Development of a compressed air demand simulation model for platinum mines

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ABSTRACT

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There is an increasing demand for companies to incorporate the fundamentals of environmental, social and corporate governance factors (ESG) into their operations. The global mining industries are under immense pressure to increase the sustainability of their operations. The South African mining industry and mineral processing play a large role in the country's economy. South Africa is currently the largest producer of platinum and platinum group metals (PGM) in the world. The operating costs to supply PGMs are high and energy intensive. Most of the electrical energy consumed on a deep-level platinum mine can be granted to the compressed air systems in the shafts.

Compressed air systems in platinum mines are intricate networks. These networks supply pneumatic equipment with the necessary pressures to be able to operate efficiently within their desired purpose. The primary objective of this study is to develop a simulation model able to predict whether the current compressed air network and supply will be sufficient for future demand. The future demand refers to development that still needs to be done in the mine and it is important to determine whether the current supply will be able to support this. Investigating the effect that compressed air inefficiencies have on the network pressure supports the above-mentioned objective. The effect that compressed air delivery pressure changes have in the working areas is also investigated.

To achieve the objectives of the study, a five-step method was developed. The method made use of various methods to source data, which included data collection from the SCADA at the mine and manual measurements that were taken. From these measurements a verified simulation model was developed that can be used in a real-life scenario. The simulation model was used to simulate three different scenarios. The three scenarios focused on the number of additional cross-cuts (X/C's) to be added in order for the development area to still receive the required pressure to operate. The three scenarios revealed that, at the current compressed air supply and demand, it will only be possible to add one additional X/C to the current three active X/C's on the level. Any further development will need to be supported by a reduction in compressed air wastage in each of the currently active and future X/C's.

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LIST OF ABBREVIATIONS

BIC	Bushveld Igneous Complex
CA	Compressed Air
ESG	Environmental, Social and Governance
MAE	Mean Absolute Error
MRD	Mean Residual Difference
PGM	Platinum Group Metals
PTB	Process Toolbox
SCADA	Supervisory Control and Data Acquisition
STP	Standard temperature and pressure
X/C	Cross-cut

CHAPTER 1: INTRODUCTION TO THE MINING INDUSTRY

1.1 Impact of environmental, social and corporate governance

1.1.1 Overview

ESG refers to the three key factors when considering the sustainability and ethical impact a company has, namely, environmental, social and governance factors. These three factors are often considered by investors to evaluate and determine the behaviour and future financial performance of a business [1].

The ESG factors are a subset of the non-financial performance of the business, which often includes the impact the company has on their direct community [1]. This means the focus is largely on the manner in which the company manages their carbon footprint [2], [3].

The environmental aspect includes climate change strategies, water and energy efficiency, and carbon intensity [2]. In the social part, focus is placed on equal opportunities, health and safety, and general human rights [2]. Governance focuses on business ethics, compliance, board independence, and lastly, shareholder democracy [4]. The above mentioned are only a few examples of what is considered when analysing each of the different categories [4].

The number of investment funds who analyse a company for their incorporation of ESG has been increasing over the past few years [5]. One of the key benefits for investors is the ability to analyse the risk-return characteristics across their range of investments based on how these different companies approach ESG. However, the current principles on which different investors score and allocate ESG ratings to different companies can differ from investor to investor [6]. This means that there are still challenges involved with the basis on which companies will be rated regarding their ESG impact [7].

The network of sustainable investment organisations has increased significantly in recent years [6]. Figure 1 provides an overview of the current and future expectations for global ESG investments in trillions of US dollars, where the dark blue bars are past and the light blue bars are future predictions [8].

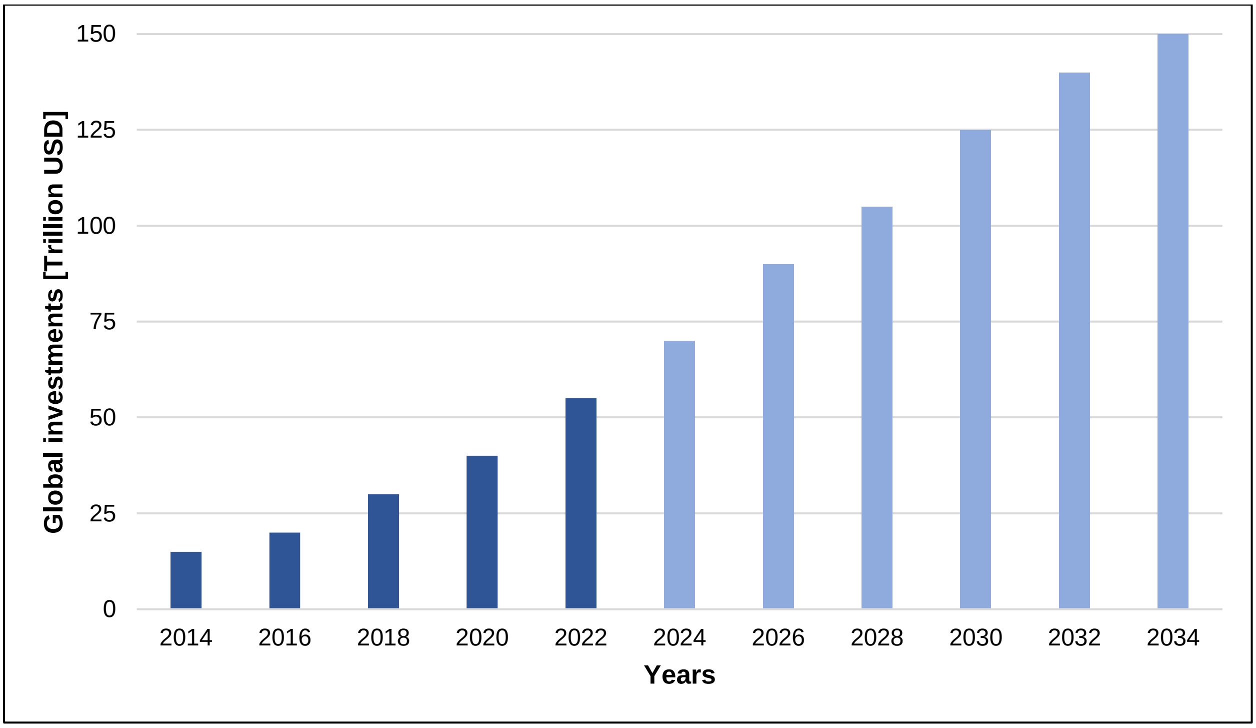

Figure 1: Current- and forecast of ESG investments globally (adapted from [4])

From Figure 1, global ESG investments are predicted to increase from 15 trillion USD in 2014 to 150 trillion USD in 2034. This increase in ESG investments within the global markets shows that investors are focusing on a sustainable approach regarding future portfolios. This will ensure that globally large companies all strive to be more sustainable and more focused on ESG [5].

