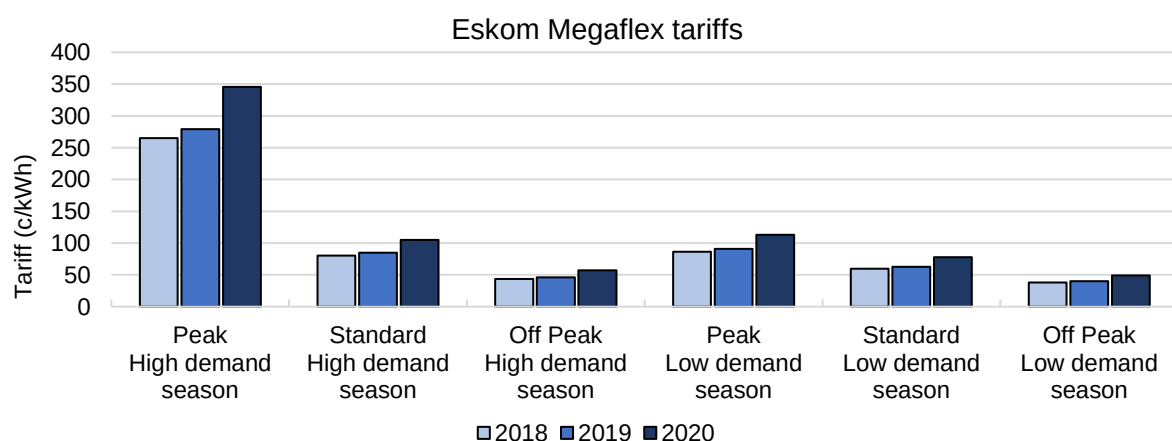


Figure 2: Annual Eskom Megaflex tariffs [6]

³ M. Garside. "World mine reserves of gold by country." Internet: www.statista.com/statistics/248991/world-mine-reserves-of-gold-by-country/. Feb. 10, 2020 [Aug. 18, 2020].

⁴ J. Desjardins. "50% of all gold ever mined on earth came from this South African gold belt." Internet: www.businessinsider.com/the-worlds-deepest-gold-mine-is-in-south-africa-2016-12?IR=T. Dec. 16, 2016 [Aug. 18, 2020].

Eskom has had to increase the cost of electricity to keep up with the increasing demand. Developing countries, such as South Africa, have seen an increase in electricity usage due to economic and population growth [6], [7]. As South Africa's demand grew, the country increasingly experienced electricity capacity shortages. Finally, these growing issues gave way to load shedding, a strategy to manage the country's energy demand [9]. Leading Eskom to increase the cost of electricity to fund capacity expansions. Assisting to keep up with increasing electricity demand. The increased cost, along with other challenges, resulted in a decrease in electricity usage [8].

Accordingly, implementation of energy-efficiency projects increased, which has assisted in resolving some of the country's capacity problems. These projects have decreased energy demand and reduced the load on power generating stations, from which a decrease in greenhouse gas emissions could also be expected [10]. Energy-efficiency projects became a part of a broader group of cost-savings projects when Eskom created the Demand Side Management (DSM) programme [6].

Essentially, a daily 24-hour profile was divided into different demand hours, resulting in three categories, each with their own electricity cost known as Megaflex tariffs. Lower tariffs were assigned to the least demanding hour to motivate companies to consume less energy during high-demand hours. To qualify for this billing system, a consumer must have a maximum electricity demand of 1 MVA. The consumer must also have the capacity to shift their energy load throughout the day. The tariffs are categorised based on the time of use (TOU) and whether it is a high- or low-demand season. The winter months are considered as the high-demand and more expensive period [10].

The TOU is further divided into weekdays, Saturdays, and Sundays. Peak hours are only allocated to weekdays. Public holidays are regarded as a Saturday or Sunday, depending on the date. Figure 3 depicts the TOU periods for a 24-hour profile [6]. The consumer's budget, energy-saving, and usage time determine which of the three types of DSM project should be implemented [14].

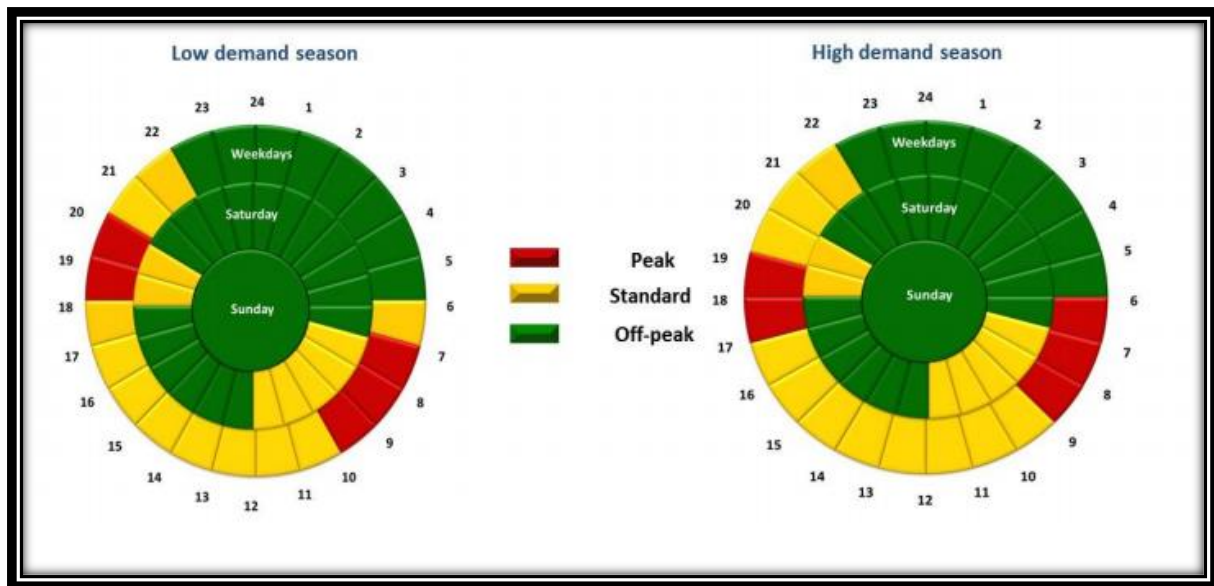


Figure 3: Eskom's Megaflex TOU tariff periods [6]

Load-shifting projects do not result in an energy saving. The daily consumption remains the same; however, the operational times are changed. Equipment that is usually operated during high-demand periods is used in lower-demand periods instead. Thus, the electricity cost is reduced by paying a less expensive fee [12].

Peak-clipping projects reduce daily energy consumption only during high-demand hours. This is done by reducing production services, which in turn decreases the electricity cost. Energy-efficiency projects reduce daily consumption throughout the entire 24-hour profile. These systems require extensive investigation and optimisation [12].

There are multiple opportunities for energy-efficiency projects in the South African gold mining industry [13]. This industry consumes approximately 15% of the total electricity generated by Eskom [14]. The largest single commodity energy demander in the gold mining industry is compressed air. It is responsible for 20% of a mine's electricity usage, although it has been seen to consume up to 50%, reaching over 880 MWh per day [14]–[16]. Compressed air was once regarded as the fourth most used utility; however, only 19% of the energy provided by compressed air is usable [17], [18].

Compressed air is, therefore, an inefficient energy commodity and more expensive to produce than steam or electricity [19], [20]. Due to the inefficiency of compressed air and the production cost, it has become one of the main focuses of DSM projects [13]. An estimated 25% of Eskom's DSM savings were realised from effectively managing compressed air systems [21].

1.2 The role of compressed air in the gold mining industry

1.2.1 Overview

The mining method is determined by the mineral type and its depth. Relatively shallow minerals such as coal are mined on the surface, known as open-pit mining, as seen in Figure 4 [22] along with deep level hoisting mining and slope mining. Deeper ore such as platinum and gold are mined underground. This requires the sinking of a shaft which is used for transportation. Originally, the shaft is built close to the ore into the ore vein. This method generates production during development [23]. As the closest ore is depleted, workers must travel further into the mining levels for a fresh supply [24].

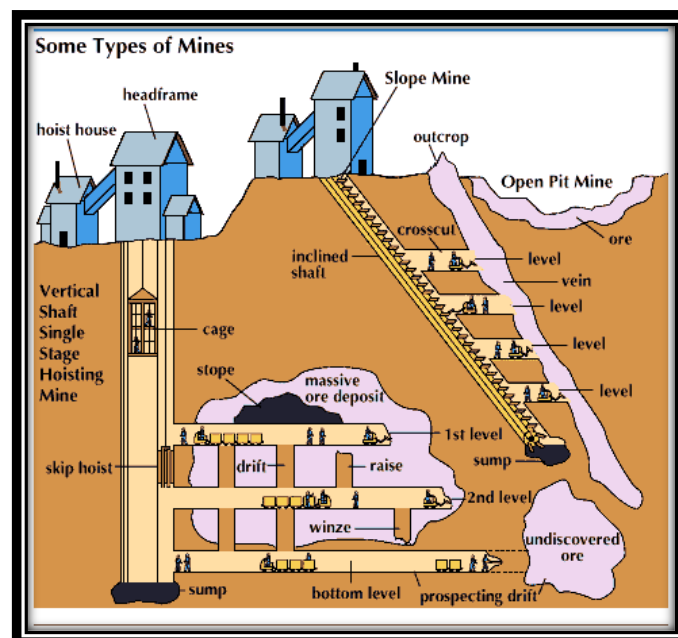


Figure 4: Types of mining diagram⁵

The daily mining activities are divided into three shifts: drilling, blasting, and sweeping. The shifts are spaced throughout the day into morning, afternoon, and evening shifts, respectively. During the drilling or morning shift, holes are drilled in the ore veins found in the stopes. This is done by using pneumatic drills powered by compressed air, as shown in Figure 5 [25]. The airflow rotates a wheel which is connected to the drill bit via gears [26].

⁵ Encyclopædia Britannica Inc. "Some types of mines." Internet: www.kids.britannica.com/students/assembly/view/53672. 2020 [Sep. 09, 2020].

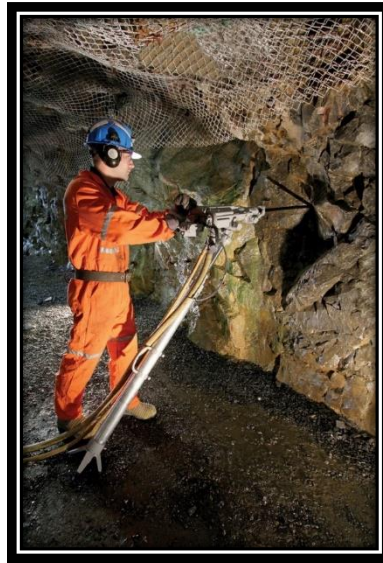


Figure 5: Pneumatic rock drill in action⁶

The drilled holes are filled with explosives during the blasting or afternoon shift to dislodge the ore. Electronic detonators are used to ensure the workers are out of the blasting zone [27]. The dislodged ore is collected during the sweeping or evening shift. The stope is cleaned out with brooms, water hoses, and winches. The ore is dumped in a central storage box [23].

The ore is then transported to the shaft via locomotive train carts on a railway. There it is gravity fed to loading boxes which function as a hopper, as shown in Figure 6. The loading-box doors at the bottom are operated with pneumatic pistons, which fill the skips. These are transported to the surface via the shaft cages in a process known as hoisting. The hoisted ore is delivered to the processing plant to produce pure metal ingots [23].

⁶ Boart Longyear. "Hand-held pneumatic rock drills." Internet: www.boartlongyear.com/product/hand-held-pneumatic-rock-drills/. 2020 [Sep. 09, 2020].

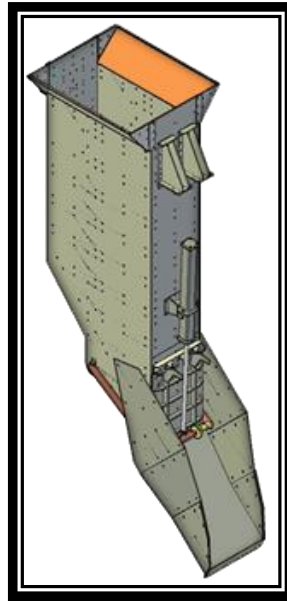


Figure 6: Loading box diagram⁷

1.2.2 Compressed air suppliers

Air is produced by means of a compressor, usually situated in a compressor house. Compressors can be divided into two sections, namely positive displacement and dynamic machines, each with its advantages and disadvantages. The different types of compressors are depicted in Figure 7 [28].

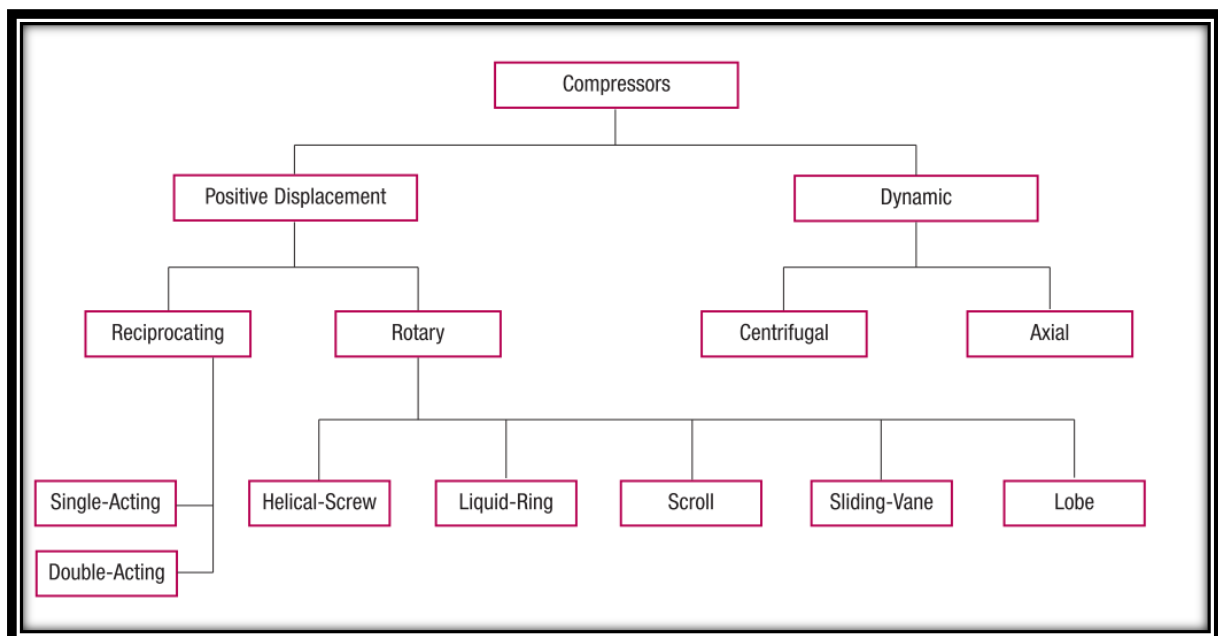


Figure 7: Compressor types [28]

⁷ Variant mining. "Variant Measuring Boxes." Internet: www.variantmining.com/variant-measuring-box/. 2020 [Oct. 1, 2020].

Positive displacement compressors increase the air pressure by adjusting the volume, while others change the velocity. Positive displacement compressors can reach higher pressures than dynamic compressors; however, dynamic compressors deliver higher airflow and have fewer frictional parts⁸.

Dynamic compressors, specifically centrifugal compressors as seen in Figure 8, are the most used compressors in the mining industry [29]. A dynamic compressor's large operating range ensures that no additional compressed air is produced for the mine's varying usage. While they are versatile, they are also compact and efficient [30]. They can control the delivery pressure by adjusting the inlet guide vane angle, making them more energy efficient [31]. This has a significant effect on deciding which compressor to purchase. Only 22% of the lifetime cost of a compressor comprises of the initial installation and maintenance. The remaining 78% comprises of the energy cost of operating the machine [32].



Figure 8: Common centrifugal compressor⁹

1.2.3 Compressed air networks

Compressed air networks are the bridge between the compressor house and the consumers. The pipe size and fixtures used to build the network are determined by the location and demand. Permanent columns, such as those found in the shaft, consist of flanged pipes that are bolted together. These range from 250 mm in diameter upwards. The pipelines in working

⁸ D. Parnell. "Back to Basics: Positive Displacement vs. Dynamic Compressors." Internet: www.thecompressedairblog.com/back-to-basics-positive-displacement-vs.-dynamic-compressors-. Apr. 10, 2018 [Aug. 18, 2020]

⁹ Personal photograph of a compressor on a deep-level mine provided by the author

areas are designed to be easily removable once the ore vein has been depleted and are usually connected with couplings and flanges [23]. The pipeline is situated from the shaft station. The farther the pipeline travels from the station, the smaller the pipes are in diameter [33].

There are two types of networks – a stand-alone network and a ring-feed network. Stand-alone networks have one supply point for multiple consumers, while ring-feed networks have multiple suppliers. Figure 9 depicts the difference between a ring-feed and a stand-alone network [34].

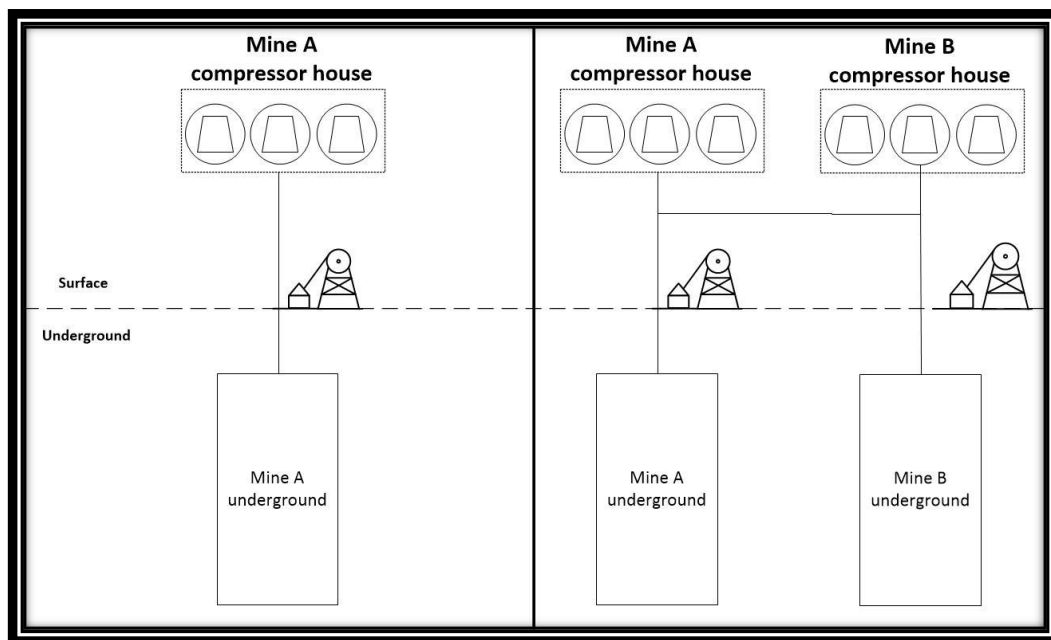


Figure 9: Stand-alone vs. ring-feed network layout

Ring-feed networks are also known as compressed air rings. An advantage of such networks is that supply sections can be isolated for maintenance without affecting the consumers. They are typically larger than stand-alone networks, resulting in higher upkeep costs. However, the network is more vulnerable to pressure drops as it has more consumer points [34].

Large compressed air networks are also more prone to develop leaks. Leaks can be responsible for up to 52% of a mine's compressed air losses. Damaged pipe couplings are the main culprit, making up 46% of compressed air leaks [35]. Dedicated teams known as air wolves used to be responsible for leak identification and repairs [36]. However, due to retrenchments, the task has been divided among the general workforce¹⁰.

¹⁰ M. Garside. "World mine reserves of gold by country." Internet: www.statista.com/statistics/248991/world-mine-reserves-of-gold-by-country/. Feb. 10, 2020 [Aug. 18, 2020].

1.2.4 Compressed air consumers

Compressed air is used for critical tasks in mining, as discussed above. The main consumer, rock drills, determines the minimum air pressure the compressor house must supply during the drilling shift. Other pieces of equipment such as the diamond drills, rock shovels, and loading boxes are independent of shifts, meaning they can be operated at any time and thus require constant air pressure [23].

