Future mine compressed air planning using digital twin simulations

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Dissertation accepted in fulfilment of the requirements for the degree *Master of Engineering in Mechanical Engineering* at the North-West University

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Graduation: May-June 2023

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ACKNOWLEDGEMENTS

As the author of this study, I would like to express my gratitude to and acknowledge the following for their contribution towards the completion off my study:

- Carla Hartman for her unending support and love.
- My parents, Natacha and Bernard Burger, whom without I would never have been in the position to pursue my master’s study.
- My family and friends for always believing in me and supporting me.
- Enermanage (Pty) Ltd for their generous funding of this research study.
- Dr JC Vosloo for his guidance and support; his vast knowledge of the mining industry and compressed air systems contributed greatly to the completion of this study.
- My Creator for blessing me with the opportunity and ability to complete this study.

I apologise to everyone who was not acknowledged directly: I would like to thank all the mentors, teachers and people who have made a positive contribution in my life. Finally, to quote a song by Kip Moore, “Thanks to the bulls that bucked me off”.

ABSTRACT

Title: Future mine compressed air planning using digital twin simulations
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Degree: Master of Engineering (Mechanical)
Keywords: Compressed air; Digital twin simulations; Proactive planning

Most deep-level gold mines use compressed air services for various applications that directly influence gold production. Amongst others, these applications include drilling, agitation and loading boxes. However, similar to other supporting mining systems, compressed air planning is often overlooked. A lack of compressed air planning can lead to unforeseen problems and unscheduled maintenance. In turn, this can lead to significant downtime, during which valuable production is lost. Therefore, a need exists for a proactive compressed air planning strategy for preventing these problems and solving production challenges. This will help ensure that compressed air services meet the requirements for planned mining.

A literature study was completed on compressed air services planning and how digital twin simulations can be used to advance this field. Simulations can effectively identify and develop solutions to compressed air inefficiencies, but no research has been conducted on applying these methods to the planning of mine compressed air services. This study used digital twin simulations to identify and solve future problems and inefficiencies in mine compressed air systems. A proactive compressed air planning methodology was developed based on a detailed literature study. The developed methodology included digital twin modelling, full data analysis, proactive solution development and, lastly, implementing the developed solution to validate the study.

The developed methodology was applied to Mine A. The method identified a problem on the compressed air services system of the main production level. This system would have been unable to meet the required compressed air pressure for mining in the stoping ends. Implementing the solution, produced by the proactive planning strategy, increased the compressed air pressure by 32%. The developed proactive planning methodology was successful in identifying problems and inefficiencies that the compressed air services system would have faced in the future. The methodology successfully developed proactive solutions to these identified problems. In the case of Mine A's compressed air services system, it ensured that the required compressed air pressure was available for all planned mining activities and avoided unnecessary production loss.

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ABBREVIATIONS

DSM	demand-side management
DXF	drawing exchange format
HLGE	haulage
KPI	key performance indicator
L	level (for example, 85L and 92L)
MAE	mean absolute error
PTB	Process Toolbox
SCADA	supervisory control and data
XC	cross-cut

NOMENCLATURE

Baseline models	The models based on the current system that are developed and calibrated using known data. These simulation models are compared with other simulations to determine the effect of changes on the system performance.
Drilling shift	The period in the mining schedule when holes are drilled into the rockface for explosives to be placed.
Peak drilling shift	The period during drilling shift when most drills are actively drilling in the active mining areas. During this time, the demand on the compressed air system is at its peak.
Blasting shift	The period in the mining schedule when explosives are detonated to break the rockface for mining.
Cleaning shift	The period in the mining schedule when all the ore that was blasted is collected and transported. During this shift, the mining areas are also cleaned and prepared for the drilling shift.
Compressor house	A structure for storing the supply-side equipment of the compressed air system, including compressors and air treatment facilities.
Cross-cut	The travelway that connects the stope areas with the haulages.
Raise	An incline development that leads to a stope.
Stope	The void left after ore has been extracted for mining; most active mining takes place in stopes. This is the location containing the rockface.
Development end	The voids left after ore has been extracted for expansion of new mining areas.
Rockface	The furthest point of development or mining that can be found in the development ends or stopes. The rockface is drilled and blasted.
End user	Components and equipment that use compressed air to perform various mining activities.
Supply pressure	The pressure at which compressed air is supplied.
Supply flow	The quantity of compressed air supplied.
Demand flow	The quantity of compressed air required by the compressed air end users to perform various activities.

INTRODUCTION AND LITERATURE STUDY

1.1 Introduction

This section of the study will discuss the literature and research completed regarding deep-level mine compressed air systems and the planning thereof. This section will attempt to identify a novelty for the use of digital twin simulations to develop a proactive planning strategy for deep-level gold mine compressed air systems.

1.2 Background

Gold was first discovered in South Africa in 1886 on the Langlaagte farm. This led to the founding of numerous towns and cities, such as the metropolitan city of Johannesburg, around the gold diggings. Today, South Africa has some of the deepest gold mines in the world [1]. Gold mining is an important part of the global mining sector as it contributes immense value. Locally, deep-level gold mining makes a significant contribution to the South African economy and provides employment to thousands of South Africans [2, 3]. Trends show that the global mining industry is currently growing while the South African gold production industry has been declining. This is due to increasing operational costs, gold price volatility, escalating cost of production, depth and mining method, and a unique set of production challenges faced by this industry [1, 3, 4].

Due to the nature of the mining process, equipment with high energy consumption is used throughout the industry. Most gold mines use compressed air systems that form the backbone of several mining processes [5, 6]. Compressed air services are used for various applications that directly influence gold production. Amongst others, these applications include drilling, agitation, loading boxes, and loading [3].

Compressed air has a number of advantages such as delivery of smooth power, infinitely variable speed, torque control, and low heat build-up [7]. When planned, implemented, and maintained correctly, compressed air systems provide a safe and sustainable energy source for deep-level mining [7]. Thus, compressed air is a vital source of energy for deep-level gold mines, but it is considered one of the most expensive utilities [1, 8]. Compressors can contribute up to 21% of the total electricity demand of a typical mine [9]. However, compressors are still regarded as the norm for supplying energy to underground equipment in South African mines [10] because of their ease of use, consistency and scalability [11]. It is therefore alarming that most compressed air systems on mines are inefficient [6].

The inefficiency of deep-level gold mine compressed air systems can be ascribed to these systems being complex, with piping networks extending over several kilometres [3, 12]. Insignificant compressed air consumers such as open ends for cooling and other losses in contribute up to 70% of the total underground compressed air demand [11, 13].

Compressed air systems are complex and require proper planning to ensure continuous production and, in turn, the mine's profitability. Current mine planning strategies focus primarily on ore extraction and neglect proper planning for compressed air services [6, 14]. This leads to the system being inadequate for the planned mining strategies, leading to higher production costs and unforeseen pressure and flow problems, which result in production losses.

1.3 Compressed air systems in deep-level mining

This section will discuss the process followed by deep-level mines to extract gold from the earth. In this section, focus will be placed on the workings and requirements of the compressed air systems used in the mining operations.

1.3.1 Deep-level mining operations and compressed air requirements

Deep-level gold mines follow a standard schedule when mining, which includes all the processes necessary for mining and transporting ore to the gold plant. During the various periods, there are different requirements for the compressed air system. The three main shifts are the drilling, blasting and cleaning shifts. During each of these shifts, the requirements of the compressed air system vary [3]. Figure 1, shows a typical compressed air demand schedule [6].

During the drilling shift, the demand on the compressed air system is at its peak since miners are drilling 1.8 m deep holes into the rock. The stopes are situated deep in the mine where the ore is located. Thereafter, the blasting shift commences, and explosives are placed inside the drilled holes. During the blasting period, no one is allowed underground. The demand on the compressed air system is very low as there are no labour activities during the blasting shift. The cleaning shift takes place after blasting. All the ore that has been blasted is collected and transported to the shaft first, then to the surface and, finally, to the gold plant. During this shift, the mining areas are cleaned and prepared for the drilling shift.

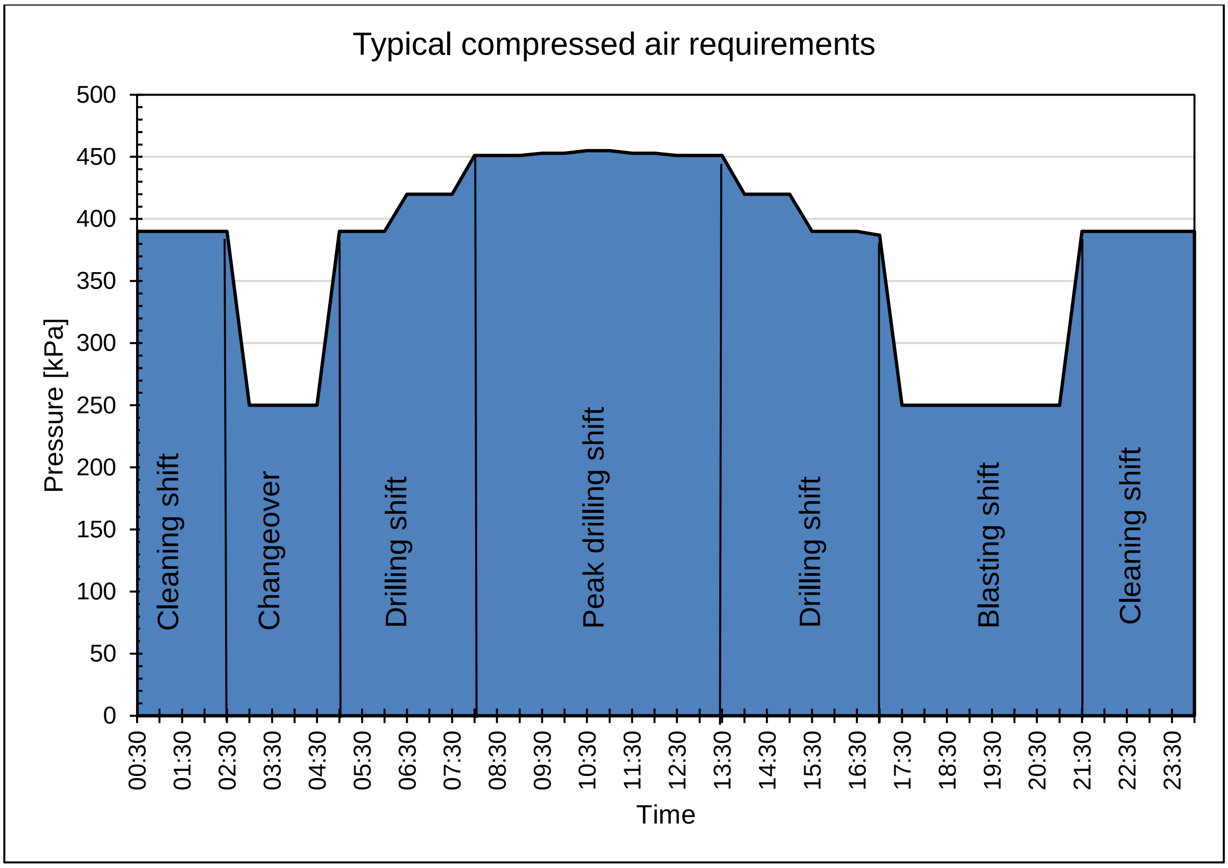


Figure 1: Mining shifts [6]

1.3.2 Compressed air systems

Compressed air systems consist of three major subsystems, namely a supply side, a reticulation system, and a demand side. The supply side includes compressors and air treatment equipment (dryers and filters). The reticulation system is the means of distribution between the demand side and supply side, and the demand side includes end-use equipment [1, 3, 6, 15, 16].

There are two different types of compressed air network in a mining compressed air system, namely, standalone and ring feed networks [17]. A ring feed compressed air system mainly consists of several compressor houses that distribute compressed air into a surface pipe network that supplies more than one shaft and end user at the same time. A standalone compressed air system consists of a single compressor house that contains multiple compressors with a common manifold. The compressors discharge compressed air into one pipeline and distribute it to surface users and down the shaft to underground users [6, 8, 18]. An example of a typical deep-level mine's compressed air system can be seen in Figure 2.

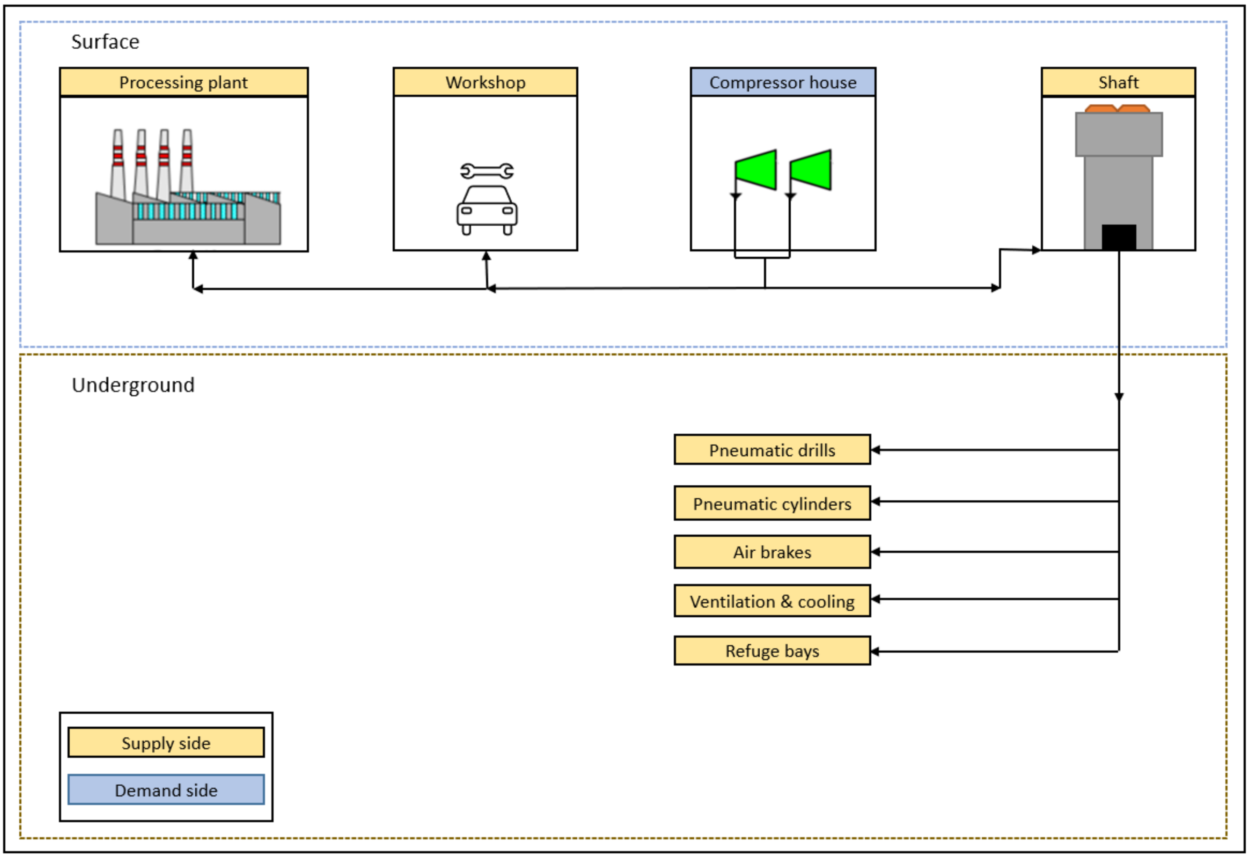


Figure 2: Typical deep-level mine compressed air system

The reticulation network is the distribution system for transporting compressed air from the compressor house to the end users [19]. This network consists of a vast system of pipes connecting the supply side with the demand side [3]. Some working areas are up to eight kilometres away from the connection to the surface compressed air system [1, 3, 15, 16].

Different types of pipes are installed in deep-level mine compressed air systems depending on the specific demand and location. Larger incoming pipe lines are usually constructed from more permanent fixtures, namely flanged pipe sections that are bolted to one another [20]. The compressed air network construction is much more dynamic in nature at the developing ends and working areas, and quick clamp-on pipes are used in these sections. There is a wide variety of pipe sizes and couplings that are available for this application and it primarily depends on the application [3, 21]. These reticulation systems usually have a low efficiency due to the complexity, size and the dynamic nature of the planning and construction of these systems [22]. Figure 3 illustrates a simplified example of such a system.

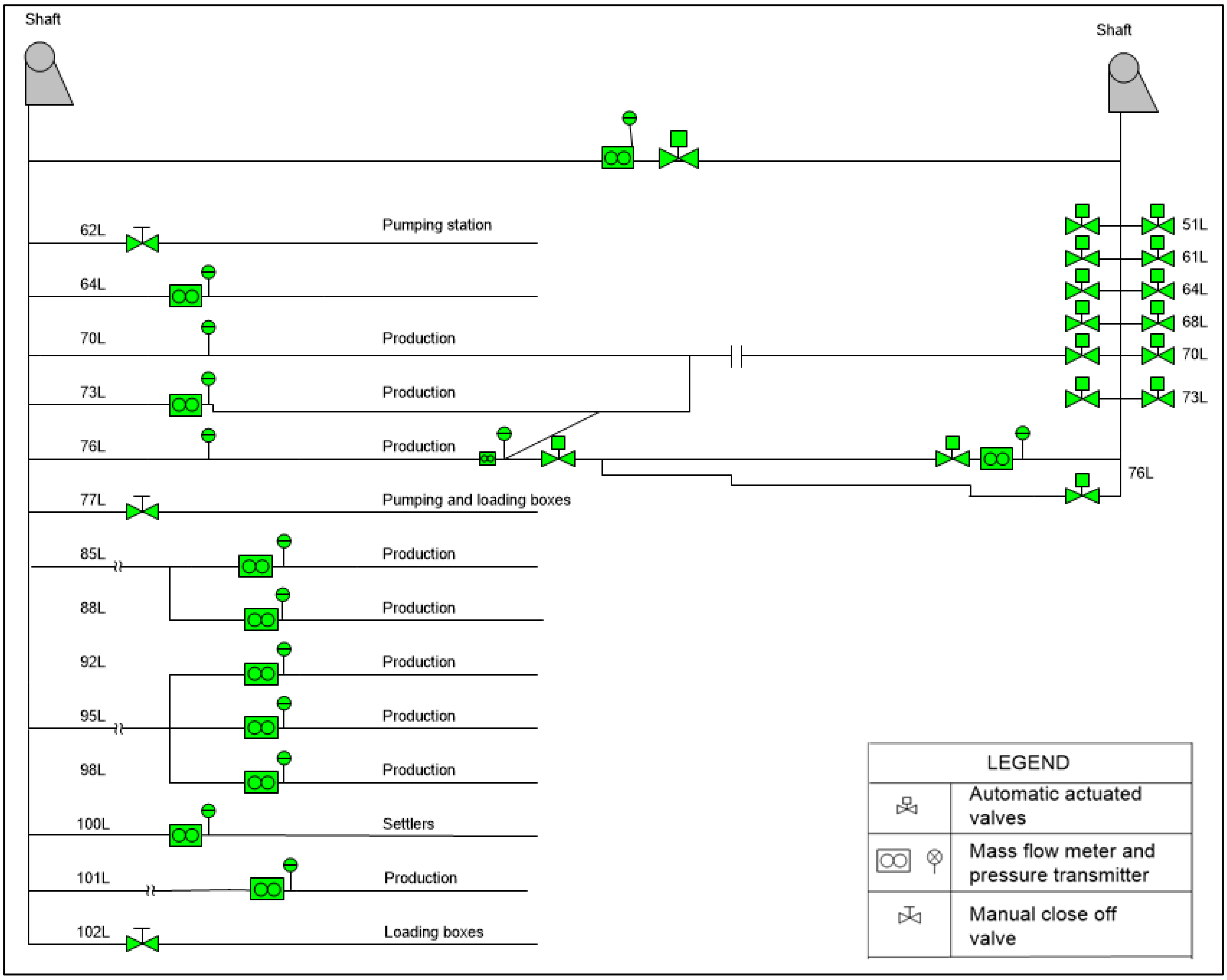


Figure 3: Complex compressed air systems

End users make up the demand side of the compressed air system [19]. Compressed air is used as the power source to the end users and can be converted into other forms of energy as required. Table 1 shows some of the most common end users in a compressed air system.

Table 1: Compressed air users [6, 13, 22]

Type	Application	Consumption rate [m^3/h]	Operating pressure [kPa]	Period
Pneumatic rock drills	Drilling shift	190–320	400–620	07:00–14:00
Pneumatic loaders	Sweeping and cleaning	348	400–490	21:00–14:00
Pneumatic cylinders	Sweeping and cleaning	11	400–500	21:00–14:00
Refuge bays	All	Site-specific	200–300	Continuous
Agitation	All	Site-specific	400	Continuous

1.4 Mine planning and the effect of compressed air on production

The single greatest determining factor of a gold mine’s profitability is gold production. The amount of gold produced directly correlates to the income the mine can produce, and the cost of production determines the mine’s profit [1]. It is essential that gold mines have optimal operations to have high rates of constant gold production.

Literature shows that compressed air systems have a large impact on production as they are used during drilling, which is a critical part of the gold mining process [3]. However, the compressed air system is regarded as one of the most inefficient and energy-intensive systems on a deep-level mine [1, 3, 20]. The inefficiencies directly influence production by affecting the service delivery conditions supplied to active mining areas in deep-level gold mines. This affects gold production as an insufficient supply of compressed air can result in costly production losses. The inefficiencies in the system further make the system even more energy intensive, which increases the cost of production [23]. In most gold mines, only between 10% and 30% of generated compressed air reaches the consumer [13, 24].

The delivered compressed air supply directly correlates to the drilling rate, and because of poor service delivery, production trends decrease when drilling targets are not met [3]. If drilling is not completed due to inefficient compressed air pressure, explosives cannot be set, resulting in production losses [3, 22]. Insufficient compressed air pressure is responsible for 4% of missed production shifts [25].

Deep-level mining in South Africa focuses on producing precious metals; thus, resources are often only focused on delivering production targets [22, 26-29]. As can be found in other industries, services such as compressed air will often only receive the required attention when they start to fail to meet requirements and affect production negatively [22, 30]. Compressed air systems that are not maintained and planned properly can lead to unforeseen problems that need to be rectified before production can continue. This can take considerable time while valuable production is lost. These system problems should rather be identified and solved proactively.

Mine planning mainly focuses on ore extraction and neglects proper planning for compressed air service [20, 22]. Mines use standards and other guidelines for planning compressed air infrastructure and other systems [20, 31]. Most mines have little structure when constructing compressed air systems and often few to no people know the complete layout of the underground compressed air reticulation network [3, 12, 22, 32].

To increase the life-of-mine period of South African mines, mines have to extend to deeper depths [33]. Mine infrastructure is old and was designed for specific requirements that have since changed. As a result, compressed air systems have to supply more compressed air over larger distances than originally designed for. The complexity and age of most typical mine compressed air systems increase the difficulty in planning for future expansion [12, 22, 34, 35].

The mining environment is dynamic regarding both service delivery and production areas [13]. The number of mining crews and active stoping and development panels change over time, affecting the compressed air infrastructure. Deep-level gold mine compressed air systems are complex and regularly undergo non-project related changes that influence system performance [8, 16, 36]. The established standards and guidelines do not always take the effects of the dynamic compressed air system into account, and this together with outdated infrastructure lead to inefficient compressed air systems [3, 13, 19].

Other industries have avoided production losses and system inefficiencies by using proactive planning strategies and simulations [37]. Proactive planning has the potential to resolve similar issues in mine compressed air systems and avoid unnecessary production losses. South African mines have demonstrated success in deep-level mining, but the industry has not shown innovative thinking to develop new methods [13]. Studies have shown that the mining sector's future depends on modernisation [13]. Various studies have been completed on improving production strategies for mines. These studies were analysed and are discussed below.

A study was completed by Vermeulen titled, "Methods to optimise underground mine production" [37]. This study investigated conventional systems for underground platinum mining and addressed labour problems that led to production losses. During this study, a new mine production planning system was developed to address these labour problems. Vermeulen's study developed a new planning system for addressing labour problems but did not investigate the effects of the compressed air system planning on the production of the mine.

Valery, Jankovic and Sonmez published an article titled, "New methodology to improve productivity of mining operations" [38]. This study developed a methodology that used process integration and optimisation to increase a mine's efficiency. The methodology optimised the mining process by evaluating the whole mine instead of looking at individual systems. This study used rock characteristics, data collection and auditing to build models for simulating the integrated mine systems. The crushing and grinding operations were improved, which increased production but failed to take the effects of compressed air pressure on drilling and production into account.

Van Zyl completed a study titled, “Practical approach to analyse mine pneumatic drilling performance” [13]. He developed a practical holistic approach to analyse mine production outputs against pneumatic drilling performance. This study investigated the effects of compressed air services on drilling performance and production and identified a production loss of R3.5 million over a five-month period. This study developed a method for analysing the effect of compressed air system inefficiencies on production but did not provide a solution.

A study titled, “Optimising production through improving the efficiency of mine compressed air networks with limited infrastructure” was published by Nell [3]. This study addressed inefficiencies in compressed air reticulation networks that led to increased compressed air delivery pressures and, subsequently, increased production. This study succeeded in identifying and addressing inefficiencies in compressed air systems but did not look at the potential of solving these problems proactively by developing a planning strategy.

As can be seen, significant research has been completed to increase mine production. Most research focused on identifying and solving issues in mining systems, but there has not been any research on developing a proactive planning strategy for mine compressed air systems to avoid production losses and solve inefficiencies before they appear.

1.5 Simulations used in mining

Simulations provide outputs by integrating and solving a variety of complex mathematical equations regarding the system at hand [22, 39]. Simulation packages can reduce the time and effort required to construct a simulation by incorporating the required mathematical models into a single visual user-friendly platform [22].

Mining system simulations usually consist of a series of integrated components that are dependent on one another. The outlet conditions of one component are the input for the next component. Each component represents a component of the actual system and is calibrated to perform in the same way [40]. The individual components are brought together in the simulations and operate together to create a digital twin of the actual system. Benefits of using simulations to assess systems include [22]:

- Identification of project scope
- Cost-effective use of resources
- Identification of system design improvements
- Reduction in implementation period for projects

Simulation software has been used in the mining sector to address a variety of different problems and has shown big potential in identifying problem areas in compressed air networks [41].

The mining industry uses outdated technology and equipment that are no longer efficient due to the expanding life-of-mine periods [22, 33]. Improvement strategies to address these problems have been identified by creating digital twin models of the mine’s different systems. Digital twin simulations have been proven to be the most effective way of predicting the impact of system changes [15, 42].

Simulation software has been used for different applications for mine compressed air systems. These include simulations for determining the feasibility of energy and cost saving interventions on compressed air systems and investigating potential optimisation strategies on these systems. Using simulations to determine the effectiveness of high-risk projects such as integration is encouraged, as seen in studies by Maré, Bredenkamp and Marais [23] and Van Niekerk, Kleingeld and Booysen [43]. These previous studies have proven that mine compressed air systems can be simulated accurately [44].

Upadhyay and Askari-Nasab stated that simulation models are designed and created to address specific problems [45]. These simulations have focused on solving current and specific problems, and once they are resolved, the model is discarded. There is no focus on using simulations to develop methods for addressing similar problems in the future [41].

Therefore, a need exists to use digital twin models to identify and address future problems in mining compressed air systems. A compressed air network simulation can be a powerful tool for planning compressed air system projects [46, 47]. By creating a digital twin simulation, different high-risk system changes can be evaluated without any physical effect on or risk to workers or the system [48]. These digital twin models can assist in mine compressed air planning to develop a more proactive planning strategy.

1.6 Literature review and state-of-the-art concept

This section will provide an overview and critical analysis of previous studies completed, relating to the scope of this study. This section will determine the focus of previous studies and identify where a need exists for more research to be completed.

1.6.1 Previous studies performed

This section provides an overview of studies conducted on optimising compressed air systems and using digital twin simulations for compressed air systems and mine planning strategies. To ensure the research reviewed is compared accurately and falls within the boundaries of this study, it was evaluated according to the following criteria:

- Research relating to compressed air system inefficiencies
- Research relating to compressed air systems and production
- Research relating to compressed air systems and mine planning
- Research relating to the use of digital twin simulations in deep-level mining
- Research relating to digital twin simulations for engineering systems planning and design
- Research relating to future mine compressed air planning using digital twin simulations

Twenty-seven studies based on the criteria were evaluated, and eleven studies found to be most relevant to the topic were identified. These studies will be discussed to evaluate their relevance and determine what can be learned from them.

Study 1 [6]

Title: Improving efficiency of a mine compressed air system.
Author: SJ Fouché.
Relevant criteria: Compressed air system inefficiencies; Digital twin simulations in deep-level mining.

Overview

This study researched and identified different initiatives available for improving the energy efficiency of deep-level mine compressed air systems to identify cost savings for a mine.

Results

This study proved that initiatives such as leak identification, system control philosophies and level pressure control are all effective for improving the energy efficiency of deep-level mine compressed air systems and decreasing operational costs.

Relevance

This study was relevant to the topic as it matched the previously mentioned criteria. Different initiatives were researched and developed to improve the energy efficiency of the deep-level mining compressed air system. Simulations closely related to digital twins were used in some cases to determine the effectiveness of the identified initiatives.

Gained from study

Knowledge gained from this study includes identifying different initiatives that can be implemented on deep-level gold mine compressed air systems to improve efficiency. The study used simulations to test the effectiveness of these initiatives and showed that simulation software can accurately determine the effect of different initiatives on a compressed air system.

Shortcomings and recommendations

This study focused on identifying initiatives to improve the compressed air system's energy efficiency, which helped to improve existing situations in the system. However, the study lacked the effectiveness of a proactive solution that would prevent problems in the system. It is recommended that further research be done on initiatives that focus on planning compressed air systems.

Study 2 [49]

Title: Investigation of compressed air losses on production cost for Mosul dairy factory.
Authors: MS Al-Dabbagh, Z Kreshat, and R Farhat.
Relevant criterion: Compressed air system inefficiencies.

Overview

This study analysed the number of field losses resulting from inefficiencies on a compressed air system in a dairy factory. It analysed the effect of inlet temperature, pressure ratio, electric motor inefficiency and leakage on production cost.