The mining industry is in the process of developing strategies that aim to reduce carbon emissions and encourage sustainability, which integrates well with the principals of ESG [7]. This sustainability of the mining industry is important when considering the future of mining and how it affects the environmental part of ESG [6].

ESG is becoming more apparent within industries as an approach to benefit the planet, people, and profit successfully to decrease the overall negative impact on the environment. One of the main difficulties when incorporating ESG in the mining industry is to identify the important aspects and report methods [6], [9]. When considering future involvement in the mining industry, companies could focus less on the financial statements and more on the ethics, competitive advantage and culture of a mining organisation as well as the reduction in CO_2 emissions [6].

Mining companies should have a proactive response to ESG as this will become of utmost importance in the near future [7]. Not only will investors and the government be imposing stricter regulations regarding ESG, but the risk of losing community support as well as the security of resources for mining operations should be considered [5]. The importance of securing a track record of good performance and strong stakeholder relationships could ensure access to necessary resources and capital in future projects and mining development [5].

The mining industry is already taking steps on their ESG agenda, and will need to go beyond measurement to reap the real benefits [6]. The benefits of the integration of ESG into the mining industry will provide a larger insight into how energy efficient the mines operate. The focus of the next section is on platinum mining in South Africa.

1.2 Platinum mining industry in South Africa

1.2.1 Importance of mining in South Africa

The South African mining industry and mineral processing primarily focus on coal, gold and platinum mining [10]. South Africa is currently the largest producer of platinum and platinum group metals (PGM) worldwide, with almost 80% of the total global platinum output production [7], [11]. Most of the platinum mining in South Africa is done in the Bushveld Igneous Complex (BIC), which is found in the North-West and Limpopo provinces [8]. The two main reefs from which the ore is mined (from conventional shaft mines) are the Merensky Reef and the UG2 Reef [8].

The decreasing supply of platinum from the Bushveld Complex in South Africa and the increasing global demand for PGMs add financial pressure on the mining industry [12, 13]. The primary demand for platinum is ever increasing because of the use of PGMs in the automotive industry and jewelry [14].

The platinum availability from the Bushveld Complex is one of the major sources of the world's supply [15]. The ore availability in the area will not be depleted for many years to come [15].

However, in the short term, social, political, environmental, and economic factors could possibly have an effect on the supply [16], [17].

The sale of PGMs in South Africa contributes significantly to the economic growth of the country and has been on the increase in recent years [18]. PGMs accounted for 28% of the country's total mining revenue during this time [19].The increase in sales also adds pressure on the production side of the industry. The following aspects have an influence on production: PGM prices, labour strikes, and increasing production costs [8].

The production process and costs are directly correlated to the profits— a significant amount of the operating expenses is incurred, irrespective of the volumes produced. The market prices also have a major impact on profitability [20]. The operating costs for platinum mines are mainly employment benefits and contractors, consumables and mining supplies, utilities, transportation costs, royalties, and other expenses [21]. The utility usages are proportional to the energy demands within a platinum mine and typically contributes to 9% of overall expenditure [21]. Figure 2 provides an overview of the expenditure of costs in conventional platinum mines in South Africa.

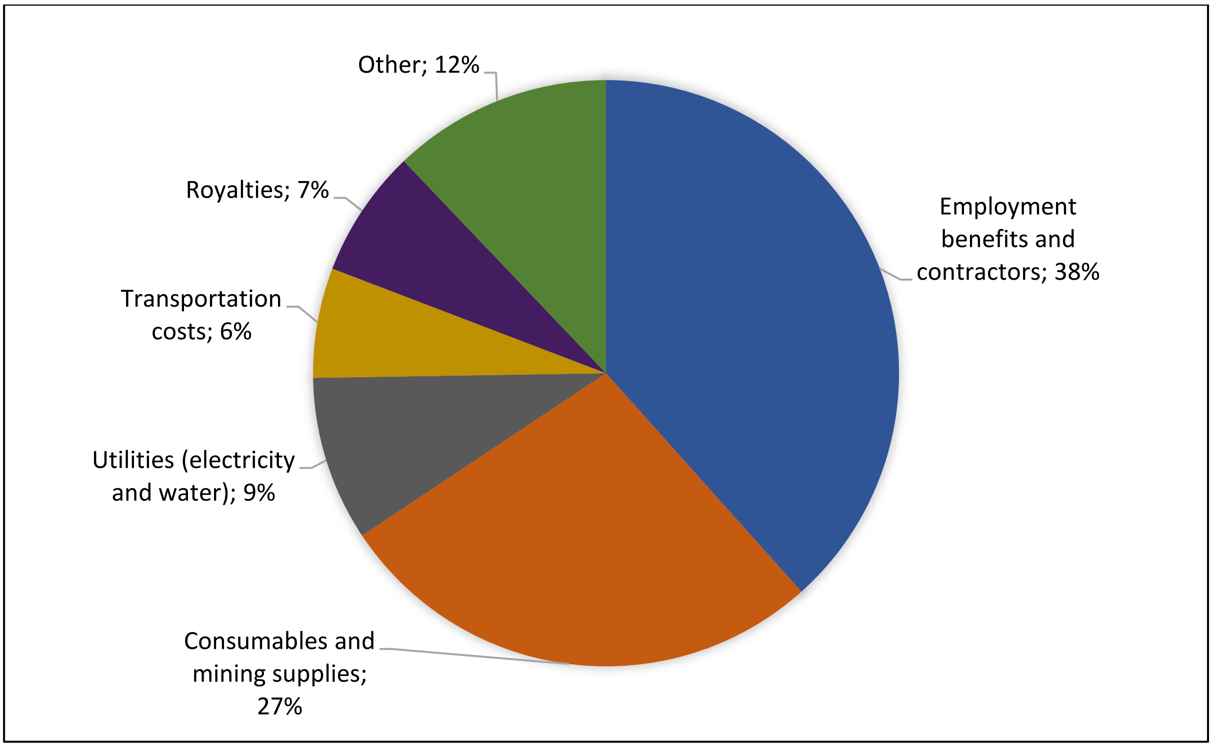

Figure 2: Conventional shaft mine typical expenditure (adapted from [21])

The electricity costs are not the highest expense and can be reduced with proper energy management [22]. Electricity tariff increases negatively influence profitability and sustainability of operations [23]. This means that, to increase profitability, the main users of electricity should be targeted to reduce consumption. The main consumers of electricity in conventional platinum mines are discussed in the next section.

1.2.2 Energy demand in platinum mines

There are a few main energy consumers in a platinum mine, namely ventilation, compressed air, dewatering systems, winder operations, and refrigeration. Of these, the main consumer is compressed air [24]. Figure 3 below provides a percentage breakdown of the main energy consumers and how much they contribute to the total use [25].