Safety precautions such as refuge bays are also dependent on compressed air. Refuge bays are isolated rooms or chambers which can be used in the event of an emergency. The chamber is constantly supplied with fresh air through air compression. This limits the amount of smoke or other toxic gases which could enter the room [37].

Compressed air pipes can be used to assist in ventilating hot and humid mining sections. However, this is an inefficient use of compressed air [23]. The pressure requirement for underground mining equipment to function optimally ranges from 150 kPa to 500 kPa [29].

Mines use pressure control systems to provide the equipment with the required compressed air pressure. Deep-level mines are divided into levels, each one with different equipment, working hours, and compressed air requirements. The delivery pressure is determined by the level with the highest demand [38]. This becomes a concern for compressed air rings as the whole network must be pressurised to meet the requirements of the highest consumer [34].

Mines also have surface consumers, the largest being ore processing plants. The compressed air is used to agitate the leach tanks with high flow. The pneumatic instrumentation requires a constant pressure [39].

1.3 Data representation

1.3.1 Preamble

An important consideration for large systems such as deep-level mines is how to monitor the system. Some mines have a central control room with a supervisory control and data acquisition (SCADA) system. This system is designed to indicate the running status of machines such as the compressors, water pumps, and ventilation fans. Some systems also indicate the open or closed status of compressed air valves found on the station. The compressed air pressure and flow transmitter can also be monitored with the SCADA system [40].

1.3.2 Portable measuring equipment

Some sections of the mine may not have such compressed air pressure and flow transmitters fitted on the pipelines or, due to the harsh conditions found in mines, these transmitters may have been broken, stolen, or never connected to the SCADA system. Thus, there are times where it is necessary to measure the flow, pressure or even power manually [25]. The parameters and capabilities of such equipment are summarised in Table 1. Examples of the equipment can be seen in Figure 10, Figure 11, and Figure 12.

Table 1: Portable measuring equipment general information [41 - 43]

	Compressed air mass flow meter	Compressed air pressure logger	Power logger
Power source	Battery or external	Battery	Battery
Battery Life	6 hours	200 days	160 days
Range	0 – 224 kg/s	0 – 2000 kPa	0 – 5 A
Accuracy	0.00001	0.01	0.01
Minimum logging intervals	2 min	2 min	2 min

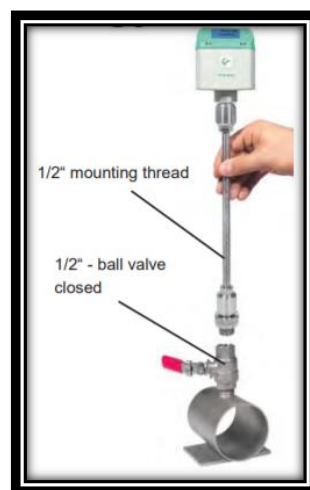


Figure 10: Portable compressed air mass flow meter [41]



Figure 11: Portable compressed air pressure logger [42]

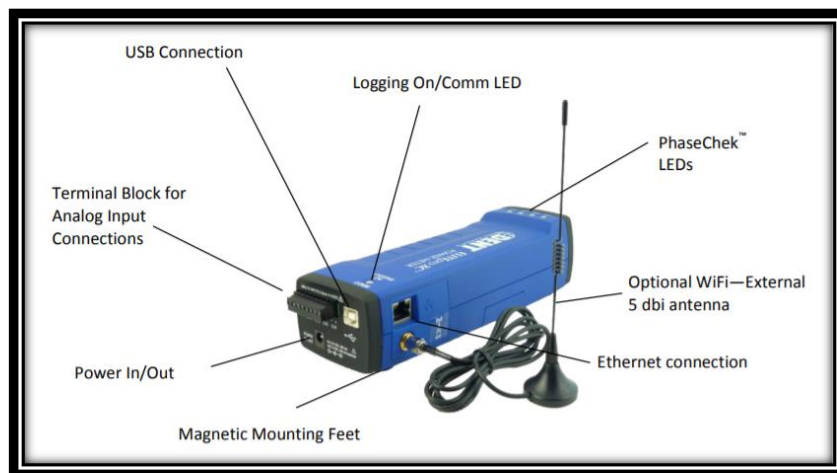


Figure 12: Portable power logger [43]

1.3.3 Simulation packages

Data, be it manually measured or retrieved from the SCADA historian, can be interpreted in a variety of ways. Graphs and figures can be used to assist in explanations or for further calculations and investigations. Simulations can also be used as an investigative tool to test the feasibility of implementing a new project, test safety factors, and accurately depict different flow scenarios [44].

SolidWorks® flow simulator uses the Navier-Stokes equation to calculate flow. Given that the flow package is an add-in of SolidWorks®, part modelling is required before the flow can be simulated. This requires a high level of detail for a basic simulation [45]. KYPipe® uses energy equations and mass continuity for its simulations. This package also focuses on steady-state liquid flows [46]. Flonex® includes compressed air in their simulations; however, it is costly to acquire [47]. Process Toolbox (PTB®) is designed to simulate mine systems and their thermal hydraulic flows. This package can accurately calculate complex compressed air networks in a single simulation [48].

1.4 State of the art

1.4.1 Categories

There are multiple studies on reducing energy costs by optimising compressed air systems. The most relevant studies to this research are described in more detail below. They are categorised according to the compressed air system sections to which their methods apply. The discussions' layout consists of the study title, author, brief overview, and shortcomings. The method and results are discussed where applicable.

1.4.2 Supply-side improvements

Given that a compressor is the heart of the compressed air system but also one of the most electricity-intensive systems, reducing its energy cost can be highly profitable. However, to do so it is important to determine the abilities of the system's compressors. It is highly unlikely that a compressor is unfit to meet demand requirements, as they usually over-supply as per their design specifications. Leading compressors are used to release the additionally generated compressed air back into the atmosphere, and this functions as a safety measure to protect the impeller from surging. However, it is seen as wasted compressed air and energy. The following studies have focused on investigating methods to address such issues.

Study 1 (2020) [49]

Title	: Energy Savings Measures in Compressed Air Systems
Author	: H. Hernandez-Herrera
Overview	: The study investigated the potential of different methods to reduce the compressor energy consumption for different manufacturers. These methods entailed decreasing the compressor set point, lowering inlet air temperature, automatic control, and leak repairs. The study proved that reducing demand would result in more savings than reducing the compressor set point.
Shortcomings	: Automation and increased control had the highest potential to realise savings. However, it is expensive to install these controllers on compressors. The results were generated by using mathematical expressions.

Study 2 (2012) [29]

- Title : An integrated approach to optimise energy consumption of mine compressed air systems
- Author : J. H. Marais
- Overview : The study addressed multiple methods for reducing compressor energy consumption of deep-level mines. One method entailed optimising the compressor combinations by opting rather to operate more, smaller compressors to meet the demand instead of operating one large compressor that oversupplies. Another method involved investigating the effect of repairing leaks. Both methods proved to be financially beneficial.
- Shortcomings : The combination optimisation was based on large-scale ring-feed networks with a high capacity; thus, there were multiple compressors to choose from. However, this is usually not the case with smaller mines. Furthermore, the wastage effect was limited to leaks formed by damages to the pipeline and the study did not investigate other sources of wastage.

Study 3 (2020) [50]

- Title : Potential energy savings in compressed air systems in industrialized cities. A case study in Barranquilla and Cartagena
- Author : H. Hernandez-Herrera
- Overview : The study investigated different methods for reducing the energy consumption of the compressor in the European industrial sector. These methods investigated the effect of the compressor set point, inlet air temperature, filter maintenance, and installing a variable speed drive (VSD). Reducing the demand resulted in more potential savings than both reducing the compressor set point and installing a VSD.

Shortcomings : Equipment such as a VSD is expensive to install. The results were generated by using mathematical expressions from a previous study. The saving potentials was not verified.

Study 4 (2017) [51]

Title : Improving efficiency of a mine compressed air system

Author : S. J. Fouché

Overview : The study investigated which energy initiatives were the most effective for reducing compressor energy on a deep-level mine. These initiatives included leak repairs, guide vane control, adjusting pressure set points, compressor combinations, replacing compressor air filters, and offloading compressors. The leak repair proved to be the most effective method for reducing compressor power.

Shortcomings : The research was based on a mine with limited control and monitoring systems. Thus, the offloading procedure's effect could not be fully evaluated.

Study 5 (2015) [11]

Title : DSM strategies to reduce electricity costs on platinum mines

Author : J. A. Deysel

Overview : The study simulated the effects of DSM strategies on the compressed air, refrigeration, pumping, and ventilation systems. These strategies included adjusting compressor set points, guide vanes, and peak clipping.

Shortcomings : The strategies implemented on the compressed air system were limited to surface operations. The clipping was only performed during high-demand hours.

Study 6 (2018) [52]

- Title : Practical low-cost method to sustain mine compressed air savings
- Author : J. Taljaard
- Overview : The study used simulations to predict the delivery pressure requirements of a deep-level mine network. The results indicated what the over-supplying compressors' set points should be. Given that the compressors' capabilities were different, the combinations were adjusted accordingly.
- Shortcomings : The methodology was implemented on a large ring-feed network with multiple compressors. There was a scope for the compressors to reduce their delivery pressure. However, this is not always possible on smaller networks. The author recommended that further research be done on the maintenance cost saving of running fewer compressors, but not on the effects on those running on lower guide vane angles.

Study 7 (2017) [53]

- Title : Improving mine compressed air network efficiency through demand and supply control
- Author : B. Pascoe
- Overview : The study used simulation tools to test the feasibility of future projects on a deep-level mine. Supply- and demand-side projects such as installing automated valves and replacing compressors were investigated. The simulation proved that both projects were feasible.
- Shortcomings : Only the demand-side projects could be implemented on the case study due to cost implications. The supply-side projects would have resulted in a payback period of 4.5 years.

Study 8 (2016) [54]

- Title : A dynamic optimal control system for complex compressed air networks
- Author : S. W. van Heerden
- Overview : The study investigated optimal compressor operating schedules and set points by using a dynamic compressor controller (DCC). The DCC increased the possibility to operate at a lower running cost with a stabler compressed air supply. The DCC was also able to select different compressor stations that were far apart.
- Shortcomings : The DCC was designed to operate on modern computer processing systems. The author stated that the simulation time could be improved.

Study 9 (2016) [55]

- Title : Automated mine compressed air control for sustainable savings
- Author : J. Jonker
- Overview : The study investigated the possibilities for implementing a dynamic compressor selector (DCS) controller on a deep-level gold mine. The DCS controller calculated the compressors' set points. An improved control strategy was developed based on these results to control the compressed air supply automatically, including when to start and stop a compressor as well as the optimal guide vain control that was possible in this strategy.
- Shortcomings : The controller had to be updated manually. The DCS controller was only installed on the compressor house system. The author suggested that the strategy could be applied to underground valve operations as well.

Study 10 (2012) [56]

- Title : Strategic placement of compressors for future mine developments
- Author : H. G. Brand
- Overview : The study used simulations to determine the optimal position to install a replacement for the existing compressor house on a deep-level mine. This would have shrunk the ring-feed network and the additional demand that the pipeline generated. The cost of building an additional supply point was expected to be more than the energy-saving it would bring. Hence, isolating part of the network was investigated next, but the isolated shaft's compressor houses were deemed unfit and could not supply the isolated shafts.
- Shortcomings : The research was based on installing additional equipment to benefit the network rather than optimising the already existing ones. The simulation recommissioned compressors which were already underspecified for the isolated networks.

Study 11 (2018) [57]

- Title : Using specific energy as a metric to characterise compressor system performance
- Author : W. Shaw
- Overview : This study developed a method to measure the performance of a compressed air system using a single metric, namely specific energy. The method required minimal information, such as compressed air supply and energy consumption. The specific energy before and after an initiative was implemented, was compared to assess the performance. Increased specific energy indicated a decreased efficiency of the compressor.

Shortcomings : The performance measuring method was based on the surface operation of a platinum mine. The author suggested that the method be used as a driving point for automated compressor operations.

Study 12 (2016) [58]

Title : Benchmarking electricity use of deep-level mines

Author : C. Cilliers

Overview : The study scored the efficiency of high-demand systems using regression analysis. These scores could be compared with industry averages. The scores highlighted inaccuracies such as budget errors and prioritised energy efficiency initiatives.

Shortcomings : The benchmarking model is sensitive to data availability. The model prioritised the overall electricity usage of a commodity.

Study 13 (2019) [59]

Title : Failure prediction of mine compressors

Author : J. Jacobs

Overview : The study created a prediction model for when a compressor will fail based on Weibull analysis. The model was adapted from dewatering pumps for compressors. The model assisted in creating a proactive maintenance schedule, improved safety for continuous compressed air systems, and increased system reliability. Additionally, given its generic nature, the model was not limited to only the compressed air system. The study proved that awareness can also lead to reduced compressor energy.

Shortcomings : The model can only be applied to systems which fit the Weibull criteria. The model is only used as a tool to predict the remaining time until the next failure, not the cause of the issue.

1.4.3 Demand-side and network improvements

Another effective method for reducing the compressors' energy consumption is reducing the number of consumers or throttling their supply. When the compressed air demand is reduced, the previously wasted pressure builds up in the network, allowing the compressor's impeller to deliver the same pressure with less load. Thus, decreasing the energy needed to run the impeller motor. The following studies consist of methods for reducing the wastage of consumers.

Study 14 (2016) [60]

Title	: An integrated energy management strategy for the deep-level gold mining industry
Author	: J. I. G. Bredenkamp
Overview	: The study created a strategy which could be used as a framework by gold mines to manage their energy consumption effectively. With the help of a guide, fewer resources are required such as outside personnel.
Shortcomings	: The strategy focused on electrical cost savings. The author suggested that it be applied to other areas such as environmental impact and other energy sources. The long-term impact of the management strategy must still be determined.

Study 15 (2018) [61]

Title	: A compressed air cost savings identification model for deep-level mines
Author	: C. J. Oosthuizen
Overview	: The study optimised methodologies of previous studies on investigating deep-level mines. The time and resources required were decreased through the process. The model proved to be an accurate prediction tool for potential cost savings.

Shortcomings : Time schedules had a substantial effect on the model due to the large databases that were used. Major changes such as large section closures and infrastructure collapses were not considered in the model.

Study 16 (2018) [62]

Title : Implementation of energy efficiency measures in compressed air systems: barriers, drivers and non-energy benefits

Author : T. Nehler

Overview : This study investigated how additional benefits from reducing energy consumption can affect the decision-making process. Non-energy benefits (NEB's) included increased production, improved equipment lifetime, and reduced carbon emissions. Capital avoidance and reduced maintenance proved to be the most sought-after benefits.

Shortcomings : The research was conducted through a questionnaire. Thus, the results could have included a combination of biased opinions from compressed air users, experts, and suppliers. Affecting the results in a negative way.

Study 17 (2018) [63]

Title : Continuous evaluation of operational risks on deep-level mine equipment

Author : S van Jaarsveld

Overview : The study developed a methodology to supervise the maintenance schedules based on already-summarised information. This removed the need to manually inspect the inventory list regularly. The methodology was further automated to avoid unnecessary capital costs. Automated alarms were implemented to notify personnel when the set parameter had been exceeded. The study proved that awareness can also lead to reduced compressor energy.

Shortcomings : The alarms depended heavily on a proper monitoring system. Some of the limits were too low and kept causing false alarms. Other limits were set too high and resulted in missed alarms.

Study 18 (2017) [25]

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

Author : D. Nell

Overview : This study utilised simulation tools to determine the effect of proper pipe sizes on pressure losses to improve a deep-level mine's production. The study verified that using the correct pipe sizes at the correct level length did increase the pressure. Thus, the need to pressurise larger vessels was reduced.

Shortcomings : The focus was mainly on production profit and not the effect that these changes had on the compressor energy.

Study 19 (2019) [64]

Title : Holistic analysis of the effect on electricity cost in South Africa's platinum mines when varying shift schedules according to time-of-use tariffs

Author : W. Shaw

Overview : The study investigated the effect of the shift schedule on the power demand of a deep-level mine. The shift schedule changes were dependent on the mining personnel. The overall shift schedule was optimised to align with each shaft's operation and hence lower energy cost periods.

Shortcomings : The schedule was not implemented practically. The concept was tested in theory with limited influence from the human factor.

Study 20 (2010) [40]

- Title : Cost and time effective DSM on mine compressed air systems
- Author : H. P. R. Joubert
- Overview : The study focused on the effect of using control valves to throttle pipelines and reduce demand on deep-level mines. Actuated valves were installed on multiple surface ring-feed networks to better control the compressed air flow. The additional control proved to reduce the energy cost significantly.
- Shortcomings : The additional installed control valves were limited to surface operations in the proximity of the compressor houses.

Study 21 (2007) [65]

- Title : Investigating the effects of different DSM strategies on a compressed air ring
- Author : J. W. Lodewyckx
- Overview : The study identified the advantages of using simulations to optimise the control valves' operations on a ring-feed network. The simulation was used as a feasibility tool for different control schedules. The optimised schedules reduced the energy cost considerably.
- Shortcomings : The simulation results were limited to surface operations only. The author suggested that the program also be applied to underground operations.

Study 22 (2018) [44]

- Title : Simulating operational improvements on mine compressed air systems
- Author : B. Friedenstien
- Overview : The study utilised simulations to test the feasibility of compressed air optimisation projects on deep-level mines. The simulations proved to

be a valuable feasibility tool. Methods such as adjusting compressor set points, throttling underground levels and refuge bay consumption were simulated.

Shortcomings : The simulations could not be implemented for all the case studies because the research was based on a large scope. The author recommended that the methodology be tested on different systems.

Study 23 (2019) [66]

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

Author : P. de Villiers

Overview : The study used simulations to determine the feasibility of reducing compressed air demand in deep-level mine refuge bays. The proposed solution proved to be successful and was implemented for verification. Ball valves with a 4-mm hole through them were installed to reduce the demand.

Shortcomings : The research was limited by the cost of installing additional infrastructure. The author stated that more expensive methods could have been considered, based on the results.

Study 24 (2015) [67]

Title : Challenges faced during implementation of a compressed air energy savings project on a gold mine

Author : J. I. G. Bredenkamp

Overview : The study highlights the challenges of implementing an energy-efficiency project on a deep-level mine. The challenges included operational changes, installation delays, and control limitations. The study proved that even though the projects were delayed, reduced compressor energy was still possible.

Shortcomings : The study focused mainly on identifying the issues of implementing new projects. The projects were delayed due to multiple factors which limited their effects.

Study 25 (2018) [68]

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

Author : J. Vermeulen

Overview : The study created a methodology to further reduce time, resources, and cost when investigating potential projects. Audits were prioritised by the potential saving of each area's compressed pressure profile. A ratio between the average pressure and that of the drilling period was calculated and the study found that a lower ratio indicated that more wastage could be expected.

Shortcomings : The ratio was based on the drilling shifts' demand. Some consumers have a constant pressure profile. The methodology is used to determine the scope of projects and not the required demand reduction to realise savings.

Study 26 (2019) [69]

Title : Local benchmarking in mines to locate inefficient compressed air usage

Author : D. du Plooy

Overview : The study proposed a method to effectively identify inefficient compressed air usage in deep-level mines. This is done by comparing the compressed air demand with the production of each level. The method proved that the top three prioritised levels were responsible for most of the wastage.

Shortcomings : The method is based on the active levels with available instrumentation to log compressed airflow. The author suggested that controls be developed to normalise this method for inactive levels.

Study 27 (2020) [70]

Title : A Practical Method for Compressed Air Leak Localisation in Deep-Level Mines

Author : L. N. Zietsman

Overview : The study proposed a new method to identify leaks on the levels themselves. The compressed air flow supplied to the level was monitored while closing off sections of the level. This reduction in flow after each close off indicated the consumption of each section. The sections were prioritised by their consumption for further investigate.

Shortcomings : Testing a level in this way is not much less time-efficient than performing a full audit on the level, although the method helps to identify possible problem areas if there is still an issue after an audit.

Study 28 (2018) [48]

Title : Trade-off between simulation accuracy and complexity for mine compressed air systems

Author : J. Watkins

Overview : The study investigated what components were needed to build an accurate simplified compressed air simulation. The study proved that simplified and detailed simulations had similar accuracies. Thus, the time spent on adding more detail to simulations could be better utilised.