Results

The study developed a mathematical program for finding and calculating the effect of compressed air leaks in all the parts of a production line. Furthermore, the model was used to calculate and quantify the total cost of all the compressed air losses.

Relevance

This study was relevant as it researched a method for identifying and quantifying compressed air system inefficiencies and losses.

Gained from study

Knowledge gained from this study includes a method for identifying and quantifying compressed air losses and inefficiencies. It further provides insight into the effect of different inefficiencies on a compressed air system.

Shortcomings and recommendations

This study focused on identifying and quantifying the effect of different inefficiencies on a compressed air system but did not investigate solutions. It is recommended that similar studies be applied to the mining sector and be expanded to include research on solutions to these problems.

Study 3 [3]

Title: Optimising production through improving the efficiency of mine compressed air networks with limited infrastructure.
Author: D Nell.
Relevant criteria: Compressed air system inefficiencies; Compressed air systems and production; The use of digital twin simulations in deep-level mining.

Overview

This study conducted research to create a methodology for identifying and evaluating the effects of inefficiencies in deep-level mining compressed air systems on compressed air pressure and production.

Results

This study successfully developed a methodology for identifying compressed air inefficiencies in a deep-level mine. It evaluated the effect on production by correlating compressed air pressure to the drilling rate. The methodology was also used to provide a solution to these inefficiencies.

Relevance

This study is relevant to the topic as it used digital twin simulations to identify and develop solutions to problems in deep-level mining compressed air systems in order to improve production.

Gained from study

This study provided insight into a methodology that uses digital twin simulations for identifying and providing solutions to inefficiencies in compressed air systems. Furthermore, the study helped to gain knowledge on the correlations between compressed air pressure and drilling rate, which in turn directly correlates to production.

Shortcomings and recommendations

This study mainly focused on identifying and solving problems in existing deep-level mining compressed air systems by using limited infrastructure. However, it did not look at the advantages of implementing a similar methodology when planning such a system to avoid these types of problems.

Study 4 [50]

Title: Experimental digital twins for a modelling and simulation-based engineering approach.
Authors: D Ulrich and R Juergen.
Relevant criterion: Digital twin simulations for engineering systems planning and design.

Overview

This study researched a systematic approach for a methodology that connects the worlds from different engineering domains to create a modelling and simulation-based engineering concept that can be used to design and manage ever-increasingly complex engineering systems.

Results

This study successfully developed a systematic methodology that connects the worlds from different engineering domains. It created a modelling and simulation-based engineering concept that can be applied to different fields of engineering design and management. This approach was applied to a space project where it helped to reduce the number of prototypes to be developed.

Relevance

This study is relevant to the topic as it uses digital twin simulations for engineering design and a methodology that can be applied to different engineering fields.

Gained from study

This study helped to establish a methodology for using digital twin simulations in engineering design and planning. This methodology could be useful for deep-level mining compressed air systems design.

Shortcomings and recommendations

This study helped to establish a methodology for using digital twin simulations in engineering design and planning across different engineering domains. While this is helpful, a methodology more specific to deep-level mining systems needs to be developed.

Study 5 [51]

Title: Ultra-deep level mining – future requirements.
Author: DH Diering.
Relevant criterion: Deep-level mine planning.

Overview

This study conducted research to identify the requirements for establishing a new idealised ultra-deep level mine. This study focused on the philosophy of accessing ore at ultra-depths as well as the individual technologies required for ultra-deep level mining.

Results

This study successfully completed research that provides valuable information necessary when determining the requirements of an ultra-deep level mine.

Relevance

This study is relevant to the topic as identifies the requirements necessary in ultra-deep level mining. When planning a system, a crucial step is determining the requirements of the system.

Gained from study

This study provides information on what the future requirements of a ultra-deep level mine will be. The information could assist in determining what the future requirements of a deep-level mining compressed air system will be.

Shortcomings and recommendations

This study helped to identify the future requirements of an ultra-deep level mine regarding accessing ore and other individual technologies such as refrigeration and ventilation. However, it did not look at the compressed air systems that could be used for drilling. This study could be expanded to help identify the requirements of ultra-deep level mine compressed air systems and could also use digital twin simulations to determine the future requirements more accurately.

Study 6 [11]

Title: Local benchmarking in mines to locate inefficient compressed air usage.
Authors: D du Plooy, P Maré, J Marais, and MJ Mathews.
Relevant criteria: Compressed air system inefficiencies; Compressed air systems and production.

Overview

This study developed a novel method for locating inefficiencies in deep-level compressed air systems by using local benchmarking and the correlation between the compressed air supply and production of tonne ore per level.

Results

The study succeeded in creating a method for identifying inefficiencies in deep-level compressed air systems and implemented initiatives that reduced compressed air consumption while increasing productivity. The developed methodology showcased the potential for compressed air wastage reduction. It can be implemented to improve compressed air systems in individual mines.

Relevance

This study was relevant to the topic as it developed a method for identifying inefficiencies in deep-level mine compressed air systems to increase production and decrease energy wastage.

Gained from study

This study provides a methodology for identifying compressed air inefficiencies on deep-level mine compressed air systems by using benchmarking and the correlation between compressed air supply and tonne ore production. The study found that the ratio of compressed air usage to the amount of output production is an applicable key performance indicator (KPI) for evaluating and locating inefficiencies in the compressed air system.

Shortcomings and recommendations

The study successfully developed a method for identifying inefficiencies in the current system of the mine but did not look at applying a similar method to the future planning of deep-level compressed air systems. It is recommended that a similar methodology in collaboration with digital twin simulation be applied to the planning of deep-level mining compressed air systems.

Study 7 [52]

Title: Simulating operational improvements on mine compressed air systems.
Authors: BM Friedenstein, C. Cilliers, and J. van Rensburg.
Relevant criteria: Compressed air system inefficiencies; Use of digital twin simulations in deep-level mining.

Overview

This study developed a simulation methodology for modelling and simulating proposed improvements on a deep-level mine compressed air system.

Results

The study successfully developed and implemented a simulation-based methodology that helped to reduce the inefficiency of a deep-level mining compressed air system.

Relevance

This study is relevant to the topic as it uses a simulations-based methodology to improve deep-level mining compressed air systems.

Gained from study

This study provides a simulations-based methodology for identifying problems in deep-level mines’ compressed air systems.

Shortcomings and recommendations

This study provides a simulations-based methodology for identifying problems in deep-level mining compressed air systems. However, the study did not apply the methodology to future planning of the compressed air system. In this study, KYPipe Gas software was used for the simulations and thus the system had to be simplified for the simulation. It is recommended that more detailed compressed air models and software be used to develop a more detailed simulation model.

Study 8 [23]

Title: Evaluating compressed air operational improvements on a deep-level mine through simulations.
Authors: P Maré, JIG Bredenkamp, and JH Marais.
Relevant criteria: Compressed air system inefficiencies; Use of digital twin simulations in deep-level mining.

Overview

This study developed a new approach using simulations to investigate operational efficiency and service delivery solutions to deep-level mining compressed air systems.

Results

This study successfully developed a new approach using simulations to investigate operational efficiency and service delivery solutions. This is helpful as the magnitude of deep-level mining compressed air systems makes it difficult and economically unviable to do these investigations in other ways.

Relevance

This study is relevant to the topic as it investigated a new approach for using simulations to evaluate operational efficiency and service delivery solutions of deep-level mines. The study thus meets the required criteria.

Gained from study

The approach can be used to evaluate the effect of operational improvements included in the future planning of deep-level mining compressed air systems.

Shortcomings and recommendations

This study developed an approach that used simple simulations to investigate operational efficiency and service delivery solutions to deep-level mining compressed air system inefficiencies. It is recommended that more detailed simulations be used to determine the advantages.

Study 9 [53]

Title: A simulation-based prediction model for coal-fired power plant condenser maintenance.
Authors: I Mathews, EH Mathews, JH van Laar, W Hamer, and M Kleingeld.
Relevant criterion: Digital twin simulations for engineering systems planning and design.

Overview

This study developed a semi-empirical thermohydraulic simulation model for a coal-fired power station to assist with cost-effective decision-making.

Results

This study successfully developed a semi-empirical thermohydraulic simulation model. It integrated with economics and maintenance models, which can be used to investigate the effect on plant performance and economic viability of any change to any component in a coal-fired power plant.

Relevance

This study is relevant to the topic as it used a Process Toolbox (PTB) digital twin simulation as part of a prediction model used for maintaining a coal-fired power station. This prediction model can provide valuable information for developing simulation-based prediction models for other systems.

Gained from study

A coal-fired power station uses engineering designs and systems to operate. The prediction model can be adapted for the mining sector.

Shortcomings and recommendations

This study developed a semi-empirical thermohydraulic simulation model for a coal-fired power station to assist with cost-effective decision-making for maintenance. This model can be adjusted for the mining sector and be developed further for decision-making in engineering systems design and planning.

Study 10 [54]

Title: Improving mine compressed air network efficiency through demand and supply control.
Authors: B Pascoe, HJ Groenewald, and M Kleingeld.
Relevant criteria: Research relating to compressed air system inefficiencies; Research relating to the use of digital twin simulations in deep-level mining.

Overview

This study focused on using compressed air simulations to determine the effect of demand-side management (DSM) initiatives on the annual electricity cost of a mine.

Results

This study successfully used compressed air simulations to determine the effect of DSM initiatives on the annual electricity cost of a mine. A control philosophy was developed for the bypass valves to limit the compressed air supply when it was not required. The implementation of the control philosophy led to an annual electricity cost saving of R1.9 million.

Relevance

This study is relevant to the topic as it used compressed air simulations to determine the effect of a control philosophy on a compressed air system.

Gained from study

This study developed a method that uses compressed air simulations to determine the effect of a control philosophy on the compressed air system. It can estimate the effect of changes made on a compressed air system’s valve control philosophy.

Shortcomings and recommendations

This study successfully determined the effect of DSM projects on a mine compressed air system and developed a control philosophy for the mines valves. This study did not use the simulations to identify and solve future problems. Thus, it is recommended that a similar method be used to identify and solve future compressed air system problems proactively.

Study 11 [13]

Title: Practical approach to analyse mine pneumatic drilling performance.
Author: CJJ van Zyl.
Relevant criteria: Research relating to compressed air system inefficiencies; Research relating to compressed air systems and production.

Overview

This study developed a practical holistic approach for analysing mine production outputs against pneumatic drilling performance.

Results

This study successfully developed a method for analysing mine production outputs against pneumatic drilling performance in relation to compressed air pressure. It identified a production loss of R3.5 million over a five-month period.

Relevance

This study is relevant to the topic as it investigated the effects of inefficiency in compressed air systems on production.

Gained from study

This study successfully developed a method for analysing mine production outputs against pneumatic drilling performance. This method can estimate the effect of identified inefficiencies regarding compressed air pressure on drilling performance.

Shortcomings and recommendations

This study developed a method for analysing mine production outputs against pneumatic drilling performance in relation to compressed air pressure. However, it did not develop a strategy for proactively identifying and solving the inefficiencies that can lead to production losses.

1.6.2 Critical analysis of previous studies

Table 2 summarises the previously discussed studies to show their focus. The first column shows the relevant criteria while the header row shows the studies included in the matrix. An X indicates that the study is relevant to the specified criterion.

Table 2: Research matrix

Criteria	**Study 1**	**Study 2**	**Study 3**	**Study 4**	**Study 5**	**Study 6**	**Study 7**	**Study 8**	**Study 9**	**Study 10**	**Study 11**
Compressed air system inefficiencies	X	X	X			X	X	X		X	X
Compressed air and production			X			X					X
Mine compressed air systems planning					X						
Simulations for mining	X		X				X	X		X	
Simulations for planning				X					X		
Simulations for compressed air mine planning											

Table 2 shows that considerable research was conducted on evaluating and improving mine production by identifying mine compressed air system inefficiencies and other problems. Simulations play a significant role in the mining sector in terms of these aspects. Research relating to simulations used for mine compressed air DSM and energy saving projects was also widely conducted. Simulations were used for planning future systems in the mine and other industries, but they have not been applied to the planning of compressed air systems in deep-level mines.

Table 2 shows that multiple studies were completed on the first five criteria. No study has been completed on simulations used for compressed air mine planning. This clearly indicates that there is a need for a study that directly investigates future mine compressed air planning using digital twin simulations.

1.7 Problem statement and objective

Current mine planning strategies primarily focus on ore extraction and neglect proper planning for compressed air services. This leads to the system being inadequate for the planned mining strategies and, in turn, can lead to unforeseen pressure and flow problems, which result in production losses.

The critical analysis in Section 1.6.2 showed that multiple studies were completed on the specified criteria but no research is available on a combination of these criteria. This indicates a need for a proactive planning strategy that uses digital twin simulations for identifying and avoiding problems and other inefficiencies in the compressed air system. Therefore, the objectives of this study are:

- Develop a digital twin model of a compressed air system that accurately portrays the system’s performance.
- Expand the digital twin model to include future mining activities and estimate the future performance of the compressed air system.
- Identify future compressed air system problems and inefficiencies.
- Develop proactive solutions to the identified system problems to fulfil a proactive planning strategy.

1.8 Study overview

This section of the study will provide a brief overview of each chapter of this document:

Chapter 1

Chapter 1 introduced the study. This chapter provided the reader with the necessary background knowledge to understand the basic workings of compressed air systems of deep-level gold mines. This chapter completed a literature review on deep-level gold mine compressed air systems, planning and simulations. It identified the need for a proactive planning strategy that uses digital twin simulations for identifying and avoiding problems and other inefficiencies in the compressed air system. This chapter clearly identified and defined the objectives of the study.

Chapter 2

Chapter 2 discusses the development of the methodology. The methodology was developed to address the identified need and meet the objectives of this study, as identified in Section 1.7. This chapter provides the reader with the necessary information and background from literature. The chapter discusses the development of each step of the methodology and provides guidelines on how each step is to be implemented.

Chapter 3

This chapter discusses the implementation of the developed methodology on Mine A, a deep-level gold mine in South Africa. Each step of the methodology and the results obtained are discussed. Chapter 3 validates the developed methodology through case study results.

Chapter 4

Chapter 4 concludes the study and provides the reader with recommendations for future work in this field of study.

METHODOLOGY

2.1 Introduction

This section of the study will focus on developing a methodology using digital twin simulations to assist with the planning of deep-level gold mine compressed air systems. The methodology will be developed by using literature, data, system information and simulation software to create a digital twin model of the system. The individual steps in the developed methodology will be based on various methodology's that have been developed in other studies. Where necessary the already existing methodology's will be altered to better suit the specific purpose of planning for deep level mine compressed air systems. The developed digital twin simulation model will be used to identify problems and determine the effect of different solutions on the system [48]. illustrates the developed methodology. Each step and its development will be discussed in this section.

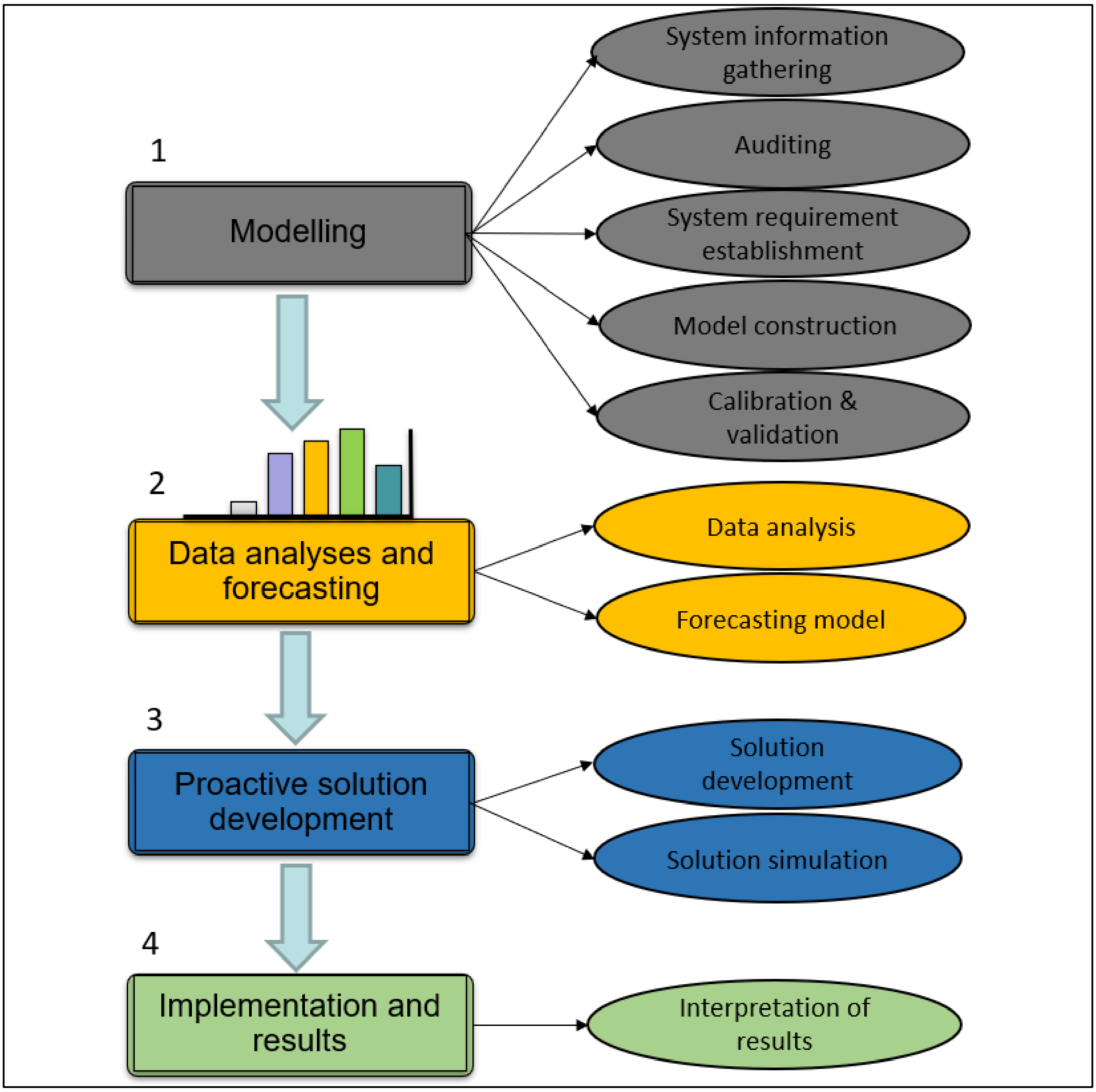


Figure 4:: Summary of the developed methodology

2.2 Modelling

This section will discuss the method developed for constructing a digital twin simulation to assist with the proactive planning of deep-level gold mining compressed air systems. The digital twin simulation will provide a virtual representation of the mine, which will estimate the future conditions and requirements of the compressed air system. The digital twin model can be changed to test different improvement scenarios and further development of the system to estimate the results of these changes [55, 56].

Various studies have been completed on methods to develop digital twin simulation models. Most studies consist of a series of steps that should be followed iteratively until the desired output for each step is achieved [23, 41, 54]. Table 3 shows the two methods developed by Maré et al. and Pascoe et al., respectively [23, 54].

Table 3: Methods for constructing compressed air digital twin simulations [23, 54]

Steps	Maré et al.	Pascoe et al.
1	Select level of detail required in the simulation	Build initial simulation
2	Acquire necessary information	Build additional simulation
3	Select simulation application	Calibrate flow
4	Select project properties	Calibrate pressure
5	Construct systems in simulation	Iterate steps
6	Calibrate the simulation	Determine accuracy
7	Run simulation	
8	Evaluate results	

Using the information gained, a similar method will be developed for constructing a digital twin model for future mine compressed air planning. The following steps will be followed:

1. Gather all available system information regarding the system demand, supply side and reticulation network.
2. Determine the system’s targeted requirements.
3. Complete a full audit of the compressed air system to gather and verify information.
4. Construct the digital twin simulation using the gathered system information.
5. Test and verify the accuracy of the digital twin model.
6. Calibrate the model if necessary.

Figure 5 provides a visual representation of the process for constructing a digital twin model for a deep-level gold mine compressed air system for the purpose of future planning.

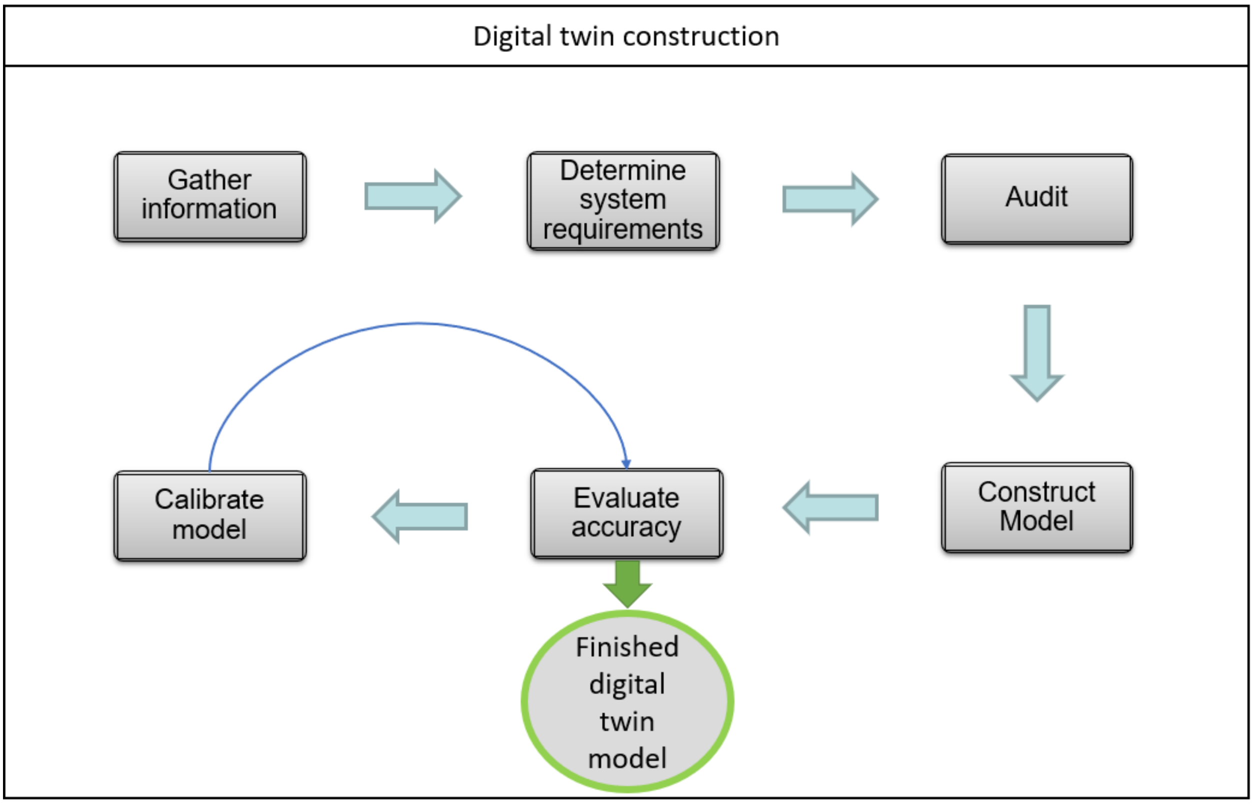


Figure 5: Steps for constructing a digital twin model

The digital twin model will be constructed to represent the supply side, reticulation network, and demand side. The supply side of the model will include the compressors in the compressor houses; the reticulation network will include the piping and valves that distribute the compressed air; and the demand side will include the refuge bays and other compressed air users as shown in Figure 2. The demand side will be represented by compressed air demand components that require the same demand flow and pressure represented by the compressed air users [57].

To simplify the model, it will be constructed to simulate in a steady state at peak drilling shift conditions. This shift is the critical time frame of the system. More information is given in Section 2.3.1. The model will only be constructed up until the cross-cut entrances of the mining areas to reduce the number of required components in the model. Reducing the number of components in a simulation reduces the time and financial aspects of creating the simulation with little effect on the model's accuracy [23, 54].

2.2.1 System information gathering

It is crucial that all required information and data be obtained before creating a simulation model [41]. The information to be gathered for constructing a digital twin model of a mine's compressed air system includes all the information on the supply and demand side of the system as well as the reticulation network used to distribute the compressed air [3, 23, 41].

DXF mine level layouts of current and future mining will also have to be obtained. The layouts will be used as an overlay with the right geographical coordinates to construct the model. Other information needed includes the compressed air system configuration and the dynamic operation of the mining complex [23].

The supply side of the compressed air system includes the compressors and compressor houses. It is important to establish the type and performance of compressors used in the system. Other necessary compressor information to be collected includes [41]:

- Compressor supply pressure
- Compressor characteristic curve
- Compressor efficiency

The information necessary for the reticulation network includes all the available information on the system configuration, pipe and valve dimensions, and other characteristics. The required pipe dimensions include [48]:

- Pipe length
- Pipe diameter
- Pipe surface roughness

Important information to be gathered for the demand side of the compressed air system includes all the users of compressed air in the system. Compressed air is consumed by many end users on deep-level gold mines. End users range from surface to underground operations and include the workshops and plants on the surface as well as all the underground compressed air users as specified in Table 1 [12]. These end users require a combination of high pressure and flow outputs, and it is important to establish these requirements [9].

Some information is not available; for example, some valves do not appear on the supervisory control and data (SCADA) system. To gather the information not available from the relevant mine personnel or other sources, audits will have to be completed [48].

Figure 6 illustrates the data and information that will be gathered and used to construct the digital twin model for this study, as well as the sources of the information.

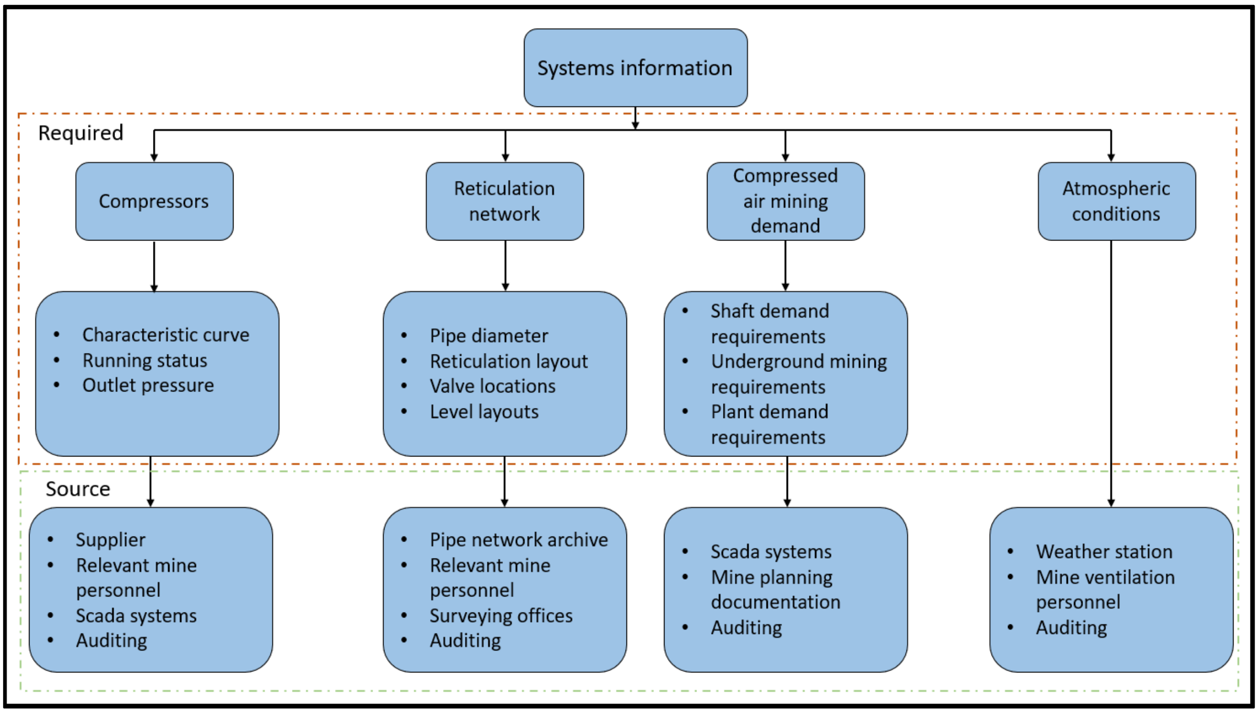


Figure 6: System information gathering process [22, 41]

2.2.2 Auditing

This study requires a comprehensive walk-through audit of the entire compressed air system. These audits are difficult and time-consuming but are necessary as the compressed air system needs to be known and understood for the developer to construct an effective digital twin model [22]. The process of completing the compressed air system audit consists of three parts, namely the surface audit, shaft audit, and level audits. A walk-through audit entails visiting the subsections of the compressed air system and walking along the compressed air pipelines, visually inspecting and recording the system [48]. The audits are recorded with pen and paper, plotting the exact position and sizing of the pipelines and other system components.

It is important that the entire compressed air system be audited – especially when considering the reticulation network as mines do not always have adequate information regarding the pipeline sizing and changes that could have been made to the reticulation network [8, 16, 36]. The following aspects should be noted when completing the audit [48, 58]:

- Level layout
- Pipe configuration
- Pipe sizes
- Valve type and location
- Splits in the pipeline

Surface audits will be completed by visiting the surface compressor houses and following and documenting the pipelines all the way to the different shafts and plants. Shaft audits will be completed by making proper arrangements with mine personnel to go down each shaft and following and documenting the pipelines going down the shafts and entering each level. Level audits will be completed by visiting each level individually and following and documenting the pipelines from the station inlets to the active mining areas. Since navigating the underground levels can be difficult, it is recommended that a simplified piping and instrumentation diagram of the compressed air system and a level layout be created before starting the audit [6, 22, 59]. These documents serve as a map. Not only do they make navigation better but also assist with recording the system [48]. Figure 7 illustrates an example of a level layout with some known information that can be used as a map while completing the underground level audits.