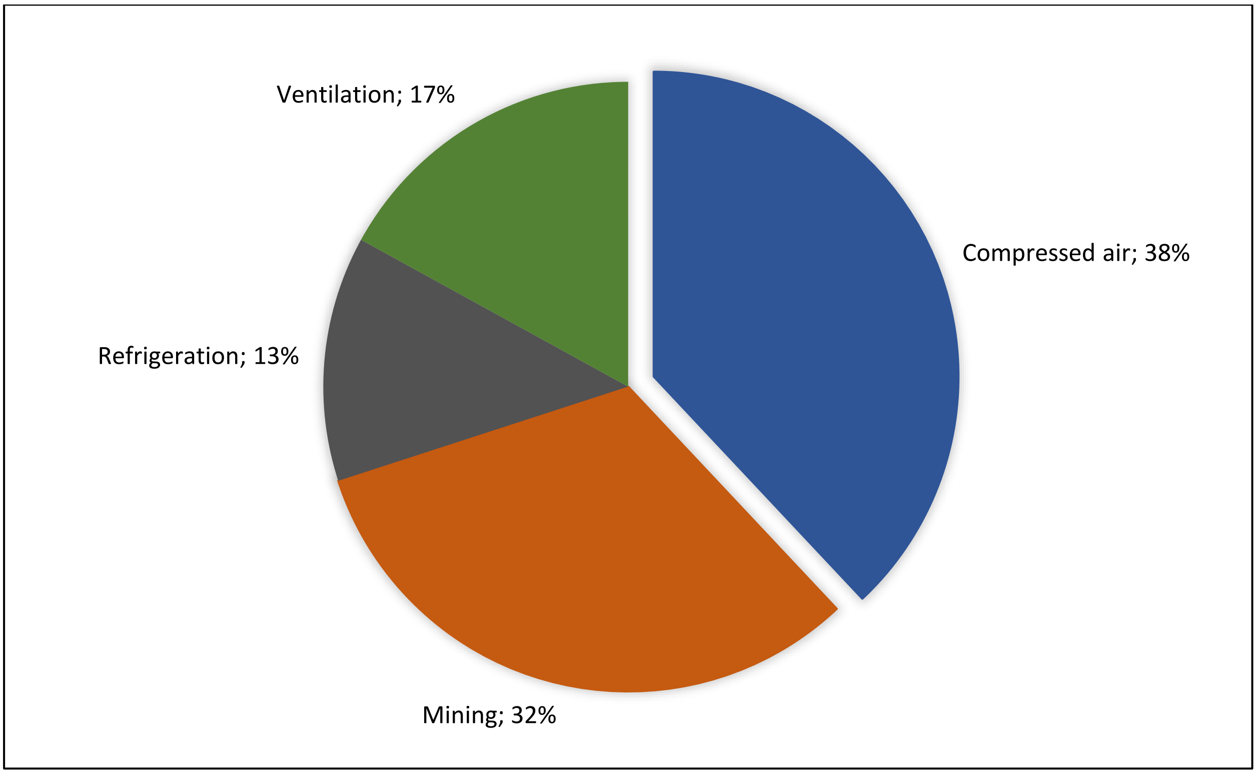

Figure 3: Electricity costs in a platinum mine shaft (adapted from [25])

The above-mentioned consumption areas are important to the daily operation of a mine. The compressed air is the largest consumer, which means that it is the ideal area to focus on when considering the improvement of energy efficiency [25], [26]. The next section provides an overview on how the energy efficiency of compressed air networks will be investigated.

1.3 Compressed air networks in platinum mines

1.3.1 Overview

Compressed air networks in the platinum mining industry are widely used as they are reliable, versatile, safe, and relatively easy to use [27]. The compressed air supply system is a network of multiple compressors that are connected to the working areas with compressed air pipelines. The supply layout to the different consumers should be in balance with the demand. The supply of compressed air to the necessary areas with the correct pressures at specific periods of the day is crucial. In many cases, the long distances that compressed air needs to travel and the general size of the network may cause large energy losses within the system. The compressed air supply and demand are monitored from a central control room. The control room is operational for 24 hours of the day and someone is continuously managing the compressed air [24].

These large systems are used to supply a range of pneumatic equipment. Most of the equipment is used in production areas and directly affect the daily operation in the mine [24], [28]. Having a stable and reliable supply of compressed air is crucial to the operation of various equipment.

1.3.2 Compressed air supply and demand

Compressed air is supplied by making use of multi-stage centrifugal compressors. These compressors are very reliable and have the ability to deliver large volumes of compressed air at a stable pressure [29]. On the compressed air demand side, equipment that requires compressed air include rock drills (handheld and drill rigs), agitators, pumps, instrumentation, venturi blowers, refuge bays, loading boxes and loaders [24], [30].

The compressed air supplied to working areas need to be at the required pressure in order for equipment to function [31], [32]. An insufficient supply of compressed air to working areas may correlate to reduced production [33]. Therefore, mines usually oversupply the air networks in order to ensure that necessary pressures are received in the working areas [34]. This approach is inefficient and often results in larger energy losses [35].

The equipment using compressed air can be divided into high- and low-pressure systems. The high-pressure equipment requires pressures between 500 and 700 kPa, whereas the low-pressure equipment requires pressures between 50 and 200 kPa. A typical example of high-pressure equipment is rock drills and of low-pressure equipment, refuge bays [31], [32].

The management of compressed air networks poses a large opportunity for improvement. Changes made to the compressed air system need to be done without affecting production. The complex nature of the compressed air systems within the mine leads to inefficiencies [27], [36] .

Compressed air network inefficiencies can mainly be categorised into two areas: complexity of a system and piping network [22], [37]. The high humidity and temperature conditions a piping system are exposed to in underground mines also add to the inefficiency and pipe deterioration. The harsh environment in which the piping network needs to function creates an ideal area for rust and moisture to form in the compressed air pipes. As soon as rust is present on the pipe the deterioration of the pipe conditions are propelled by the high humidity and any minor inefficiencies like pipe leaks become a major concern as the pipe quality worsen [27].

Some of the main inefficiencies in compressed air networks are [38]:

- Moisture in compressed air
- Pipe leaks
- Incorrect pipe sizing
- Sharp bends in pipes
- Ring feeds

These inefficiencies have a direct impact on the delivery pressure of compressed air to working areas [24]. If the pressure delivered to working areas is too low, it could have a negative impact on production. This means that there is a serious need to address the compressed air system inefficiencies. If these inefficiencies can be managed, a balance between compressed air demand and supply should be achieved, which in return provides a reduction in electrical costs and also reduces carbon emissions, which leads to improved ESG for the mine.

1.3.3 Mining activities and compressed air network evaluation

Compressed air has a wide variety of uses in the mining industry and forms the backbone of most production activities at a mine. The relationship between compressed air usage and demand can only be fully understood when the day-to-day operation of the operation is understood.