Shortcomings : The simulations were created for a complex large-scale ring-feed network. The author stated that the size of the network could lead to dimension errors. Smaller, simplified networks could be less prone to such errors.

1.4.4 Compressed air network integrations

Improving either the supply or demand side will affect the other. For example, if the demand has been reduced to such a point that the compressors are now over-supplying, the supply side should be reinvestigated. If this issue is identified at multiple compressor houses on the same site, the company can consider integrating the networks to create a ring-feed network. This increases the compressor combination possibilities as the network can be supplied from any compressor house [40]. The following studies have investigated the effects of integrating compressed air networks with different methods.

Study 29 (2007) [71]

Title	: Energy efficiency opportunities resulting from splitting a compressed air ring
Author	: H. P. R. Joubert
Overview	: This study determined the effects of isolating a ring-feed network in two distinct parts. The network was divided from a high-demand network into a high- and low-demand section. The delivery pressure of the low-demand side was reduced to save on energy costs.
Shortcomings	: The research was based on a large-scale network which was able to be divided. The networks were not fully isolated but only divided by control valves, making them still dependent on the ring-feed network.

Study 30 (2017) [72]

Title	: Evaluating compressed air operational improvements on a deep-level mine through simulations
Author	: P. Mare
Overview	: The study used simulations to determine the optimal pipe sizes and compressor combinations for reducing energy costs on deep-level mines. The simulation was used to compare three cost-saving options on two deep-level gold shafts. Increasing the delivery pressure, integrating the two shafts underground, or replacing the shaft

compressed air columns were investigated. The integration proved to be the most financially beneficial option.

Shortcomings : The simulation was not implemented practically for the case-study. The post-integration compressor combination increased the supply of the one compressor house, but there was no control for the compressed air flow between the two shafts.

Study 31 (2013) [73]

Title : The value of simulation models when implementing mine DSM projects

Author : W. F. van Niekerk

Overview : The study simulated the plausibility of using different integration points to create a ring-feed network for deep-level mines on the surface and underground. Factors such as existing pipelines, pipe sizes, and available pipes for additional installation were included in the simulation. With proper control, the surface integration option was the most feasible. The underground integration would have resulted in pressure losses.

Shortcomings : The simulation results were not implemented practically for the case-study. The pipelines for both options were not completed.

1.4.5 Summary of shortcomings

A main issue that arose from the above-mentioned supply-side methods was the compressed air network sizes. The case studies were performed primarily on mines with high compressor capacities. The same principle could be applied for a smaller ring-feed network to optimise the available combinations or at least to identify the limiting factors rather than investigating more expensive options such as installing additional compressors.

The studies on demand-side reduction methods varied by location, and most limited their control philosophies to surface operations. The authors suggested implementing these strategies to throttle the compressed air of large-scale underground consumers. Studies that focused on underground reduction were limited by measuring equipment. Furthermore,

inactive areas with no production were usually isolated from the networks. Investigating these levels only to verify whether they are isolated would be more time-efficient than auditing full-production levels.

The studies that focused on creating ring-feed networks proved to be of importance, as it is rarely possible for a previously ring-fed network to be divided into two independent sections without increasing energy costs. The studies indicated the importance of using simulations as a feasibility tool and highlighted crucial factors such as infrastructure and control that limited implementation of the projects they proposed.

Each section's studies had shortcomings that were applicable to a broader spectrum or were limiting in a certain way. These methods can be improved either by applying them to different case studies or by combining them. A summary of the abovementioned is represented in Table 2. The red blocks indicate where a study falls short and the green where it meets requirements. A detailed summary can be found in Appendix A.

,

Table 2: State of the art matrix

STUDY	SUPPLY-SIDE IMPROVEMENTS	DEMAND-SIDE IMPROVEMENTS	NETWORK IMPROVEMENTS	INTEGRATING NETWORKS	SIMULATING NETWORKS	STRATEGIES IMPLEMENTED
1 & 3						
2 & 4						
5						
6						
7						
8, 9, 11, 12 & 13						
10						
14, 20, 25, 26 & 27						
15						
16 & 24						
17						
18, 21 & 23						
19						
22						
28						
29						
30 & 31						

1.5 Problem statement and objectives

The studies highlighted above focused on optimising control strategies, installing equipment, and simulating compressed air systems, most of which resulted in reduced energy costs for the compressors.

For the red blocks, which depict what was lacking in that section, there is room for improvement on the integration front. This means that most of the studies described in the state-of-the-art section did not focus on or sufficiently address the integration of compressed air networks, and those that did, did not always implement their methodologies practically. Some studies focused solely on supply-side projects, such as adjusting compressor combinations and their set points. Some were validated through simulations and others by implementation. A large group of the studies described investigated demand-side projects but with little focus on simulation and even less on integration.

This study is meant to include all the categories and aims to investigate supply, demand, and network improvements. While integrating compressed air systems through simulations and implementing the set methodology to result in all the blocks being green for this study.

Thus, the objectives for this research will be to investigate effective methods for reducing compressor energy usage by integrating compressed air networks without affecting the flow or pressure negatively. Different investigation methods will be used, such as simulations and physical tests.

The methods will have to be more cost-effective than the case studies' current situation without affecting the compressed air flow or pressure negatively. The identified method will be implemented on a suitable mining site with a need for improved compressed air systems. The results will be documented and discussed further in the document.

Chapter 2: Methodology

2.1 Introduction

There are two schools of thought when it comes to reducing the energy usage of a compressor. One focuses on the compressor house itself, which is on the supply side. The other reduces the usage of the consumers, which are on the demand side. Even though these approaches apply to different sides of a compressed air system, they do influence one another. Thus, it will be beneficial to re-evaluate this system and which methods can be applied after each step. Optimising one part of the system could lead to a new project which may previously have been dismissed or overlooked. The same can be true for integrating and creating new networks. Figure 13 depicts a basic diagram summarising the concept.

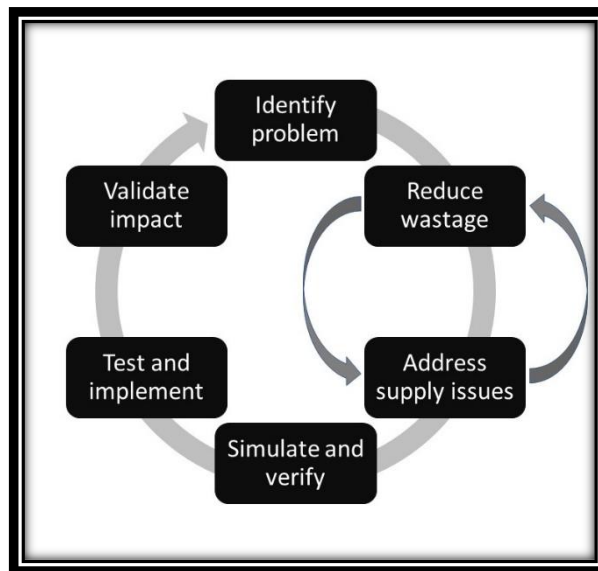


Figure 13: Steps in reducing compressor power

2.2 Identifying wastage

2.2.1 Preamble

As previously discussed, the compressed air consumers make up the demand side of the system, which include equipment such as drills, loading boxes, refuge bays and processing plants. It is important to define all consumers on the demand side to optimise the process. These consumers have their own equipment, location, importance, compressed air requirements, working schedules, control capabilities, and overall infrastructure. This information will help to prioritise where to start reducing demand. However, to achieve this, it is important to know how to interpret the given information that pertains to the demand and supply factors.

2.2.2 Data management

One of the most important steps in reducing wastage is determining how to process the data. Most investigations begin with a baseline, that is, a standard which is used for comparisons. To create a baseline, a period which accurately reflects the operation must be selected. This can be done by downloading data from the mine's historian. Some systems and equipment have a data tags assigned to them, which are saved on the historian. The type of data depends on the type of transmitter, but is usually flow, pressure, temperature, or power. The data can be downloaded for a chosen period through the historian.

The methods of displaying data depend on the type and depicted period. The data can be presented over a year with the totals for a monthly or a daily basis; averages can also be used. In some cases where the data is affected by the time of day, such as peak energy periods or mining shifts, the data should be displayed over a 24-hour period. A daily, monthly, or even yearly average can be used for each hour.

Once a baseline period has been chosen and depicted correctly, the comparisons can begin. The norm is to compare a specific data period to the baseline where a change in the operations occurred. However, the reverse can also be used where two data sets are compared to identify any operational changes.

2.3 Removing wastage

2.3.1 Optimise control schedules

Some mines have a central control room with a SCADA system. This system assists the operators in monitoring the mine for any issues that occur with the machines and valves. The valves, which are visible on the SCADA system, are usually fitted with an actuator that is connected to a programmable logic controller (PLC). The PLC receives data from either pressure or flow transmitters, processes the data, and then instructs the actuator on how the valve should be operated. Thus, if the pressure or flow is too high, the valve will close until the set point is met.

Previous research by Joubert [40], Hernandez-Herrera [49] and Lodewyckx [65] proved that implementing compressed air schedules on the actuated valve reduces energy demand. Schedulers can be added to the PLC programming so that the set points change according to the requirements. These requirements differ throughout the day. For example, the pressure requirement for the underground levels is less during a blasting shift than a drilling shift because of the equipment used. Optimising these schedules leads to saving on unnecessary wastage that results from negligence. The following information should be gathered when creating a compressed air schedule [65]:

- Locations of installed control valves,
- Whether the actuators are fitted with schedules,
- Compressed air requirements of these areas,
- Current schedules for these levels, and
- Whether the schedules can be changed

Knowing the locations of the installed control valves helps determine ways to throttle the demand. Some levels have a valve installed at the entrance. It would be better to control the compressed air flow here rather than down the pipeline. Hence, the wastage from pressurising the extra section pipeline is removed. Controlling closer to the supply point would reduce the most wastage.

It is also important to note which of the valves are fitted with control schedules. The valve can be controlled on a manual schedule, either by an underground worker or, if the valve can open and close from the SCADA system, an operator. However, manual valve control introduces the possibility for human error, where the valve could be opened or closed at the wrong time, or be operated as the controllers wish.

Furthermore, the minimum requirements play a crucial role. Comparing the current pressure supply to the requirements will give a clear indication of the wastage. If an area is receiving more flow or pressure than it requires this means that the compressed air is not properly managed in that area. The historical pressure data should be downloadable from the SCADA system. The current schedule can be found from the control room operators or the shaft engineer. For schedules, it is best to compare the pressures over a 24-hour profile.

A proposed schedule can be created by applying the minimum requirements of the current schedule. Figure 14 depicts the advantages of an optimised compressed air schedule and its effect on the compressors. This would be a scenario where the compressed air pressure set point schedule has been adjusted as needed with no accountability, thus where the set point was never reverted to the requirements of 400 kPa from 06:00 to 18:00. The rest of the time, the schedule should have been set to 150 kPa.

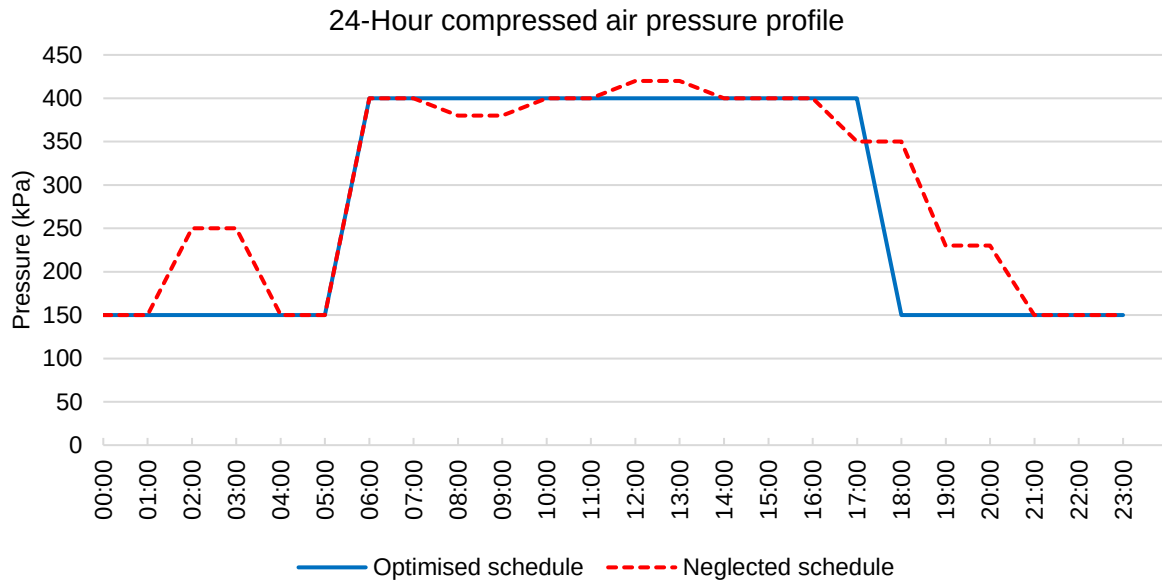


Figure 14: Comparison of an optimised and neglected compressed air schedule

Leaving the valve open for longer than necessary wasted compressed air, meaning that the compressors could have been running at a reduced power level. This also greatly affects the monetary loss, due to the compressor running during high-tariff periods.

2.3.2 Installing additional valves

Not all pipelines are fitted with control actuators. The air flow to these areas is manually throttled by workers, which can cause issues where operators neglect to close or open valves without notice. This can result in varying demand and unexpected pressure drops. Finding these valves is another issue that requires searching underground areas for these valves, as they are not on the SCADA system. This process takes up valuable time which could have been spent on optimising other parts of the system.

Friedenstein [44], Joubert [71], and Van Niekerk [73] proved that the best approach would be to install actuators and implement schedules on these valves. Increasing the control on a valve that is controlled by only one person is an advantage because it means that less compressed air would be wasted due to neglect. The advantages of schedules have already been discussed above. The following information will be needed to instal an actuated compressed air valve [40]:

- Pipe size,
- Valve type,
- The proximity of existing communication and power networks,
- Actuator compatibility with current devices for spares, and
- Locations for transmitter installation.

The pipe size is important in order to choose the correct size valve, otherwise the valve would either be too large or too small. Different valve types have different effects on how the flow is controlled. This along with the availability of communication networks determines where the valve would be installed. The valve should fit on the pipe close to a network connection, otherwise cabling must be installed to the valve, which increases the installation cost. The shaft engineer, boiler maker, or technician should have this information.

Also noteworthy is the location of the transmitter on which the PLC control is based. In terms of pressure, the PLC usually uses the downstream pressure. The pressure is measured after a valve. If the valve is installed after the transmitter, it would read upstream pressure, resulting in no or inaccurate control. As an example, if the valve must close to reach the desired set point, the upstream pressure would not decrease, meaning that the valve would close completely, cutting off the compressed air down the line.

2.3.3 Prioritising audit locations

As mentioned, there are some areas and valves which do not appear on the SCADA system. Identifying wastage in these areas requires performing underground audits. These can be time-consuming and difficult to prioritise where to start. Previous studies have created multiple benchmarking methods to prioritise level audits. The following steps help to prioritise which levels to audit first [69]:

- Identify all underground levels
- Acquire compressed air flow data for each level
- Acquire compressed air pressure data for each level
- Acquire production data for each level

The number of underground levels assists in defining the scope size. The data should be found on the SCADA system. The production data and number of levels can be found from the shaft engineer and the mining manager. How each type of data is processed depends on what investigation method is used.

Vermeulen [68] used the pressure difference in a 24-hour profile to identify wastage. Some levels had a pressure increase during drilling shifts due to the high demand. A ratio between the drilling shift peak and the rest of the day was calculated. An example of this concept can be seen in Figure 15. A low fraction indicates that less compressed air was wasted during the sweeping and blasting shifts.

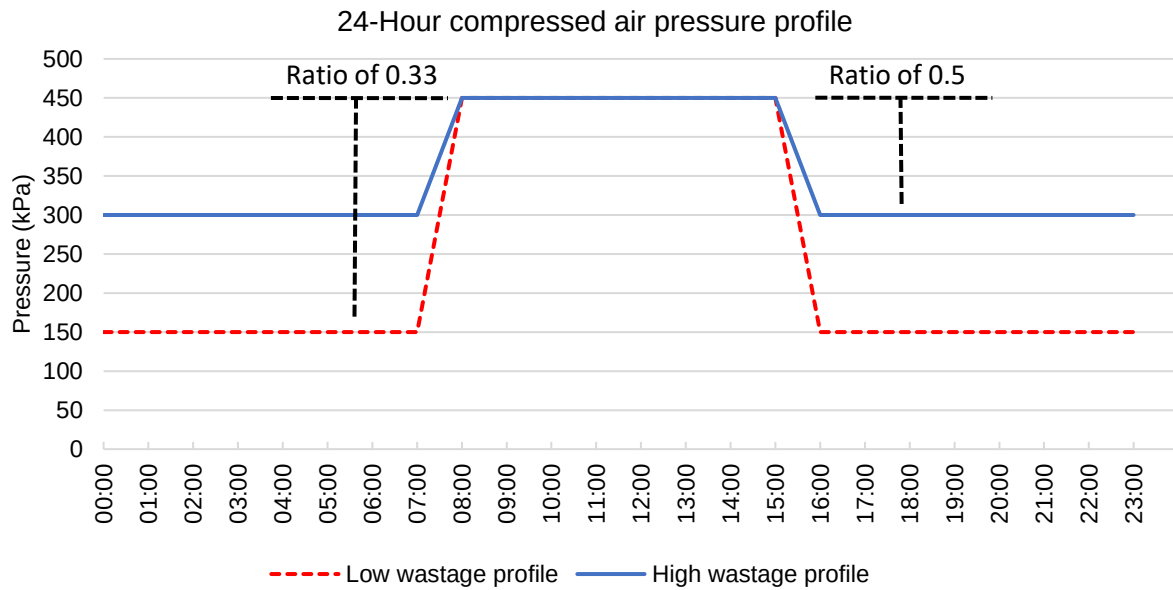


Figure 15: Comparison of a high- and low-wastage level based on pressure profiles

However, there are levels with constant pressure requirements. This may be due to the equipment used to sweep or settlers which require agitation. Du Plooy [69] used these constant requirements as an advantage. The average compressed air flow demand was compared with the daily production for each level, after which a ratio of the flow consumption against the production output was created. The higher the ratio, the more wastage could be expected on the level. An example of these ratios for five levels of varying flow and production can be seen in Figure 16. Level A, C and E do not have much wastage. Level D is the most efficient with Level B consuming the most air with the least amount of production. This is the level with the most wastage and should be prioritised for auditing.

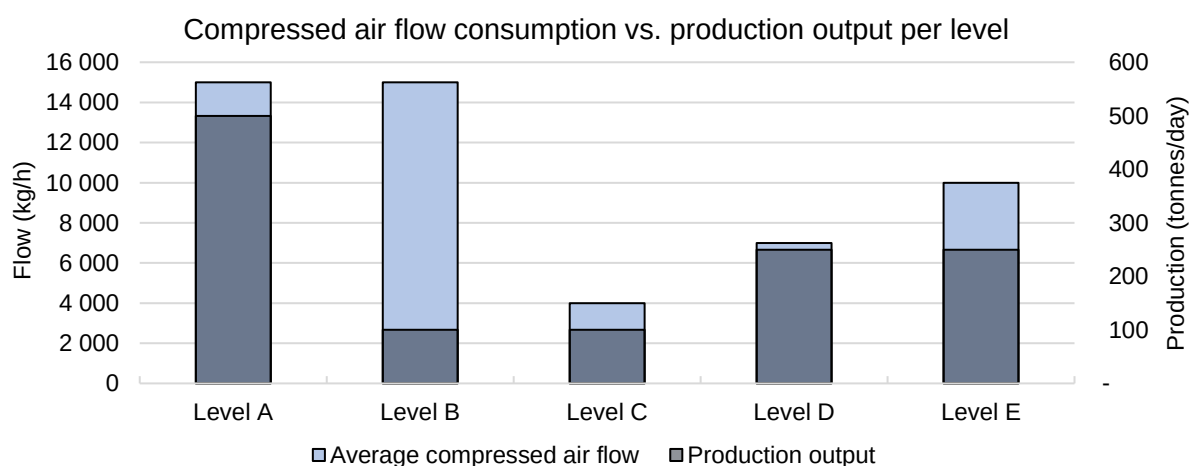


Figure 16: Comparison of a high- and low-wastage level based on flow and production

2.3.4 Auditing compressed air networks

Once the areas have been prioritised, the audits can commence. The audit entails walking along the compressed air pipeline and identifying any wastage. This will include identifying leaks, which can be identified aurally or, in severe cases, visually. Compressed air leaks of this magnitude reflect light with a white-blue hue. Hernandez-Herrera [50], Nell [25] and De Villiers [66] proved that repairing leaks is one of the most effective methods to reduce compressor energy usage.