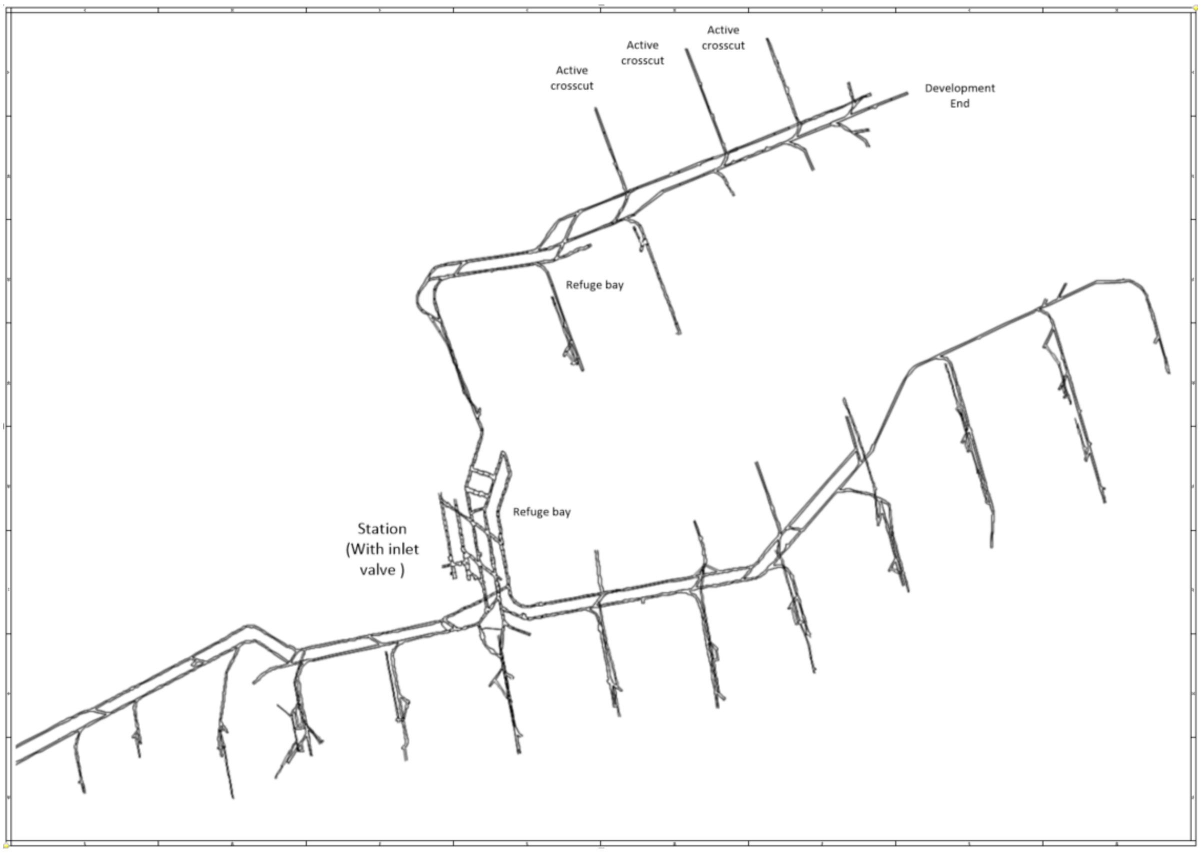


Figure 7: Example of a pre-audit level layout for navigation

While completing the audit, portable measurement instrumentation, such as pressure gauges and insertion flow meters, can be used to verify instrumentation accuracy [22, 60, 61]. After completing the audit, the handwritten documentation will be digitised for storage. Figure 8 shows an example of a level audit that has been digitised.

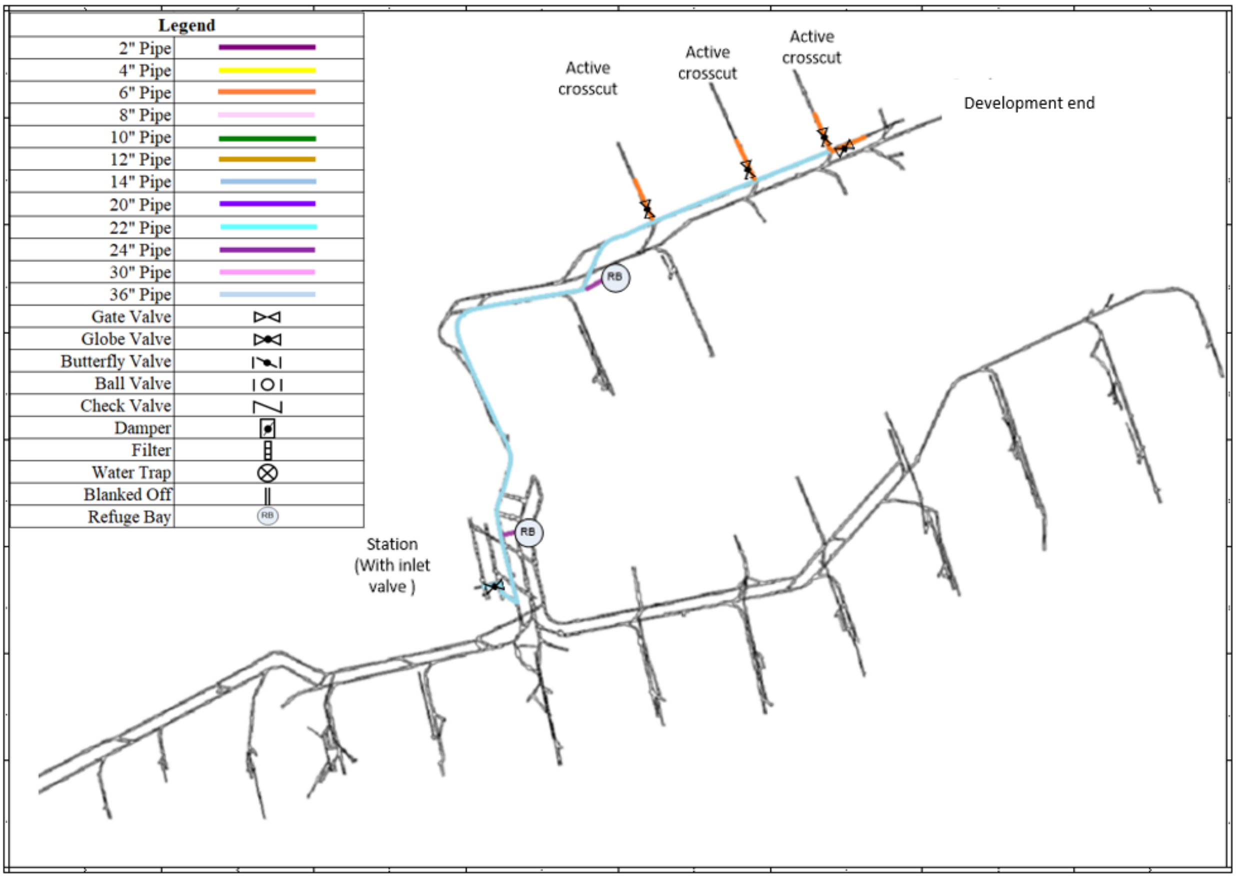


Figure 8: Example of a digitised level pipeline audit

2.2.3 System requirement establishment

It is important to establish the requirements of the specific system to be planned before creating and simulating the different planning scenarios [48]. These requirements include set points, operating conditions of the system, and targets to be reached for continuous production [48]. Establishing these requirements is crucial as they will be used as the basis of the compressed air system planning.

When considering compressed air systems in deep-level gold mining, one of the most important requirements to establish is the required pressure at specified points in the system and the required operating pressure for the demand-side equipment to function [48]. This will have a direct influence on production [1, 3]. The requirement of the demand-side equipment will vary from mine to mine due to different suppliers. Table 1 gives a good estimate of the equipment requirements [11, 23].

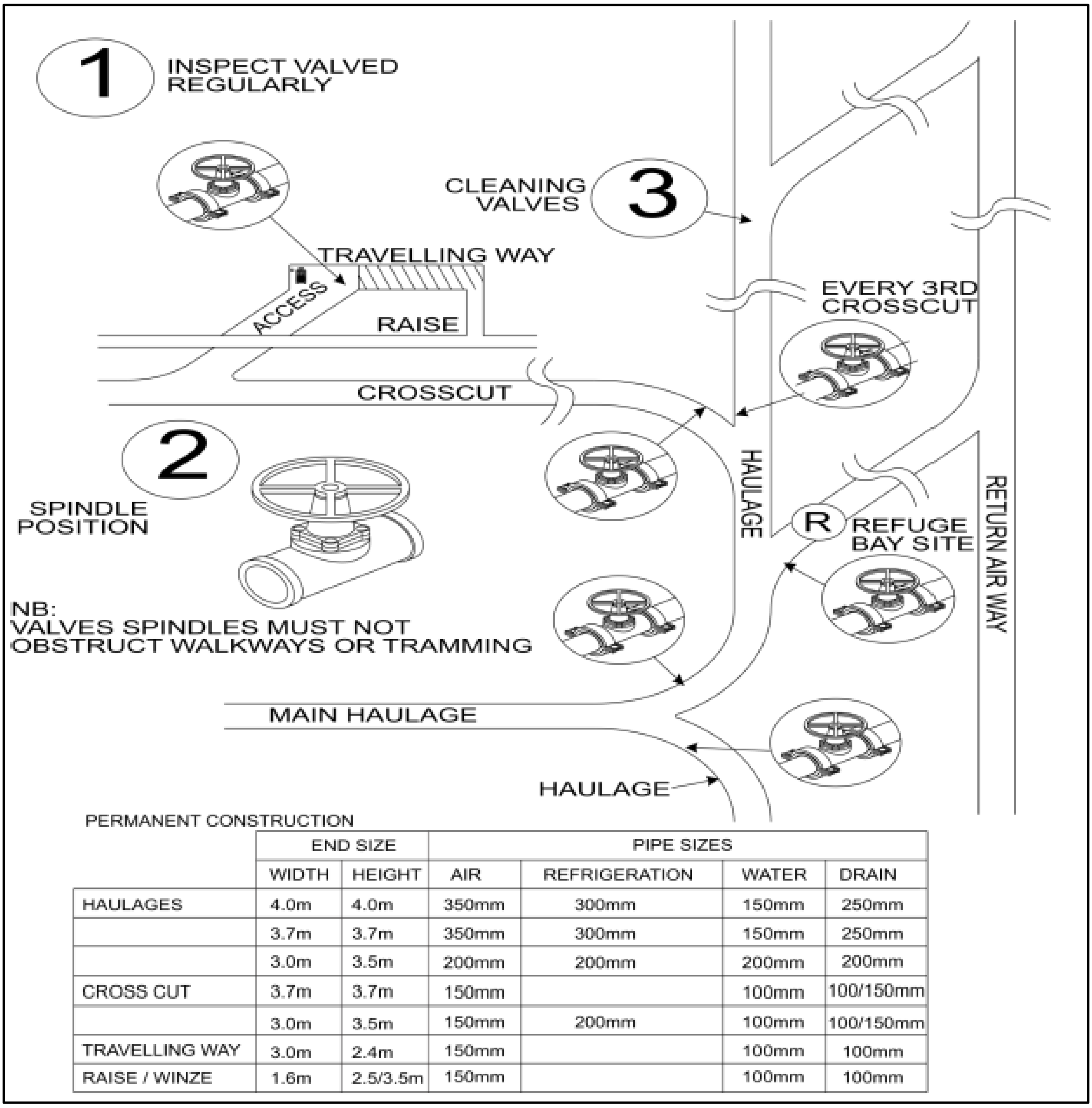
One of the most critical requirements to meet is the required compressed air pressure for the drills as the drill penetration rate and production are directly influenced by the delivered compressed air pressure [3, 62]. As previously mentioned, the digital twin model will be constructed up to the cross-cut entrance. Thus, it is crucial to establish the requirements at the cross-cut entrance.

To determine the requirements of the compressed air system at the cross-cut entrances, the following key factors need to be determined:

- What compressed air users are in these sections?
- What are the requirements for these users?
- What is the standard layout of the compressed air system in these sections?
- What effect does the geography from the entrance to the stoping or development face have on the compressed air supply?

By completing research and gathering the specifications documentation from the equipment suppliers, the compressed air users in the active mining areas and their requirements can be established, as explained in Section 2.2.1. Completing a system audit will provide further relevant information.

The standard layout of the compressed air system in these sections can be obtained from the mine itself as every mine has a standard for their infrastructure [22]. It is important to look at the manifold, valve positioning and pipe sizing in these sections as these may influence the compressed air supplied to the stoping and development faces. Figure 9 shows an example of a compressed air infrastructure standard.



PERMANENT CONSTRUCTION

	END SIZE		PIPE SIZES			
	WIDTH	HEIGHT	AIR	REFRIGERATION	WATER	DRAIN
HAULAGES	4.0m	4.0m	350mm	300mm	150mm	250mm
	3.7m	3.7m	350mm	300mm	150mm	250mm
	3.0m	3.5m	200mm	200mm	200mm	200mm
CROSS CUT	3.7m	3.7m	150mm		100mm	100/150mm
	3.0m	3.5m	150mm	200mm	100mm	100/150mm
TRAVELLING WAY	3.0m	2.4m	150mm		100mm	100mm
RAISE / WINZE	1.6m	2.5/3.5m	150mm		100mm	100mm

Figure 9: Example of a case-specific standard for compressed air infrastructure

To determine the effect of the geography on the compressed air supply, two factors need to be considered, namely the distance the air needs to be distributed in these sections and the minor head losses encountered over valves or in pipelines situated in travelling ways and raises. These effects can be calculated theoretically using Equation 1 and Equation 2.

Minor head losses are calculated using Equation 1 [63]:

Equation 1: Minor head loss

$$h_m = k_m \left(\frac{V^2}{2g}\right)$$

Where:

h_m = Minor head loss [m]

k_m = Minor loss coefficient [–]

V = Flow velocity [m/s]

g = Gravitational constant [m/s^2]

The effects of autocompression in travelling ways and raises are calculated using Equation 2 [20]:

Equation 2 : Autocompression

$$p_2 = p_1 \left[1 - \frac{g(z_1 - z_2)}{T_1 C_p}\right]^{\frac{1}{k}}$$

Where:

p_2 = Final pressure [kPa]

p_1 = Initial pressure [kPa]

g = Gravitational constant [m/s^2]

z_1 = Initial altitude [m]

z_2 = Final altitude [m]

T_1 = Temperature of the compressed air [K]

C_p = Specific heat capacity of the compressed air [kJ/kg.K]

k = Specific heat ratio of the compressed air – 1.4 [kJ/kg.K]

In this study, a simplified simulation will be used to establish the cross-cut entrance requirements for standard stoping and development ends. To construct this small model, information on the geography of the standard stoping and development ends will be gathered and used in combination with other information to determine the cross-cut entrance requirements. Simulation software considers the previously mentioned factors and has been proven to be accurate for evaluating their effect on the compressed air supply through simplified simulations [23, 41].

2.2.4 Model construction

Using the information gathered on the system, its requirements, and the information gathered from the audits, the digital twin model construction can begin. A baseline simulation of the current system is required to create a digital twin model for estimating the system performance due to changes in production or infrastructure [48]. The baseline simulation will be used to verify the model's accuracy and as the foundation against which to compare the different scenarios. The peak drilling shift with the highest demand on the system will be used as the baseline period, which the construction of the model will be based on [64, 65].

Several software packages can simulate mining systems and processes [41, 66]. However, only a few allow access to real-time system data and can simulate dynamic integrated systems [34, 67]. The simulation software for this study was chosen according to the requirements specified by Watkins for constructing simulations of deep-level mine compressed air systems [41]:

- The simulation software needs to be a transient simulation tool that can calculate the system's response for system infrastructure changes and mining demands.
- The simulation software needs to deliver various simulation outputs at a specified time step so that it can be compared with actual data.
- The simulation software needs to be suitable and easy to use for the application at hand.
- The simulation software must be accessible.

PTB, SolidWorks flow simulator, KYPipe Gas and Flownex are simulation software packages that are potential tools for simulating mining activities [52]. These simulation packages are compared and evaluated as shown in Table 4.

Table 4: Simulation software package evaluation [3, 41]

Software package	Advantages	Disadvantages
SolidWorks Flow Simulator	• Accurate • Delivers various outputs • Detailed outputs for specific components	• Expensive and requires full software licence • Time-consuming; components need to be modelled individually
KYPipe Gas	• Easy to use • Fairly accurate	• Not suitable for compressible fluids
Flownex	• Accurate • Applicable for mining solutions	• Expensive and a software licence is required • Time-consuming
PTB	• Accurate for mining application • Easily accessible • Capable transient tool • Delivers various system outputs for each time step	• Moderately user-friendly

The evaluation shows that PTB is the most suitable simulation software package for this study as it meets all the specified requirements [9]. Appendix A discusses the workings of PTB and its internal components. PTB has the following advantages aiding in the digital twin construction [22]:

- PTB can directly import underground level layout drawings. Simulation components can be placed directly on the drawing using the coordinates as geographical inputs.
- PTB has a built-in function that makes it easier to construct complex underground system simulations.
- PTB has empirical model components that can be used if data such as pipe roughness is not available.

Due to the advantages and accessibility of PTB, it will be used to construct the digital twin model and all other simulations in this study. All the compressor information will be used to construct the supply side of the digital twin model. The reticulation network will be constructed exactly to the audit’s specifications of the pipeline sizes, lengths, and layout. All relevant valves will be included in the digital twin model. The demand side of the system will be constructed in the digital twin model using the demand components available in PTB. These include all compressed air users such as plants, refuge bays and active mining areas for stoping and development. Appendix A provides more detail on how PTB will be used to construct each part of the compressed air system in the simulation.

The mine's three-year mining plan and the standard mining procedure for the compressed air infrastructure, as can be seen in Figure 9, will be used to expand the digital twin model to include future mining areas. The model will be constructed in such a manner that the active areas can be changed according to the three-year mining plan to simulate the different times of the three-year mining plan easily.

2.2.5 Calibration and validation

The baseline simulation needs to be compared with the current system using a control data set. All the required parameters must be measured and verified against the digital twin's simulation outputs. Verification and calibration are essential to ensure simulation accuracy [3, 48]. Calibration of the digital twin model plays a major role in ensuring that accurate results are obtained. The model will be calibrated using component and system design specifications and requirements [41]. Mean absolute error (MAE), by measuring the model's accuracy, is the most effective method for validating simulations [41]. These measurements are obtained by comparing the major simulation outputs (system flow and pressure) with actual data from the system [41, 52]. The MAE will be calculated by dividing each individual error with the actual value at the same time step, as shown in Equation 3 [41, 55]. As the MAE method has been shown to be the most effective method of validating simulations, the percentage error calculations in this study will be completed using this method.

Equation 3: MAE [41, 55]

$$Error = \frac{1}{K}\sum_{k=1}^{k}\left|\frac{A_k - S_k}{A_k}\right|(100\%)$$

Where:

$Error$ = Percentage error [%]

K = Total number of data points

k = Specific data point

A_k = Actual data value

S_k = Simulated data value

According to Maré et al. and other studies, the model should be calibrated until the simulation provides outputs that are accurate when compared with actual data and within a 5% error margin [23, 41, 48, 52]. To validate the accuracy of the digital twin model in this study, a day with adequate data for the compressed air system's pressures, flows and other relevant data will be chosen. Simulation accuracy is dependent on the amount of available data to ensure accurate comparisons between the simulated and actual system characteristics and events, as well as simulated estimations and predictions. It is thus critical that there is sufficient accurate data when calibrating the simulation model [68]. The known data of the day's supply side in terms of how many compressors were running and at what capacity will be used as inputs to the supply side of the digital twin model. The three-year mining plan will be used to assess the number of active mining areas and their locations, which will be the input for the demand side of the digital twin model.

Thereafter, the digital twin model will simulate the specified day. The results will be exported and compared with the actual system data for the same day. An error margin of 5% has been chosen. The model must be accurate within this error margin for it to be deemed accurate. The calibration and validation method discussed in this section will be repeated until the desired model accuracy is achieved.

2.3 Data analysis and forecasting

This section of the study will discuss the process to be followed when analysing the mine's data. The analysis will be used to forecast the mine's future compressed air system requirements. The forecasting model together with the gathered system information and the digital twin model of the mine will be used to evaluate the system's effectiveness for the planned future mining.

2.3.1 Data analysis

The data analysis will be completed by evaluating KPIs, an effective performance measurement technique. A KPI takes on the form of a statistical value for making informed decisions [69, 70]. The first step of the data analysis will be to collect data and formulate it into KPIs.

Total production output is a standard KPI used by mines to determine productivity, and it is usually recorded as tonnes mined or hoisted [13]. The historical production of the mine will be evaluated by analysing the historical three-year mining plan. The historical data on tonnes ore mined from each level and for the mine in total will be captured and analysed.

The compressed air used during the peak drilling shift is the peak production compressed air KPI [13]. During the peak drilling shift, the demand on the compressed air system is at its highest, as can be seen in Figure 1. The high compressed air consumption has a negative effect on the compressed air pressure due to friction losses in the reticulation network [13]. Thus, the system is under the most stress to meet its requirements during this period. The compressed air consumed during the peak drilling shift is also the most closely related to shaft production [22, 27, 69, 71]. Therefore, the peak drilling shift requirements will be used for designing and planning the mine's compressed air system.

As compressed air plays a significant role in the mining process of deep-level gold mines, most mines have sensors that measure the compressed air flow and pressure at specified points [13]. The data obtained from these sensors is available on the mine's SCADA system and is easily accessible [48].

The time at which the peak drilling shift takes place might vary slightly between mines according to their schedules. Thus, the peak drilling shift for the mine at hand will have to be identified by evaluating the compressed air flow and pressure data of the mine on a daily basis. The historical flow data of compressed air to all mining activities that take place underground during this period will be gathered and analysed.

The data analysis will be completed by evaluating and comparing the historical production and compressed air use of the mine. The compressed air usage compared with the output production in the form of tonnes mined is an applicable KPI for identifying and evaluating system inefficiencies [11, 13]. These factors will be compared to establish the correlation between the compressed air flow requirements and production. The correlation will be determined by using a black box method, which is also known as a data-dependent model. The black box method uses statistical regression models and offers superior accuracy and ease of use [17, 65].

Statistical regression is described as the process of estimating the relationship between two sets of variables with one set of variables being dependent and the other being independent. The relationship is established by using known data, changing the independent variable, and establishing the effect on the dependent variable [65, 70]. This is expressed mathematically as Equation 4.

Equation 4: Statistical regression [65]

$$y = f(x; w) + \varepsilon$$

Where:

y = Dependent variable (required compressed air flow)

x = Independent variable (tonnes mined)

w = Parameter that is changed (month)

The KPI results will be assessed by using a scatter plot with both axes representing a data set [72]. A trendline will be fitted to the scatter plot and the resulting R^2 value calculated. Inspecting the scatter plot and the R^2 value will give an indication of the correlation between the data sets. Any R^2 value greater than 0.5 is considered a strong correlation for compressed air models [65, 73]. The correlation between these factors will subsequently be used to forecast the future requirements of the compressed air system.

The historical data on the total compressed air flow used for underground mining activities during the peak drilling shift will also be analysed to determine the average flows during these periods and how much the flow varies during these periods. The percentage difference experienced between the average flow in the peak drilling shift, used for forecasting model, and the maximum flow will be used create a safety factor that will be built into the forecasting model.

2.3.2 Forecasting model

This section of the study will discuss the process followed to forecast the future performance of the compressed air system. Simulation techniques can be used to quantify the relationship between systems parameters [41]. The forecasting model will be completed by using the digital twin model and the correlation, established in the previous section, between the compressed air flow and production.

The three-year mining plan will be used to establish the future production in each section of the mine and the mine in total. This data with the established correlation will be used to estimate the future compressed air demand requirement for all underground mining activities during the peak drilling shift in the form of a total compressed air flow [kg/s]. The data regarding the planned tonnes to be mined in the three-year mine plan will be fed into the established correlation to estimate the required future compressed air demand.

The estimated flow will be a predicted average flow for the peak drilling shifts of all underground mining activities. To test if the estimations are accurate, a six-month estimation period will be compared with the actual flows measured during the same time period. The estimations will have to be accurate within 5% for the estimation model to be deemed accurate. If the model proves to be accurate, it will be used to estimate the compressed air demand for the full cycle of the three-year mining plan. The safety factor, as discussed in the previous section, will be implemented in the estimation model to assure that system planning caters for the worst-case scenario.

The total estimated compressed air demand for each month will be divided between the different levels and active mining areas according to the percentage of tonnes mined from each section. The estimated demands for the compressed air in each section of the mine will be used as inputs into the variable components in the digital twin model. Thereafter, the digital twin model will be simulated with the different inputs for each month of the three-year mining plan.

In the past, simulation software has proven to show big potential in identifying problem areas in compressed air networks [41]. The results obtained from these simulations have the potential to establish where future compressed air system inefficiencies and problem areas will appear.

2.4 Proactive solution development

The application of digital twin simulations for proactive solution development has avoided disruptions and delays in production in manufacturing industries [74]. This section of the study will discuss a similar process for developing proactive solutions to the inefficiencies and problems that the compressed air system will face in the future.

Depending on the identified problem, a solution will be developed to solve the problem by upgrading or changing the system infrastructure. The solution will be developed to keep costs at a minimum while still enabling the compressed air system to meet the necessary production requirements. Using the existing mine infrastructure and only making small changes to the system to solve identified inefficiencies can reduce the cost of implementing projects [3].

A key part of the solution development will be to address the identified problem as proactively as possible to minimise the effects on the mine’s production. A proactive approach controls a given situation by actively influencing the process before unwanted situations occur [75]. This study will implement a proactive approach by using the results of the forecasting model and scheduling the implementation of the solution to minimise the effects of the identified problem on the compressed air system and mine production.

Meetings will be held with the relevant planning and engineering mine personnel to develop a cost-effective solution to solve the identified problem. The developed solution will be simulated using the developed digital twin model by making the relevant adjustments and using the identified timeline to update the digital twin model accordingly to the planned mining. These simulations will consider both the effects of the changes made to the system and the effects of planned production on the system.

Proactive simulation-based procedures use the fact that computer simulations can be performed much faster than real-life production takes place [75]. This provides the opportunity to quickly assess the effects of the planned solution on the system to determine its effectiveness without wasting much time. The results from the digital twin model simulations can thus be analysed to determine the effects of the developed solution on the compressed air system. This will be done by analysing the simulation compressed air pressure outputs.

A meeting will be held with the relevant mining personnel to discuss the simulation results and the effectiveness of the solution. If the results show that the solution does not provide the desired outcome, the problem will be re-evaluated. In this case, the process will be repeated to develop a new viable solution. The final accepted solution will be handed over to the mine’s relevant personnel to install or implement the chosen solution practically.

2.5 Results

This section of the study will discuss the process to be followed to evaluate the implementation of the developed methodology and the proactive solution developed, as discussed in the previous section.

The first step in determining the results obtained from the implementation will be to evaluate the direct effects on system performance. The compressed air sensors at key points in the compressed air system, as identified during the system information gathering and auditing process, will be used to measure system performance before and after implementing the developed solution. This data will be stored on the mine’s SCADA system and analysed. The system’s delivery of compressed air pressure pre- and post-implementation will be compared to evaluate system improvement and establish whether the specified requirements have been met.

The results obtained from the implementation will be compared with estimations made by the mine’s digital twin model as constructed in Section 2.2.4. The comparison will be used to verify the digital twin model and proactive planning strategy’s success and accuracy. As a safety factor will be built into the digital twin model, it is expected that the actual results of the implementation of the developed solution will provide better system outputs than simulated.

The final step will determine the financial benefits gained by implementing the study. Depending on the system's inefficiency or bottleneck identified and the solution developed by following the proposed methodology, different methods can be followed to determine the financial benefit. This study will review two methods, but implementing the methodology on other case studies may find other applicable methods better suited to the specific problem to determine the financial benefit obtained.

The two methods that will be used in this study to evaluate the financial gain are the following:

- Evaluation of the production increase by evaluating increased drill penetration rates.
- Evaluation of electrical savings made by reducing required compressor work.

The first method will evaluate the effect of the developed solution on mine production by determining the increase in achievable drill penetration rates, which will be calculated using the increase in compressed air pressure at planned mining areas. This is a good KPI as compressed air delivery pressure has a direct influence on drilling rate and, subsequently, on production [3, 13, 58]. The penetration rate pre- and post-implementation will be calculated using Equation 5 [3, 13, 62]:

Equation 5 : Predicted rock penetration rate **[3, 62]**

$$\begin{aligned} PR = {} & 0.0879242 + 0.0111569 \times A - 0.246978 \times B + 0.0070986 \times C \\ & - 0.0000100938 \times A2 + 0.003057 \times B2 - 0.00000760976 \times C2 \\ & + 0.0000103687 \times A \times C - 0.0000546415 \times B \times C \end{aligned}$$

Where:

PR = Predicted penetration rate [mm/s]

A = Drill bit size [mm]

B = Air pressure [kPa]

C = Thrust [N]

This is an empirical formula that has been used in multiple studies and that has shown agreeable results [3]. The pre- and post-implementation penetration rates will be used to calculate the production and financial impact by using the production impact analysis developed by Nell as shown in Table 5 [3]. Index A to Index M are case variable inputs used to calculate Index N to Index AK.