The daily mining activities in a deep-level mining shaft can be categorised into three main shifts, namely a cleaning shift, drilling shift, and blasting shift, with three changeover periods between the three shifts [39], [40]. The compressed air requirement for each of these shifts is different and varies by the time of day [27]. The three shifts and the pressure requirement can be seen in Figure 4.

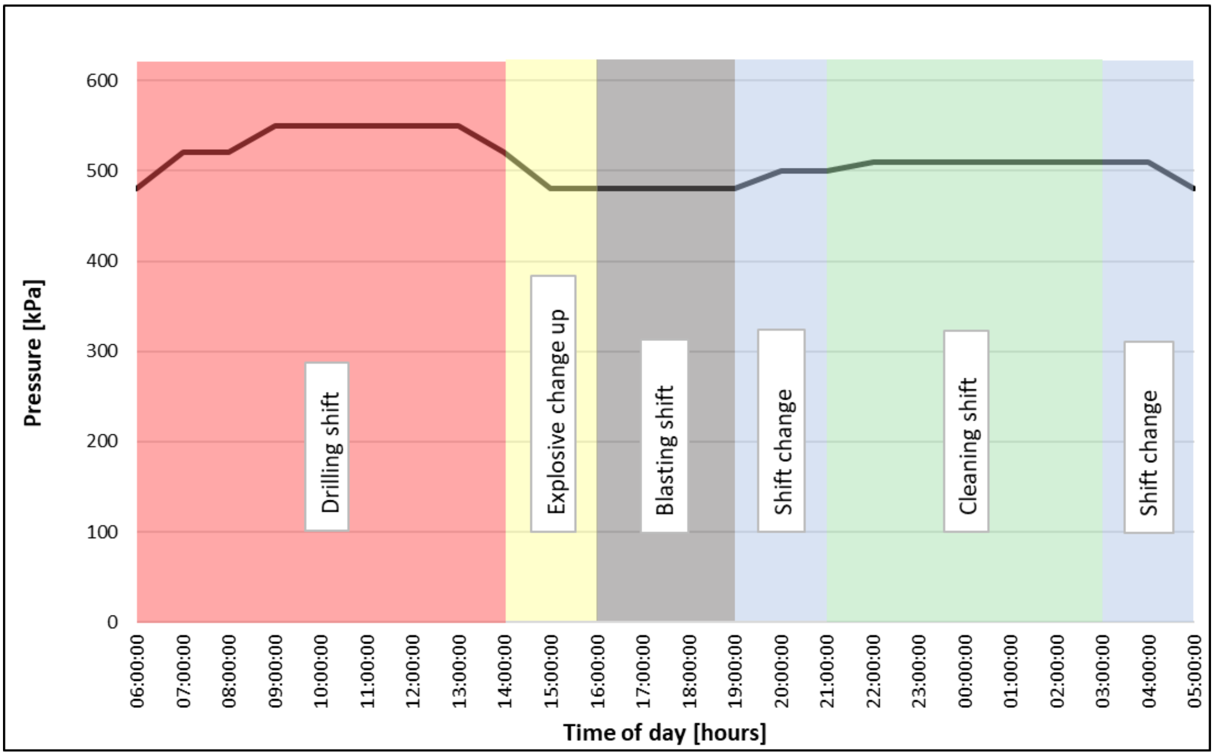

Figure 4: Daily shifts and pressure requirements [35]

The typical working day starts at 06:00 with a drilling shift. Employees make use of an enclosed transport cage to be transported from surface to their working levels from where they travel by foot to their designated underground working areas. After arriving at their different areas, the drilling for the day begins [35].

Drilling shift

The drilling shift is the crucial period during a work day where mine workers drill holes in rock faces with rock drills [41]. The most common drills that the mines make use of are pneumatic drills [42]. These drills are supplied with compressed air from the compressed air network within the mine [35], [43]. It is, therefore, very important that the required compressed air pressures are supplied to the working areas [44]. The drilling shift prepares the cavities where explosive charge-up can take place, after which blasting is done.

Blasting shift

The drilled holes are filled with explosives and wired to a centralised blasting panel. During this shift, most of the underground personnel need to be evacuated from the mine and most of the operations underground are stopped. After the shaft has been cleared, the charged explosives are detonated [43], [44], [45]. The compressed air demand is at its lowest during this shift as there are no mining activities underground during this time. The mine ventilation system is used to clear the dust after the blast for mining personnel to safely return to their working areas [35].

Cleaning shift

The blasted ore is scraped by winches and loaded onto pneumatic loaders. The process of transporting ore from the rock face to the processing plant on surface starts in the cleaning shift [46]. A platinum mine makes use of a simple method to transport ore from the rock face to surface. The system mainly consists of hoppers (train carts) that are used to collect ore from loading boxes located at each working area. The ore is then transported to a central ore pass that feeds down to a central collection point on the lower levels of the shaft, from where it is transported to surface through a process called hoisting [27].

The consumers of compressed air during the cleaning shift are mainly pneumatic loaders and loading boxes. This type of equipment needs a relatively high pressure (450 kPa) in order to operate [41].

1.3.4 Compressed air requirements

One of the factors to consider in the compressed air network is the delivery pressure of equipment. If the pressure received is too low, the equipment may fail or perform poorly [47]. The pressure requirements of different pneumatic equipment can be seen in Table 1.

Table 1: Pneumatic equipment operational specifications [35], [48], [47], [49]

Pneumatic equipment	Pressure requirement [kPa]
Rock drills	300 – 500
Rock loaders (Bushman loaders)	400 – 500
Pneumatic actuators	400
Loading boxes	300 – 500
Refuge chambers	200 – 300

Rock drills [47]

The rock drills are used to drill holes in rock faces of the platinum reef. These holes are filled with explosives that are detonated during the blasting shift. The detonated fragments of rock are then transported to be processed.

Rock loaders [27]

The fragments of rock that have been blasted are moved from the working area by rock loaders. These loaders gather and load the blasted rock into the underground locomotive hoppers that are used to transport the ore.

Pneumatic actuators [35]

The compressed air supply both on surface and underground is regulated by pneumatic control valves. It is important that the downstream pressure of the control valve is adequate for operation.

Loading boxes [35]

Loading boxes are chutes that drop fragments of rock that cannot be moved by a rock loader from the area where it was blasted into locomotive hoppers. The loading box makes use of compressed air to power a pneumatic system that opens the chute at the bottom of the box.

Refuge chambers [15], [50]

Refuge chambers located underground are enclosed chambers that are used as assembly points in case of an emergency. These refuge chambers are fitted with an open end of a compressed air supply which keeps the chamber at a positive pressure to ensure that no toxic gas or smoke can enter the chamber. The compressed air pressure inside the chamber should be maintained at 200 – 300 kPa.