Leaks are most common at the pipe connections. The constant pressure loosens the flanges over time. Large leaks, such as where the pipes have broken off, are referred to as open ends, essentially creating a leak the same diameter as the pipe. The severity of a leak is determined with a decibel meter. The higher the decibel reading, the more compressed air is escaping. If a decibel meter is not available, the naked ear can be used. However, caution should be used when using this method, as prolonged exposure to the screeching sound a leak creates could cause hearing impairment. The following should be noted when auditing a compressed air network [25]:

- Level layout,
- Compressed air pressure at the station and down the line,
- Pipe sizes,
- Valve types and their control capabilities,
- Leaks,
- Splits in the pipeline, and
- The activity of the crosscuts.

Auditing a level is easier with a map. This assists with reporting on the findings, as the locations of leaks and other inefficiencies on the layout can be indicated. This will save time during repairs as the mining personnel will not have to search for the leak themselves or risk possible repairing of the wrong leak. The activity of crosscuts and off-branches is important. If an area is supplied with compressed air where there is no activity, it means that there is wastage.

Zietsman [70] developed a method to identify wastage inside a level. Each crosscut's inlet valve is closed in intervals to determine its effect on the overall compressed air flow entering the level. Thus, the wastage for each crosscut can be identified. An example of such a test's compressed air flow profile can be seen in Figure 17. In Zietsman's study, a crosscut was closed every 20 minutes, as indicated by the black vertical lines, to allow the flow to stabilise. The pressure for the level was constant, however, as the crosscut is closed, less flow was

required to pressurise the pipeline. This reduced flow demand results in less overall demand. In the example, the first and third crosscut had the highest flow consumption.

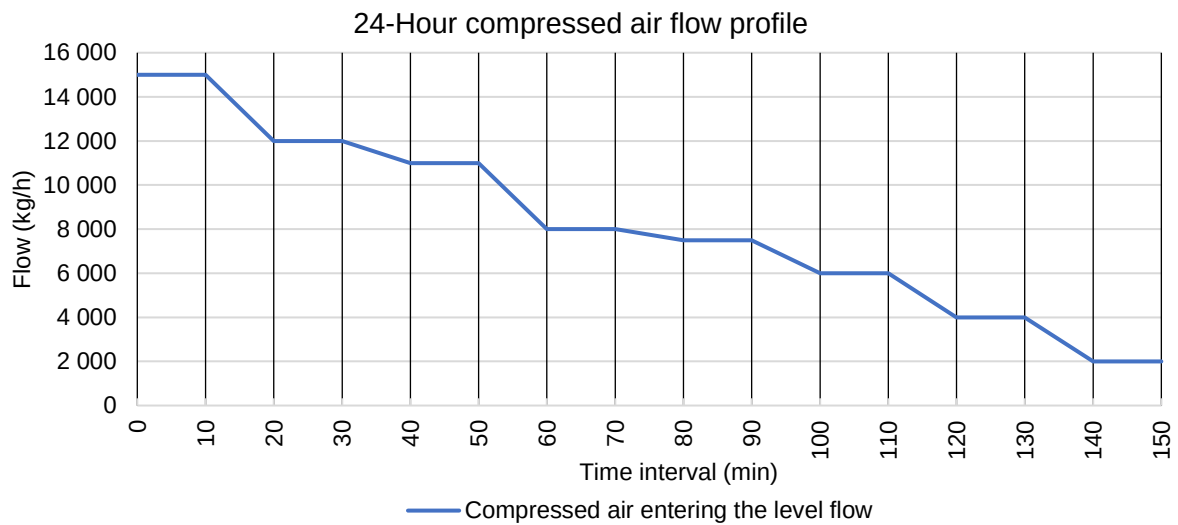


Figure 17: Effect of closing crosscuts on a level's compressed air flow consumption

Knowing which crosscuts are responsible for the most consumption allows for a more detailed audit. This will determine whether the crosscuts are still active and wasting compressed air or whether they are inactive. All pipelines leading into inactive areas should be closed off.

Thus, it would be best to prioritise the audits of inactive levels. The only consumer on these levels should be the refuge bay near the station. All the pipelines leading into the previously active level should be blanked off as close to the refuge bay tie-off as possible. Identifying these points on all the inactive levels would be faster than auditing one active level. Inactive levels are prone to be neglected and can hence contribute a high percentage to the compressed air wastage.

2.4 Supply management

As the demand is reduced, the compressors are affected by the networks, now being able to build up more pressure. The compressor is seen as the heart of the compressed air system. Thus, the compressor house must function optimally. Reducing energy on the supply side requires detailed audits of the compressor houses.

If multiple compressors are available, it would be best to start with optimising the combinations. If a network is supplied by only one compressor or all of them are online, experimenting with different combinations is not possible. However, the discharge pressure can still be adjusted to save on energy usage.

Factors such as compressor power output and guide vane range should be taken into account when considering combinations. There might be a smaller compressor or a combination of smaller compressors in the network that can provide the same discharge pressure whilst consuming less energy. This may also be a result of the guide vane control.

The compressor's guide vane regulates the amount of compressed air supplied to the network. As the network pressure builds-up, the guide vane begins to close to protect the impeller and reduces the load on the impeller motor. Once the guide vane's range limit is reached, the blow-off valve opens, discharging the excess compressed air into the atmosphere. This is high-level wastage; thus it is preferable to operate compressors with better guide vane control during low demand hours to prevent this wastage. Compressors with less control are saved for high-demand hours where the possibility of a pressure build-up is smaller.

Marais [29], Pascoe [53] and Brand [56] investigated how these compressor combinations affected the power output. An example of the power usage for two different combinations is depicted in Figure 18. The first combination used two large compressors with limited guide vane control. The second consisted of three smaller compressors with better control. Both combinations delivered the same pressure.

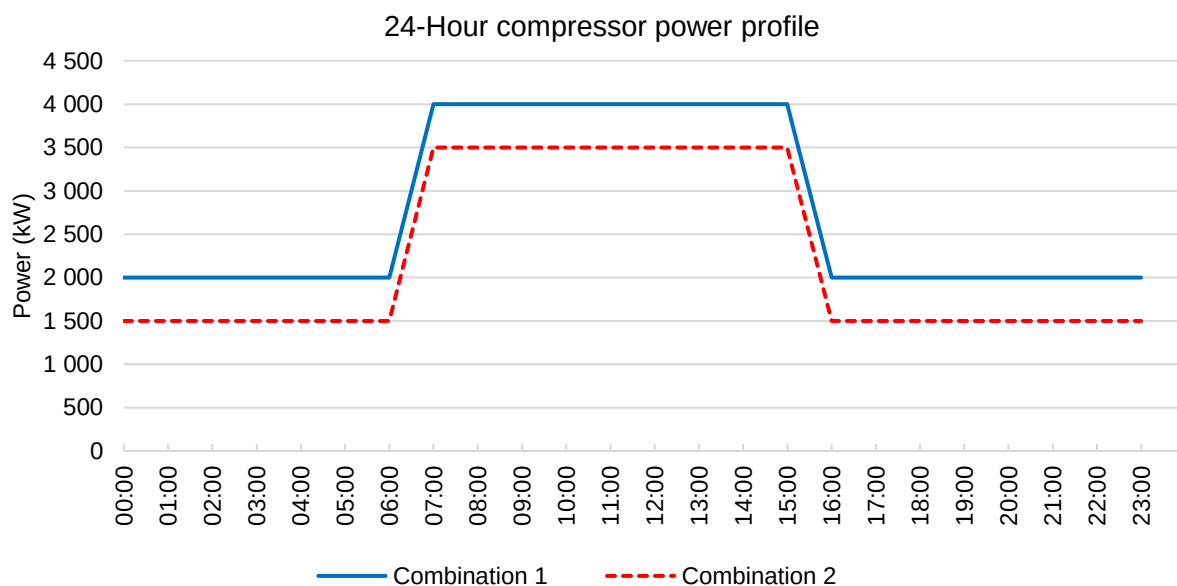


Figure 18: Comparison of two different compressor combinations

Due to the first combination's limited control, the compressors blew off during the lower-demand periods, resulting in preventable wastage. Thus, the following information is important when investigating different compressor combinations [29]:

- Number of compressors,
- Compressor capacity,
- Pressure set-point ranges,
- Guide vane control, and
- Compressor reliability.

Knowing which compressors are available to experiment on and the number of compressors is a large factor in constructing compressor combinations. Not all compressors can cut back to the same extent. Thus, it is essential to know each compressor's capabilities. All this information can be retrieved from the surface engineer.

2.5 Optimising compressed air network

Even with running the best combination, there are still issues on the supply side. There are situations where the supply does not match the demand. When operating only one compressor cannot meet the pressure requirements but operating two compressors leads to oversupplying, replacing the machines with a combination of smaller ones would resolve this issue. However, this is a costly method. Alternatives to match the demand and supply should be considered before this.

One feasible solution would be to integrate two previously isolated compressed air networks. If the networks are integrated, further supply and demand reduction options can be revisited. An extensive investigation should be launched into the compressors' capabilities before adding additional pipelines.

2.5.1 Integrating networks

Integrating networks is essentially connecting two or more compressed air networks with a pipeline, making it possible to supply consumers from any connected compressor house. Due to the complexity of these integrations, simulations are sometimes used to test the feasibility. The following information is required before compressed air networks can be integrated [72]:

- Shafts to be integrated,
- Need for integration,
- Location to be connected,
- Existing pipelines,
- State of the pipelines,
- Effect on the underground pressures,
- Effect on the compressor energy, and
- Integrated compressor operations.

Integrating networks can be a challenge. There are limiting factor such as the compressors' capabilities, that is, whether they will be able to supply all the shafts with compressed air. Hence the importance of feasibility investigations. Knowing which shafts are to be integrated and where, contributes to the feasibility. It will be necessary to investigate the pipelines between the shaft and take note of their condition. Infrastructure is known to be a limiting factor in integration. Investigating the reason for the integration could indicate potential issues that could possibly not be solved by integration. Other less costly options than integrating shafts to improve compressed air systems exist, as discussed earlier in the chapter.

A main concern with integrating shafts is the large demand increase on the compressors, if the mine plans to operate less than before. This demand could result in lower supply pressure or lead to more compressors running. All these factors can be investigated through simulations ahead of time, as will be described later.

Another issue with integration is communication. It is critical to create a procedure for opening lines and switching off compressors in the correct order. If a compressor is shut down prematurely, it could lead to areas having no pressure. How to create such a procedure is also discussed later in this chapter.

2.5.2 Throttling large-scale networks

Once the networks are integrated, previous demand reduction methods can be revisited. One valuable method is throttling an entire section of the ring-feed section. This can be done by installing control valves and implementing schedules on them as previously discussed. This will mimic the effect of reducing the delivery pressure for a level, as proven by Joubert [71].

2.6 Utilising simulation

Using simulation to determine the feasibility of high-risk projects such as integration is encouraged, as seen in studies by Mare [72] and Van Niekerk [73]. By building a simulation, different options can be experimented on with without any physical effect on or risk to the workers. Consider integrating networks as an example – there may be a situation or compressor combination that could place the worker's safety at risk or a situation where the compressors cannot supply enough pressure when opening new areas. The last instance may lead to reduced production or, in severe cases, the failure of safety precaution equipment.

2.6.1 Compiling baselines

Building a simulation requires creating baseline, that is, a foundation against which different scenarios can be compared. All baselines should be verified, meaning the accuracy between

a simulated baseline and the current operations should be compared. The accuracy can be improved by calibrating the simulations more finely. The rule of thumb for calibrating a simulation is a range of 95% accuracy. The baseline should incorporate the following [73]:

- The compressor houses details,
- The pipe network details,
- The consumers' details,
- The control valves details, and
- A common daily power usage profile.

2.6.2 Experimentation

The requirements for the simulations must be set before the different scenarios can be created. These requirements include the outcomes for the simulation and what the simulation should prove or achieve, for example, to reduce compressor energy by adjusting certain aspects in the baseline. The simulation will indicate how these changes affect the system. Another example of an outcome is how is the compressed air delivery pressure is affected by changing compressor combinations, or how the underground pressure is affected by integrating networks.

2.7 Implementation

Once a preferable result has been reached, investigations can be launched to implement or install the chosen scenario practically. Be cautious of the cost concerning the scenario. Logically, it would not make sense to install a more costly scenario if the rewards are close to that of a low cost one. Calculating a pay-back period value is an effective method for motivating feasibility.

2.7.1 Physical testing

The testing procedure depends on the changes made to the baseline simulation. The applied changes should be laid out in a series of steps which would not place anyone in harm's way. These steps should be discussed with the person in charge of the site and equipment which the simulation is based on. A testing procedure should be created based on these discussions. The procedure should state each person's responsibility, schedule, and to whom they should report.

After each person has completed their task according to the steps, they should contact one person whose main responsibility is to manage the tasks, who, in turn, should contact the next person on the list to begin their task. This would then be repeated until the test is finished. After a test has been completed, the steps should be followed in reverse to achieve the original

operations. Once the test procedure is approved, a date can be set to for the test. In the case of a failed test, the issue should be addressed, and the procedure should be re-evaluated.

2.7.2 Validating the impact

Determining the impact of the test is important. This validates the simulation's feasibility and whether the simulation was implemented correctly. Before the test, a baseline should be created from historical data found on the SCADA system. Pressure and flow are measured by the transmitters which are also used for controlling the actuated valves. Power data, such as the compressors' usage, is measured with power meters. The baseline data should be compared with data from the same equipment during the test to determine the impact. This can be displayed in multiple forms such as graphs and tables.

Chapter 3: Results and discussion

3.1 Operations

The case study focuses on two deep-level gold mine shafts – a compressed air shaft (Mine A) and a hydropower shaft (Mine B). The compressed air demand for Mine A fluctuates throughout the day. There is a higher demand during peak drilling and loading hours. During the low-demand hours, the shaft consumes a minimum amount of compressed air, feeding only the refuge bays. With Mine B, compressed air is used mainly for the refuge bays. Thus, Mine B has a constant low demand.

However, the Mine A's compressor house also supplies a gold-processing plant (GP) with compressed air for instrumentation and agitation. The plant requires a high pressure of at least 420 kPa for instrumentation and high flow for agitation. This complicates the operation of Mine A's compressor house discussed in more detail later, whose compressors must balance the GP high demand with Mine A's low demand at times.

Investigations were launched into reducing the compressor energy consumption for both shafts. The steps taken to achieve this is described below.

3.2 Reducing consumer wastage

3.2.1 Control schedules

The first step taken to reduce the compressor energy was to implement a proper control schedule. The compressed air could only be throttled for Mine A, as all the shaft's underground levels have control valve installed. The actuators are installed on the main and bypass valves leading into each level. As the air is throttled, less compressed air is needed from the compressors, which in turn forces the compressors to reduce motor speed and thus energy consumption.

The pressure set point for the main production levels on Mine A was updated, as seen in Figure 19. The pressure data was downloaded from the SCADA system and displayed over a 24-hour period. The blue line in the graph indicates the baseline that was set for the schedule changes while the red line indicates the updated schedule. For example, the compressed air pressure supplied to 40L was throttled to 150 kPa for a longer period in the evenings. A pressure reduction during the morning period was also implemented. Similar changes were implemented on all the production levels.

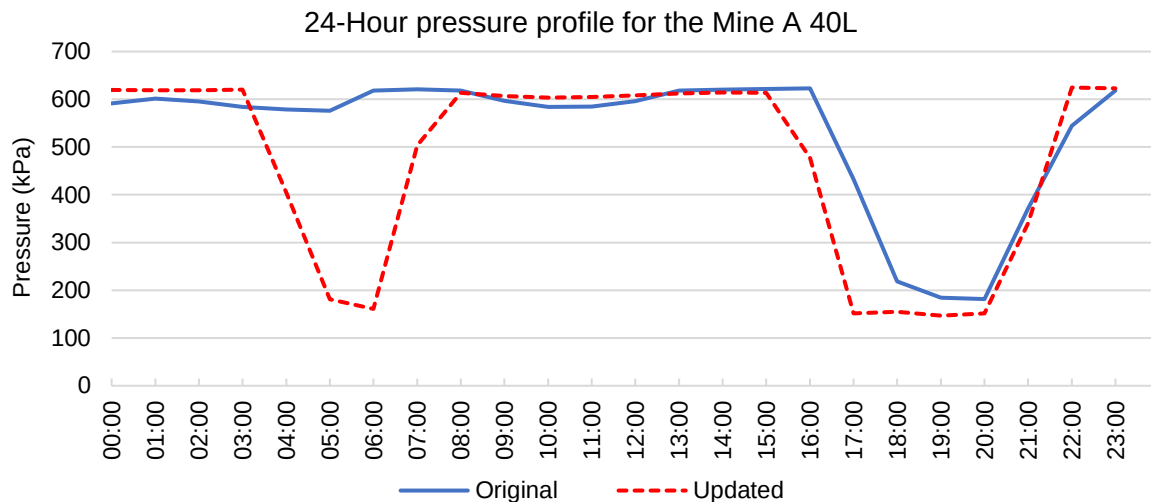


Figure 19: Schedule changes for the compressed air pressure of Mine A 40L

3.2.2 Underground audits

The next step was to audit the underground level. The levels had to be prioritised to optimise the auditing time. As discussed in the methodology, a ratio for the pressure difference was created for the active levels. However, with the assistance of the updated compressed air schedule, the ratio was already at a minimum, meaning that the levels could not be prioritised effectively in this manner. Thus, the production was compared to the flow of each level, although this could also not be implemented effectively as there is only one scale before the ore reaches the surface. Nevertheless, this investigation helped us to identify that the inactive levels had an unusually high flow without any production. The inactive levels were prioritised based on their flow.

The inactive levels, namely 26L and 29L were problematic because they were never fully closed off and therefore compressed air was supplied to neglected levels with weak infrastructure. Both levels had a high flow with low pressure. This could mean that a line might have had an open end, so the pipe could not build pressure, thus using more flow to rectify this.

The main valve on 26L was fully open with the bypass set to 50% open. The main valve was closed with the bypass set to 10% open to supply only the station refuge bay with compressed air. Only the bypass valve was open on 29L; however, the gate valve situated before the valve leaked from the bottom of the body, meaning that the valve could no longer effectively isolate the level. The compressed air pipe which was fed from this valve was broken off inside the level, causing a 200-mm open-ended leak. The gate valve was throttled, but the bypass valve was left open because there was a concern that the pressure increase could damage the gate valve even further. The effects of both audits can be seen in Figure 20 and Figure 21.