Table 5: Production impact analysis [3]

Parameters	**Index**	**Calculations**	**Unit**
Panel height	A	–	m
Panel width	B	–	m
Number of holes per panel	C	–	–
Hole depth/drill length	D	–	m
Number of drills per panel/manifold	E	–	–
Forward advancement during blasting	F	–	m
Average drill shift	G	–	hr
Previous penetration rate	H	–	m/s
New rock penetration rate	I	–	m/s
Travelling times	J	–	hr
Gram gold per tonne	K	–	g/tonne
Rock density	L	–	kg/m^3
Gold price	M	–	R/g
Square metre	N	$= A \times B$	m^2
Total drill distance	O	$= C \times D$	m
Total drill distance per square metre	P	$= \frac{O}{N}$	m/m^2
Rock volume blasted per panel	Q	$= F \times N$	m^2

Parameters	Index	Calculations	Unit
Rock weight per panel	R	$= \frac{Q \times L}{1\,000}$	tonne
Gold per panel	S	$= R \times K$	g
Previous drill time per square metre	T	$= \frac{P}{H}$	min/m^2
Previous drill time per square metre	U	$= \frac{T}{60}$	min/m^2
Previous drill time per square metre	V	$= \frac{U}{60}$	hr/m^2
Total previous drill time required	W	$= \frac{U \times N}{60}$	hr
Previous drill time per shift	X	$= \frac{X}{E}$	hr
New drill time per square metre	Y	$= \frac{P}{I}$	s/m^2
New drill time per square metre	Z	$= \frac{Y}{60}$	min/m^2
New drill time per square metre	AA	$= \frac{Z}{60}$	hr/m^2
Total new drill time required per panel	AB	$= \frac{Z \times N}{60}$	hr
New drill time per shift	AC	$= \frac{AB}{E}$	hr
Rock penetration rate improvement	AD	$= \left(1 - \left(\frac{Z}{60}\right)\right) \times 100$	%
Total time saved per panel	AE	$= X - AC$	hr
Additional squares that could be drilled	AF	$= \frac{AE \times 3\,600}{Y}$	min/m^2
Additional holes that could be drilled	AG	$= \frac{P \times AF}{D}$	–
Additional rock blasted	AH	$= AH \times F$	m^3
Additional rock blasted weight	AI	$= \frac{AH \times L}{1\,000}$	tonne
Additional gold extracted	AJ	$= AI \times K$	g
Financial benefit of additional gold	AK	$= M \times AJ$	R

The second method for determining the financial benefit of the implementation will calculate the theoretical cost of the electricity saved that the compressors would have used to achieve the same increase in pressure for the mine’s compressed air system. The power required for the compressor to compress the air will be calculated using Equation 6:

Equation 6: Power to compress air [58]

$$W = N \times P_1 \times V_1 \times (\frac{k}{k-1}) \times \left(\frac{P_2}{P1}\right)^{\frac{k-1}{((N \times k)\ -1)}}$$

Where:

W = Required power [watt per m^3/s]

N = Number of stages [–]

P_1 = Inlet pressure [kPa]

P_2 = Outlet pressure [kPa]

V_1 = Specific volume of the inlet air [m^3/kg]

k = Ratio of specific heat at constant pressure [–]

Once the required power is known, the cost of the required electricity for the compressors can be calculated.

2.6 Validation of study

This section of the study will discuss the process followed to validate the success of the study based on the objectives identified in Section 1.7. The following questions will be asked to determine whether the objectives have been met and the study can be deemed successful:

- Was a digital twin model of a compressed air system developed that accurately portrayed the performance of the system?
- Was the digital twin model expanded to include future mining activities and did it estimate the future performance of the compressed air system accurately?
- Has the study successfully identified future compressed air system inefficiencies and future of the specific mine?

- Did the study successfully develop proactive solutions to the identified system problems and fulfil a proactive planning strategy?

Evaluating the answers to these questions will give a clear indication whether the objectives have been met and whether the study was successful.

2.7 Conclusion

A need was identified in Chapter 1 to use simulations in mine compressed air planning. Chapter 1 further identified the objectives for being deemed successful. This chapter successfully developed a proactive planning methodology to meet the specified objectives and the need of this study.

The methodology in this chapter was developed from literature and consists of different steps. Each developed step was discussed and it was explained how they are to be implemented. In Section 2.2, the process for constructing the digital twin simulation was developed. Section 2.3 explained how the data analysis and forecasting model are to be completed to identify future problems. Section 2.4 provided information on how a proactive solution to the identified problems should be developed.

Chapter 2 further established the steps for interpreting the results obtained from the implementation of the methodology as well as the process for validating this study. Chapter 3 will discuss the implementation of the developed methodology in the form of a practical case study.

IMPLEMENTATION AND RESULTS

3.1 Introduction and case study background

This section of the study will focus on implementing the methodology developed in Chapter 2. The developed methodology uses digital twin simulations to assist in deep-level gold mining compressed air planning. This chapter will aim to test and validate the developed methodology by implementing the methodology on a deep-level gold mine in South Africa. The results will be analysed to determine its capability in performing successful proactive planning.

3.1.1 Case study background

The methodology was implemented on a deep-level gold mine situated in the North West province of South Africa. Due to a confidentiality agreement, this mine is referred to as Mine A. It is associated with ongoing development and uses a scattered mining method with an integrated backfill support system that uses bracket pillars.

The geology of Mine A is complex as it has large fault-loss areas between mining areas. The Vaal Reef is the primary ore body exploited by the mine, and mining typically takes place between 1 791 m and 3 052 m below the surface. Mine A has a gold ore grade average of 8.2 g/tonne. The ore is processed by a gold plant on the surface that uses the reverse gold leach method.

Mine A has a complex compressed air system that is expanded continuously as they mine deeper to increase the life-of-mine period. The compressed air system has two compressor houses with five active compressors and a total capacity of 210 000 CFM on the supply side. A standard piping reticulation system delivers compressed air to the demand side, which comprises two shafts. The mine further sells compressed air to another mine’s shaft as well. The system further provides compressed air to two gold plants and a uranium plant. The reticulation system continues down the two shafts to provide compressed air for all mining activities underground. Figure 10 provides a brief overview of the surface compressed air system of Mine A.

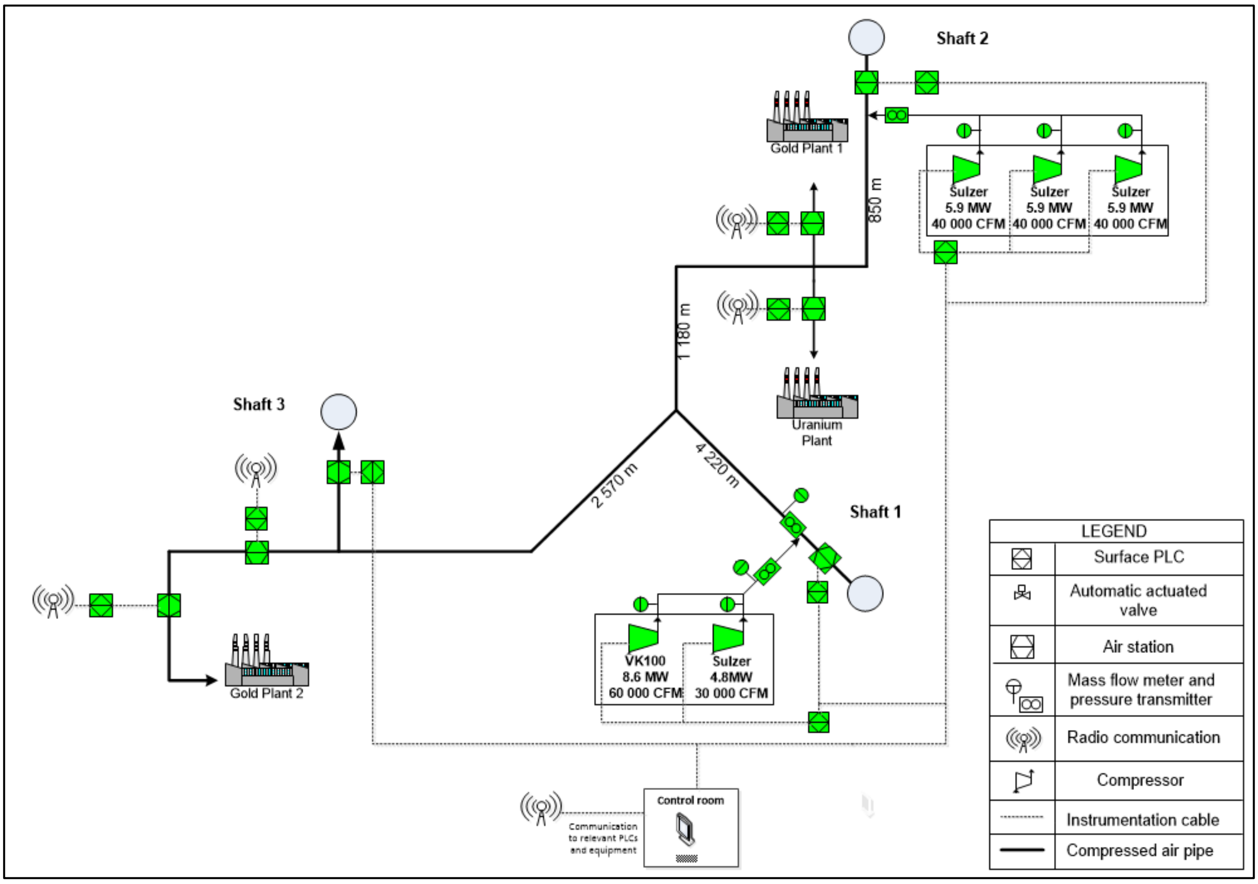


Figure 10: Mine A – compressed air system overview

3.2 Modelling

This section of the study will discuss the implementation of the methodology developed in Section 2.2. The methodology was followed to construct a digital twin model of Mine A's compressed air system. The model was used to assist in proactive planning for Mine A's compressed air system.

3.2.1 System information gathering

As discussed in Section 2.2.1, all possible information was gathered for Mine A's compressed air system by following the system information gathering process, as illustrated in Figure 6, and by researching relevant literature. This information was crucial as it was used to construct the digital twin model for Mine A.

All the required information for the supply side of the mine was collected. Appendix A shows the compressor characteristic curves for each compressor with the compressor efficiencies, supply pressure and flow. Other information on the supply side of the compressed air system is summarised in Table 6.

Table 6: Mine A – compressor specifications

Compressor	Power [MW]	Capacity [CFM]
VK 100	8.6	60 000
Sulzer	4.8	30 000
Sulzer 1	5.9	40 000
Sulzer 2	5.9	40 000
Sulzer 3	5.9	40 000

All the relevant sources of information were investigated for the reticulation network. Discussions with the relevant mine personnel provided a brief understanding of the reticulation network layout and the standard used by the mine was obtained. The piping sizes according to location can be seen in Table 7. These standards are not always followed, as mentioned in Section 1.4. No one knew the layout of the entire compressed air reticulation network, thus audits had to be completed to identify and verify the pipeline sizes and other information.

Table 7: Mine A – standard for compressed pipeline sizes

Area	Width [m]	Height [m]	Pipe size [mm]
Haulage	4.0	4.0	350
	3.7	3.7	350
	3.0	3.5	200
Cross-cut	3.7	3.7	150
	3.0	3.5	150
Raise/winze	3.0	2.4	150
	1.6	2.5–3.5	150

The necessary information for the demand side of the compressed air system was gathered from the relevant mine personnel and other sources. The underground and surface compressed air users were identified, which included all plants and equipment. The three-year mining plan was used to determine the exact number of stoping and development ends active each month. The number of refuge bays and their location were obtained from the mine and included in the digital twin model.

3.2.2 Auditing

This section of the study will discuss the process, as described in Section 2.2.2, for completing the walk-through audit of the compressed air system for Mine A. Completing the audit helped to provide a good understanding of the system and the required information that could not be obtained in the previous section.

The surface compressed air system was audited by visiting the compressor houses and verifying previously gained compressor information. The compressed air reticulation network was followed to the shafts and plants on the surface and mapped. The proper arrangements were made and shaft were examined for the reticulation network transcending in these sections. Layouts of the underground levels with known information were drawn up, which made navigation during level pipeline audits easier. The level pipeline audits were completed and the pipelines on each individual level were mapped using pen and paper. During these audits, the focus was on identifying the size and location of all pipelines in the compressed air system and valve locations. Figure 11 provides an example of a section of one of these level layouts that was created and used to record data during the 85L audit.

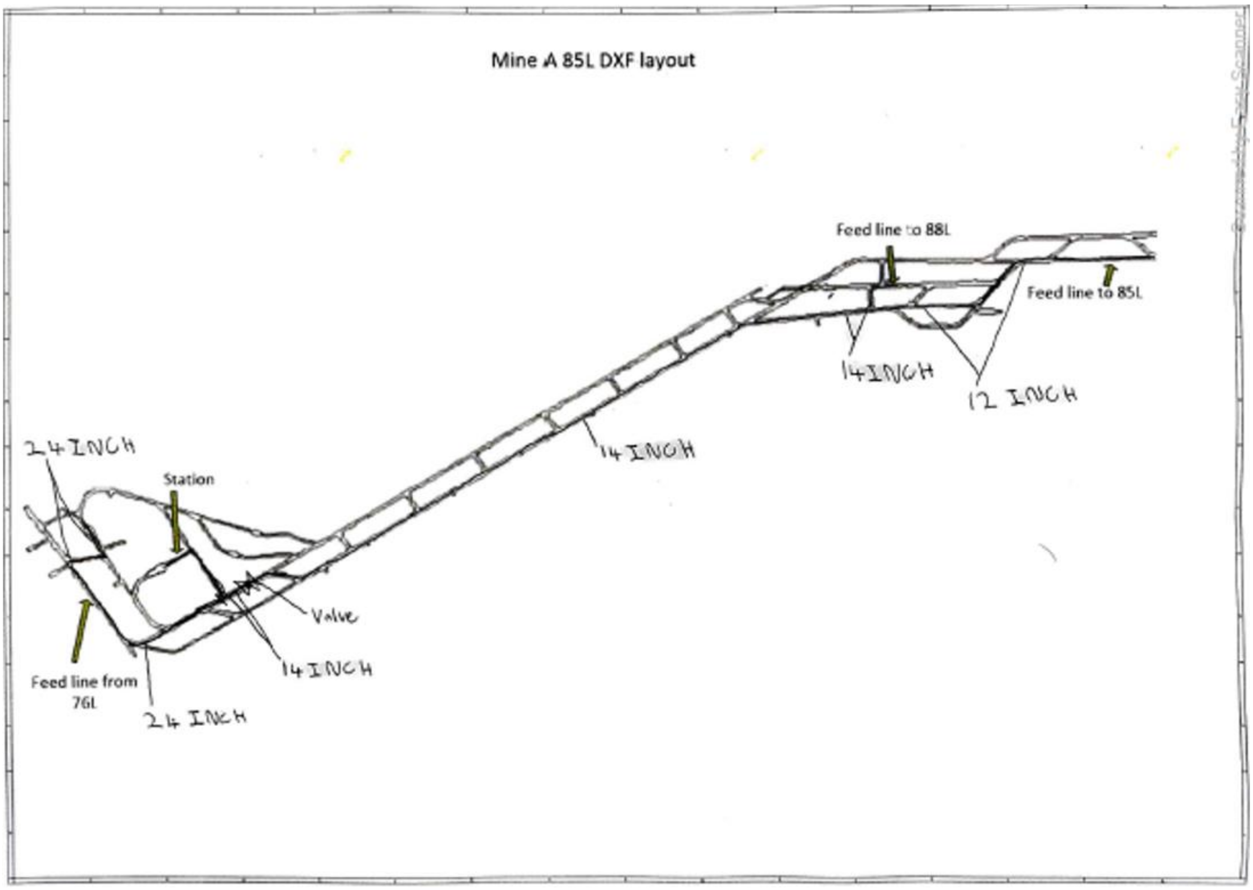


Figure 11: Mine A – 85L layout with handwritten audit data

During the auditing process, refuge bays and other compressed air users on the demand side of the compressed air system were identified and their locations pinpointed and recorded. The handwritten auditing documentation was digitised and stored. Figure 12 provides an example of a section of a digitised level layout.

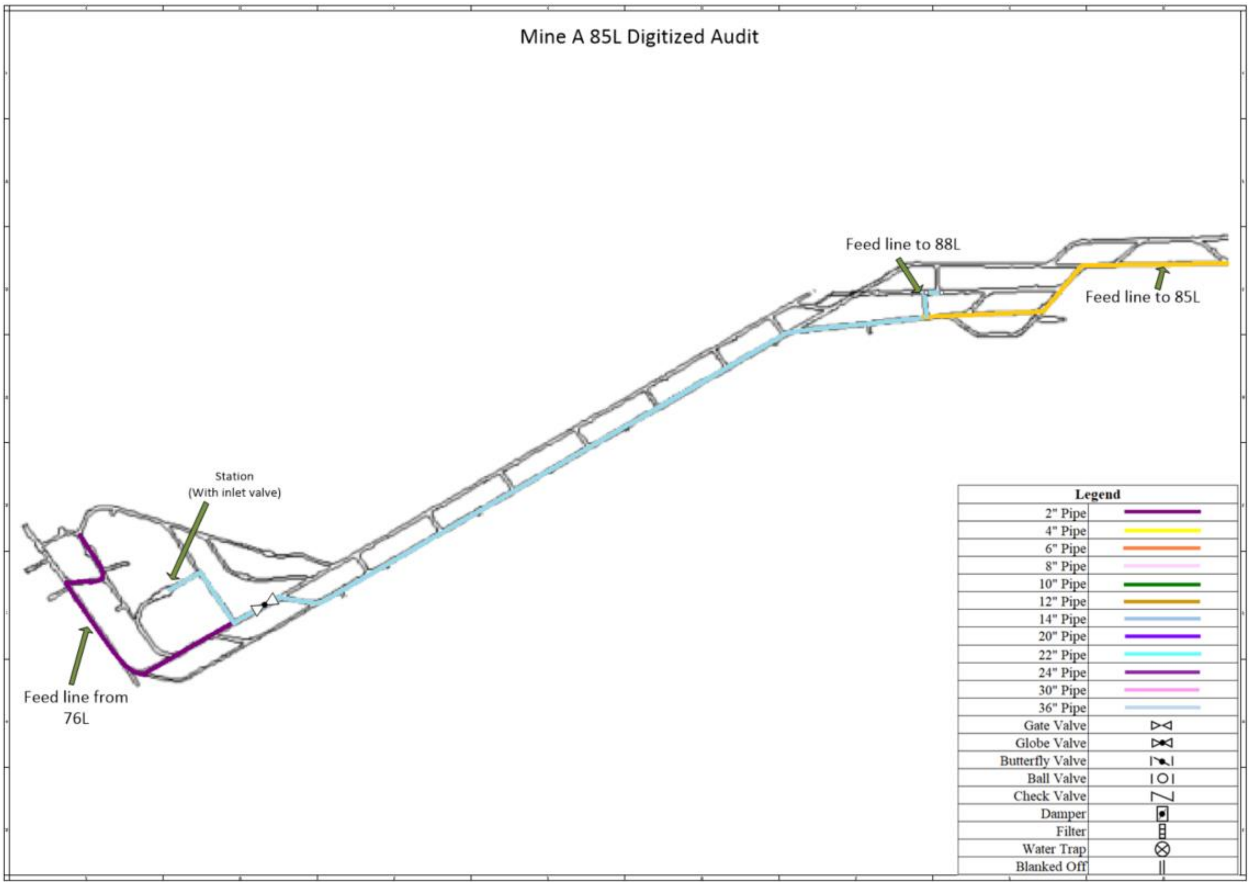


Figure 12: Mine A – 85L digitised layout

Appendix B provides the DXF level layouts and pipeline layouts of the production levels critical to this study.

3.2.3 System requirement established

This section of the study will discuss the process, explained in Section 2.2.3, for determining the system requirements of Mine A. These were used as the planning parameters for the compressed air system. The first step was to determine the targeted pressure requirements at the critical points in the compressed air system as summarised in Table 8.

Table 8: Mine A – compressed air system pressure requirements

Compressor	Required pressure [kPa]
VK 100	620
Sulzer	620
Sulzer 1	540
Sulzer 2	540
Sulzer 3	540
Ring	610
Shaft 1	590
Shaft 2	530
Gold Plant 1	450
Gold Plant 2	450
Uranium plant	450

The requirements of the demand side compressed air users were verified and were in line with the values presented in Table 1. The minimum required compressed air pressure at the stoping and development faces was 400 kPa because the drills needed a minimum compressed air delivery pressure of 400 kPa to operate effectively. During the peak drilling shift, the main compressed air users were the drills; thus, 400 kPa at the stoping and development faces was used as the minimum requirement for the compressed air planning.

The digital twin model was constructed up until the cross-cut entrances and not all the way to the stoping and development faces. Thus, the next step was to determine the compressed air requirements at the cross-cut entrance to deliver 400 kPa to the stoping and development faces. A simulation was built with PTB to simulate the stoping and development ends to determine the compressed air requirements at the cross-cut entrances. The geometry of these sections was measured by mine personnel and the results can be seen in Table 9.

Table 9: Mine A – mining area geometry

Description	Minimum	Maximum
Cross-cut length [m]	68	431
Travelway length [m]	20	121
Raise length [m]	25	130
Stope angle [degrees]	0	60
Travelway angle [degrees]	0	34

The maximum values were used to construct the models to simulate the worst-case scenario and ensure that the requirements would be sufficient for all the mining areas. Figure 13 and Figure 14 show the finished models. The models were constructed using the standard sizing for these sections as provided by Mine A.

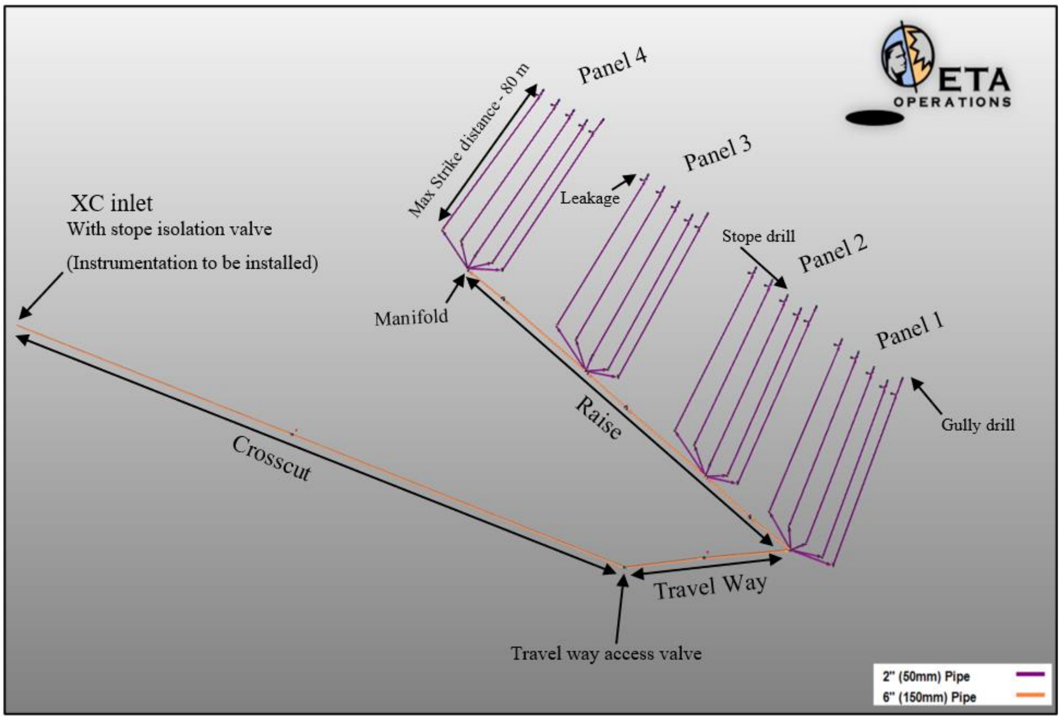


Figure 13: Mine A – standard stope

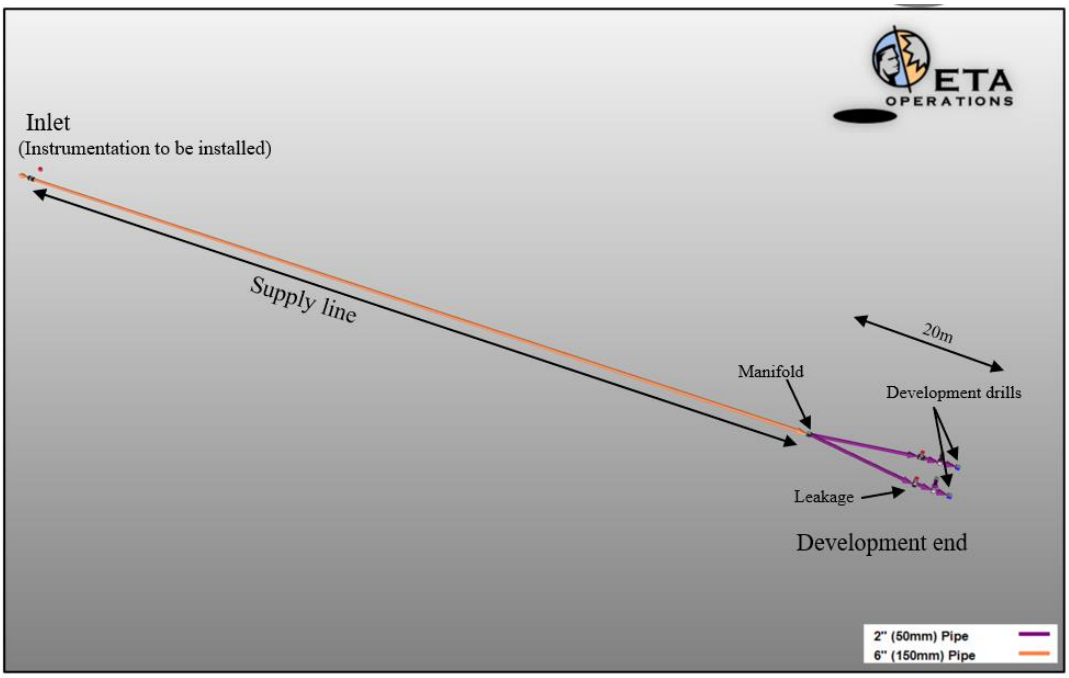


Figure 14: Mine A – standard development end

The number of active panels found in an active cross-cut for stoping was varied between one and four with different cross-cut inlet pressures. They were simulated to determine the pressure available at the drills. The results can be seen in Figure 15. It was established that an inlet pressure of 450 kPa was required to provide the drills with 400 kPa for stoping.

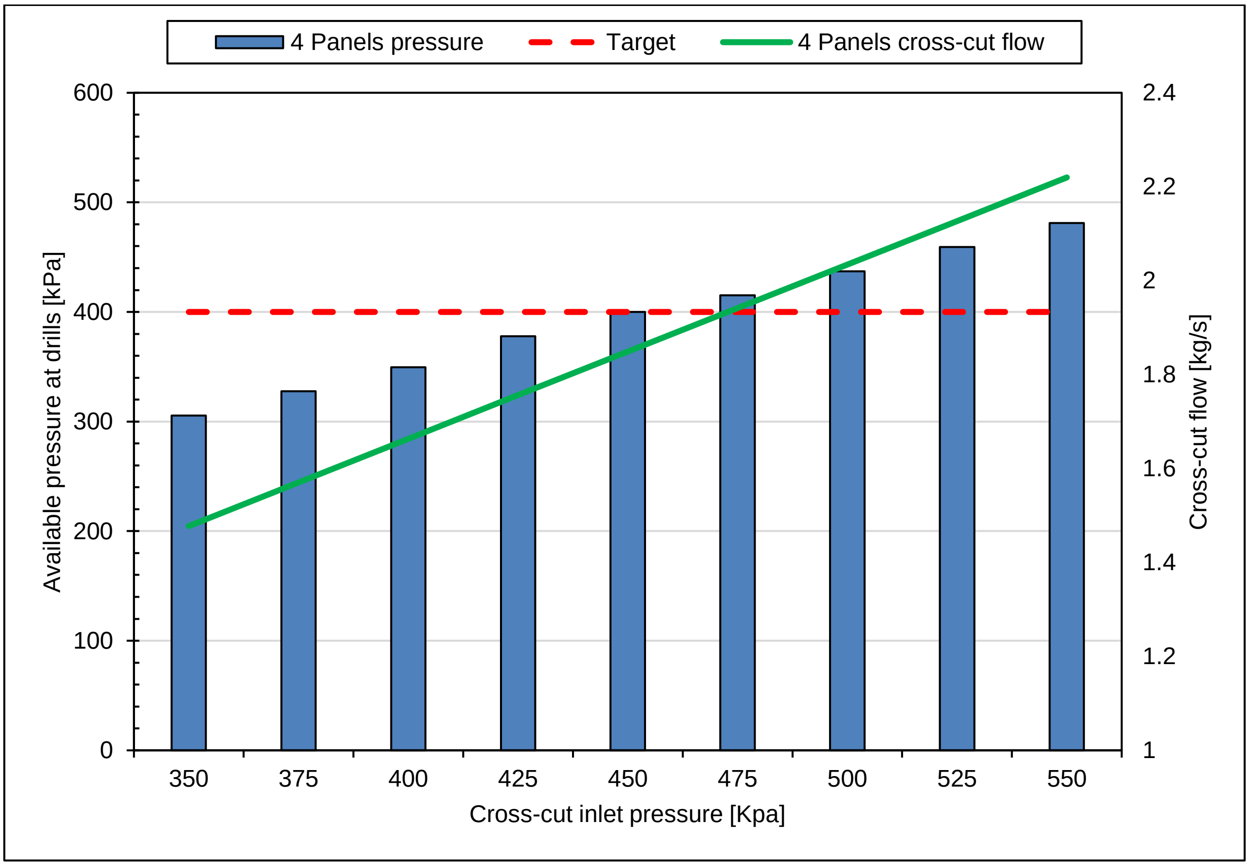


Figure 15: Mine A – compressed air requirements for standard stoping

The same process was followed for the development ends. It was found that the required pressure at the cross-cut entrance for a development end was 425 kPa.

3.2.4 Model construction

This section of the study will discuss the process followed for the actual construction of the digital twin model for Mine A, using PTB, as discussed in Section 2.2.4.

The previously gathered information from the compressed air audits and other sources was used to construct the base line digital twin model of the current compressed air system for Mine A. The digital twin model included the supply side, demand side and reticulation network. Figure 16 shows the finished compressed air digital twin model of Mine A’s compressed air system.