The background regarding the operations and equipment in the mining operations have been discussed. The following section focuses on the inefficiencies in a compressed air network.

1.3.5 Compressed air network inefficiencies

The evaluation of a compressed air network needs to take various aspects into consideration. One of the key aspects to consider are inefficiencies within the system. The analysis of inefficiencies mainly focused on how compressed air pressure is wasted within the system [38], [51].

Compressed air system wastages are one of the key areas where compressed air pressure is reduced [38]. This is a common issue in conventional shaft mines that make use of compressed air as a supply to operate equipment [38], [52]. A poorly maintained compressed air network can lose 40% - 50% of its generated compressed air through leaks and wastages [48]. However, a well maintained system can reduce its losses to approximately 10% - 15% of the total generated air [48], [38], [53].

The reduction in compressed air pressure in the system is not the only issue regarding wastages. The power lost by the compressors due to leaks is also substantial [38], [51]. The financial loss per leak size can be calculated by making use of a series of calculations. A compressed air drop test can be done to provide actual current statuses of consumption [38].

The financial loss that compressed air leaks cause are quite significant. The process of repairing compressed air pipe leaks has a financial benefit and increases the pressures to working areas [27].

A key aspect to manage the above-mentioned inefficiencies successfully is to be able to monitor the data received from the central system used by most mines. The next section will focus on data gathering in mines.

1.4 Data availability on platinum mines

Most mines make use of a supervisory control and data acquisition (SCADA) system to monitor the many processes and parameters in real time. The SCADA system also has the ability to save data to a historian to be viewed or analysed in future [35], [44].

The compressed air network in the mines are one of many systems that are monitored by using the SCADA. Data regarding compressor statuses, valve statuses, line pressures, and flow measurements are available to be viewed in real time from the central system. There are still mines that collect the above-mentioned data manually. In a case where the data need to be collected manually, the mines makes use of portable pressure loggers, portable air flow meters, portable power meters, and analog pressure meters (Range 0 – 1 000 kPa) [27].

The compressed air systems that are being monitored from a SCADA system provide real time data, which result in an effective system to use when any physical changes or new installations are made to the compressed air system. The use of simulation software for a compressed air system can be very helpful as changes or operational scenarios should be investigated without making physical changes to the compressed air network. The use of simulation software in mining operations is discussed in the next section.

1.5 Simulation software for compressed air networks

A wide variety of compressed air flow simulation packages exist. These packages can accurately and quickly simulate and visualise various flow scenarios [54], [55], [56]. A few of the available simulation software packages are discussed below.

KYPipe [57]

KYPipe is often used to calculate steady state flows and pressures for pipe distribution systems. The program can be used to simulate any liquid, but does not generally specialise in gas flow unless the assumption of constant density can be made. The program has the ability to accommodate any pipe configuration and multiple hydraulic components.

However, KYPipe is a program that specialises in fluids and the lack of variability regarding gas calculations reduces the versatility of the program.

SOLIDWORKS Flow Simulator [54]

The SOLIDWORKS simulation package makes use of the Navier-Stokes equation to simulate and solve the flow characteristics for a certain scenario. The flow simulation is an add-in function to the SOLIDWORKS program.

The ability to develop and simulate accurate flow measurements (both internal and external flow) makes this a very powerful simulation package. A typical flow simulation on SOLIDWORKS can be seen in Figure 5.

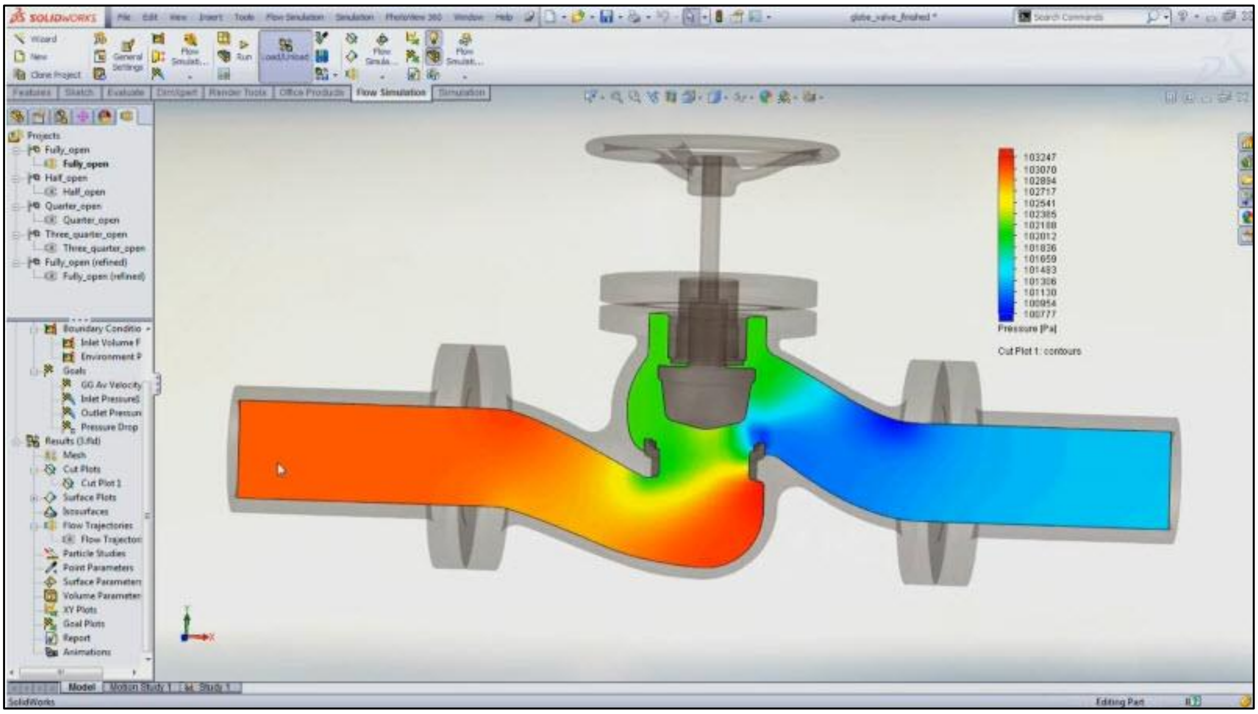

Figure 5: SOLIDWORKS flow simulation [54]

Flownex® [58]

The Flownex® simulation software offers the ability to analyse both compressible gasses and incompressible liquids. The demonstration version only allows a maximum of ten pipe sections to be added with ten nodes.

The software can be used for a wide variety of mining applications. The only downside to the package is the high price and limited demonstration version. Figure 6 shows an overview of a valve closure scenario on Flownex®.