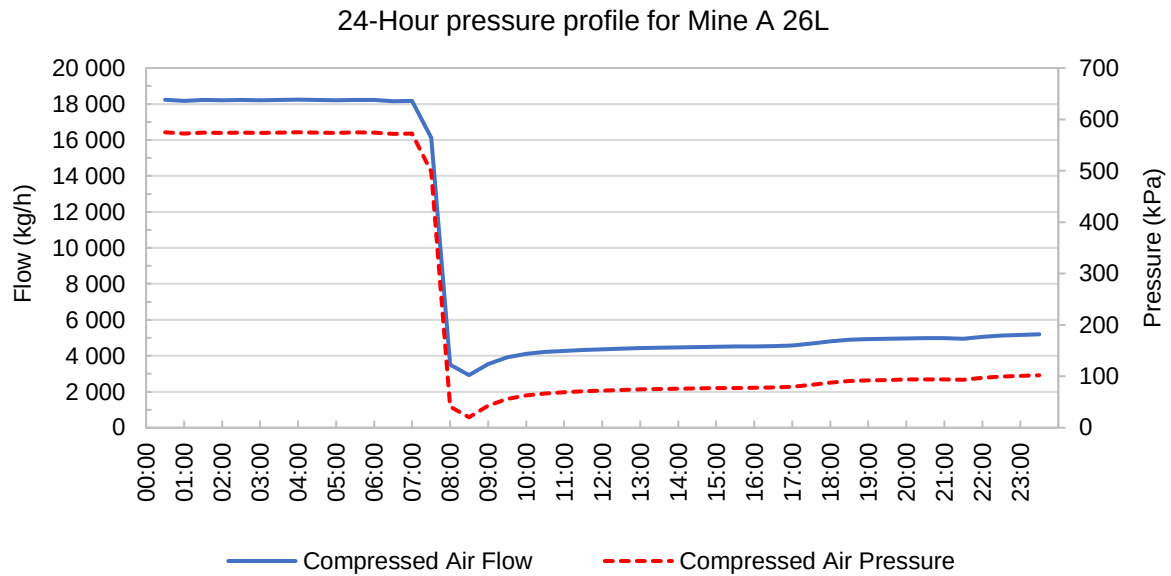


Figure 20: Audit results for the compressed air changes of Mine A 26L

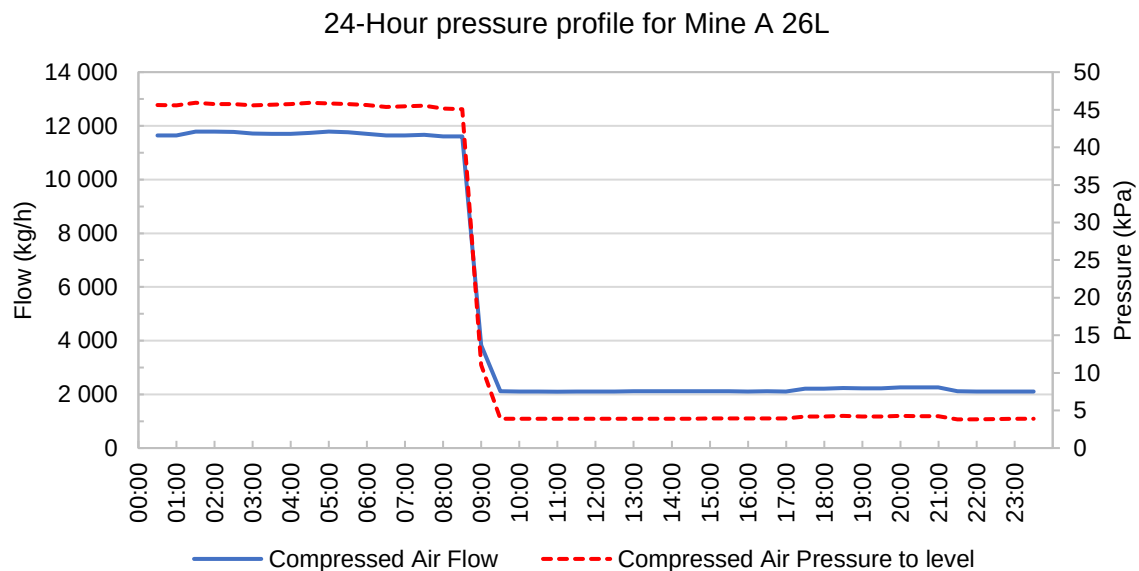


Figure 21: Audit results for the compressed air changes of Mine A 29L

Both graphs display the flow and pressure for the audit date over 24-hours. One line indicates the compressed air flow plotted on the left y-axis, and the other the compressed air pressure plotted on the right y-axis. This was done in a way that would allow us to observe both decrease at the same time. The large drops on both graphs were due to the changes during the audits at around 08:00 and 09:00 on 26L and 29L, respectively. The wastage on these two levels alone was decreased by more than 20 000 kg/h. It should be noted that the 29L pressure is lower than the minimum 150 kPa, as the pressure transmitter is installed after the isolating valve. Closing the valve reduced the pressure further down the line.

The initial investigations started in May 2019. Thus, the operations in May were chosen as the study's baseline. The first investigations, audits and implementations into demand reduction were concluded in November 2019. Figure 22 depicts the 24-hour power profile for the Mine A compressors before and after the demand reduction.

A clear clip in power usage can be seen in the morning and evenings of November 2019 when comparing the red and the blue baseline lines on the graph. This clip was caused mostly by using proper control schedules. The average power usage per day was reduced by 547 kW, resulting in an average usage of 6 056 kW per day. This is equivalent to an approximate cost saving of R 5.25 million per annum.

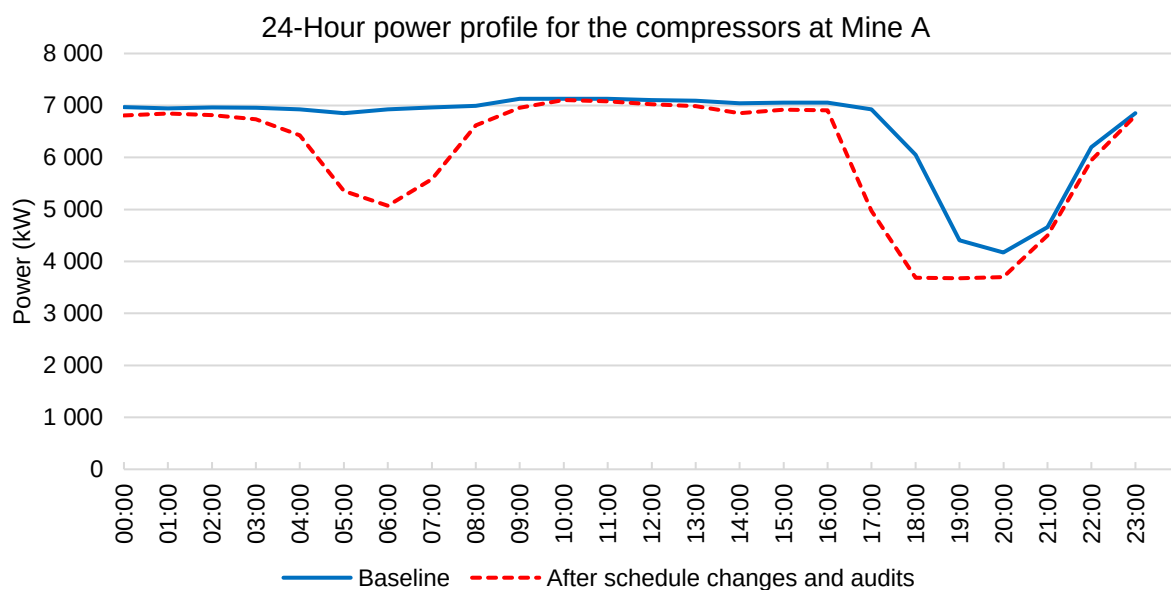


Figure 22: Power comparison before and after stage one demand reduction

3.3 Supply issues

Most of the demand reduction was done at Mine A, as Mine B has no control valves underground. Thus, more time was spent on investigating the Mine B compressor house supply reduction. The same was done for the Mine A compressors.

The Mine A compressor house consists of four compressors, two 4.2-MW Sulzer machines, one 4.2-MW Demag, and a 3.75-MW GHH. These compressors supply Mine A as well as GP with compressed air. The Mine B compressor house only has one 4-MW Sulzer machine in operation.

Two compressors are operated at the Mine A compressor house during high-demand hours and only one compressor during the low-demand hours. However, the low demand is below

the compressor's minimum supply, which causes the compressors to blow off the excess air back into the atmosphere. This is seen as wasted energy. The same happens during the high-demand hour with two compressors running. Unfortunately, the demand is too high for just one compressor and not enough for two.

The Mine B compressor was operating at 2.8 MW by setting the guide vane angle to 18%. The compressor consumed less energy but required frequent maintenance because operating at such low angles causes unnecessary stress on the machine.

3.4 Network layout

As the compressors for each shaft were too large for the respective network, investigations were launched into merging the networks. There was an abandoned underground compressed air pipeline between the two shafts. Mine B was originally also a compressed air shaft. During this time, Mine A assisted in supplying Mine B with compressed air.

The pipeline is situated on 23L, approximately 1.8 km below the surface. The pipe runs from Mine A to Mine B via a third shaft (Mine C). Since Mine B was converted to a hydropower shaft, the line was closed and the shafts were isolated. Figure 23 shows the underground layout of the compressed air pipes as seen from above. Figure 24 represents the compressed air layout between the shafts, compressor houses, and GP from the side.

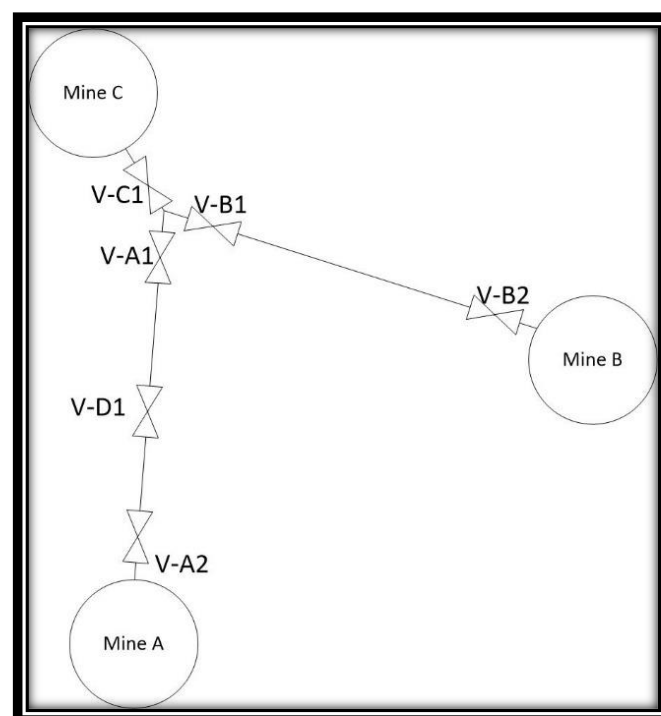


Figure 23: Compressed air network side view top view

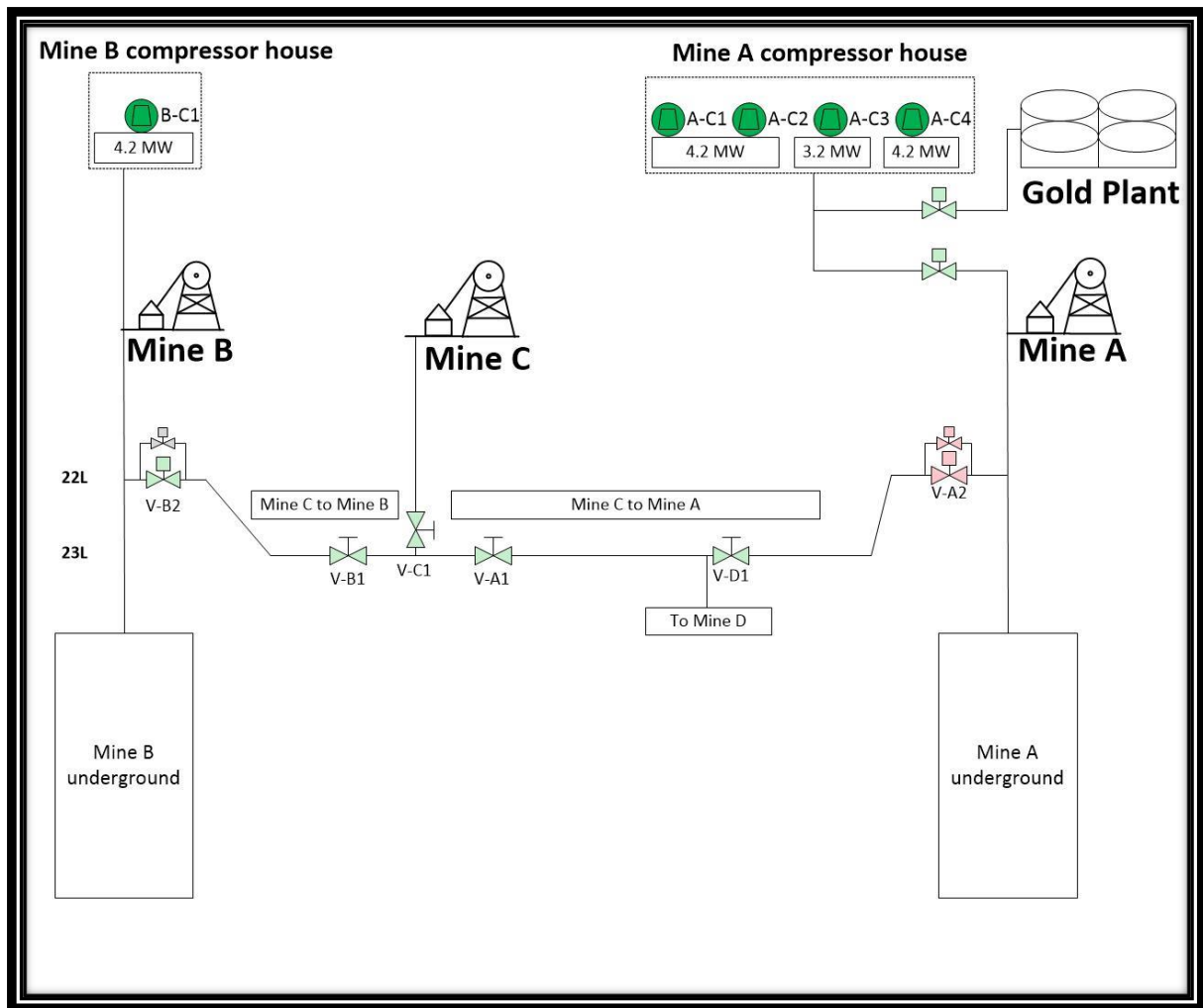


Figure 24: Compressed air network side view

The V-A2 valve configuration at Mine A consists of a main and bypass valve. Both valves are controlled by actuators. The same setup is found at valve V-B2, where only the bypass valve has an actuator installed. Valve V-C1, V-B1, V-D1 and V-A1 are manually operated. These manual valves are used to isolate the shaft networks.

Due to the complexity of the system, simulations were used to determine the possibility of the integration. Thus, scenarios could be tested safely without placing anyone underground in danger by undersupplying the refuge bays. Any pressure problems which would negatively influence the production can be investigated ahead of time.

3.5 Simulating the network

3.5.1 Building and verification

The simulation would depict the power consumption for each compressor, the Mine A surface pressure, flow, and the Mine B 39L pressure. The 39L compressed air pressure meter is the first pressure transmitter on Mine B below 23L. The reader is allocated at a depth of approximately 3 km, so some auto compression can be expected. PTB® was used to create the simulation due to the availability. A basic model of the Mine A and Mine B compressor houses was created with additional detail such as the line between the shafts. The compressor houses can be seen in Figure 25 and Figure 26.

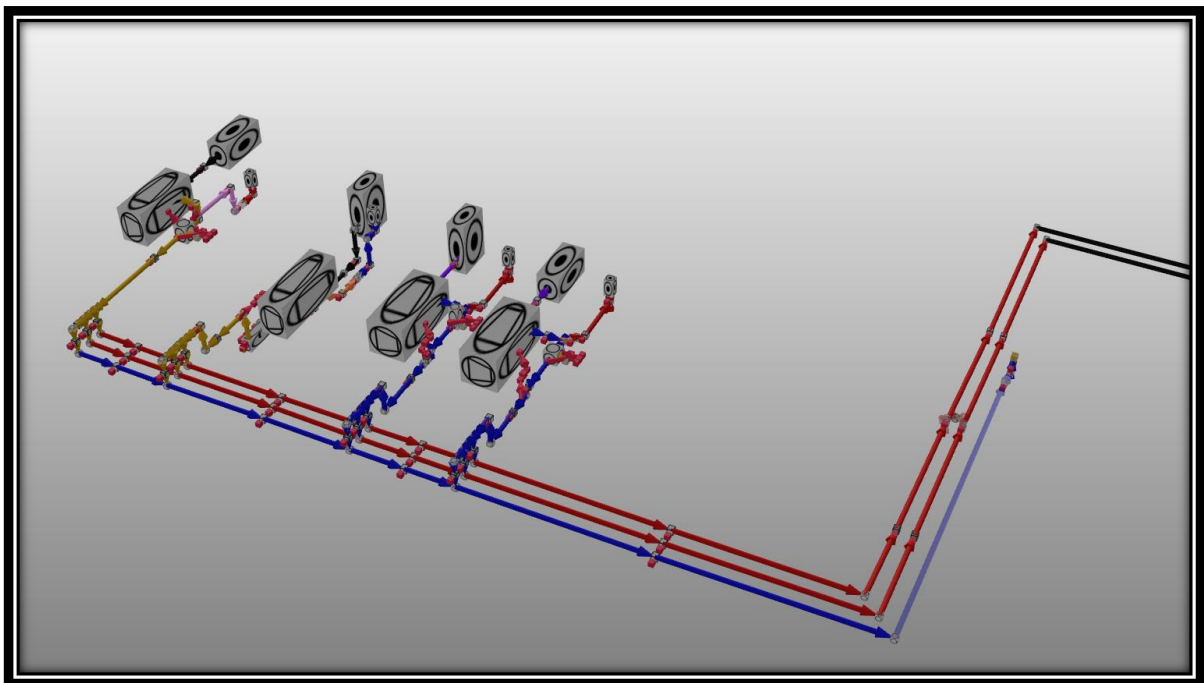


Figure 25: Simulated model of Mine A's compressor house

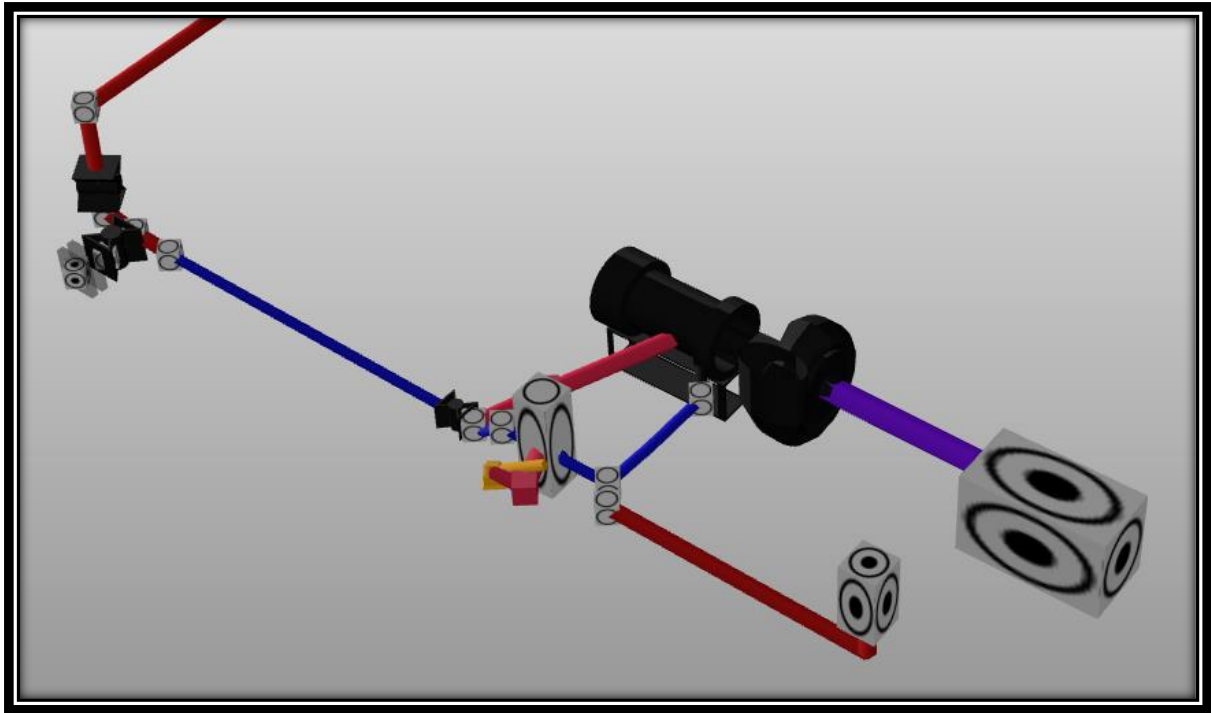


Figure 26: Simulated model of Mine B's compressor house

The model was expanded to include the underground levels of both mines to assist with calibrating the demand. The simulation had to be calibrated to create an accurate baseline. The baseline would be used as a comparison for all further investigations done by using the simulations. PLC controllers were added to each level as well as the compressor houses with a set point based on actual data from the case study's SCADA historian. Only the on and off status of the Mine A compressors had to be adjusted through trial and error to mimic the actual power profiles. The simulation was calibrated to an accuracy of 99.6%. A comparison of the simulated and actual baseline can be seen in Figure 27. The red line generated by the simulation follows the blue line's profile created from actual data.