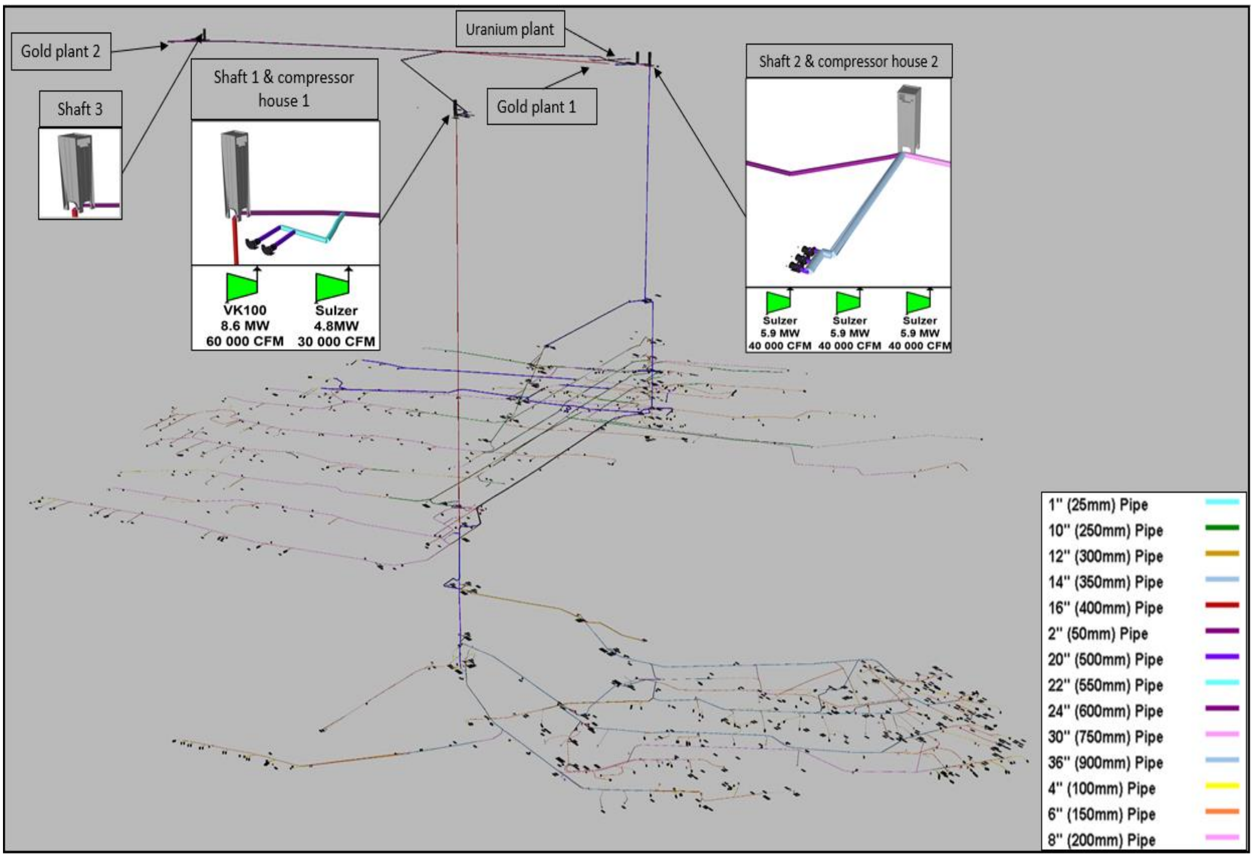


Figure 16: Mine A – finished compressed air digital twin model

The three-year mining plan obtained from Mine A’s planning department was used to expand the digital twin model to include future mining areas. The expansion was constructed according to the mine’s standards for stoping and development.

3.2.5 Calibration and validation

This section of the study will discuss the process for calibrating and validating the constructed digital twin model for Mine A so that it can assist in the mine’s compressed air planning.

The calibration and validation process described in Section 2.2.5 was followed. A day with adequate data of system conditions was chosen as a reference data set to determine the model’s accuracy. The model was simulated and recalibrated until the error margins were sufficient. Table 10 and Figure 17 compare the final digital twin model’s compressed air pressure outputs with the actual pressure for the same positions in the compressed air system on the chosen day.

Table 10: Mine A – level pressures for calibration check

Position	Actual pressure [kPa]	Simulated pressure [kPa]	Error [%]
85L Inlet	556.3	585.0	5
85L Haulage	567.5	551.3	3
88L Inlet	535.7	552.8	3
95L Inlet	542.2	570.6	5
95L Haulage	432.4	449.6	4
92L Inlet	442.3	437.2	1
98L Inlet	425.6	431.3	1
101L Inlet	490.1	480.6	2

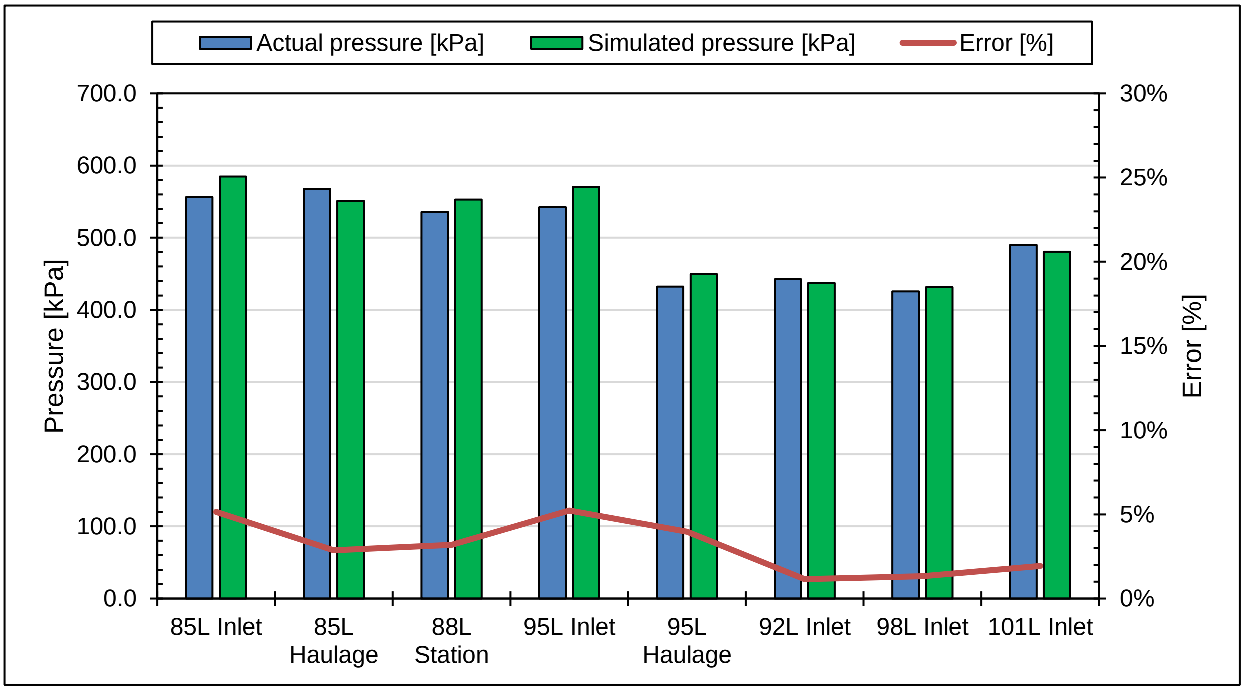


Figure 17: Mine A – comparison of actual vs simulated level pressures for calibration

The results showed that the digital twin model accurately estimated the compressed air pressure with a MAE of 3%, calculated using Equation 3. This was within the specified 5% error margin required to validate the model.

The same process was followed for the compressed air flow. Table 11 and Figure 18 compare the results of the outputs of the digital twin model for the compressed air flow with the actual flows measured in the system.

Table 11: Mine A – level compressed air flows for calibration check

Position	Actual flow [kg/s]	Simulated flow [kg/s]	Error [%]
85L Haulage	1.4	1.5	7
85L before split	5.5	5.8	5
88L Station	4.1	4.5	9
95L Inlet	15.0	15.8	5
95L Haulage	6.7	6.9	3
92L Inlet	6.6	7.0	6
98L Inlet	2.8	2.9	2
101L Inlet	4.4	4.4	0

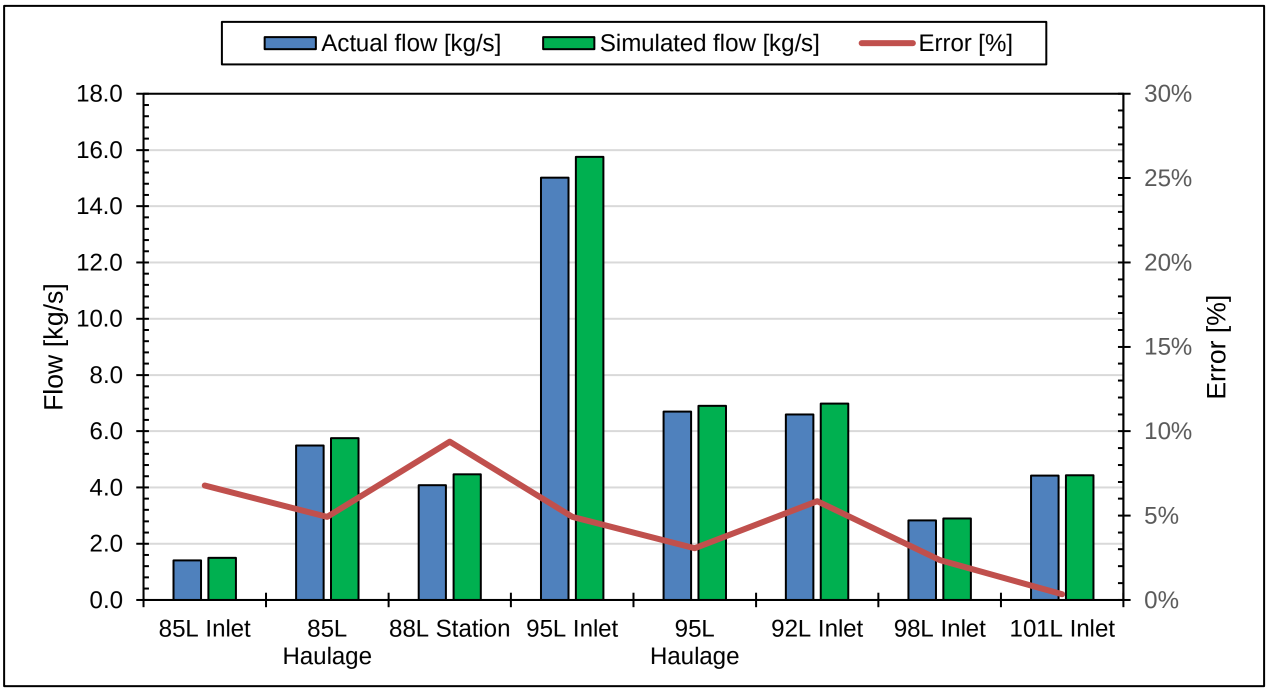


Figure 18: Mine A – comparison of actual vs simulated level compressed air flows for calibration

Some estimated individual points had error margins greater than 5% when compared with the actual compressed air flow due to the small flow values measured. With small flow values, a small numerical difference in flow still provides a relatively large error. As shown in Table 11, a 0.4 kg/s difference in flow on 88L represented a 9% error. Flow meters are more accurate when measuring larger flows and start to lose accuracy as the measured flow values become smaller.

The MAE for the compressed air flow was calculated using Equation 3. It was equal to 5%, which met the specified requirements for validating the model. The results showed that the digital twin model was accurate with a MAE within 5% when comparing the actual and estimated compressed air system conditions. Thus, the digit twin could be used to assist in the compressed air future planning.

3.3 Data analysis and forecasting model

This section of the study will discuss the data analysis and forecasting model implemented on Mine A as discussed in Section 2.3. The forecasting model, gathered system information and digital twin model of the mine will be used together to evaluate the system performance for planned future mining.

3.3.1 Data analysis

The data analysis were completed by first gathering the required information regarding the mine's production output and compressed air usage. The acquired data for Mine A was formulated into the required KPIs.

The compressed air to all mining activities that take place underground flows down Mine A's two shafts. The sum of the flow down these two shafts was thus seen as the total flow used for underground mining activities. Mine A has flow meters in place that measure the compressed air flow [kg/s] sent down the shafts. The flow sensors store the obtained data on Mine A's SCADA system.

As specified in Section 2.3.1, the peak drilling shift is the period when the compressed air flow and thus the system demand is at its highest. Peak drilling takes place between 08:00 and 13:30 at Mine A. The historical flows down the two shafts during the peak drilling shift were obtained from the mine's SCADA system. The data was formulated into a peak production compressed air KPI. Mine A's three-year mining plans provided information on the future and historical tonnes to be mined for the mine in total and for each level and cross-cut. The total historical tonnes mined was analysed and captured, and this data was used to formulate the total production output KPI.

As stated in Section 2.3.1, the compressed air usage to the output produced in the form of tonnes mined is an applicable KPI for identifying and evaluating system inefficiencies [11]. Thus, the historical compressed air flow during the peak drilling shift and the total tonnes mined for Mine A were analysed and compared using a black box method to formulate this KPI.

The KPI results were assessed using a scatter plot with both axes representing a data set, as can be seen in Figure 19. Microsoft Excel™ was used to determine the best trend line for the data set. The total compressed air flow during the peak drilling shift had a linear corelation to the total tonnes mined. The regression analysis of the data revealed an R^2 value of 0.646, which is considered a strong linear correlation for compressed air models [65].

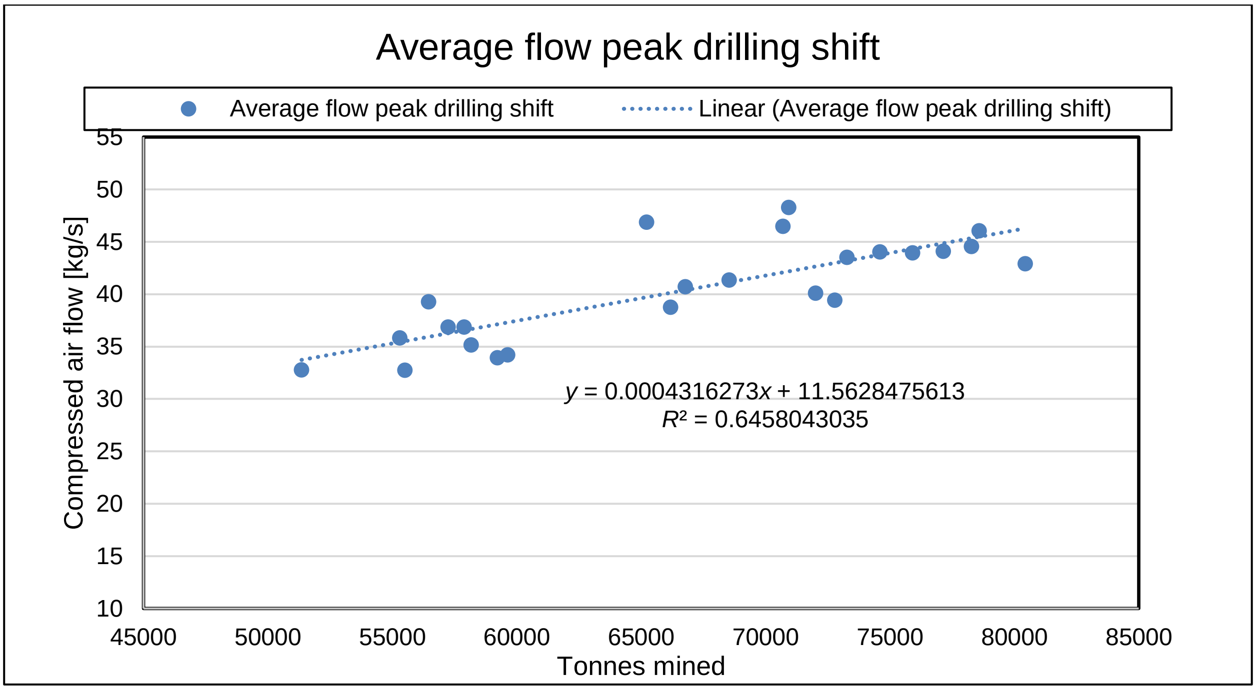


Figure 19: Mine A – historical planned tonnes and flow for peak drilling shift

3.3.2 Forecasting model

This section of the study will discuss the implementation of the methodology, as explained in Section 2.3.2, to forecast the future performance of the compressed air system. The forecasting model was completed using the developed digital twin model and the established correlation between compressed air flow and production.

The three-year mining plan was used to establish future production in each section and for the mine in total. The established correlation and the data gained from the mine's three-year-plan were used to estimate the future average compressed air flow requirements for all underground mining activities during the peak drilling shift. To validate the accuracy of these estimations, they were tested for six months and compared with the actual average flow during the peak drilling shift for these months, as can be seen in Figure 20. The estimations proved to be accurate within the error margin of 5%.

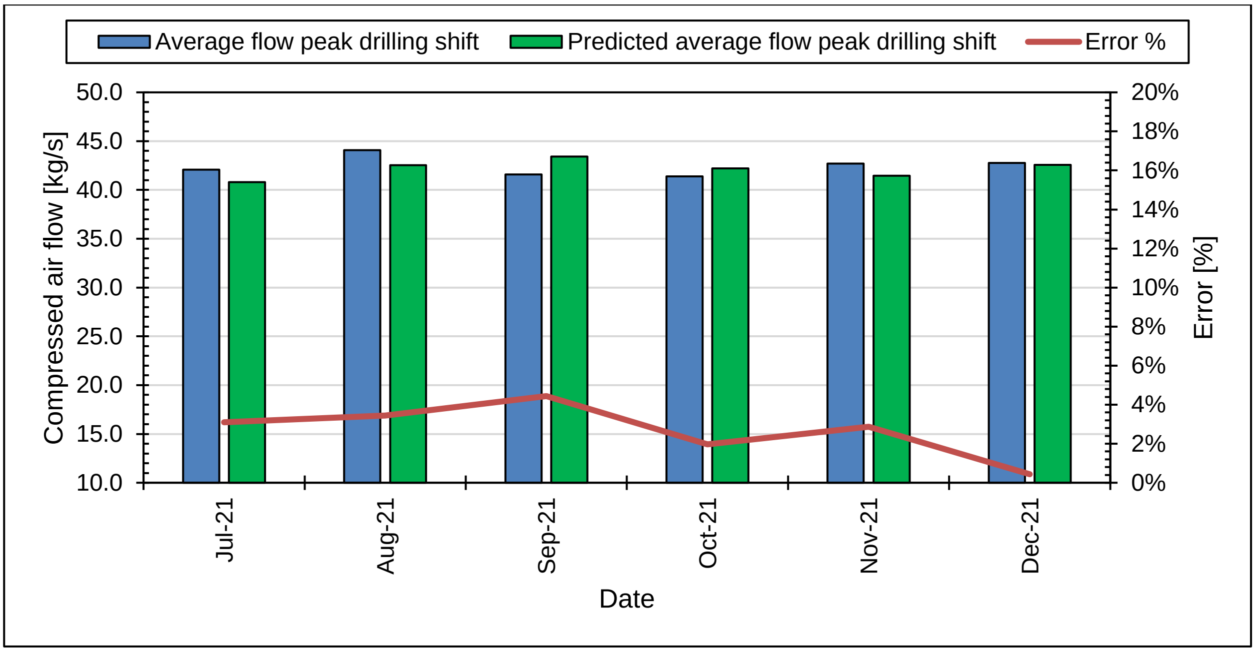


Figure 20: Mine A – actual vs predicted flow for peak drilling shift

The six-month flow used to validate the estimations was further analysed to see how much the maximum flows varied from the average flows during the peak drilling shift, as seen in Figure 21. The analysis of the data showed that the maximum flow did not vary more than 15% from the average flow during the peak drilling shift.

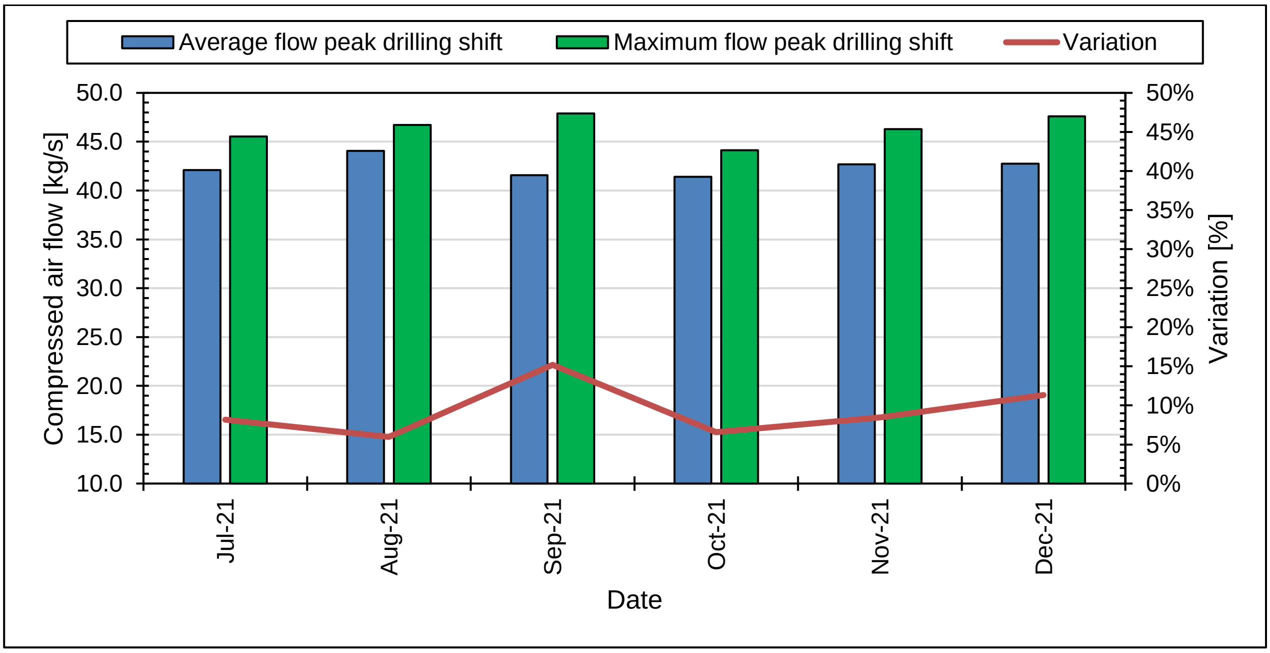


Figure 21: Mine A – variation in flow during the peak drilling shift

The analysis provided a good safety factor that was incorporated into the forecasting model. Figure 22 compares the actual compressed air flow during the peak drilling shift with the estimated average flow. It shows the estimated upper limit determined by using the established safety factor of 15%. The actual flow was never more than the estimated upper limit.

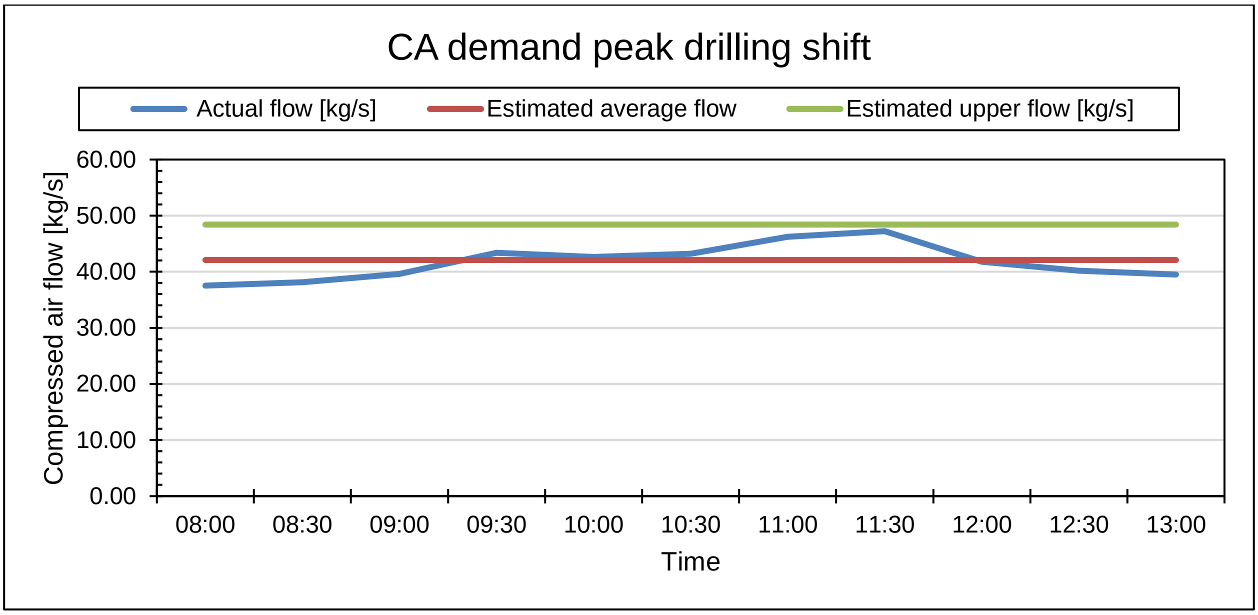


Figure 22: Mine A – compressed air flow for a random day

The developed model was used to estimate the future total compressed air demand requirements for underground mining according to the total planned tonnes in the three-year mining plan. Figure 23 shows the estimated future compressed air flow requirements for the average flow and the upper flow limit for the compressed air flow during the peak drilling shift.

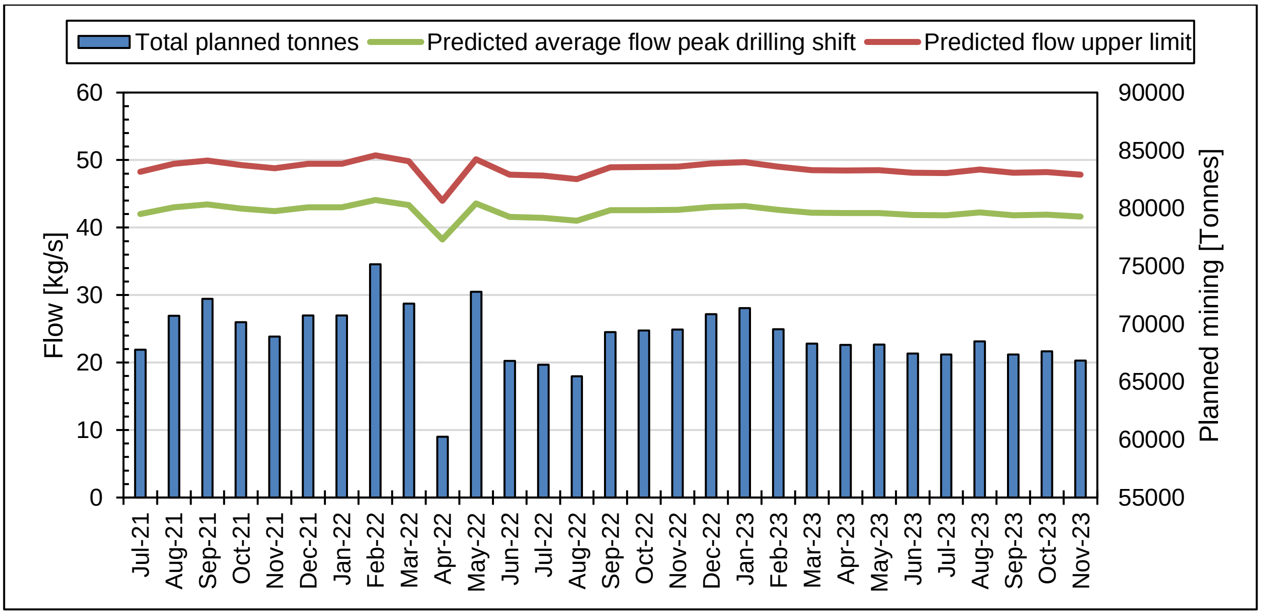


Figure 23: Mine A – estimated future total compressed air demand

The estimated upper flow limits were divided between the different production levels to estimate the future compressed air flow demand requirements for each level as shown in Figure 24.

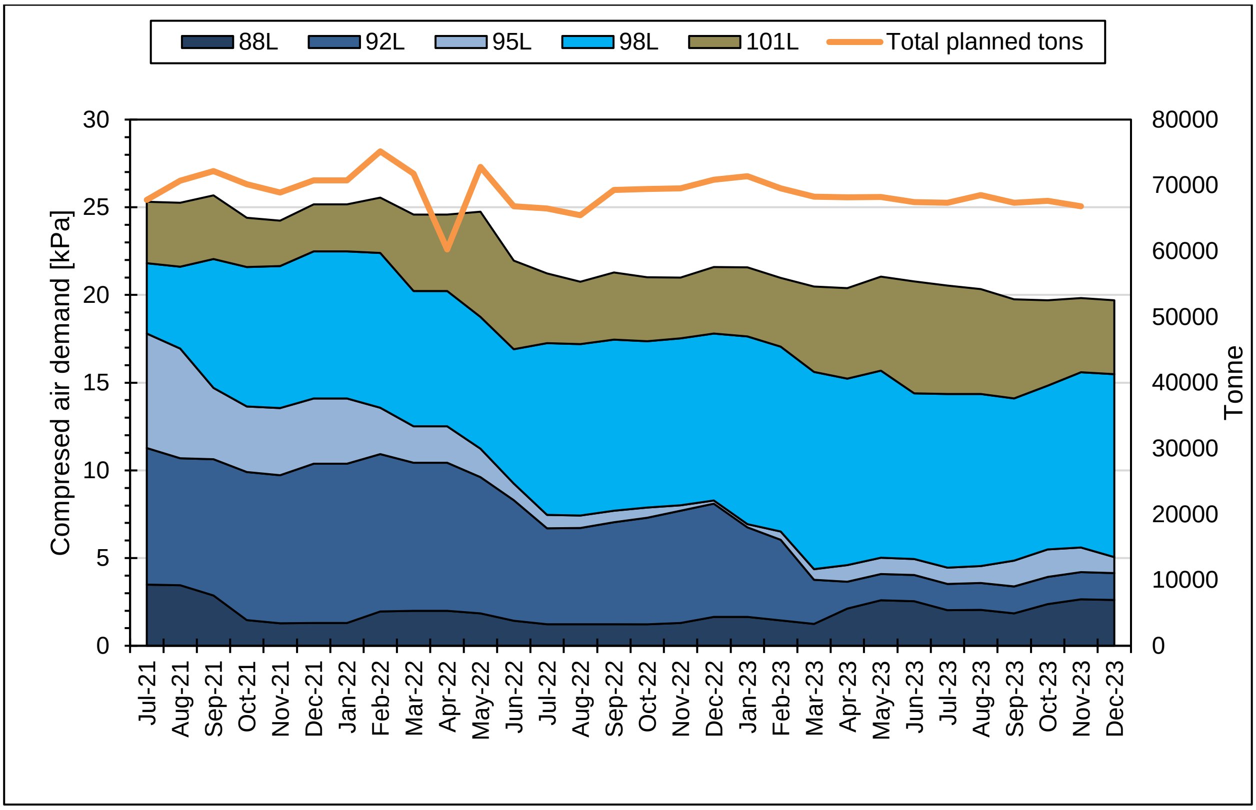


Figure 24: Mine A – estimated future compressed air demand

Figure 24 shows that the total required demand for compressed air remained reasonably constant and started to decrease slightly. At the same time, the compressed air demand on 98L drastically increased over the same period. This was an indicator that 98L was a potential problem area as the originally installed infrastructure was not intended to supply such large compressed air demands.