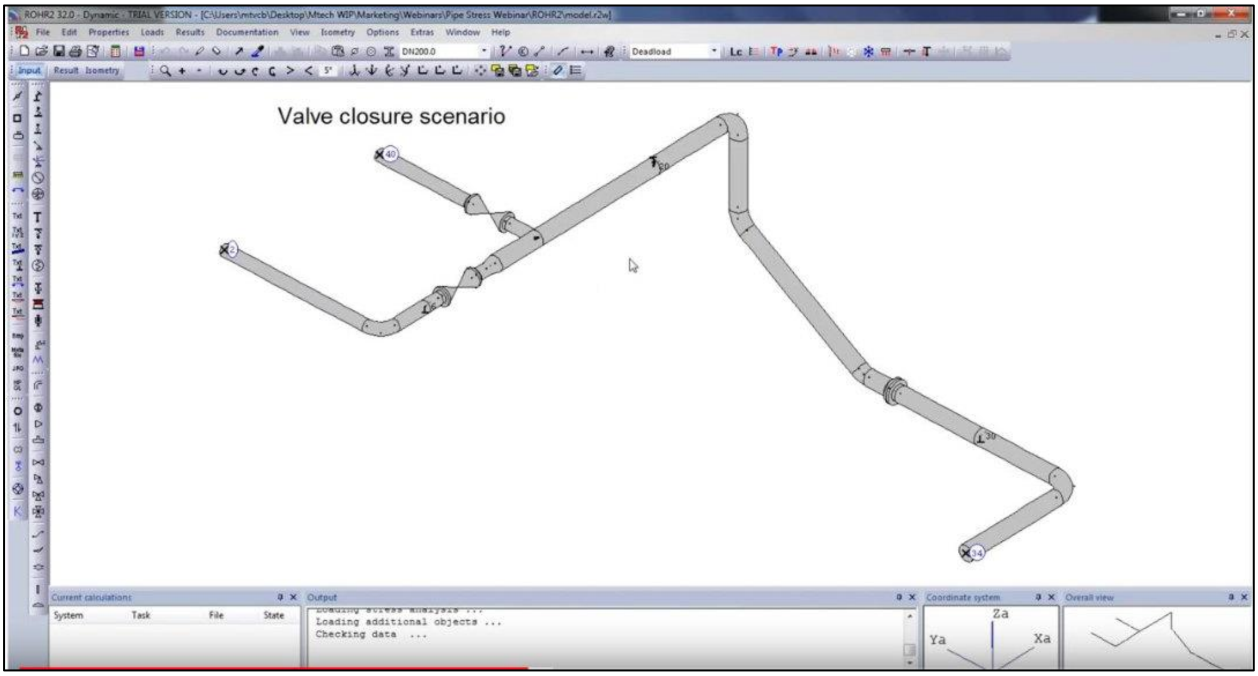

Figure 6: Flownex® demonstration package [58]

Process Toolbox (PTB) [59]

Process Toolbox (PTB) is a thermal hydraulic simulation software package. It is used to simulate a mine’s dewatering, refrigeration, and compressed air systems. The simulation package can simulate and accommodate all the components in a compressed air network into a single simulation model. An overview of a simple compressed air piping layout that can be simulated can be seen in Figure 7.

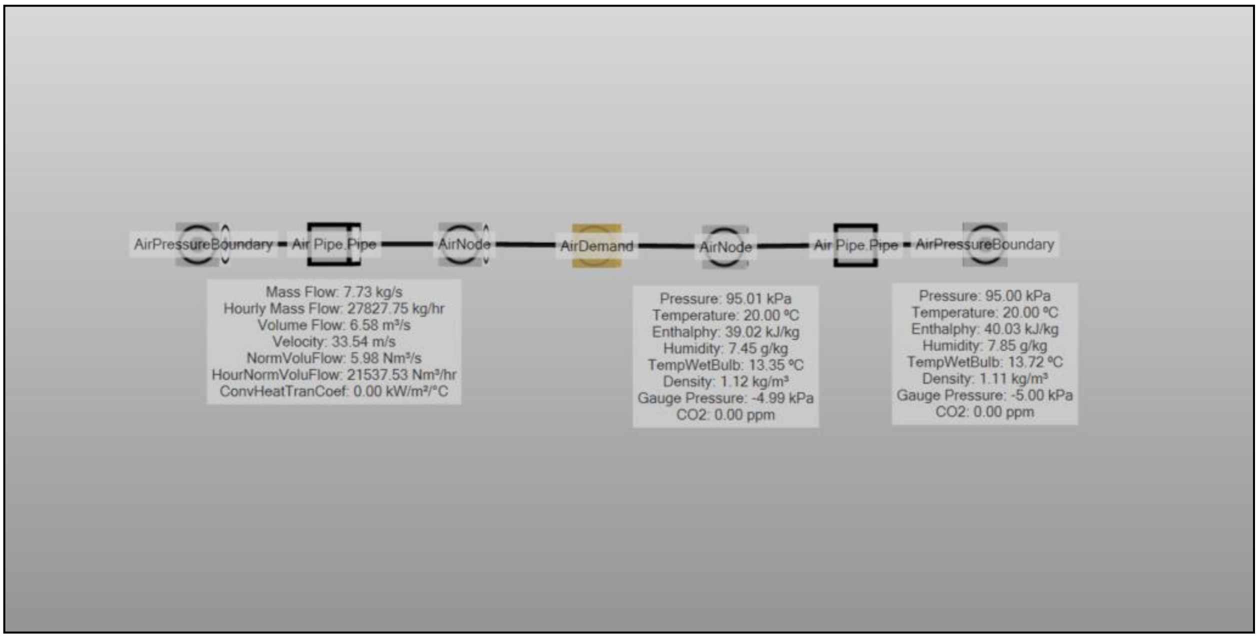

Figure 7: Simple PTB simulation layout

Simulation software selection

Table 2 provides a comparison between the different simulation software packages mentioned above.

Table 2: Simulation software selection

Simulation package	Advantages	Disadvantages
KYPipe	- User friendly - Fairly accurate	- Not recommended for compressible gasses
SOLIDWORKS Flow Simulator	- Detailed design ability - High accuracy - Wide variety of flow characteristics	- Time-consuming to model individual components

Flownex®	- Accurate - Widely used in mining applications	- Demonstration account is very limited
Process Toolbox (PTB)	- Easy to use - Specialises in mining applications - Program considers compressor supply and demand when simulation is developed.	- Data required for every component - Fairly new package

From the comparison in Table 2, it is clear that there is a few different options of simulation software that can be selected for this specific study. The different simulation software packages provide a wide variety of uses within the mining industry – especially for compressed air-related simulations [13], [59], [60]. Process Toolbox (PTB) is the selected simulation software for the study. PTB specialises in mining operations and is relatively easy to use. The fact that the entire compressed air supply and demand for the network can be simulated makes it the ideal package to make use of for the study.