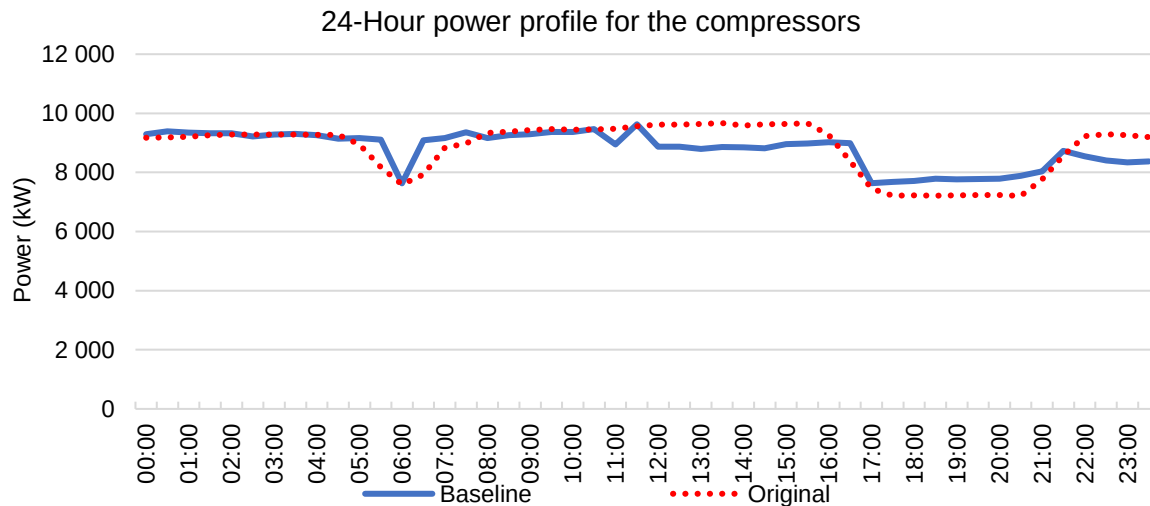


Figure 27: Comparison of simulated and actual baseline

3.5.2 Testing feasibility

The calibrated simulation was used to test the project's feasibility. The surface pressure at Mine A was taken as the main limiting factor. If the plant pressure is insufficient, gold production will suffer, making the production dependant on Mine A's surface pressure. The first scenario indicates the effects of Mine A is supplying Mine B with compressed air, with an additional compressor running during high demand hours. The Mine B compressor would be offline with the Mine A 22L V-A2 valve fully open. Figure 28 depicts the 24-hour power profile for the compressors after scenario 1. All the graphs below were plotted over a 24-hour profile with data generated by the simulation. The blue line depicts the baseline and the red line the results from scenario 1.

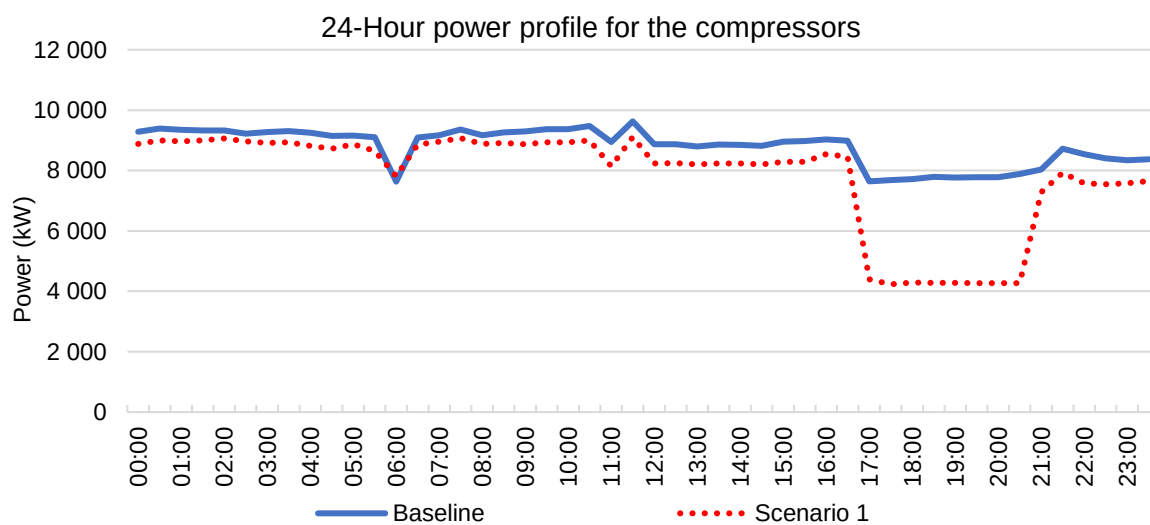


Figure 28: Simulation results of scenario 1 for the compressor's power usage

Switching off the compressor at Mine B reduced the overall compressor power significantly. This could only be observed in the low-demand hours, with the red line being almost 4 MW lower than the baseline line. Three compressors were left running to account for the increased demand for the rest of the 24-hour profile. Figure 29 depicts the 24-hour surface flow profile for the Mine A as a result of scenario 1.

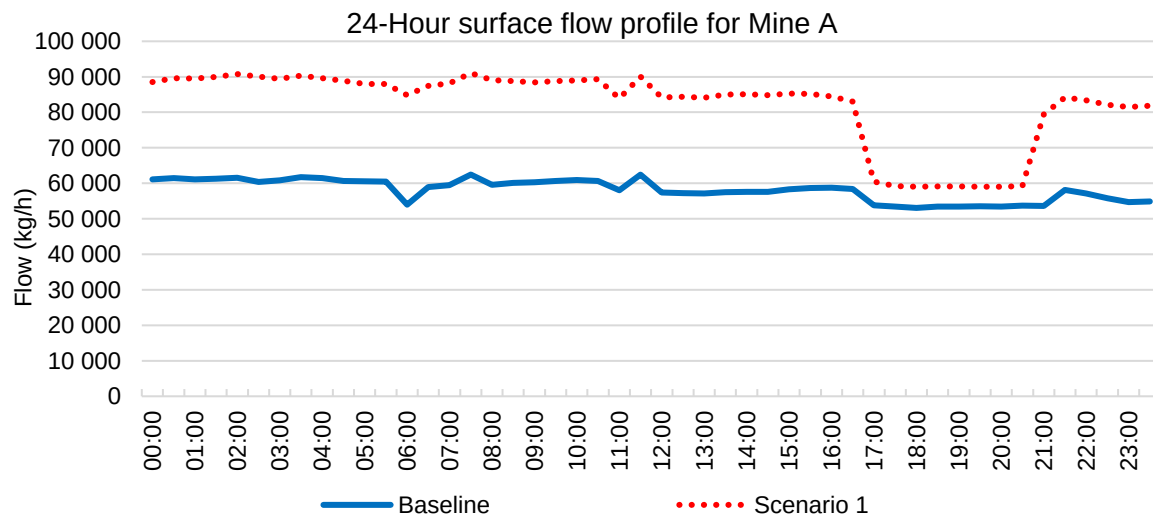


Figure 29: Simulation results of scenario 1 for the compressed air surface flow of Mine A

The compressed air flow supplied to Mine A was expected to increase, as it must pass through the main column to reach 22L. From here it travels to Mine B. This increased flow demand is evident on the surface flow of Mine A. The red line, indicating the flow during scenario 1, increased by 30 000 kg/h over the blue baseline line. Figure 30 depicts the 24-hour station pressure profile for the Mine B 39L of scenario 1.

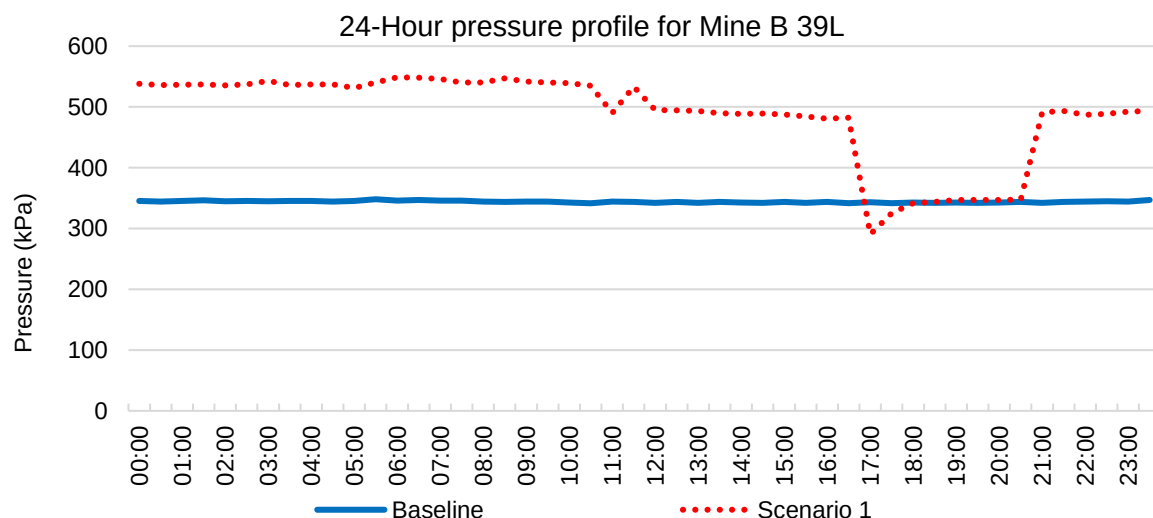


Figure 30: Simulation results of scenario 1 for the compressed air pressure of Mine B 39L

Even though the compressed air flow was high with the third compressor, a similar flow was supplied during the low-demand hours. A likewise trend was seen on the 39L station pressure at Mine B. The station pressure was higher than the baseline, much higher than the minimum requirements. Figure 31 depicts the 24-hour surface pressure profile for Mine A after scenario 1.

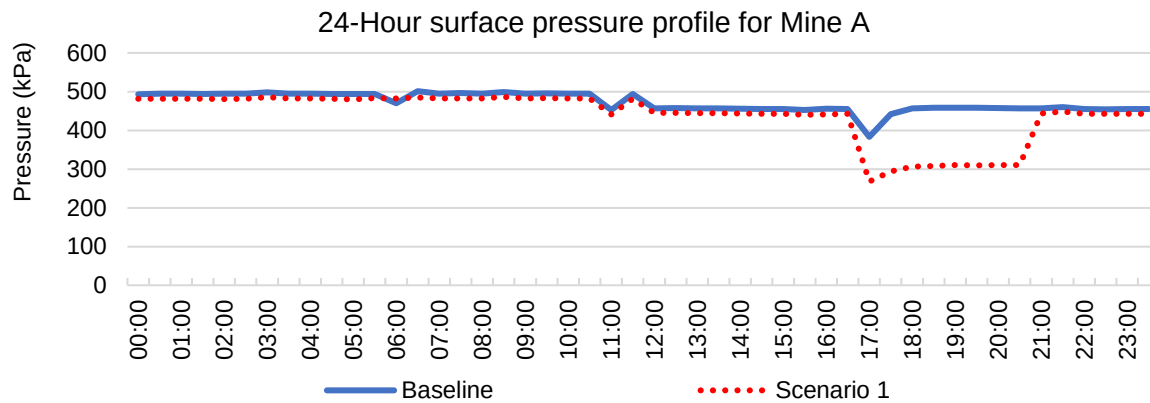


Figure 31: Simulation results of scenario 1 for the compressed air surface pressure of Mine A

Scenario 1 was able to reduce power and supply enough flow and station pressure at Mine B. However, the surface pressure at Mine A was below the set limit during low-demand hours. The increased demand resulted in a surface pressure drop, as seen with the red line being lower than the blue baseline line, leaving GP with insufficient compressed air for their equipment. This means that scenario 1 could work but would affect the production.

Thus, scenario 2 was simulated where the Mine A 22L V-A2 valve was set to control the supply to Mine B at only 200 kPa. The results for the simulation are depicted in Figure 32, which shows the 24-hour power profile for the compressors after scenario 2. The blue line in the graph below depicts the baseline the red line the results from scenario 1 already discussed, and the green line the results from scenario 2.

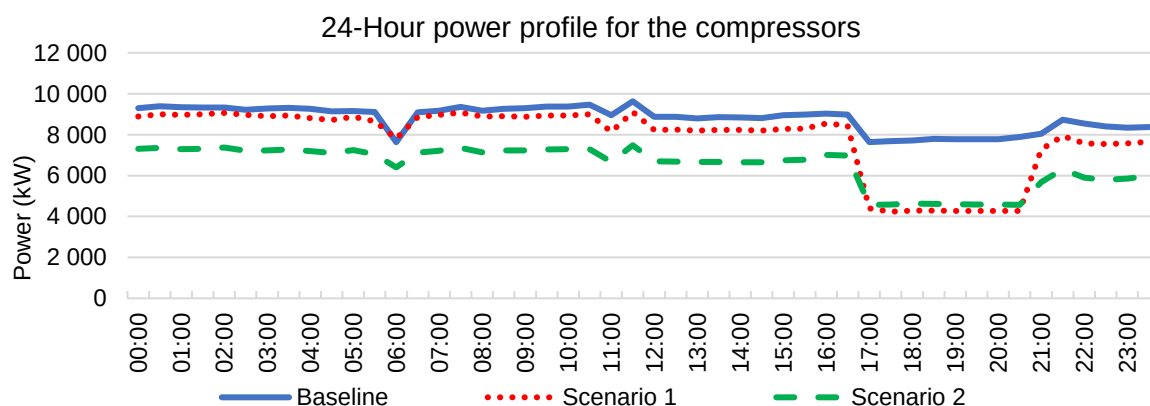


Figure 32: Simulation results of scenario 2 for the compressors' power usage

By constantly throttling the compressed air pressure supplied to Mine B, the Mine A compressors were able to operate at with more reduced power than both the baseline and scenario 1. The green line is lower than both the red and blue by 1.5 MW. However, scenario 1 and 2 had similar profiles during the low-demand hours. Figure 33 depicts the 24-hour surface flow profile for the Mine A as a result of scenario 2.

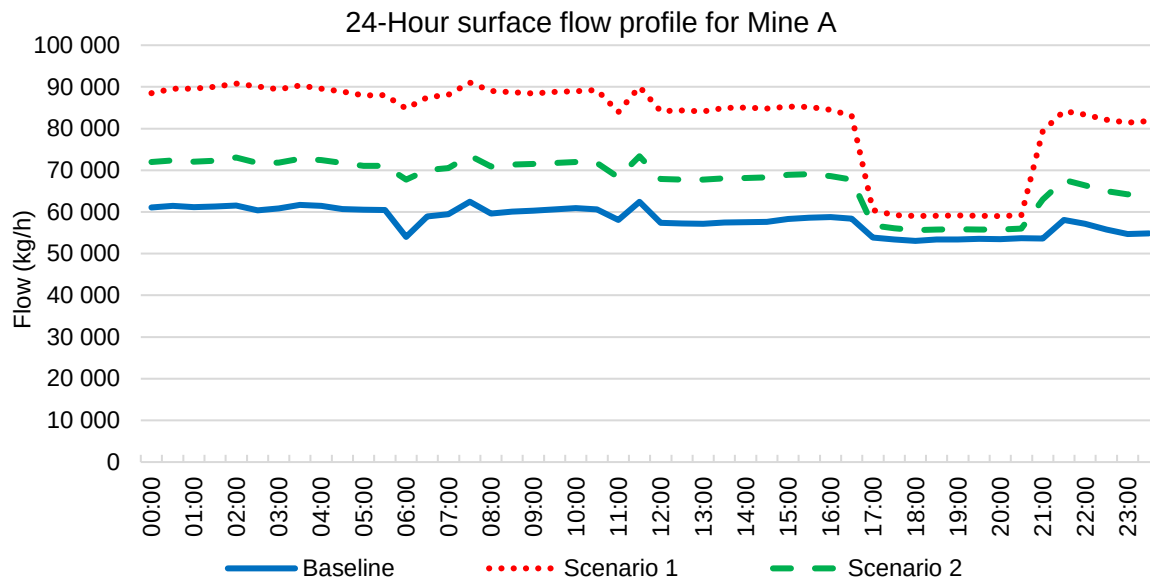


Figure 33: Simulation results of scenario 2 for the compressed air surface flow of Mine A

The surface flow in scenario 2 also decreased due to the limited supply to Mine B. The surface flow increased by 15 000 kg/h – half of the increase seen in scenario 1. Figure 34 depicts the 24-hour station pressure profile for the Mine B 39L of scenario 2.

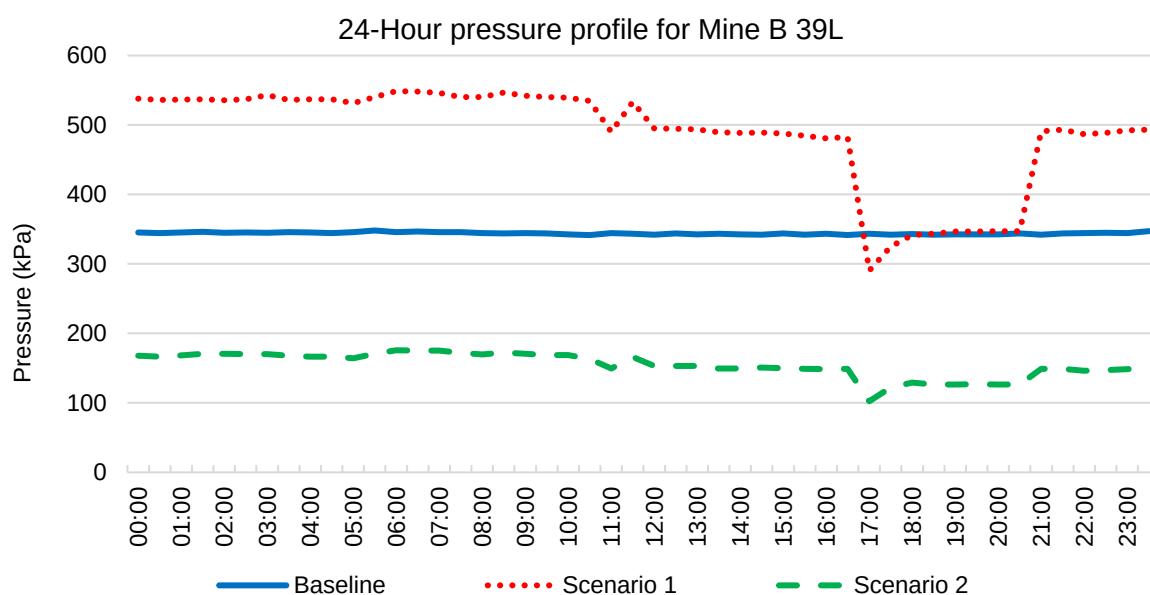


Figure 34: Simulation results of scenario 2 for the compressed air pressure of Mine B 39L

The new control resulted in a constant station pressure of 230 kPa at Mine B, which is depicted by the green line. This is more than the set-point due to the auto compression. This is still more than enough to supply the hydropower shafts' refuge bays with the minimum legal limit of 150 kPa. Figure 35 depicts the 24-hour surface pressure profile for Mine A after scenario 2.

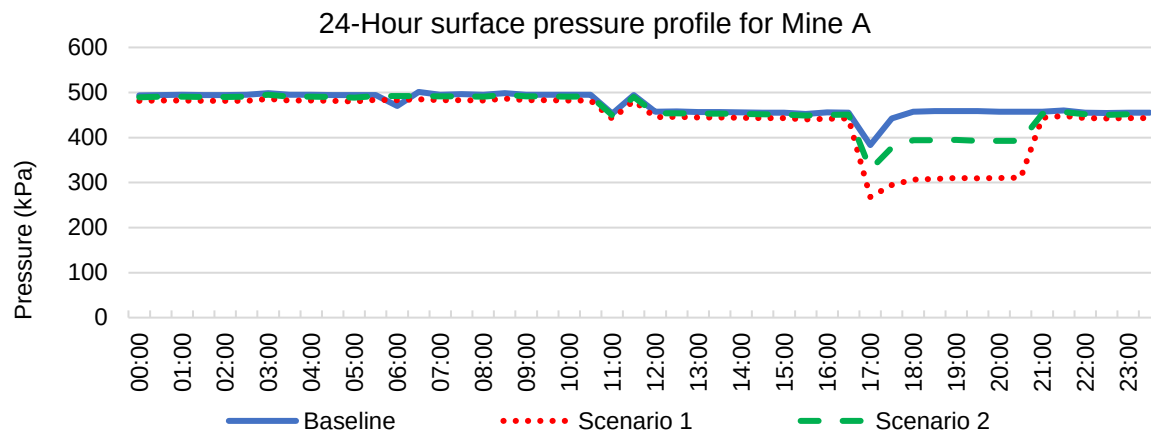


Figure 35: Simulation results of scenario 2 for the compressed air surface pressure of Mine A

Scenario 2 also provided adequate flow and station pressure while reducing power. However, the problem of low surface pressure during low-demand hours could not be solved by implementing a pressure set point for Mine B, as it was still affecting the production by providing insufficient compressed air to GP.