Using the digital twin model developed in Section 3.2 and simulating Mine A for each month of the three-year mining plan, it was identified that 98L was going to struggle with insufficient compressed air pressure for mining activities. Figure 25 demonstrates that the compressed air pressure at 98L East Haulage fell below the 450 kPa target from July 2021 onwards. The 98L Inlet pressure also fell below 450 kPa from October 2021 onwards.

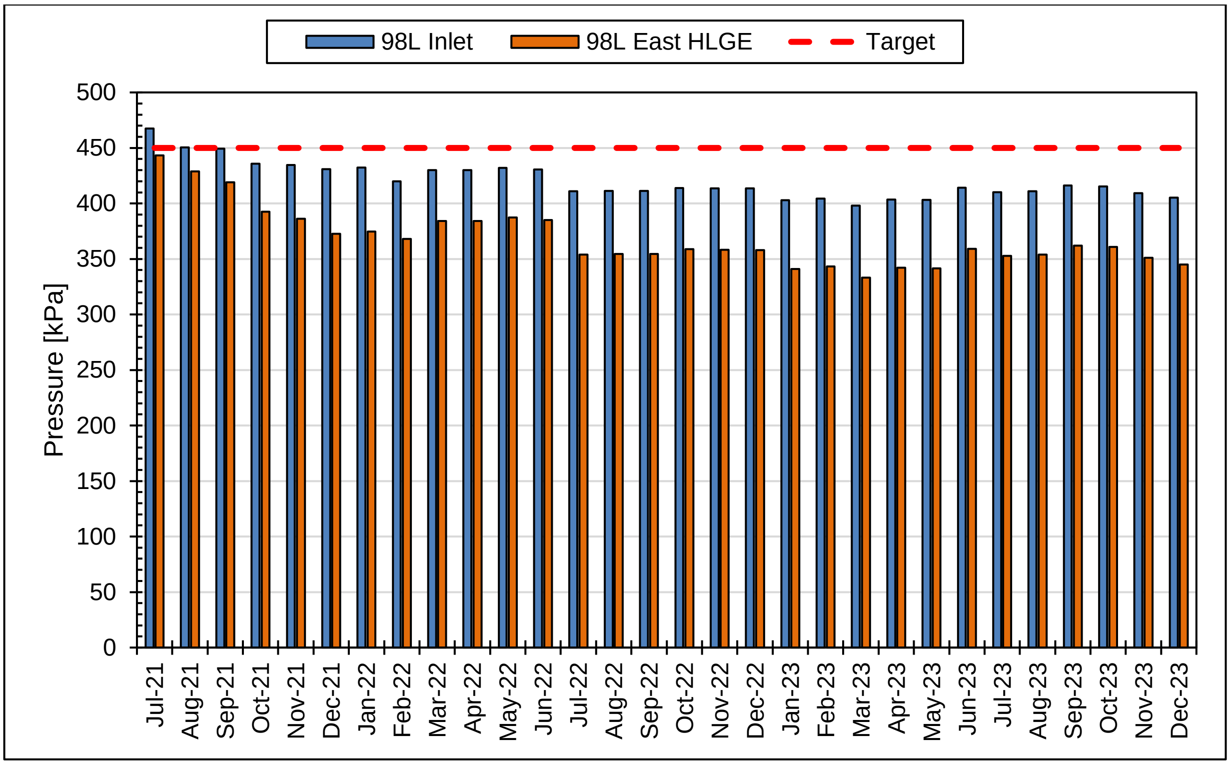


Figure 25: Mine A – estimated future compressed air pressure

Appendix C provides the additional data obtained during the compressed air system forecasting.

3.4 Proactive solution development

This section of the study will discuss the proactive solution for solving the problem identified during the data analysis and forecasting model, according to the developed methodology as examined in Section 2.4.

When considering the results of the data analysis and the forecasting model it was clear that the compressed air reticulation network would experience problems with supplying adequate compressed air pressure to 98L for the necessary mining activities. 98L forms part of the middle mine of Mine A. Figure 26 shows a representation of the compressed air system of the middle mine. The shaft supplies compressed air to 85L and 95L; 85L supplies 88L; and 95L supplies 92L and 98L.

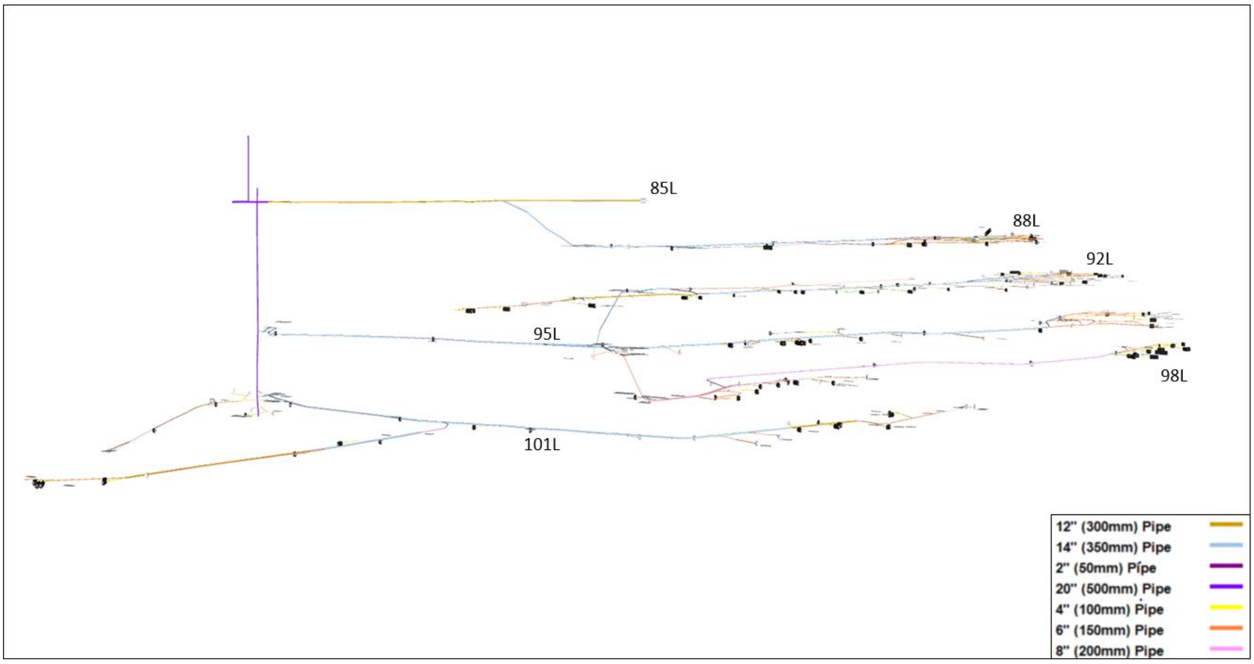


Figure 26: Mine A – middle mine

Figure 24 demonstrates that the compressed air demand for 98L would increase over time while the demand for compressed air on 88L, 92L and 95L would decrease. The decrease in demand on 88L, 92L and 95L provided the opportunity for these levels to supply other sections of Mine A with the surplus compressed air their infrastructure could support.

The pipeline supplying 98L from 95L was a 6″ pipe, which was too small to supply the level with the compressed air flow and pressure required. Considering this, a solution was developed to create ring feeds between the levels of this section. This would help to distribute the surplus compressed air from the levels where the demand decreased to 98L where the demand increased. Table 12 shows the steps to the developed solution.

Table 12: Mine A – developed solution

Step	**Description**
1	Install an additional 8 Inch pipe from 95L to 98L.
2	Install a 14 Inch pipe from 88L to 92L.

The first step of the solution, installing an additional 8″ pipeline between 95L and 98L, would distribute the compressed air surplus from 95L to 98L. The second step of the solution, installing a 14″ pipeline from 88L to 92L, would distribute the surplus air from 85L and 88L to provide for a portion of the compressed air demand on 92L. In turn, this would reduce the amount of compressed air that had to be supplied from 95L to 92L. It would further assist 95L with providing more compressed air at higher pressures to 98L. Implementing this solution would solve the identified problem by providing the required compressed air pressure while mostly using existing infrastructure. Using existing infrastructure would aid in keeping the cost of the project as low as possible. Figure 27 shows the compressed air system after implementing the proposed solution.

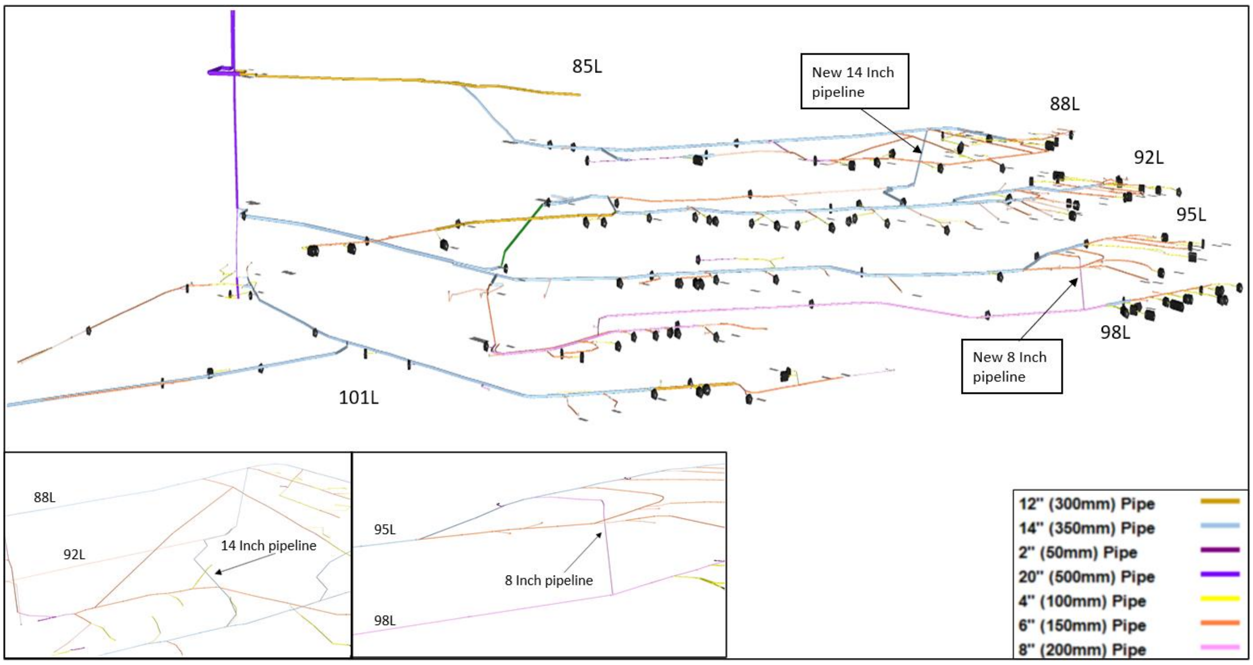


Figure 27: Mine A – middle mine with the installed solution

The developed solution was discussed with the relevant mine personnel to determine the fastest time frame for installing the new pipelines in the compressed air reticulation network. This was necessary before the scenario could be simulated as the demand on the compressed air system would change over time. The mine personnel established that Step 1 could be completed by 11 December 2021 and Step 2 could be completed by 12 July 2022. The faster the solution could be implemented, the better it would be; however, due to external influences, this was the fastest viable time frame for implementing the solution.

The developed solution was simulated as discussed in the methodology to determine the effect of these changes on the system. As the solution would be implemented in two phases, the implementation of the solution was simulated in the same way. Table 13 and Figure 28 show the results obtained from the digital twin simulation for the completion of the first step of the solution.

Table 13: Mine A – estimated compressed air pressures for completing Step 1 of the solution

Position	95–98 closed [kPa]	95–98 open [kPa]	Improvement [kPa]
85L Inlet	588	586	−2
85L Haulage	546	554	9
88L Station	547	549	2
95L Inlet	567	561	−7
95L Haulage	449	445	−4
92L Inlet	429	452	23
98L Inlet	431	458	27
98L East Haulage	373	417	44
101L Inlet	488	489	1

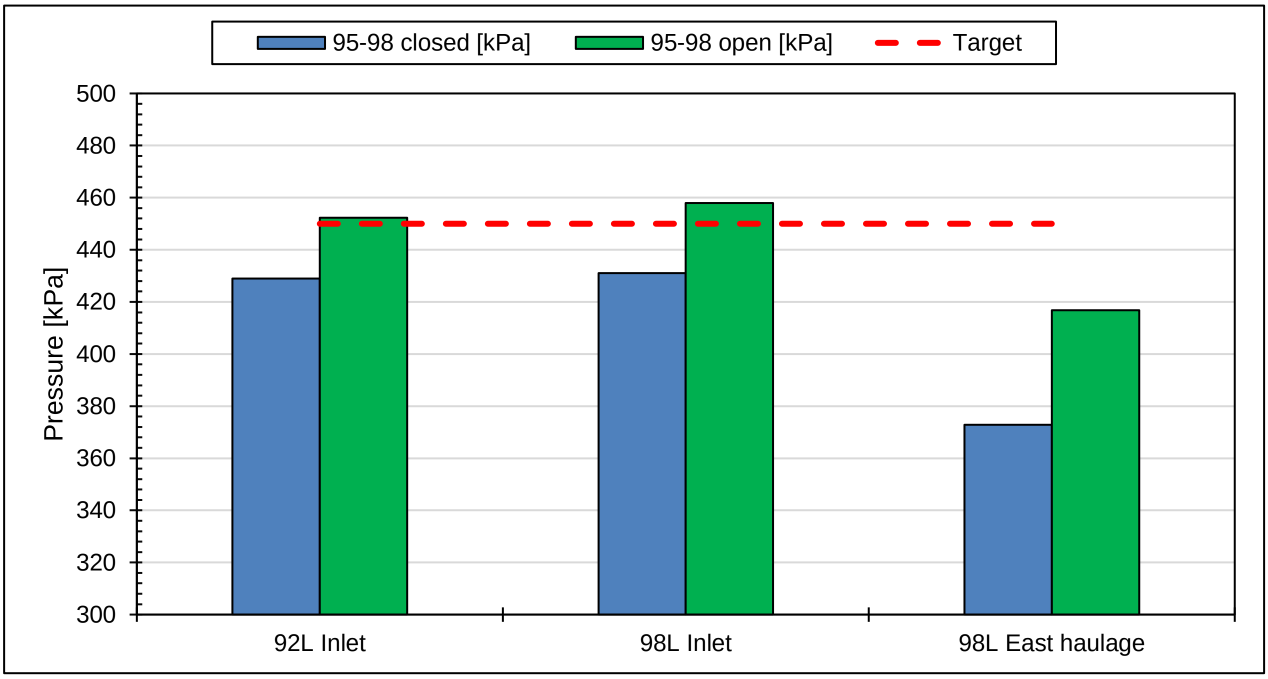


Figure 28: Mine A – estimated compressed air pressures for completing Step 1

The results showed that the implementation of the first step would increase the compressed air pressure on 98L Inlet by 27 kPa and the 98L East Haulage pressure by 44 kPa. Some other levels showed a minor drop in pressure, but the pressure they had left was still more than enough for their required mining activities.

The second part of the solution was simulated. The results obtained from the digital twin simulation can be seen in Table 14 and Figure 29.

Table 14: Mine A – estimated compressed air pressures for the completion of Step 2 of the solution

Position	85–92 closed [kPa]	85–92 open [kPa]	Improvement [kPa]
85L Inlet	566	563	−2
85L Haulage	544	554	9
88L Station	546	542	−4
95L Inlet	531	554	23
95L Haulage	427	489	62
92L Inlet	438	502	63
98L Inlet	428	484	56
98L East Haulage	399	455	56
101L Inlet	485	483	−2

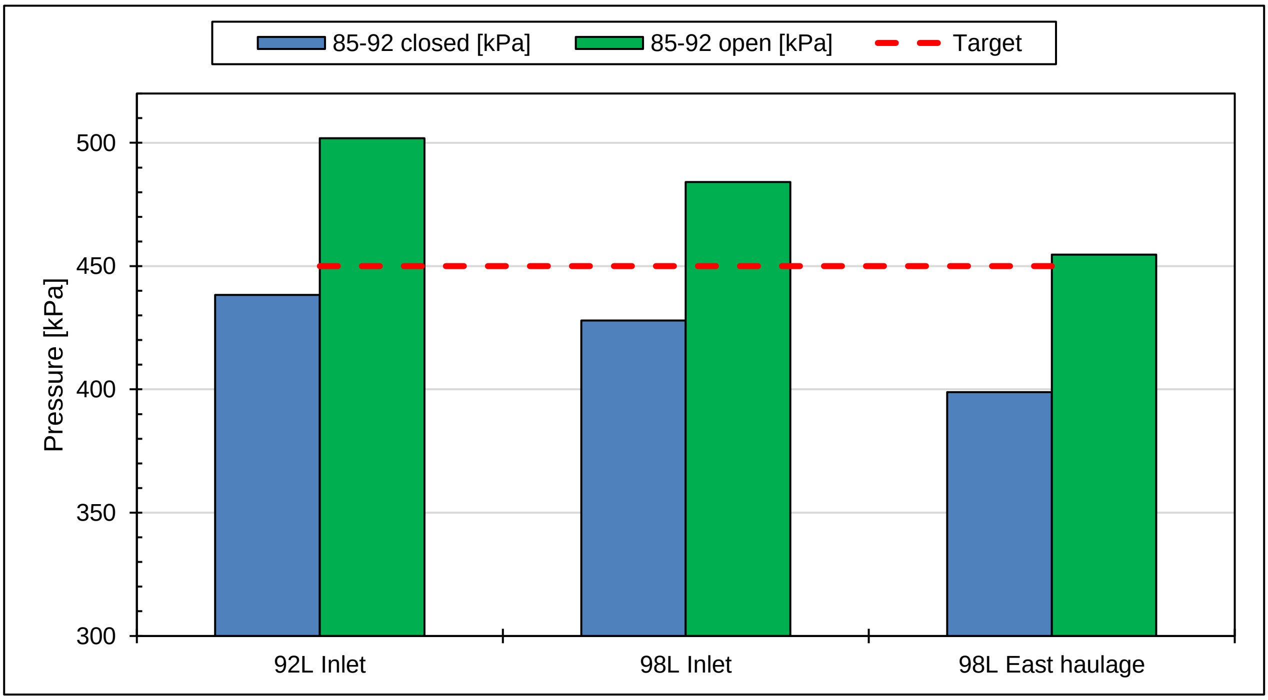


Figure 29: Mine A – estimated compressed air pressures for completing Step 2

The results showed that the implementation of Step 2 of the solution would increase the pressure at the 98L Inlet and at the 98L East Haulage by 56 kPa. This would provide 98L with the required pressure to meet the target pressure of 450 kPa. The 85L Inlet and 88L showed a small decrease in pressure, which was anticipated as these levels also supplied a portion of 92L’s compressed air. These decreases were small and the levels still had enough pressure for all the required mining activities.

Figure 30 compares the results obtained from the simulation of the system pressures for the completion of the project with the pressures pre-implementation. All the levels would have sufficient pressure for the required mining activities after implementing the developed solution.

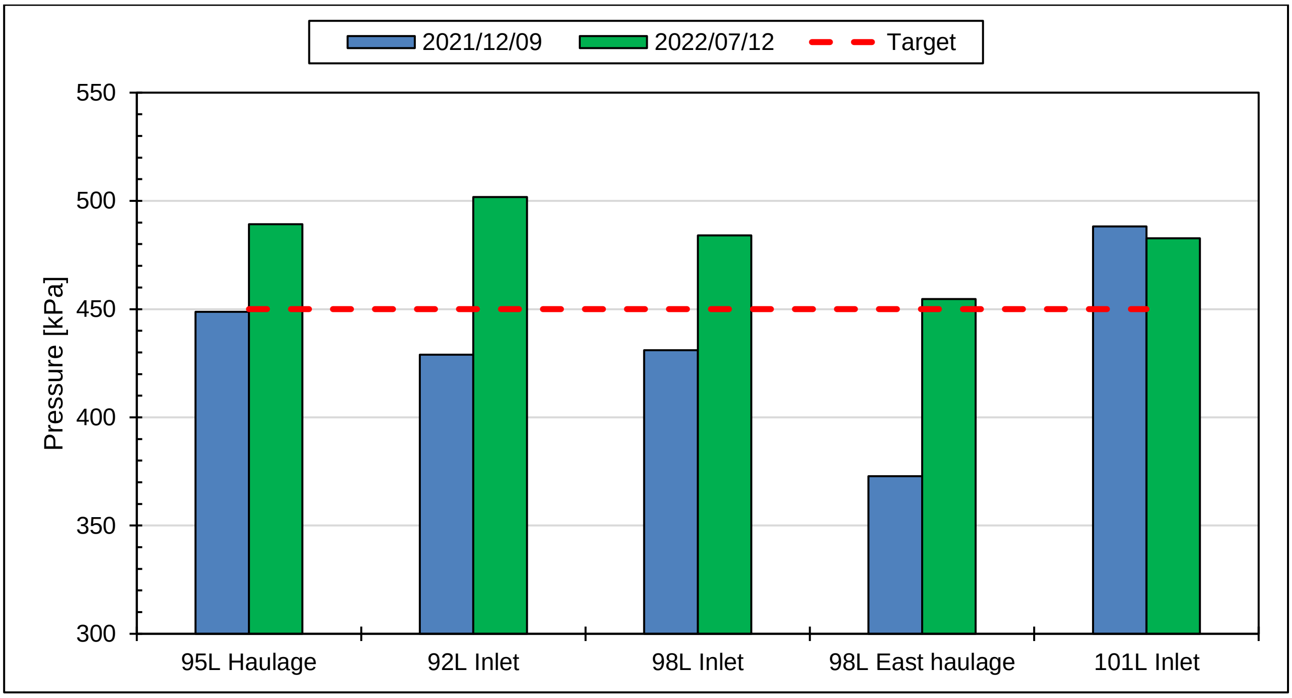


Figure 30: Mine A – estimated compressed air pressures after completing the solution

Table 15 compares the results for the simulated compressed air pressure on 98L for the completion of the project with the compressed air pressure pre-implementation as well as what the pressure would have been if there was no intervention. The pressure at 98L Inlet was 18% higher and the pressure at 98L East Haulage was 29% higher than it would have been if no intervention had been taken.

Table 15: Mine A – simulated results after completing the project

Position	**2021/12/09 (Pre-intervention)**	**2022/07/12 (No intervention)**	**2022/07/12 (Solution implemented)**
98L Inlet pressure [kPa]	431	410	484
98L East Haulage pressure [kPa]	373	353	455

The results of the investigation were presented to the relevant mine personnel and the project was approved for implementation.

3.5 Results

This section will interpret the results gained from the implementation of the methodology and the developed solution. This will help to determine the success of the methodology in fulfilling a proactive planning strategy.

3.5.1 Effect of implementation on system

This section of the study will analyse the actual results obtained from the implementation of the methodology and the developed solution, as described in Section 2.5, to verify its effectiveness.

The pressure sensors required to measure the level and haulage inlet pressures, as identified during the systems information gathering process in Section 3.2, were used to measure the pressures pre- and post-implementation of each step of the developed solution. The data was stored on the mine’s SCADA system.

The 8″ pipeline was installed between 95L and 98L on 11 December 2021. The data from the relevant pressure sensors was collected pre- and post-implementation from the mine’s SCADA system and analysed and compared. The results can be seen in Table 16 and Figure 31.

Table 16: Mine A – compressed air pressures for completing Step 1 of the solution

Position	95–98 closed [kPa]	95–98 open [kPa]	Improvement [kPa]
85L Inlet	595	591	−3
85L Haulage	567	577	9
88L Station	547	548	1
95L Inlet	551	548	−3
95L Haulage	439	451	12
92L Inlet	435	460	26
98L Inlet	422	451	29
98L East Haulage	378	425	47
101L Inlet	502	500	−2

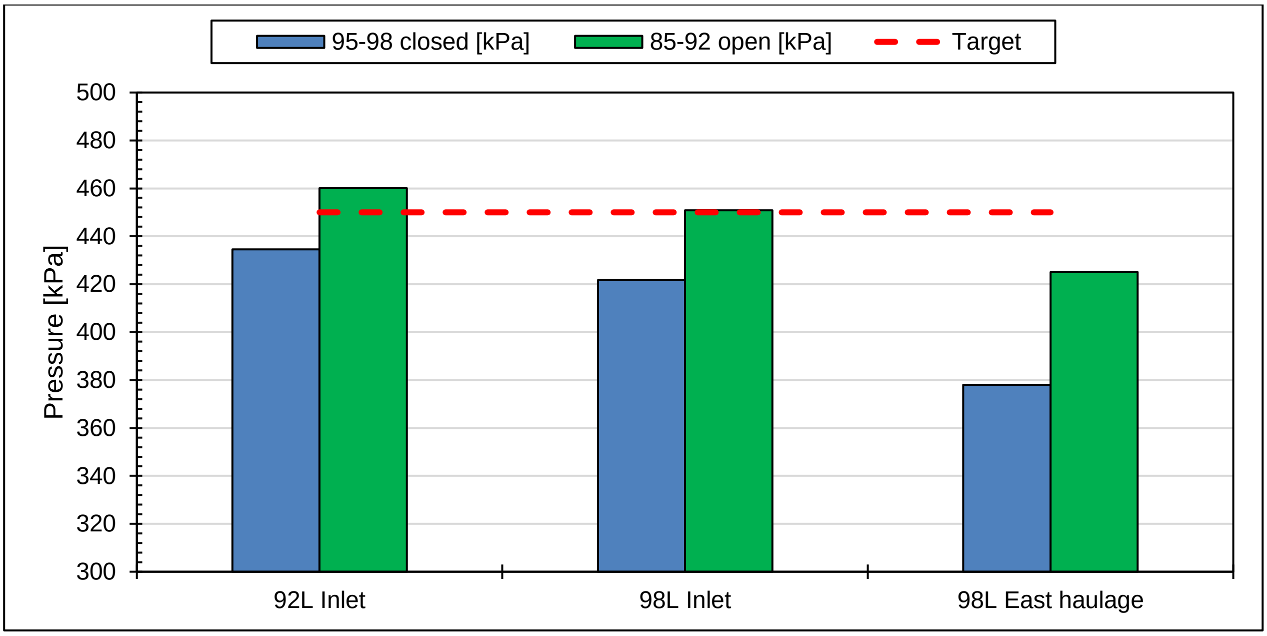


Figure 31: Mine A – compressed air pressures for completing Step 1 of the solution

The results showed that the implementation of the first step of the solution increased the compressed air pressure on the 98L Inlet by 29 kPa and the 98L East Haulage pressure by 47 kPa. Some other levels showed a minor drop in pressure, but it was still more than enough for the required mining activities on these levels.

The second part of the solution was implemented on 12 July 2022. The data from the relevant pressures sensors was collected from the mine's SCADA system pre- and post-implementation and analysed and compared. The results obtained can be seen in Table 17 and Figure 32.

Table 17: Mine A – compressed air pressures for completing Step 2 of the solution

Position	85–92 closed [kPa]	85–92 open [kPa]	Improvement [kPa]
85L Inlet	566	567	−2
85L Haulage	552	561	9
88L Station	550	547	−4
95L Inlet	539	567	23
95L Haulage	435	497	62
92L Inlet	444	510	63
98L Inlet	434	495	58
98L East Haulage	407	465	59
101L Inlet	497	500	−2

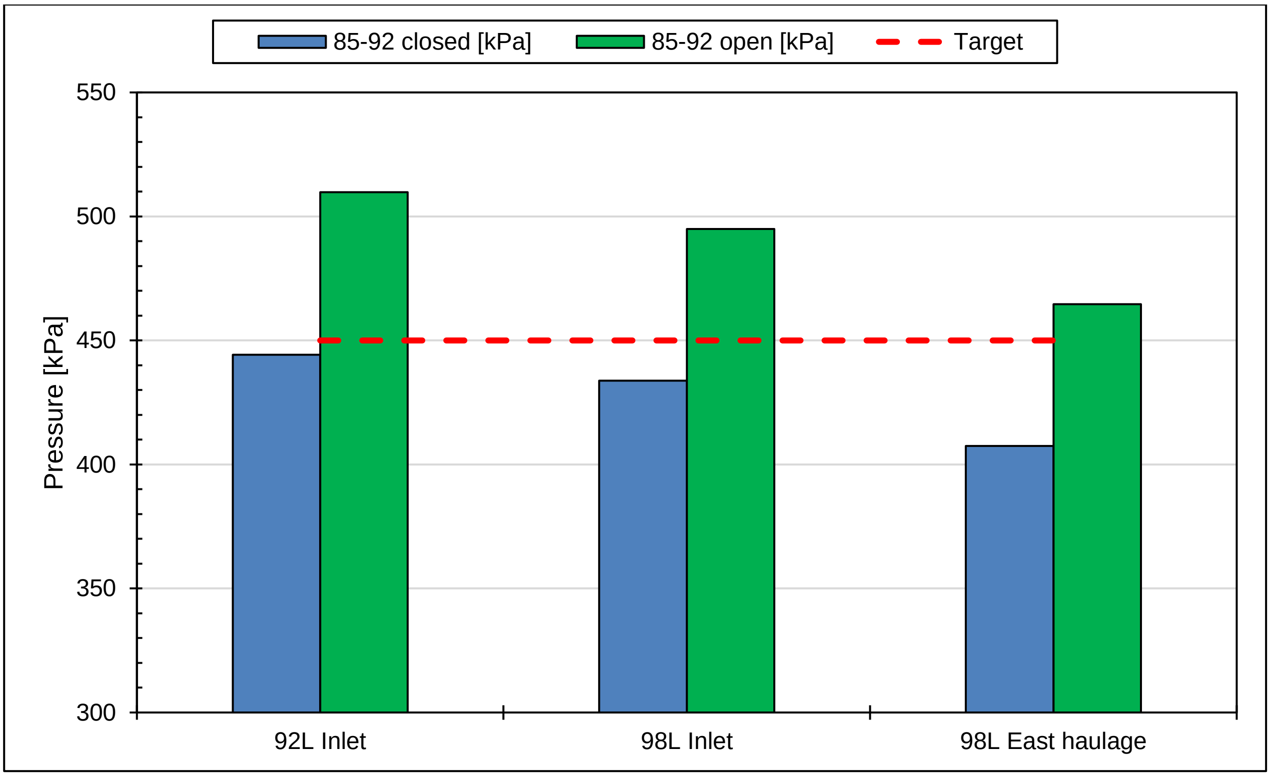


Figure 32: Mine A – compressed air pressures for completing Step 2 of the solution

The results showed that the implementation of Step 2 of the solution increased the pressure at 98L Inlet and at the 98L East Haulage by 58 kPa and 59 kPa, respectively. This ensured that 98L had sufficient compressed air pressure to meet the target pressure of 450 kPa. The 85L Inlet and 88L showed a small decrease in pressure, which was anticipated as these levels also supplied a portion of 92L's compressed air. These decreases were small, and the levels still had enough pressure for all the required mining activities.