1.6 Compressed air network development

The future planning for a compressed air network depends on the development of the mine. Continuous development of the mine leads to larger compressed air networks. One of the key indicators of the development of a mine is face advance. The face advance is the total length mined and the distance advanced by mining teams underground [61].

It is important that the compressed air network is expanded as the mine expands. The core of this study is to focus on the development of the compressed air system and how the network will meet demand. The next section provides the problem statement, need for the study and objectives for the study.

1.7 Problem statement

The platinum mining industry is under immense pressure when considering sustainable mining and ESG [5]. The variation in daily production also adds a new set of challenges to be able to produce and remain within the prescribed principles of the environmental part of ESG. This variation in production can mostly be allocated to mining infrastructure challenges, of which compressed air plays a large role [27].

When considering the current infrastructure in the mines, it is important to address the fact that the compressed air network needs to expand and be adjusted as the mine expands and develops. The problem that the mines experience is the fact that the current compressed air infrastructure can not necessarily supply the working areas with the required supply of compressed air as the mines develop. The mines do not have the ability to predict how much development can be done before the current infrastructure will not be sufficient to supply the necessary compressed air.

Without the current method to determine how the supply and demand for compressed air can be predicted, the current compressed air infrastructure in mines will continue to expand and the maximum output from the supply side will be reached. This maximum supply of compressed air to mine’s network will lead to increased electrical energy use which then leads to a negative impact on the environment. This negative impact on the environment is a major part of ESG that can be addressed with the development of a simulation model as mentioned above.

1.8 Previous studies on compressed air networks

The following section takes the problem statement, need for the study and objectives for the study into consideration and provides an overview of previous studies done on compressed air network supply and demand in mining. The studies need to fall within the scope of this study and need to have research on one or more of the key elements mentioned below. The studies used were sourced from journal articles, dissertations, and theses from sources like Elsevier, Google Scholar, NWU Libraries and IEEE.

The keywords below were the deciding factor on which studies to analyse:

- Compressed air network efficiency
- Compressed air simulation modelling
- Compressed air supply and demand
- Compressed air network development

The studies analysed are presented in the following structure:

- Title of the study
- Author of the study
- Overview of the study
- Shortcomings

Study 1 [35]

Title	:	Practical low-cost method to sustain mine compressed air savings
Author	:	J Taljaard
Overview	:	The development of a low-cost method to sustain compressed air savings of mines with limited instrumentation and infrastructure. The objectives were to balance supply and demand and implement cost saving initiatives. The implementation of a control strategy with no capital funding led to sustainable saving from the compressors.
Shortcomings	:	The focus was on the supply and demand of compressed air; however, there is no mention of inefficiencies. The optimisation of compressed air supply based on demand requirements was investigated; however, the costs to perform this balance is not discussed.

Study 2 [24]

Title	:	Improved control of compressed air networks using machine learning
Author	:	GJ Matthee
Overview	:	Machine learning and simulation modelling were used to develop a method to assist with compressed air network control. The study focused on predicting pressures and assisting in real-time feedback on network performance and energy savings.
Shortcomings	:	The study mainly focused on surface supply of compressed air from the compressors without considering underground results.

Study 3 [25]

Title	:	Developing a framework for managing compressed air in the Platinum Group Metal mining industry in South Africa
Author	:	HJ Groenewald
Overview	:	The study had a primary and secondary objective which emphasised reducing operating costs and increasing energy efficiency of compressed air networks.
Shortcomings	:	The demand side management of compressed air in platinum mines was not investigated. This is one of the key aspects to consider regarding compressed air management.

Study 4 [27]

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

Author	:	D Nell
Overview	:	The study investigated the reduction of compressed air network inefficiencies in gold mines with limited infrastructure. Compressed air network inefficiencies such as pipe sizes, pipe restrictions, leaks, and incorrect installation strategies were identified, evaluates, and addressed. Quantify The impact of compressed air inefficiencies on production was quantified. The use of a simulation package was also present in the study.
Shortcomings	:	The focus was on the supply and demand of compressed air; however, there is no mention of inefficiencies. The optimisation of compressed air supply based on demand requirements was investigated; however, the costs to perform this balance is not discussed.

Study 5 [31]

Title	:	Improving mine compressed air network efficiency through demand and supply control
Author	:	B Pascoe
Overview	:	The control of compressed air to reduce flow and pressure is one of the key objectives of the study. The study aimed to balance the supply and demand to reduce electricity costs. A simulation was used to test changes that can possibly be made to the compressed air system.
Shortcomings	:	The influence that inefficiencies have on the compressed air system is not discussed.

Study 6 [32]

Title	:	Energy management of compressed air systems. Assessing the production and use of compressed air in industry.
Author	:	J. J. C. Eras, A. S. Gutiérrez, V. S. Santos, and M. J. C. Ulloa
Overview	:	The importance of compressed air management is discussed. The solution strategy took a six-step local energy benchmarking technology into consideration. The study permitted a rapid detection of inefficiencies in the supply and demand sides of a compressed air system.
Shortcomings	:	The study did not make use of a simulation model and was not specifically based on the mining industry.

Study 7 [48]

Title	:	Reconfiguring mining compressed air networks for cost savings
Author	:	JIG Bredenkamp
Overview	:	The study considered the effect of compressed air network reconfiguration and how it affects supply. Simulation modelling was used to investigate the theoretical changes and how viable these changes were. A focus of the study was also to determine what the cost savings would be should the strategies be implemented.
Shortcomings	:	Focus was on reconfiguration to influence the supply. The simulations did not necessarily take variable demand into consideration.

Study 8 [34]

Title	:	Evaluating compressed air operational improvements on a deep level mine through simulations
Author	:	P. Mare, J. I. G. Bredenkamp and J. H. Marais
Overview	:	The focus of the study was to develop a solution to increase operational efficiency and service delivery regarding compressed air in deep level mines.
Shortcomings	:	The study did not focus on the delivery pressure of the compressed air, but only emphasised the way the entire network can be improved.

Study 9 [42]

Title	:	Energy savings through automatic control of underground compressed air demand
Author	:	H Neser
Overview	:	The main objective of the study was to examine the possibility of implementing an appropriate control strategy on the demand side of a compressed air network in a mine for increased energy savings. The investigation of optimal infrastructure upgrades, an automated demand control system, and the implementation of optimised control schedules and parameters formed part of the study.
Shortcomings	:	The effect of compressed air network inefficiencies on energy savings was not investigated.

Study 10 [43]

Title	:	Improvements in stope drilling and blasting for deep gold mines
Author	:	A. J. A. White, Joughin, N.C. & Cook N.G.W.
Overview	:	The focus of the study was to improve drilling and blasting processes in conventional shaft mines. Compressed air pressures were considered when analysing drilling efficiency.
Shortcomings	:	The use of a simulation model was not discussed, and the focus was on the production process instead of the supply of compressed air to perform the production process.