This gave way to scenario 3, where an additional compressor was operated during the low-demand hours. The blue line in the graph below depicts the baseline, the red line the results from scenario 1, the green line the results from scenario 2 already discussed, and the black line scenario 3. Figure 36 depicts the 24-hour power profile for the compressors after scenario 3.

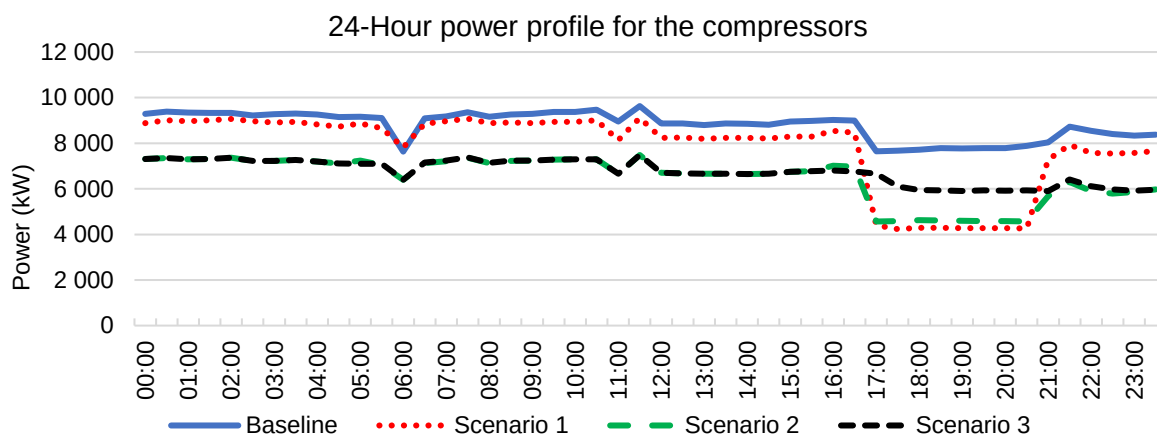


Figure 36: Simulation results of scenario 3 for the compressor's power usage

The continuous operation of a third compressor resulted in an increased power consumption of 1.5 MW during the low-demand hours. The power indicated by the black line was between that of the baseline and the previous scenarios – it was still 1.8 MW less than that of the baseline. Figure 37 depicts the 24-hour surface flow profile for the Mine A as a result of scenario 3.

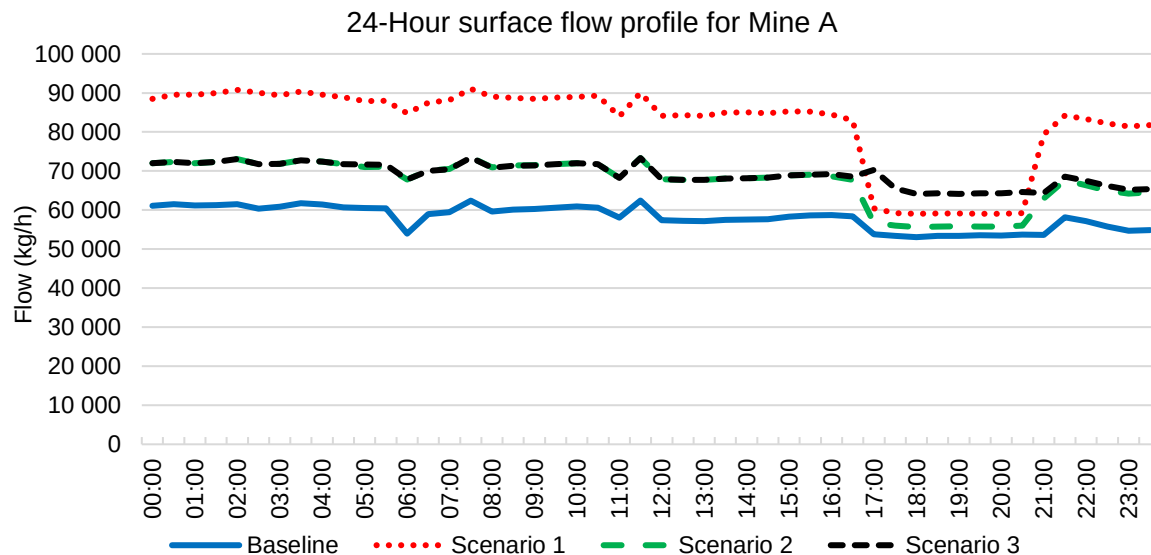


Figure 37: Simulation results of scenario 3 for the compressed air surface flow of Mine A

The high-demand hours of the surface flow mimicked scenario 2, which was expected as the supply to Mine B was limited. The only change between the black and green lines was an 15 000 kg/h increased flow in the low-demand hours. Figure 38 depicts the 24-hour station pressure profile for the Mine B 39L of scenario 3.

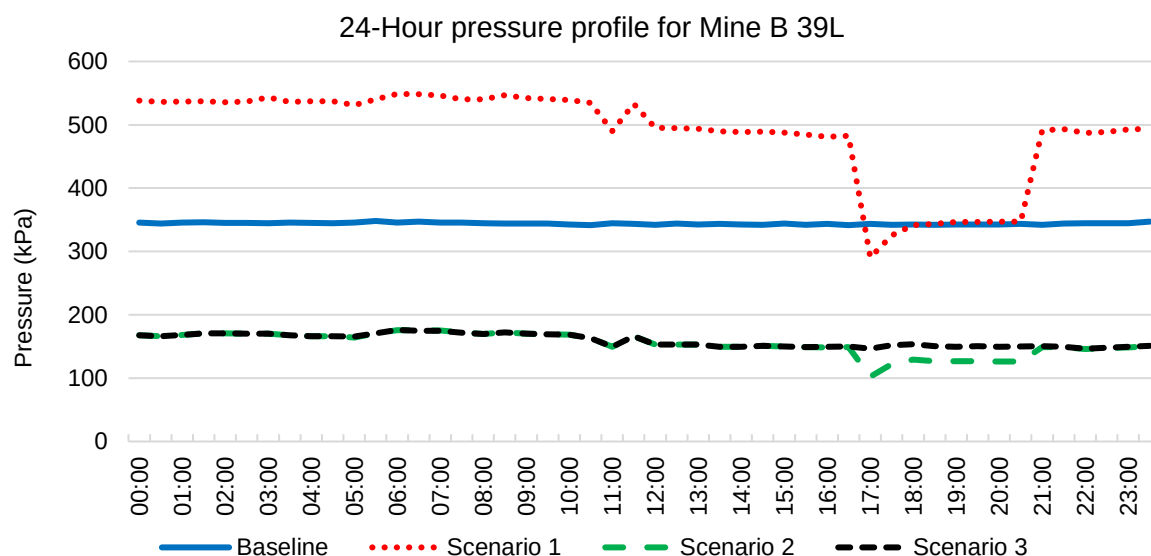


Figure 38: Simulation results of scenario 3 for the compressed air pressure of Mine B 39L

The station pressure at 39L Mine B in scenario 3 was more stable than that of scenario 2 due to the additional compressor. The rest of the profile was similar, as the pressure for both scenarios were throttled. Figure 39 depicts the 24-hour surface pressure profile for Mine A after scenario 3.

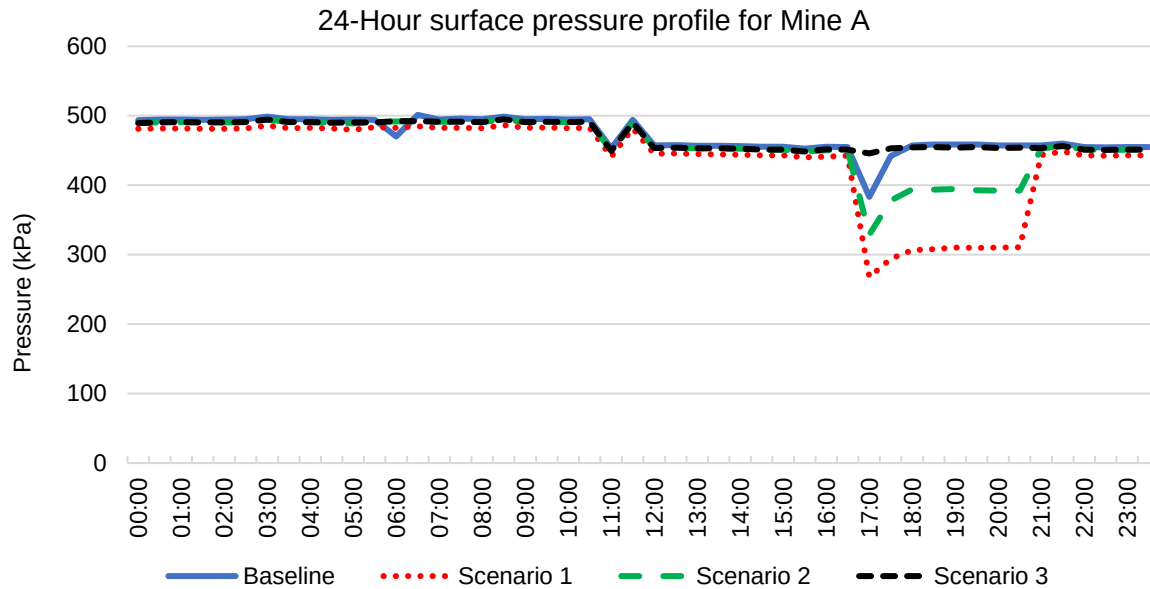


Figure 39: Simulation results of scenario 3 for the compressed air surface pressure of Mine A

Scenario 3 was able to reduce the compressor energy and supply enough pressure to Mine B and GP. The main issue of a pressure drop was solved during scenario 3, with the assistance of a third compressor and the 22L valve controlling, and all the parameters were met. This implies that that scenario 3 was the most feasible and would form the basis of the tests.

3.6 Validation through tests and implementation

Once the simulation proved that the integration was possible, the physical test could begin. Two test procedures were compiled for normal and maintenance conditions. During normal conditions, the shafts are isolated, meaning that the Mine B compressor supplies Mine B with compressed air. However, during this testing period, the Mine B compressor was offline for maintenance. Thus, Mine C was responsible for the compressed air supply. A similar testing procedure for normal operations can be found in Appendix B.

The testing procedure for maintenance conditions was as follows:

1. The engineer and control room operators of each shaft as well as Central Control were informed that the test would begin.
2. Central Control contacted the Mine A personnel to open their valves.

3. The Mine A personnel opened valves V-A2 and V-D1. The V-A2 valve schedule was set to the desired pressure.
4. The Mine A personnel contacted Central Control once their valves were open.
5. Central Control contacted the Mine C personnel to open valves V-B1 and V-A1 and close valve V-C1.
6. The Mine C personnel contacted Central Control once they were done.
7. Central Control started an additional compressor at Mine A.
8. The pressure and compressor power were noted and the pressure stabilised.
9. The engineer and Central Control were informed that the compressed air pipeline would be closed.
10. Central Control contacted the Mine C personnel to close valves V-B1 and V-A1 and open V-C1.
11. The Mine C personnel contacted Central Control once the valves were closed.
12. Central Control took a compressor offline at Mine A.
13. Central Control contacted the Mine A personnel to close their valves.
14. The Mine A personnel closed valve V-A2 and V-D1. The V-A2 valve schedule was set to 150 kPa.
15. The Mine A personnel contacted Central Control once they were done.
16. This marked the end of the test.

The first test consisted of supplying from Mine A to just Mine C by opening all the valves on the line. During the second test, only the line from Mine C to Mine B was opened.

Audits were performed on the underground line while the individual lines were charged. The compressed air pressure was measured at different points to identify if the lines were charged. General leaks that were found were reported for repair. Large compressed air leaks were found at the V-D1 valve on the line between Mine C and Mine A. Problems arose with the first test as the line did not charge with a pressure higher than 100 kPa due to closed valves. The second test was successful.

After the failure of the first test, the line as well as the compressed air column feeding down the shaft to 22L was reinvestigated. The shaft replaced the supply column due to old age with an identical column. However, the line to 22L was still connected on the old column.

A 150-mm pipe was installed between the two 600-mm columns to supply 22L. This choked the compressed air entering the level. A 500-mm pipe was connected from 22L to the new column to solve this problem. Figure 40 depicts the previous and current piping layout in the shaft.

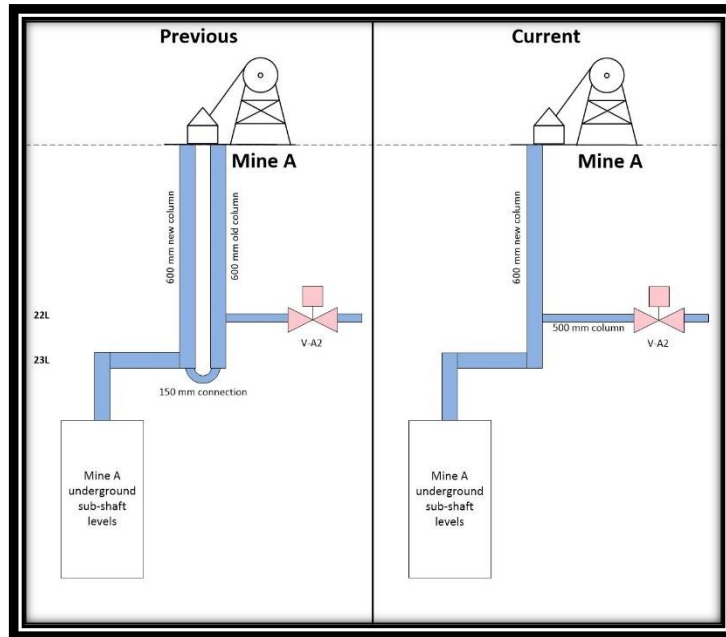


Figure 40: Shaft piping layout for Mine A

Once the new pipes were installed, the first test could be repeated. The test was successful with the new connection. A third test was created to test the control abilities of the V-A2 actuator valve. The results of which can be seen in Figure 41. The station pressure at Mine B was plotted over the test period of 30 minutes. The fact that the pressure reduced and evened out at a constant value of around 150 kPa indicated that the test was successful. The valve could throttle the compressed air flow to Mine B.

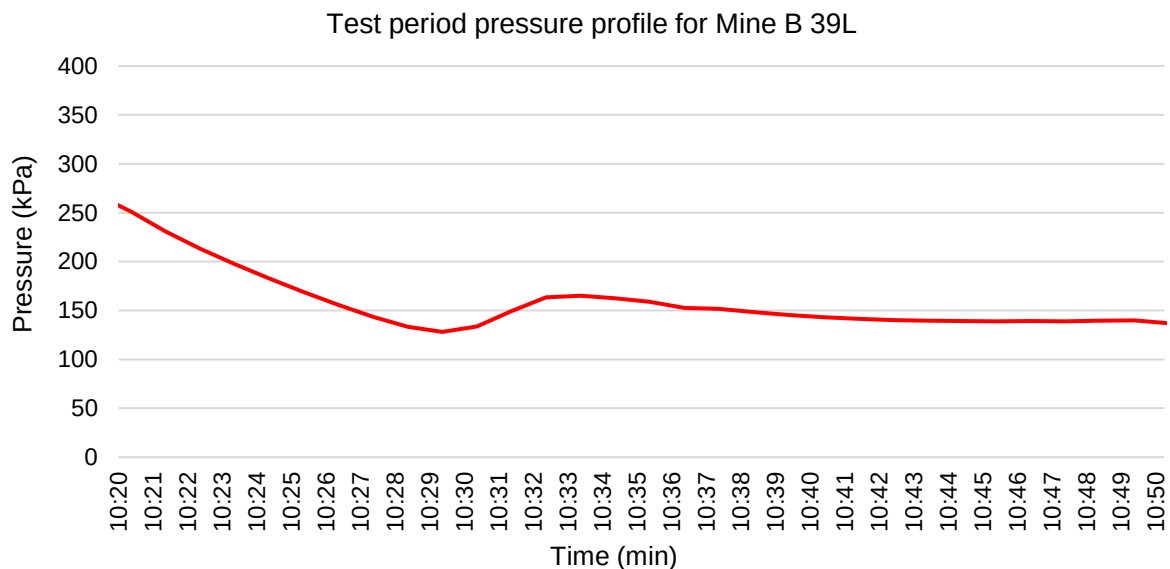


Figure 41: Compressed air pressure of Mine B 39L during the test

3.7 Comparisons

Since the tests proved that Mine A could supply Mine B with compressed air, the most feasible scenario was permanently implemented. The procedures were used as guidelines for the implementation. Constant and sufficient surface pressure was possible. The results of the integration were compared to a baseline from before it was implemented. This comparison is depicted in Figure 42.

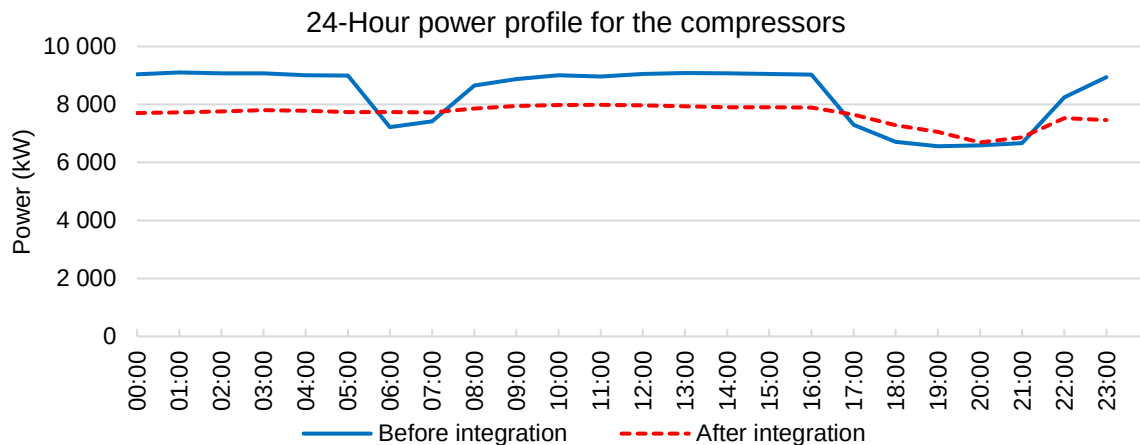


Figure 42: Power profile comparison for the compressors before and after the integration

By integrating the two shafts, the power depicted by the red line was less than the blue baseline line. Unfortunately, the morning power clip was no longer possible, as the compressed air requirements changed. The schedules had to be adjusted to supply 40L of compressed air to further develop levels during the morning shift. However, the power was still reduced by 703 kW, resulting in an approximate cost saving of R 3.89 million per annum. The results of the integration were compared to the simulation results as well. This comparison can be seen graphically in Figure 43.