Figure 33 compares the results for the system pressures post-implementation with the pressures pre-implementation. The results show that the implementation of the developed solution helped to provide all the levels with the required pressure for all mining activities.

Figure 33: Mine A – compressed air pressures for the completion of the solution

Table 18 compares the results for the compressed air pressure on 98L post-implementation with the compressed air pressure pre-implementation and the estimated pressure if there had been no intervention. The pressure at 98L Inlet is 21% higher and the pressure at 98L East Haulage is 32% higher than it would have been if no intervention had been taken.

Table 18: Mine A – actual results for the completion of the project

Position	**2021/12/09 (Pre-intervention)**	**2022/07/12 (No intervention)**	**2022/07/12 (Solution implemented)**
98L Inlet pressure [kPa]	422	410	495
98L East Haulage pressure [kPa]	378	353	465

The implementation of the solution was a success as it improved the compressed air pressure for 98L and ensured that all the levels had sufficient compressed air pressure for all mining activities.

Figure 34 compares the simulated results from the digital twin with the actual results for the completion of the implemented solution. The simulation proved to be accurate as the outcome predicted by the simulations was correct. It should be noted that the actual pressures for the implementation are a bit higher than the simulated pressures due to the safety factor included in the simulation. The safety factor increased the size of the compressed air flow demands used in the simulation. As pressure is inversely proportionate to flow, this made the simulated pressure a bit lower than the actual pressures.

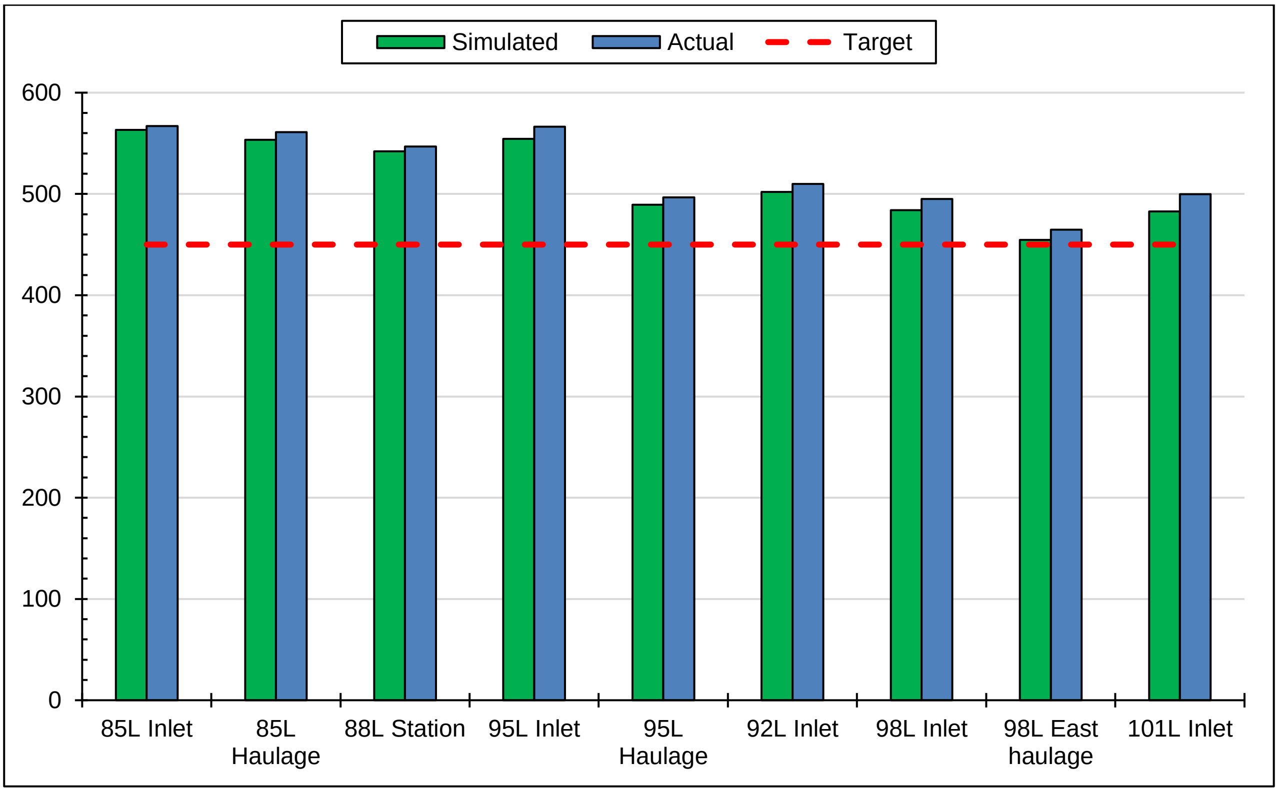


Figure 34: Mine A – comparison of the simulated and actual results for the completion of the proposed solution

3.5.2 Production improvement analysis

This section of the study will discuss the theoretical analysis, as explained in Section 2.5, to estimate the financial benefit of implementing the developed solution in conjunction with the improved compressed air reticulation network. The calculations are based on many variables and it is unknown what the mine would have done to meet the compressed air requirements if the planning methodology had not been implemented. Therefore, this section will only provide an indication of the possible magnitude of the financial benefit for the project.

As mentioned in Section 2.5, two methods were used to analyse the financial impact of the implemented solution. The first method analysed the effect of the increased pressure on the drills' penetration rates and, subsequently, on production. The rock penetration rate was calculated using Equation 5, as discussed in Section 2.5. The penetration rates were calculated for a drill bit size of 25 mm at a design thrust pressure of 700 N. The estimated pressure for no intervention and the post-implementation pressure to 98L East Haulage was used as inputs to calculate the improved rock penetration rate. Table 19 shows the improved rock penetration rate resulting from the service delivery improvement.

Table 19: Mine A – improvement on penetration rate

	No intervention	**Post-implementation**
98L haulage pressure [kPa]	353	465
98L stope penetration rate [m/s]	0.0011	0.0025

The production analysis as developed by Nell [3] and discussed in Section 2.5 was used to calculate the impact of the increased penetration rates on the production. Table 20 and Table 21, respectively, show the inputs used and the output results calculated using the production analysis.

Table 20: Mine A – production analysis input

Parameter	**Index**	**Value**	**Unit**
Panel height	A	1.5	m
Panel width	B	28	m
Number of holes per panel	C	144	–
Hole depth/drill length	D	1.2	m
Number of drills per panel/manifold	E	5	–
Forward advancement during blasting	F	0.98	m
Average drill shift	G	4	hr
Previous penetration rate	H	0.001121	m/s
New rock penetration rate	I	0.002516	m/s
Travelling times	J	4	hr
Gram gold per tonne	K	8.2	g/tonne
Rock density	L	2 700	kg/m^3
Gold price	M	954.77	R/g

Table 21: Mine A – production impact analysis output

Parameter	Index	Value	Unit
Square metres	N	42.00	m^2
Total drill distance	O	172.80	m^2
Total drill distance per square metre	P	4.11	m/m^2
Rock volume blasted per panel	Q	41.16	m^2
Rock weight per panel	R	111.13	tonne
Gold per panel	S	911.28	g
Previous drill time per square metre	T	3 670.16	s/m^2
Previous drill time per square metre	U	61.17	min/m^2
Previous drill time per square metre	V	1.02	hr/m^2
Total previous drill time required	W	42.82	hr
Previous drill time per shift	X	8.56	hr
New drill time per square metre	Y	1 635.55	s/m^2
New drill time per square metre	Z	27.26	min/m^2
New drill time per square metre	AA	0.45	hr/m^2
Total new drill time required per panel	AB	19.08	hr
New drill time per shift	AC	3.82	hr
Rock penetration rate improvement	AD	55.44	%
Total time saved per panel	AE	4.75	hr
Additional squares that could be drilled	AF	10.45	m^2
Additional holes that could be drilled	AG	35.83	–
Additional rock blasted	AH	10.24	m^3
Additional rock blasted weight	AI	27.65	tonne
Additional gold extracted	AJ	226.73	g
Financial benefit of additional gold	AK	R216 471.13	daily

98L serves as the main production level in Mine A and has fourteen cross-cuts that will be active for stoping during the three-year mining period. This means that there will be between eight and up to twenty-three active stoping faces in each month according to the three-year mining plan. The increase in pressure on 98L will directly influence these working areas by increasing their drilling penetration rates and, subsequently, their production. This could give Mine A a financial benefit of R800 million per annum.

It is unknown what the mine would have done to solve the identified problem if the developed methodology was not implemented. It is unlikely that the mine would have operated with low compressed air pressures. Thus, the theoretical cost of the electricity that a compressor would have used to achieve the same increase in pressure for the mine’s compressed air system was calculated using Equation 6. It is estimated that this would have cost the mine R9.6 million per annum.

The analysis completed in this section indicated that the implementation of the developed solution provided Mine A with potential financial savings between R9.6 million (energy impact) and R800 (potential production impact) million per annum.

3.6 Validation of study

This section will discuss the process that was followed as described in Section 2.6 to validate the success of this study. The study had to meet all the established objectives as presented in Section 1.7 to be deemed successful. The following questions and answers regarding the objectives were evaluated to determine whether the objectives were met.

Was a digital twin model of a compressed air system developed that accurately portrayed the performance of the system?

As discussed in Section 3.2, a digital twin model of Mine A’s compressed air system was successfully developed and accurately portrayed the system’s performance. The digital twin model had a MAE smaller than 5%, which indicates that the model is accurate.

Was the digital twin model expanded to include future mining activities and did it estimate the future performance of the compressed air system accurately?

The digital twin model of Mine A was successfully expanded to include all the future mining activities according to Mine A’s three-year mining plan. It further successfully estimated the future performance of Mine A’s compressed air system.

Has the study successfully identified future compressed air system inefficiencies and future of the specific mine?

Yes, the study succeeded in Section 3.3.2 in identifying that inadequate future compressed air pressure would be supplied for mining on 98L of Mine A due to inadequate infrastructure to supply the increased production on this level.

Did the study successfully develop proactive solutions to the identified system problems and fulfil a proactive planning strategy?

In Section 3.4, the study successfully developed a solution to the identified future problem that helped to increase the pressure on the 98L East Haulage of Mine A by 112 kPa. These solutions helped to avoid production losses and unnecessary costs to the mine, fulfilling a proactive planning strategy.

The evaluation of these questions and answers clearly indicate that all the objectives were met successfully. This indicates that the study is validated and successful.

3.7 Conclusion

This chapter focused on implementing the developed methodology in the form of a practical case study. Mine A, a deep-level gold mine in South Africa, was selected and the developed methodology was used for the mine’s compressed air planning. A digital twin model of the mine was constructed as discussed in Section 3.2. The model was tested for accuracy and proved to be accurate within the predefined limit for validation, namely a MAE smaller than 5%. The model was expanded to include future mining activities.

In Section 3.3, the steps as discussed in Section 2.3 were followed to complete a historical data analysis of the mine’s compressed air system and to forecast future performance. This process helped to identify a problem that the system would have faced if no intervention had been taken. In Section 3.4, a proactive solution to the identified problem was developed and tested using the digital twin simulation. Section 3.5 discussed the results and the financial gain obtained from the implementation of the proposed solution.

The implementation of both the developed methodology and its developed solution was a success. The developed methodology proactively identified and provided a solution to a future compressed air system problem and helped to avoid production losses and unnecessary costs. Section 3.6 provides validation for the study as all the study objectives were met successfully.

CONCLUSION AND RECOMMENDATIONS

4.1 Introduction

This section will summarise the study and discuss the potential opportunities identified for future work and research.

4.2 Executive summary

Most gold mines in South Africa use compressed air services for various applications in the gold extraction process. These include drilling, agitation, loading boxes and many more services that directly influence production. Compressed air services have several advantages. When planned, implemented, and maintained correctly, compressed air provides a safe and sustainable energy source for deep-level mining.

The main priority of deep-level mining is the production of precious metals; thus, resources are primarily focused on delivering production targets. Services, including compressed air, often only receive the required attention when they start to fail.

In Chapter 1, a literature study was completed on mine compressed air systems, the planning thereof, and how simulations can be used to advance this field. The literature study showed that mine compressed air services lack proper future planning and this, together with outdated infrastructure, leads to inefficient compressed air systems and production losses.

Most mines have little structure regarding how compressed air systems are constructed and regularly undergo non-project related changes that influence system performance. These undocumented changes often lead to no one knowing the complete layout of the underground compressed air reticulation network. The complexity and age of most typical mine compressed air systems further increase the difficulty when planning for future expansions.

Mines use standards and other guidelines when planning compressed air system infrastructure. This is problematic as the mining environment is dynamic in terms of both service delivery and production areas, which leads to system requirements changing on a regular basis. The established standards and guidelines do not always take the effects of the dynamic compressed air system into account.

The lack of proper planning of mine compressed air services can cause unforeseen problems that need to be rectified before production can continue. This can lead to substantial downtime and the loss of valuable production. These losses and system inefficiencies could have been avoided by proactive planning.

Studies have shown that the mining sector's future depends on modernisation. Simulation software has been used in the mining sector to address a variety of different problems and has proven to show considerable potential in identifying problem areas in compressed air networks. The focus of these simulations is on solving current problems, but there is no focus on using these simulations to develop methods to address similar problems in the future.

A need, therefore, exists for a modernised, proactive compressed air planning strategy to prevent problems and solve compressed-air-related production challenges. To achieve this goal, this study developed a methodology that used digital twin simulations to identify and solve future problems and inefficiencies in mine compressed air systems. The methodology was successfully developed from literature in Chapter 2. The developed method entailed digital twin modelling, full data analysis, proactive solution development and, lastly, the implementation of the developed solution to validate the study.

The objectives of the developed methodology were the following:

- Develop a digital twin model of the compressed air system at hand that accurately portrays the system's performance.
- Expand the digital twin model to include future mining activities and estimate the future performance of the compressed air system.
- Identify future compressed air system problems and inefficiencies.
- Develop proactive solutions to the identified system problems to fulfil a proactive planning strategy.

The developed methodology was tested and validated in Chapter 3 by implementing it on a practical case study. Mine A, a deep-level gold mine in South Africa, was selected and the developed methodology was used for the mine's compressed air planning. All the required information on the compressed air system was gathered and a walk-through audit of the entire compressed air system was completed. A digital twin model of the mine's compressed air system was constructed. The simulation was tested for accuracy and proved to be accurate within the predefined limit for calibration, namely a MAE smaller than 5%. The model was expanded to include future mining activities.

The steps as described in Section 2.3 were followed to complete a historical data analysis of the mine's compressed air system and forecast future performance. A future problem was identified on the compressed air services system of the main production level of Mine A. This system would have been unable to meet the required compressed air pressure for mining in the stoping ends. The methodology was followed and a proactive solution to the identified problem was developed. The developed solution mainly used existing infrastructure and only required two small additional pipelines to be installed. This helped keep the cost of implementing the project to a minimum.

A key part of the solution development was to address the identified problem as proactively as possible to avoid production losses. Meetings were held with the relevant mining personnel and the results of the forecast were used to establish the schedule for implementing the solution. The digital twin model was used to simulate the developed solution by making the relevant adjustments associated with the solution to the digital twin model. The results from the simulations were analysed, and they showed that the implementation of the solution would enable the compressed air system to meet the future requirements for planned mining. The project was handed over to the mine's relevant personnel to implement the solution practically. The implementation of the solution increased the compressed air pressure in the haulage of the level where the problem was identified by 32% and avoided unnecessary production losses.

The implementation of both the developed methodology and its developed solution was a success. The developed methodology proactively identified and provided a solution to a future compressed air system problem and helped to avoid production losses and unnecessary costs. The methodology developed in this study can easily be implemented on other mine compressed air systems to help them plan proactively.

All the objectives set out by this study were met. A digital twin model of the system was developed successfully and expanded to include future mining activities. The developed proactive planning methodology was effective in identifying problems and inefficiencies that the compressed air services system could face in the future. The methodology successfully developed proactive solutions to these identified problems and ensured that the system met all requirements for the planned mining activities.

4.3 Recommendations for future work

This study successfully developed a proactive planning methodology for future mine compressed air planning using digital twin simulations; however, there is still scope for future research regarding similar topics. The recommendations for future work are summarised as follows:

- The development methodology used a black box method and historical data as mentioned in Section 2.3 and Section 3.3. This method helped the developed planning methodology to anticipate certain present inefficiencies in the existing system. A zero-wastage digital twin model of the same system, which excludes all inefficiencies, should be developed. The system performance outputs thereof can be compared with the system performance outputs of the digital twin model developed in this study. This will help to determine the overall system efficiency and can be used to further identify system inefficiencies.

- The proactive planning methodology was implemented on Mine A and successfully identified and provided a solution to a future problem, thereby avoiding unnecessary production losses. It is recommended that this planning methodology be implemented on other deep-level gold mines to help them plan more proactively and avoid unnecessary production losses.

- As mentioned in Section 1.4, compressed air systems and other services lack attention until they start to affect production negatively. Deep-level mine water systems lack proper planning and are affected by similar aspects that affect compressed air systems negatively. Thus, there is an opportunity to develop a similar modernised, proactive planning methodology that uses digital twin simulations for deep-level mine water systems planning.

- This study focused on future planning for mine compressed air systems using digital twin simulations. Compressed air systems are widely used in other industries and, similar to the mining industry, they lack proper planning. There is thus scope for future compressed air planning using digital twin simulations in other industries such as the Mosul dairy factory as mentioned in Section 1.6.

- This study forecast compressed air system performance using digital twin simulations and established correlations. The correlation used was between the required compressed air flow and the production output in the form of tonnes mined. It is recommended that research be done on the correlation between the required compressed air flow and other mining aspects. An example is the correlations between the required compressed air flow and the number of active stoping and development panels. This research will help to provide a better understanding of factors influencing the compressed air demand and can be used to further advance the planning of these systems.

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APPENDIX A – PROCESS TOOLBOX FUNCTIONALITY

This section of the study provides and discusses information on how some main components in PTB were used to construct the compressed air digital twin model in this study. PTB is a tool that is used for transient thermal hydraulic system simulations and optimisation. The system networks used in PTB consist pressure nodes and pipes that are used to specify flow paths. The nodes are used to calculate thermal hydraulic properties, while the pipes are used to calculate pressure drops [57]. PTB mathematically calculates systems response to components that are characterised by the user. PTB can accurately simulate systems after the model has been constructed from various characterised individual components [41].

Supply side

As mentioned in Section 1.3, the supply side of the compressed air system consists of the compressors and air treatment. This study used the air dynamic compressor components available in PTB to simulate the supply side of the compressed air system. The air dynamic compressor component induces an air flow through the compressed air system by generating a pressure difference over the compressor component [57]. The induced air flow rate is a function of the pressure difference over the compressor [57].

The air dynamic compressor component is modelled by obtaining an equation for the corrected mass flow as a function of the pressure ration [52]. A quadratic curve is fitted through three points of operations for the compressor to be simulated. In this study, the characteristic curves and data sheets of Mine A's compressors were obtained from the suppliers. This data was used to obtain the function for the corrected mass flow in relation to the compressor's pressure ratio. Figure 35 and Figure 36 show the curves for the two compressors located in the compressor house of Shaft 1 of Mine A. The compressor house of Shaft 2 of Mine A has three of the same compressors in its compressor house. Figure 37 shows the compressor curve of these compressors.

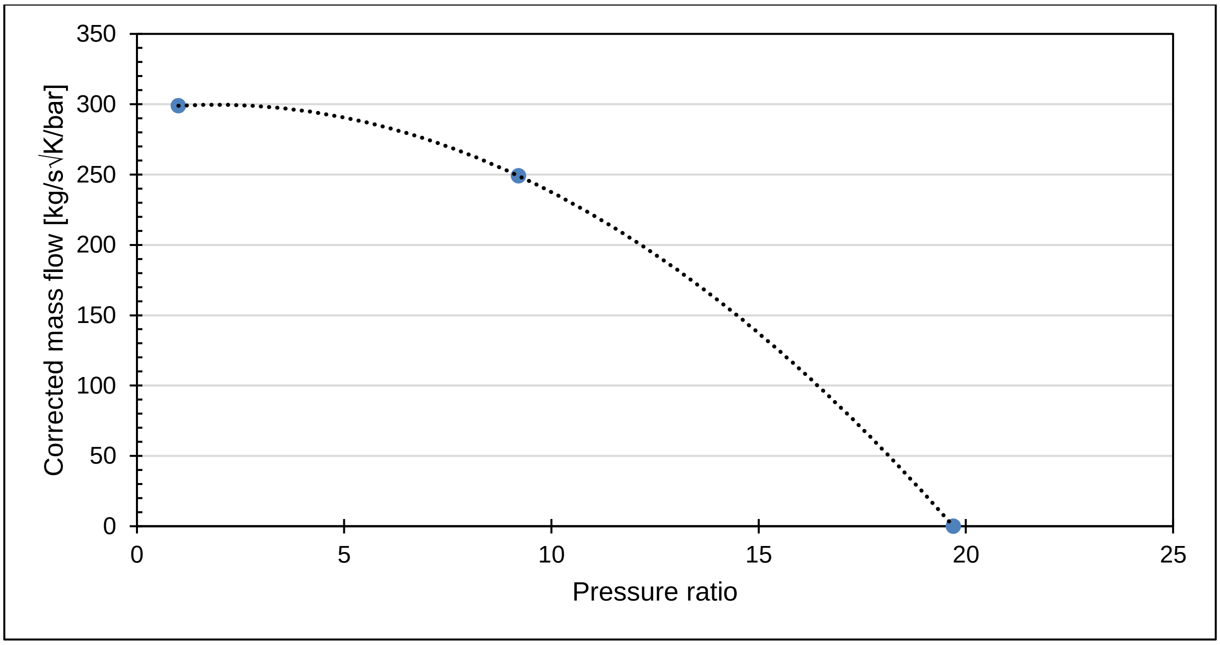

Figure 35: Mine A – Shaft 1, Compressor 1 characteristic curve

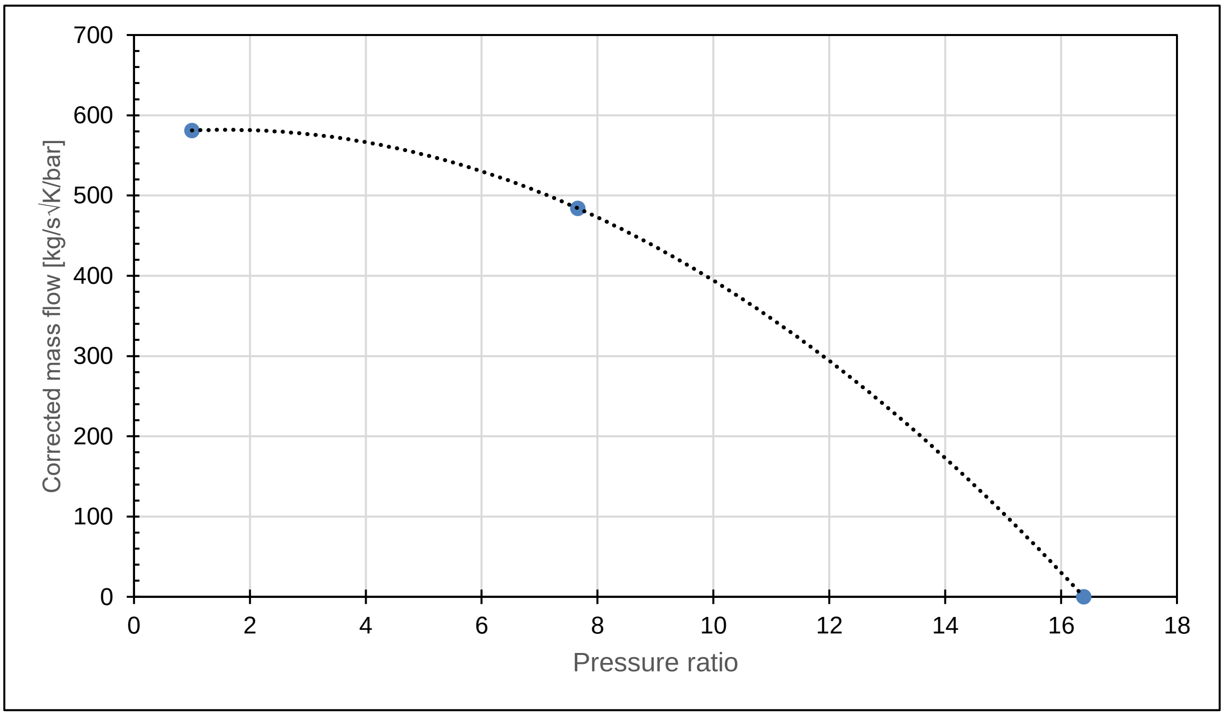

Figure 36: Mine A – Shaft 1, Compressor 2 characteristic curve

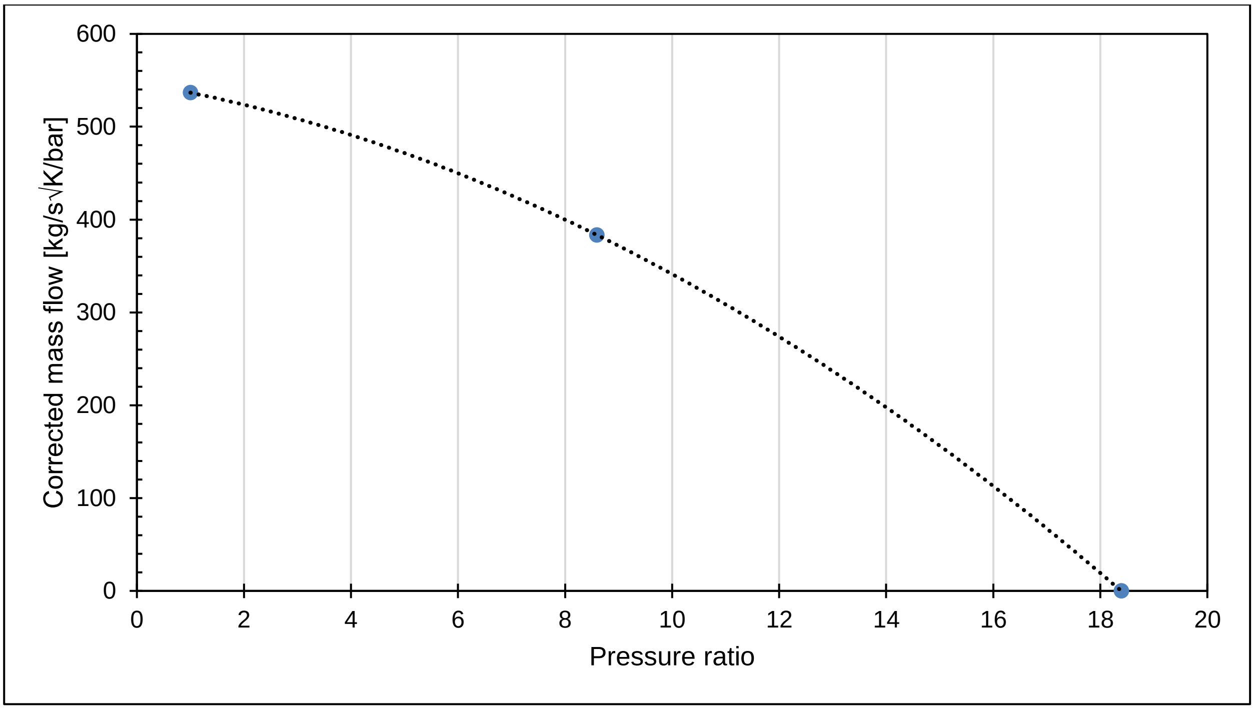

Figure 37: Mine A – Shaft 2, Compressors 1 to 3 characteristic curve

Reticulation network

The reticulation network of the compressed air system, as mentioned in Section 1.3, is the vast system of pipes that deliver the compressed air from the demand side to the supply side. This study used the air pipe and air node components available in PTB to model the compressed air system of Mine A. PTB has a variety of pipe and valve sizes available for components that incorporate the Darcy–Weisbach equation to account for pressure losses [52].

The air node components in the simulation use elevation and air volume as inputs to calculate the air network pressure, temperature, density and other properties [57]. The air pipe components take factors such as material surface roughness into account and are used to calculate the compressed air flow, network pressure losses and autocompression [57]. The audits completed during this study as discussed in Section 3.2 were used to specify the input parameters for the air pipe components. Table 22 shows the surface roughness used for the pipe components according to their material [57].

Table 22: Air pipe surface roughness [57]

Surface	Absolute roughness [mm]
Copper, lead, brass, aluminium	0.001–0.002
PVC and plastic pipes	0.0015–0.007

Surface	Absolute roughness [mm]
Stainless steel	0.045–0.09
Stretched steel	0.015
Welded steel	0.045
Galvanised steel	0.015
Rusted steel (corrosion)	0.15–4
New cast iron	0.25–0.8
Worn cast iron	0.8–1.5
Rusted cast iron	1.5–2.5
Sheet or asphalted cast iron	0.01–0.015
Smoothed cement	0.3
Ordinary concrete	0.3–1
Coarse concrete	0.3–5

Demand side

The demand side of the compressed air system includes all compressed air users, as mentioned in Section 1.3. These users not only include equipment such as drills and loaders but also air losses from leaks and open pipes.

This study used the air demand component in PTB to model all demand-side compressed air users. The flow of the compressed air leaving the system through the compressed air users is dependent on the resistance to flow and pressure difference over the user. The air demand component uses inlet pressure, outlet pressure and the required user flow to determine the demand resistance and output flow [52].

APPENDIX B – LAYOUTS OF PIPELINES AND PRODUCTION LEVELS

This section of this study provides the DXF level layouts and the pipeline level layouts of the production levels of Mine A that are critical to this study.

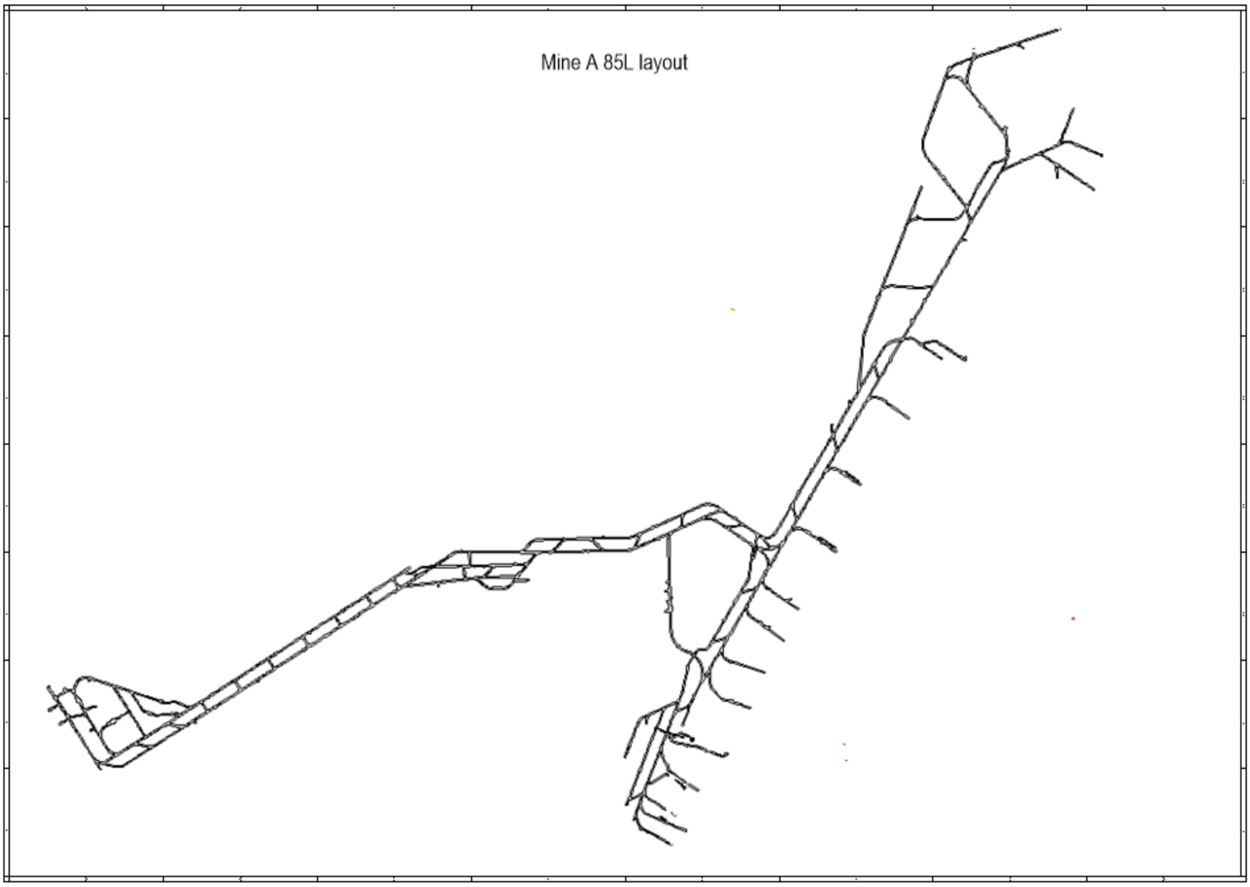

Figure 38: Mine A – 85L layout

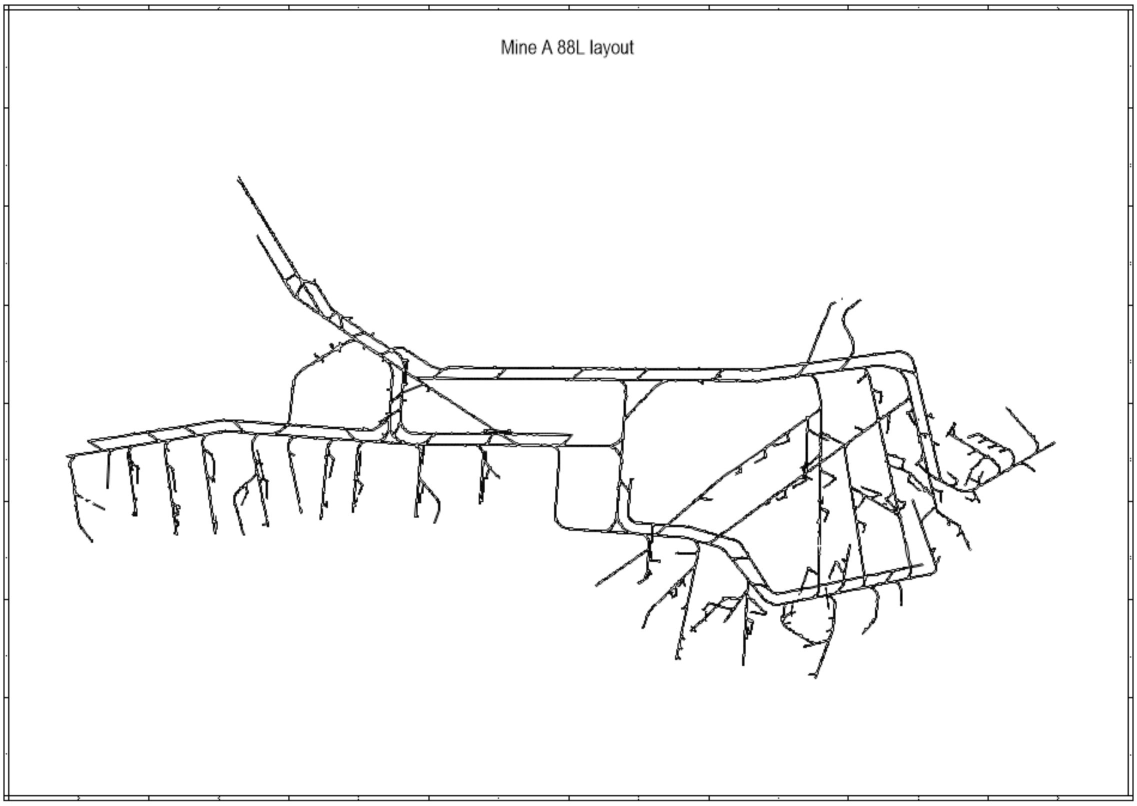

Figure 39: Mine A – 88L layout

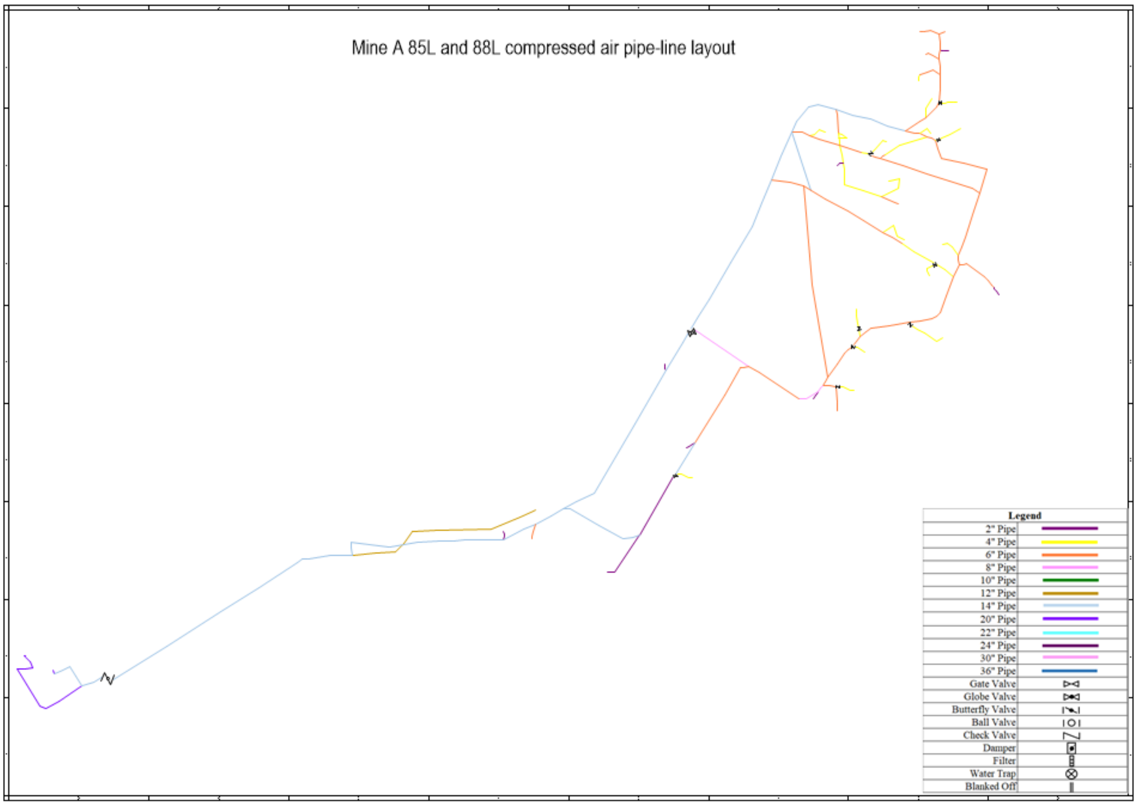

Figure 40: Mine A – 85L and 88L pipeline layout

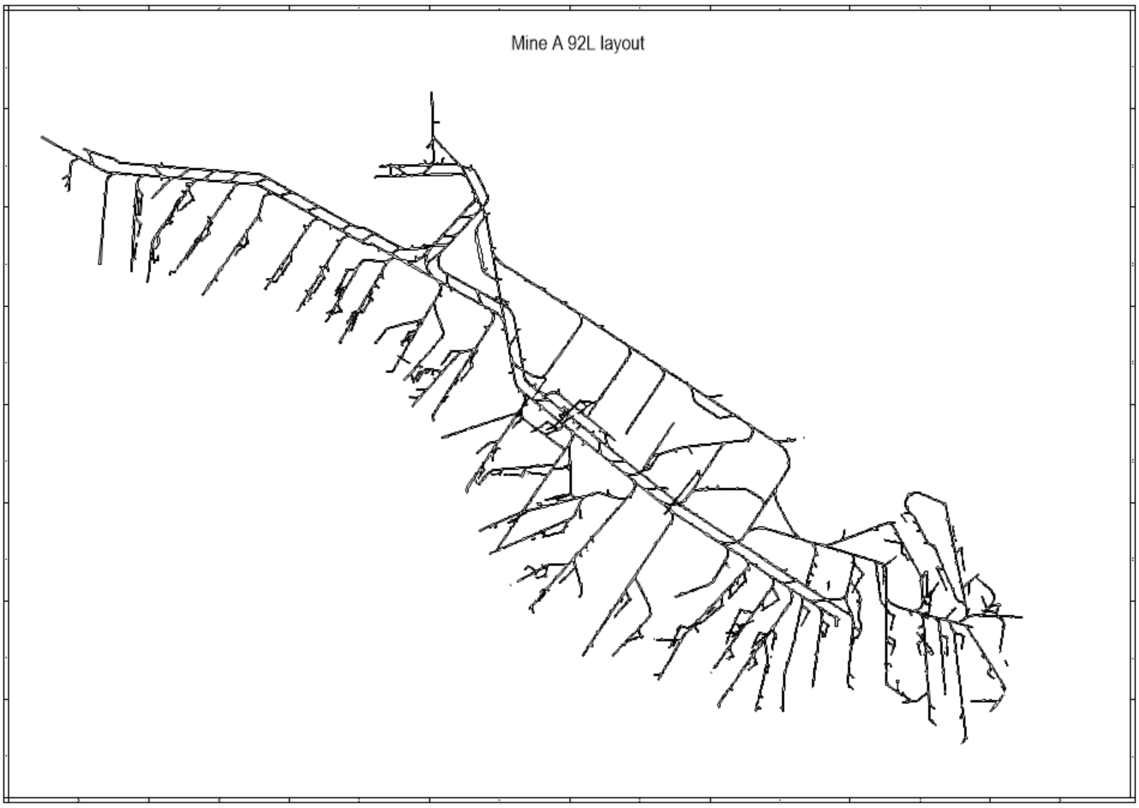

Figure 41: Mine A – 92L layout

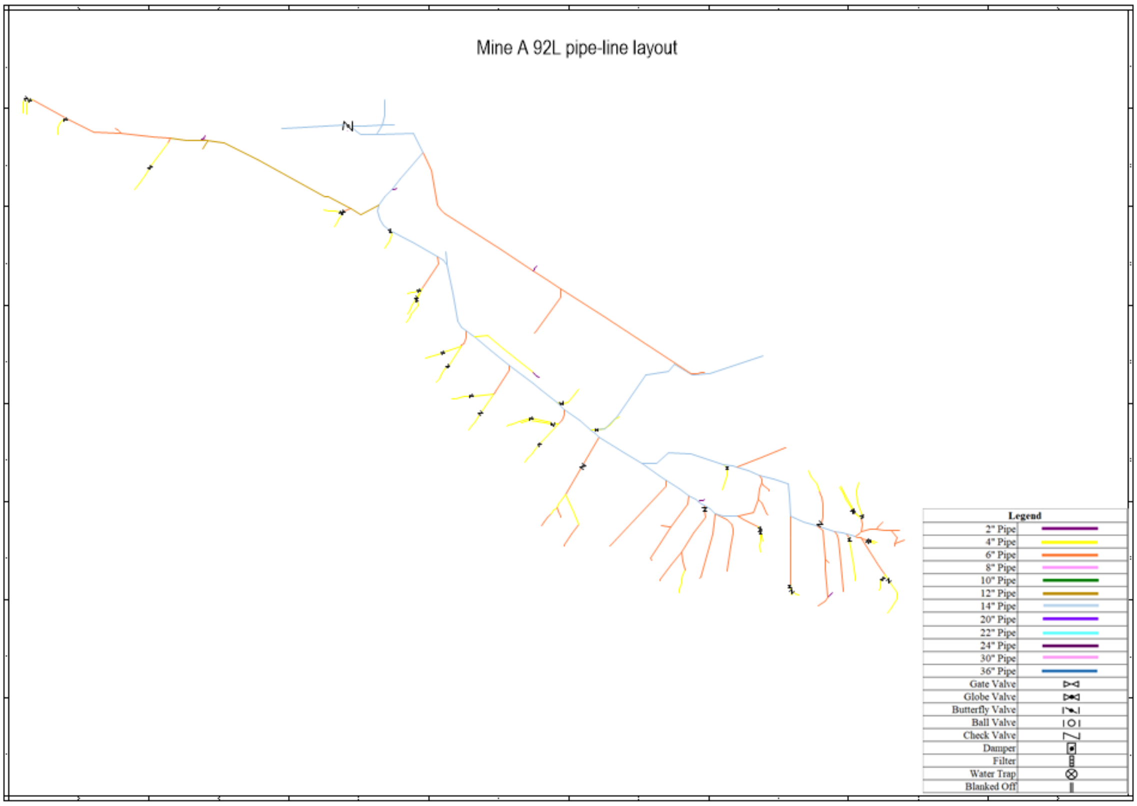

Figure 42: Mine A – 92L pipeline layout

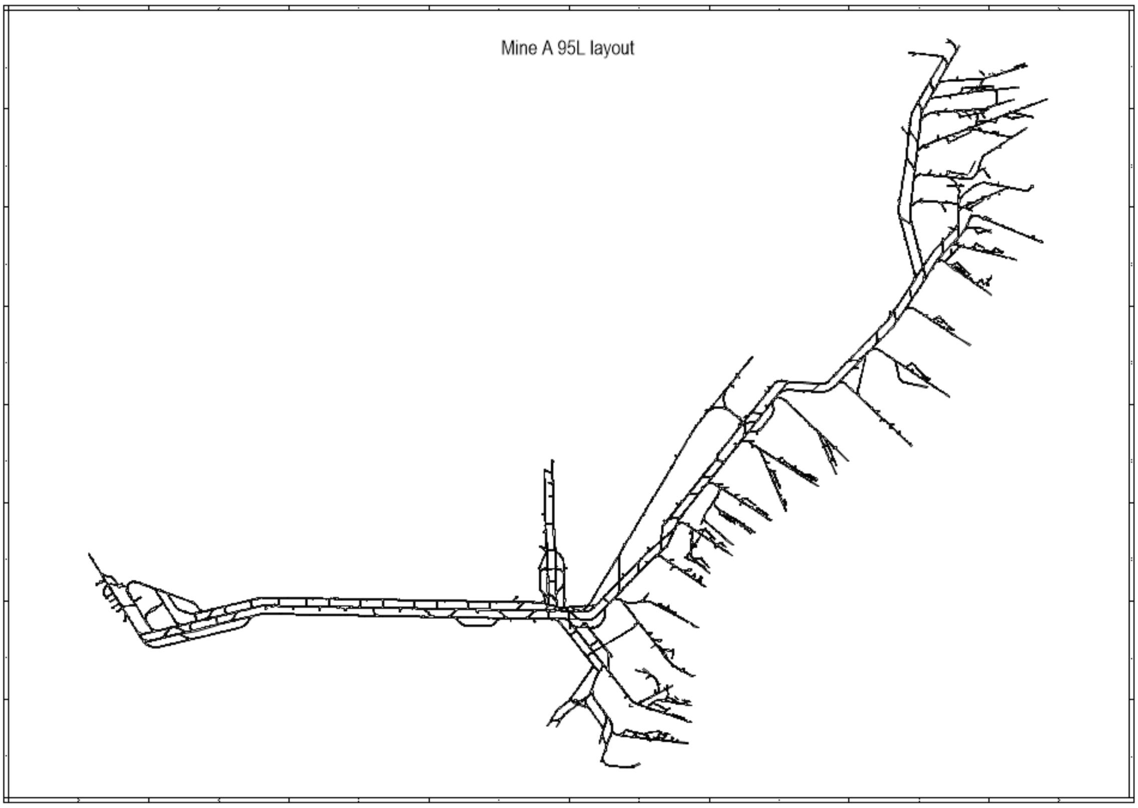

Figure 43: Mine A – 95L layout

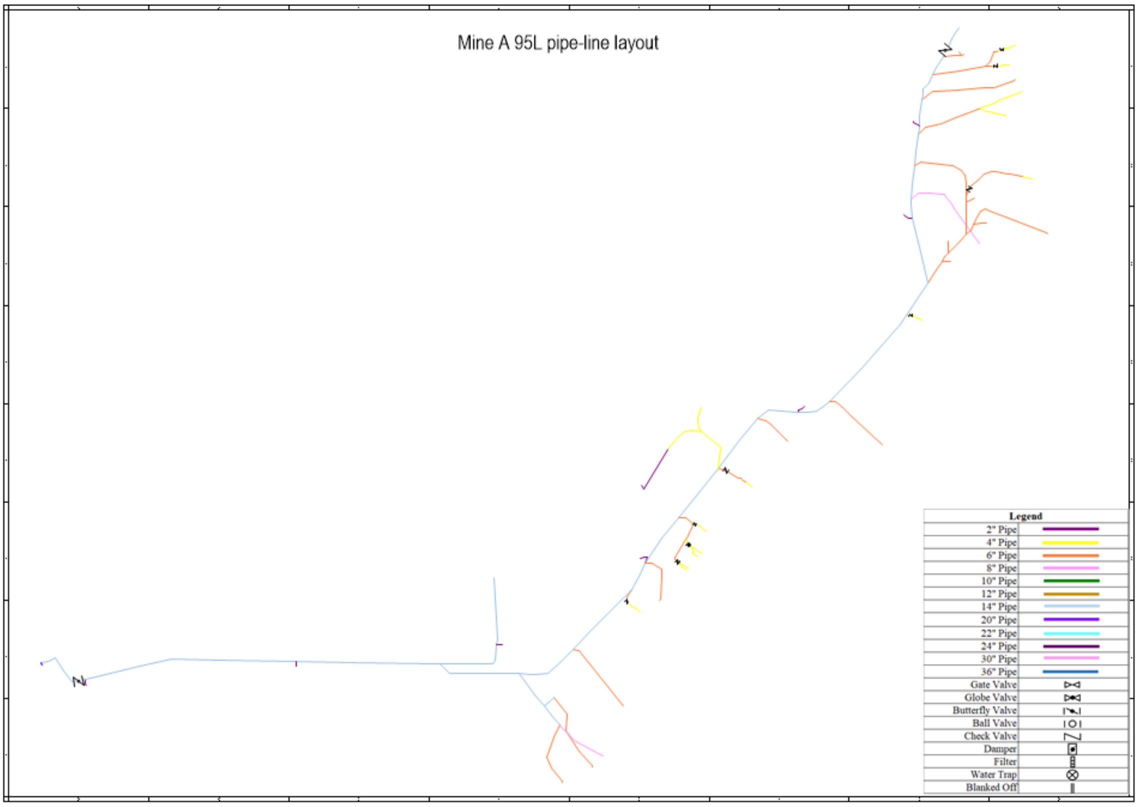

Figure 44: Mine A – 95L pipeline layout

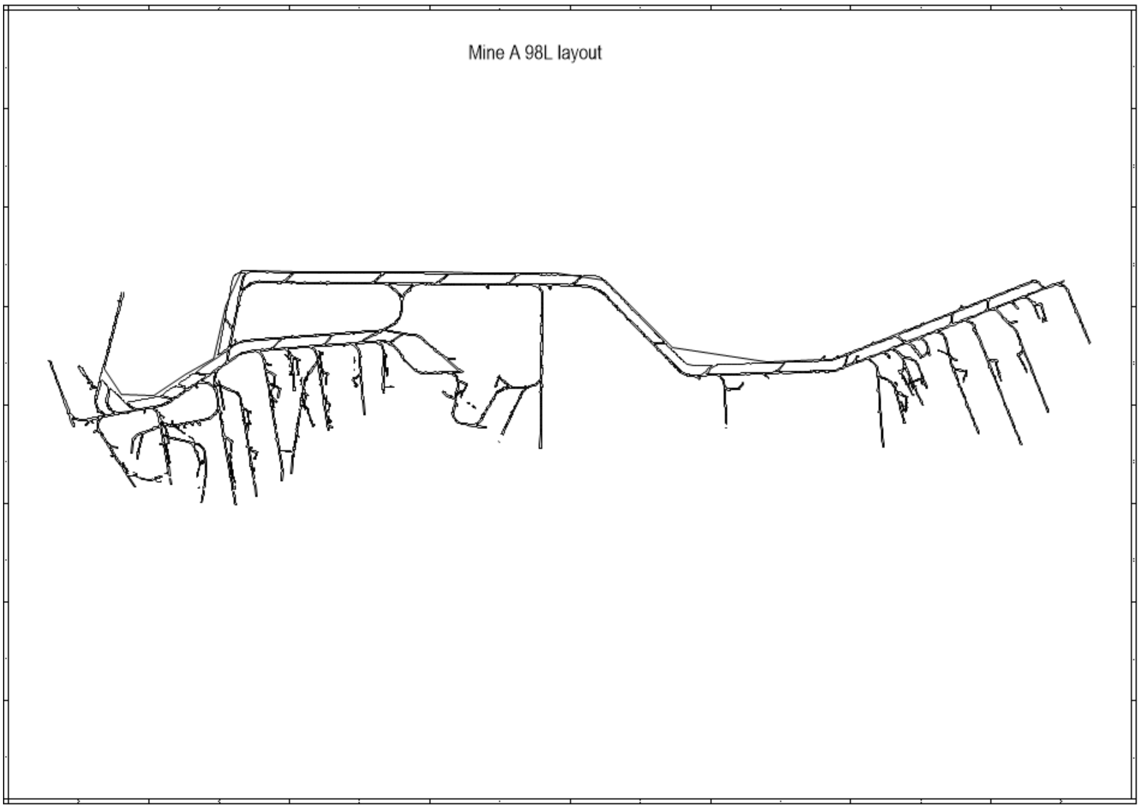

Figure 45: Mine A – 98L layout

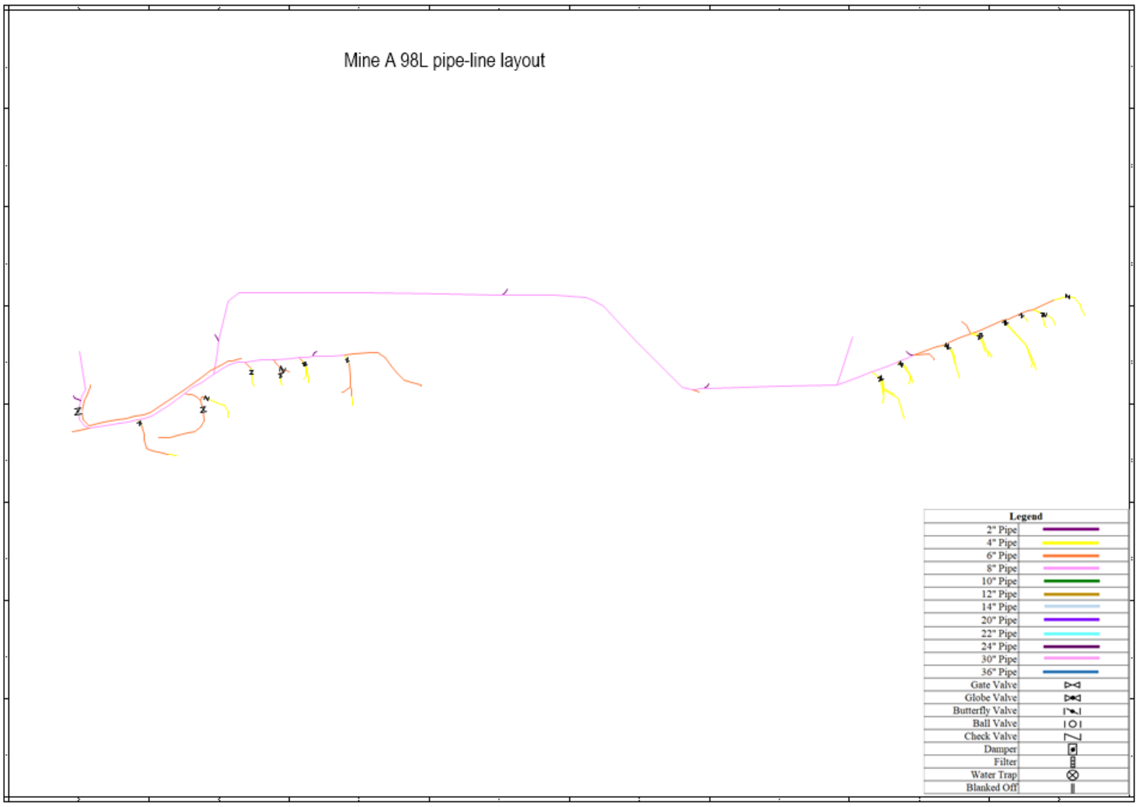

Figure 46: Mine A – 98L pipeline layout

APPENDIX C – ADDITIONAL DATA

This section of the study provides the additional data obtained during the data analysis and forecasting, proactive solution development and the implementation of the solution as discussed in Section 3.5.

Table 23: Actual and predicted flow for peak drilling shift

Date	Average flow peak drilling shift [kg/s]	Predicted average flow peak drilling shift [kg/s]	Error [%]
Jul-21	42.1	40.8	3
Aug-21	44.1	42.6	3
Sep-21	41.6	43.4	4
Oct-21	41.4	42.2	2
Nov-21	42.7	41.5	3
Dec-21	42.8	42.6	0

Table 24: Variation in flow during the peak drilling shift

Date	Average flow peak drilling shift [kg/s]	Maximum flow peak drilling flow [kg/s]	Variation [%]
Jul-21	42.1	45.5	8
Aug-21	44.1	46.7	6
Sep-21	41.6	47.9	15
Oct-21	41.4	44.1	7
Nov-21	42.7	46.3	8
Dec-21	42.8	47.6	11

Table 25: Actual and estimated compressed air flow for a random day

Time [hours]	Actual flow [kg/s]	Estimated average flow [kg/s]	Estimated upper flow [kg/s]
08:00	37.53	42.09	48.41
08:30	38.14	42.09	48.41
09:00	39.59	42.09	48.41
09:30	43.40	42.09	48.41
10:00	42.65	42.09	48.41
10:30	43.23	42.09	48.41

Time [hours]	Actual flow [kg/s]	Estimated average flow [kg/s]	Estimated upper flow [kg/s]
11:00	46.23	42.09	48.41
11:30	47.23	42.09	48.41
12:00	41.76	42.09	48.41
12:30	40.18	42.09	48.41
13:00	39.51	42.09	48.41

Table 26: Estimated total future compressed demand

Date	Total planned [tonnes]	Predicted average flow peak drilling shift [kg/s]	Flow upper limit [kg/s]
Jul-21	67 781	42	48
Aug-21	70 718	43	49
Sep-21	72 168	43	50
Oct-21	70 152	43	49
Nov-21	68 906	42	49
Dec-21	70 742	43	49
Jan-22	70 742	43	49
Feb-22	75 169	44	51
Mar-22	71 772	43	50
Apr-22	60 257	38	44
May-22	72 783	44	50
Jun-22	66 801	42	48
Jul-22	66 476	41	48
Aug-22	65 474	41	47
Sep-22	69 311	43	49
Oct-22	69 444	43	49
Nov-22	69 532	43	49
Dec-22	70 851	43	50
Jan-23	71 381	43	50
Feb-23	69 537	43	49
Mar-23	68 299	42	49
Apr-23	68 202	42	48
May-23	68 233	42	48
Jun-23	67 437	42	48

Date	Total planned [tonnes]	Predicted average flow peak drilling shift [kg/s]	Flow upper limit [kg/s]
Jul-23	67 354	42	48
Aug-23	68 498	42	49
Sep-23	67 376	42	48
Oct-23	67 640	42	48
Nov-23	66 830	42	48

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