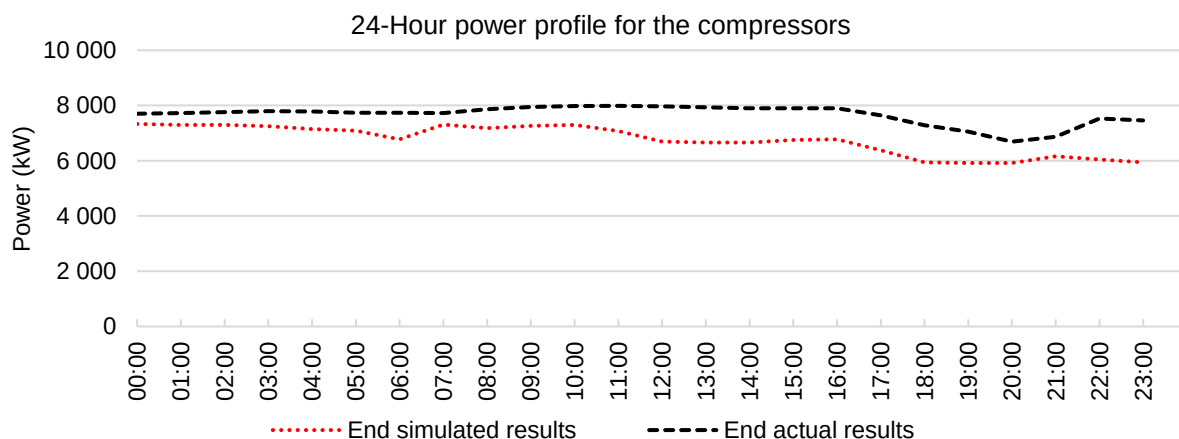


Figure 43: Power profile comparison for the compressors for the actual and simulated integration

The actual results were within 14% of the simulated values. One reason could be that the demand of Mine B was understated. Mine B consumed double the compressed air that the simulation predicted. This could be due to compressed air leaks or other wastage, resulting in a higher consumption because of leaks, wastages, or other inefficiencies. The baseline on which the simulation was built already included the schedule changes for 40L discussed above. The surface flow changes seen on Mine A are depicted in Figure 44.

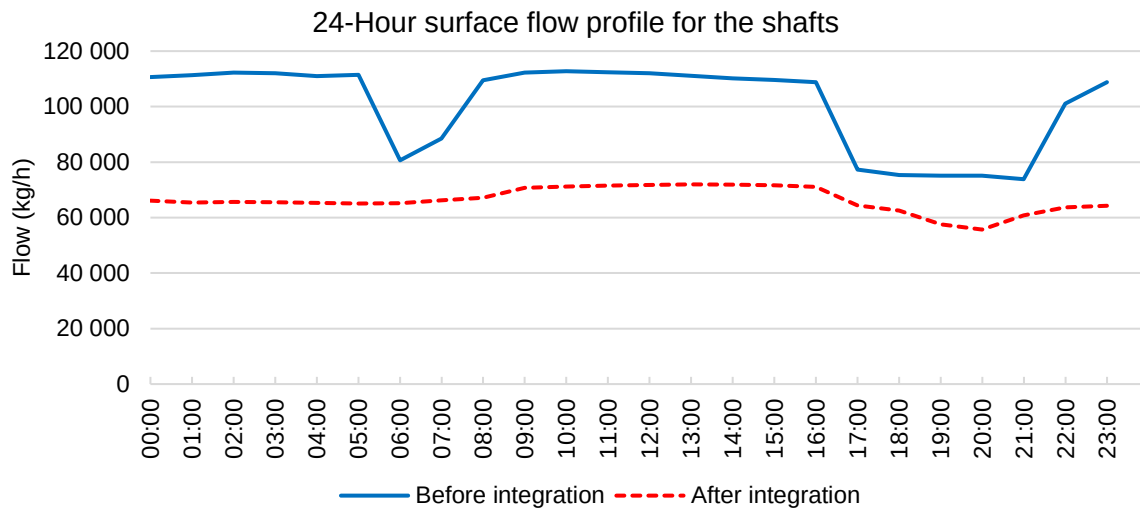


Figure 44: Compressed air profile comparison for before and after the integration

The results for the entire study were compared with the baseline from when the initial investigations began. The comparison is depicted graphically in Figure 45. The actual power usage at the end was less than that of the May 2019 baseline. The average power usage per day was reduced by 1 466 kW from the baseline, equivalent to an approximate cost saving of R 10.85 million per annum, respectively.

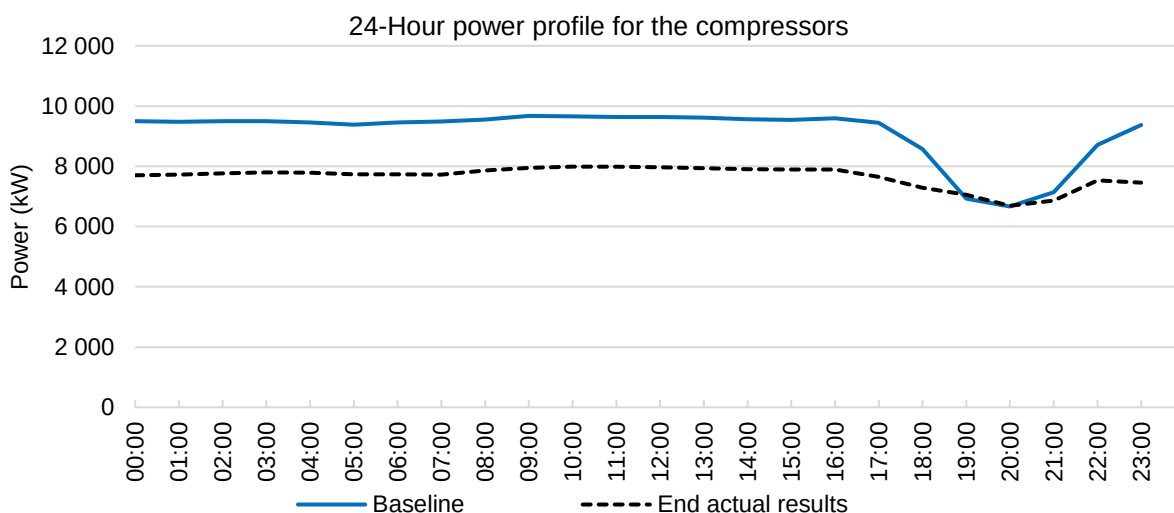


Figure 45: Power profile comparison for the compressors over the course of the study

3.8 Review of objectives

The objectives of this research were to investigate effective methods for reducing compressor energy usage. This was done by simulating the integration of compressed air networks and implementing them on a suitable mining site. The results discussed above proved that the methods were more cost-effective than the case studies' current situations, without affecting the compressed air flow or pressure negatively.

Chapter 4: Conclusion

4.1 Summary

The South African metals and mining industry is divided into categories of coal, precious metals and minerals, aluminium, iron and steel, and base metals. Precious metals and minerals make up 28.3% of the total mining segments. A forecasted volume increase of 3.6% from 2016 to 2021 is expected for the South African metals and mining industry. Such an increase highlights the challenges mining industries are facing with respect to the development and expenditure of their operations. These challenges include productivity challenges and access to financing. Primarily, the highest expenditures are transportation and energy, both of which have increased during the past years.

As the South African economy developed and the population grew, so did the energy demand. The subsequent rapid growth in South Africa's electricity usage has necessitated the implementation of energy-efficiency projects, which have led to a reduced energy demand. The South African gold mining industry consumes approximately 15% of the total electricity generated by Eskom. A large consumer of energy in this industry is compressed air, which makes up about 20% of a mine's typical electricity usage. Due to the inefficiency of compressed air operations and the high production cost, mines have begun to look to Demand Side Management (DSM) projects for assistance.

Compressed air is mainly used for drilling equipment, loading machines, agitation, and safety measures. Each mining level has its own equipment, working hours, and compressed air requirements. Mines use pressure control systems to provide even amounts of compressed air pressure to all the levels based on the highest demand. The compressed air demand of deep-level mines can be reduced through many methods. Compressed air inefficiencies such as leaks and open valves can be quickly addressed and resolved. Pipe sizes also influence compressed air wastage.

Some mines have processing plants, which require compressed air from a shaft compressor house for their instrumentation. This need can be counteracted by installing standalone compressors at the plant to reduce the demand. Compressors often oversupply their systems, causing them to blow-off excess air into the atmosphere, which is also considered to be wastage. This issue is mainly due to incorrect compressor combinations or compressors being over-specified for the network in which they operate. Alternatives that can reduce air compressor wastage include installing smaller compressors or increasing the network size.

Some mines increase their network size by linking compressed air pipelines of different shafts, thus creating a compressed air ring. These rings make it possible to supply any shaft connected to that ring from any connected compressor house. With the increased demand, it may be possible to switch off an over-specified compressor and operate another compressor situated closer to the designed supply. Recent studies have resorted to creating simulations of compressed air networks. These simulations supply accurate data to determine whether a future project will be feasible. Some studies used simulations to calculate the pressure requirements when creating a new compressed air ring.

Previous studies have focused on large scale mines with multiple compressors. The same methods could have been applied to smaller mines to determine the most efficient compressor combination. The control philosophies for the compressor houses were applied to the surface operations. The authors recommended that they also be applied to underground networks. However, those studies that applied to underground networks were limited by measuring equipment. The areas with limited instrumentation were inactive levels, which in theory should have no production requirements and minimal flow requirements. Auditing these levels to verify that they are closed off close to the station could prove to be time-efficient.

The studies that investigated the effects of integrating compressed air system proved the importance of simulations. However, the simulations could not be implemented due to infrastructure and pressure control issues. The previous methods could be improved by either combining the various methods or applying them to different case studies.

The objective of this research was to investigate effective methods for reducing compressor energy usage. In these methods the integration of compressed air networks can be simulated and implemented on a suitable mining site. The methods had to be more cost-effective than the case studies' current situation without affecting the compressed air flow or pressure negatively.

The case study focused on a compressed air shaft (Mine A) and a hydropower shaft (Mine B), both deep-level gold mine shafts. There was a higher demand during peak drilling and loading hours for Mine A, with Mine B mainly using compressed air for the refuge bays. The Mine A compressor house also supplied a gold processing plant (GP) with compressed air for instrumentation and agitation with a requirement of 420 kPa.

Investigations were launched into reducing the compressor energy consumption for both shafts. The first step was to implement a proper control schedule. Only Mine A was fitted with control valves on the compressed air pipelines. Throttling the flow reduced the amount of

compressed air was needed. The second step, level audits, was prioritised according to low activity and high compressed air consumption.

General inefficiencies that were found were reported for repair. Some of the inactive levels were found to never have been fully closed off. All the inactive levels were closed off after the station's refuge bay. A decrease in power usage was seen in the morning and evenings thanks to the proper control schedules and audits. The average power usage per day was reduced by 642 kW, equivalent to an approximate cost saving of R 6.38 million per annum.

More time was spent on investigating the Mine B compressor house supply reduction, since the underground level had no control valves. The Mine A compressor house consisted of four compressors, with the Mine B compressor house having only one. Two compressors were operated at the Mine A compressor house during high-demand hours, and only one compressor during the low-demand hours. However, the low demand was below the compressor's minimum supply, causing the compressors to blow-off. The same happened during the high-demand hours with two compressors running, but the demand was too high for just one.

The Mine B compressor was operating at a guide vane angle of 18° to prevent blow-off. The compressor consumed less energy but required more maintenance, as operating at such low angles causes unnecessary stress on the machine.

As the compressors for each shaft were too large for the respective networks, investigations were launched into merging the networks. There was an abandoned underground compressed air pipeline between the two shafts 1.8 km below the surface. The pipe runs from Mine A to Mine B via a third shaft (Mine C). Both shafts have a control valve for isolation with three additional manual valves on the pipeline.

Due to the complexity of the system, simulations were used to determine the possibility of the integration. Any problems which would negatively influence the production or safety could be spotted ahead of time. A basic simulation model was created using PTB®. A baseline simulation was constructed by digitally recreating the shafts, network, and compressor houses for comparison. The simulations highlighted the power consumption for the compressors, the Mine A surface pressure, and the Mine B underground pressure.

The first scenario indicates the effects when Mine A supplied Mine B with compressed air with an additional compressor during high-demand hours. The Mine B compressor was offline with the underground pipeline open. Scenario 1 was unable to provide a constant surface pressure. Scenario 2 utilised the Mine A control valve to throttle the supply to Mine B at 200 kPa.

An additional compressor was needed during low-demand hours. The third and final scenario achieved an acceptable surface pressure with the assistance of a third compressor and the control valve. Scenario 3 provided an underground pressure of 230 kPa at Mine B, enough to supply the shaft's refuge bays with the legal pressure requirement of 150 kPa. The compressed air supplied down the shaft sharply increased as the Mine A compressor house was supplying an additional shaft. The flow to Mine B was throttled to 15 000 kg/h. The scenario consumed less energy than the baseline.

Once the simulation had proven that the integration was possible, the physical test was started. The first test consisted of supplying compressed air from Mine A to only Mine C by opening all the valves on the line. During the second test, only the line from Mine C to Mine B was opened. Individual audits were performed on the line while they were charged. The line did not charge with a pressure higher than 100 kPa during the first test. The second test was successful.

The line, as well as the compressed air column feeding down the shaft, was reinvestigated. The underground pipeline was connected directly to the main supply column. Large compressed air leaks were found on the line between Mine C and Mine A. A 150-mm pipe was installed between 600-mm columns choked the compressed air entering the underground line. This was replaced with a 500-mm pipe. The second time testing the pipeline between Mine C and Mine A was successful with the new connection.

A third test was created to determine the abilities of the Mine A control valve. The test was successful with the valve being capable of throttling the compressed air flow to Mine B. With all the tests deemed successful, the shafts were integrated fulltime.

The implemented integration results were compared to the baseline when the initial investigations started, as well as the simulation results. The actual power usage after the integration was less than that of the May 2019 baseline. The usage was within 14% of the simulated values. The average daily power usage was reduced by 703 kW due to the integration and by 1 466 kW from the baseline, equivalent to an approximate cost saving of R 3.89 million and R 10.85 million per annum, respectively.

The objectives of this research were to investigate effective methods to reduce compressor energy usage. This was done by simulating the integration of compressed air networks and implementing them on a suitable mining site. The results discussed above proved that the methods were more cost-effective than the case studies' current situation, without affecting the compressed air flow or pressure negatively.

4.2 Challenges

The major challenge with integrating the two shafts' compressed air networks was communication. As the underground pipeline spanned over three shafts with five isolation valve, seven people were needed. They were divided into surface and underground teams. The underground team consisted of one person for the V-C1, V-B1 and V-A1 valves, one for the V-D1 valve, and one to operate the control for the V-A2 valve.

The surface team had someone to open the V-B2 valve remotely, one to start up a compressor at Mine A if needed, one to take the Mine B compressor offline, and one to monitor the whole system. The surface team was also responsible for informing the underground team when to open which valves.

The second communication issue was arranging for a date to perform the tests, as the two shafts have different planning schedules. Both shaft engineers had to agree on a date and provide people to assist.

4.3 Recommendations

GP has a 250-kW standalone compressor on site. Investigations should be launched into whether the compressor will be able to supply the pneumatic valves used for instrumentation. If possible, the pressure supplied by the Mine A compressor house must be reduced.

Alternatives to the pneumatic actuators for the GP instrumentation should be investigated. An analysis should be done on which option would be more cost-effective – operating the standalone compressor or installing electric actuators.

A further investigation could be to determine what the plant requires to be self-sufficient. It should be possible to isolate the plant by installing a blower for agitation and addressing the instrumentation issue. A comparison should be done on the cost implications of isolating GP from the Mine A compressor house.

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Appendix A

Table 3 is a detailed summary of Table 2 found in Section 1.4.5.

Table 3: Detailed state of the art matrix

STUDY	SUPPLY-SIDE IMPROVEMENTS	DEMAND-SIDE IMPROVEMENTS	NETWORK IMPROVEMENTS	INTEGRATING NETWORKS	SIMULATING NETWORKS	STRATEGIES IMPLEMENTED	METHOD TO REDUCE POWER	SHORTCOMING OF METHOD
1							Automated compressor control	Too expensive
2							Compressor combinations	Requires compressor capacity
3							VSD on the compressor	Too expensive
4							Guide vane control	Limited control systems
5							Peak clipping	Only applied to high demand hours

STUDY	SUPPLY-SIDE IMPROVEMENTS	DEMAND-SIDE IMPROVEMENTS	NETWORK IMPROVEMENTS	INTEGRATING NETWORKS	SIMULATING NETWORKS	STRATEGIES IMPLEMENTED	METHOD TO REDUCE POWER	SHORTCOMING OF METHOD
6							Adjusting discharge pressure set-points	Requires compressor capacity
7							Replacing compressors	Too expensive
8							DCC for compressor selection	Require modern computer processing systems
9							DCC for compressor selection	DCC had to manually updated
10							Moving compressor for optimal discharge pressure	Too expensive
11							Performance through specific energy	Only monitoring tool

STUDY	SUPPLY-SIDE IMPROVEMENTS	DEMAND-SIDE IMPROVEMENTS	NETWORK IMPROVEMENTS	INTEGRATING NETWORKS	SIMULATING NETWORKS	STRATEGIES IMPLEMENTED	METHOD TO REDUCE POWER	SHORTCOMING OF METHOD
12							Performance assessment of compressors through regression analysis	Only monitoring tool
13							Compressor failure prediction	Only an awareness tool
14							Cost-saving guide	Only an awareness tool
15							Model to improved underground auditing time	Based only on active sections
16							Awareness of non-energy benefits	Only an awareness tool base on a questionnaire
17							Alarm systems	Only an awareness tool

STUDY	SUPPLY-SIDE IMPROVEMENTS	DEMAND-SIDE IMPROVEMENTS	NETWORK IMPROVEMENTS	INTEGRATING NETWORKS	SIMULATING NETWORKS	STRATEGIES IMPLEMENTED	METHOD TO REDUCE POWER	SHORTCOMING OF METHOD
18							Replacing pipes with correct sizes	Focussed on improved production
19							Adjusting shift schedules	Limited by the human factor
20							Installed control valves	Limited to surface operations
21							Implementing valve pressure schedules	Limited to surface operations
22							Simulation on a project feasibility	Not implemented
23							Replaced refuge bay valves	Requires additional infrastructure

STUDY	SUPPLY-SIDE IMPROVEMENTS	DEMAND-SIDE IMPROVEMENTS	NETWORK IMPROVEMENTS	INTEGRATING NETWORKS	SIMULATING NETWORKS	STRATEGIES IMPLEMENTED	METHOD TO REDUCE POWER	SHORTCOMING OF METHOD
24							Awareness of possible challenges during implementation	Only a preparation guide
25							Audit underground levels based on pressure profiles	Requires varying pressure profiles
26							Audit underground levels based on production	Requires scales on each level
27							Audit underground levels based on flow	Requires accurate flow transmitters
28							Improved building time for simulations	More accurate on smaller networks
29							Dividing a network into high- and low-pressure sections	Pressure supply was still dependent on the ring-feed

STUDY	SUPPLY-SIDE IMPROVEMENTS	DEMAND-SIDE IMPROVEMENTS	NETWORK IMPROVEMENTS	INTEGRATING NETWORKS	SIMULATING NETWORKS	STRATEGIES IMPLEMENTED	METHOD TO REDUCE POWER	SHORTCOMING OF METHOD
30							Simulated feasibility of integration two shafts	Not implemented due to infrastructure limitations
31							Simulated feasibility on how to integrate two shafts	Not implemented due to infrastructure limitations

Appendix B

The testing procedure for normal conditions was as follow. A similar testing procedure for maintenance operations can be found in section 3.6.

1. The engineer and control room operators of each shaft as well as Central Control was informed that the test will begin.
2. Central Control contacted the Mine A personnel to open their valves.
3. The Mine A personnel opened valve V-A2 and V-D1. The V-A2 valve schedule was set to the desired pressure.
4. The Mine A personnel contacted Central Control once their valves were open.
5. Central Control contacted the Mine C personnel to open valves V-B1, V-A1 and keep valve V-C1 close.
6. The Mine C personnel contacted Central Control once they were done.
7. Central Control contacts the Mine B personnel to open the V-B2 valve.
8. The Mine B personnel contacted Central Control once their valve was open.
9. Central Control took the Mine B compressor offline.
10. Central Control started an additional compressor at Mine A.
11. The pressure and compressor power were noted the pressure stabilised.
12. The engineer and Central Control were informed that the compressed air pipeline will be closed.
13. Central Control contacted the Mine B personnel to close the V-B2 valve.
14. The Mine B personnel contacted Central Control once their valve was closed.
15. Central Control started the Mine B compressor.
16. Central Control took a compressor offline at Mine A.
17. Central Control contacted the Mine C personnel to close valves V-B1, V-A1 and V-C1.
18. The Mine C personnel contacted Central Control once the valves were closed.
19. Central Control contacted the Mine A personnel to close their valves.
20. The Mine A personnel closed valve V-A2 and V-D1. The V-A2 valve schedule was set to 150 kPa.
21. The Mine A personnel contacted Central Control once they were done.
22. This marked the end of the test.