Study 11 [44]

Title	:	Automated mine compressed air control for sustainable savings
Author	:	J Jonker
Overview	:	The demand and supply side of compressed air systems were investigated and characterised. The running periods for compressors and how an optimised network can achieve savings were determined.
Shortcomings	:	The compressor supply side was investigated. The general demand was determined, but not the source of the demand. The use of simulation modelling is also absent.

Study 12 [51]

Title	:	Evaluation of energy losses in pipes
Author	:	Yasmina Lahiouel and Rachid Lahiouel

Overview	:	This study focused on the energy losses in piping systems And looked at the general energy loss in pipes when transporting fluids and the power needed to perform the actions. The calculations to determine losses in a piping network was investigated.
Shortcomings	:	The investigation did not focus specifically on compressed air networks. The pipe losses were investigated, but the general causes of these losses are not discussed. Also, general piping network inefficiencies are not addressed.

Study 13 [55]

Title	:	Novel solutions for compressed air demand management on deep level mines
Author	:	LN Zietsman
Overview	:	The various objectives in the study prioritise the demand side management of compressed air in platinum mines. The improvement of leak auditing techniques and a compressor energy savings method were investigated. The use of simulation software and a mathematical model is also evident in the study.
Shortcomings	:	The study did not focus on the possibility of predicting how the demand will change over time when future development is done. The supply of compressed air was also not balanced with the demand.

Study 14 [56]

Title	:	Simulating operational improvements on mine compressed air systems

Author	:	BM Friedenstein and JF Van Rensburg
Overview	:	The general operational improvements for a compressed air system in deep level mines were investigated. The study made use of a simulation to identify and verify the improvements.
Shortcomings	:	The simulation did not make use of compressed air in the development ends. The compressed air delivery to the shaft and in the active areas was the focus.

Study 15 [61]

Title	:	Characterizing a mining production system for decision-making purposes in a platinum mine
Author	:	T. Sebutsoe and C. Musingwini
Overview	:	A mining production system was analysed regarding the number of teams working underground and the advance in metres developed. The key performance indicators with reference to the demand and supply when human factors are involved were considered.
Shortcomings	:	There was no consideration for compressed air usage and wastage. The focus was on the human involvement in supporting systems and how this influences production.

The studies discussed above provide a summary of what has been done and where the shortcomings of previous studies were. Table 3 below provides a summary of the literature review of the studies discussed above. The topics that are emphasised in Table 3 are the key aspects of this study. These topics were chosen as they are the key elements from which the simulation model and the study will be based on.

1.9 Need and objectives for the study

When considering the Problem statement in Section 1.7 and the previous studies done on compressed air systems, regarding compressed air efficiency, simulation modelling, supply and demand analysis, and development. There is a need for a compressed air simulation model that is able to determine whether the current compressed air supply and compressed air network of a deep-level mine will be sufficient for future development, regarding distance developed and demand, with current pressure requirements for equipment.

From the need for the study the following objectives can be identified:

1. Identify what the inefficiencies are in the compressed air system and address the influence they have on the network.
2. Develop a simulation model that can accurately predict how changes in a certain area will influence the network.
3. Simulate how much further development can be done in a specific area if general compressed air pressure operating specifications are adjusted for the simulation model.

From the objectives above, a literature review can be formulated to determine which studies mentioned in Section 1.8 addresses the mentioned topics that will be addressed in the study.

Table 3: Literature review

Source	Compressed air network efficiency	Simulation modelling	Supply and demand analysis	Development
[35]	Red	Green	Green	Red
[24]	Green	Red	Red	Red
[25]	Green	Green	Red	Red
[27]	Green	Green	Green	Red
[31]	Red	Green	Green	Red
[32]	Green	Red	Green	Red
[48]	Green	Green	Red	Red
[34]	Green	Green	Green	Red
[42]	Green	Green	Green	Red
[43]	Green	Red	Red	Red
[44]	Green	Red	Green	Red
[51]	Red	Red	Green	Red
[55]	Green	Green	Green	Red
[56]	Green	Green	Green	Red
[61]	Red	Red	Green	Green

Green = Study addresses the mentioned topic

Red = Study does not address mentioned topic

1.10 Dissertation layout

Chapter 1

This chapter focuses on providing an overview on platinum mining in South Africa and the importance of mining in the country. The chapter also focuses on the various operations of mines and what is essential for a mine to function. The importance of compressed air in the mining industry is emphasised, and the shortcomings of compressed air networks are discussed.

Finally, the chapter focuses on past studies done on compressed air management systems, whereafter the need for this specific study is discussed.

Chapter 2

Chapter 2 provides the research methodology. The essence of Chapter 2 is to provide the method followed to achieve the desired outcome of the study. The outcome of this study is the development of a simulation model. This chapter shows how the model was developed and what necessary steps and procedures were followed in order to create an accurate and functioning model.

Chapter 3

This chapter provides the results and the case study investigation from the methodology described in Chapter 2. These results were validated to determine whether the method described was successful or not. An analysis was also done to determine how the results can be interpreted to ensure that the mine can continue with future development.

Chapter 4

Chapter 4 delivers the study summary and recommendations for future work. The summary consists of an overview of the study and how the methodology was developed and implemented. The recommendations provide suggestions on what can be achieved after the study has been completed.

1.11 Conclusion

Chapter 1 largely focused on an overview on mining both globally and in South Africa. The importance of incorporating ESG principals and understanding how the environmental aspects of ESG impact the mining industry. With the focus on South Africa, it is important to recognise the challenges regarding the mining industry in the country. Despite the challenges in the mining industry, it is one of the cornerstones of the South African economy, and needs to be managed in such a manner that it can be sustainable.

The platinum mining industry and the processes involved in its operation are a key focus of the chapter. The fundamental aspects of the platinum mining industry and the importance of compressed air are discussed. The compressed air networks within these deep-level mines are analysed and the shortcomings of these systems are identified.

The need for a simulation model that can predict how much future development can be done has been identified. This sustainable future development and energy efficiency of the mine integrates well with ESG and the principles thereof.

The simulation model as described throughout the chapter makes use of the specific simulation package for the development of the model. The possible software packages that can be used for the development have been identified and compared to investigate which software package will be the most suitable for the simulation. PTB has been chosen as the most suitable package for the simulation model.

Previous studies that investigated compressed air systems were analysed and those that align with this study were identified and their findings considered. The shortcomings in some of these studies have been identified. These shortcomings are a key part of the way in which Chapter 1 has been formulated and how the simulation was developed.

From the information gathered in Chapter 1, a need for the simulation model is evident. Chapter 2 will use the information gathered in Chapter 1 and provide the method for the development of the simulation model as described by the need.

CHAPTER 2: COMPRESSED AIR MANAGEMENT METHOD

2.1 Introduction

Chapter 2 focuses on the method followed to develop and implement the possible solution to the need and objectives as discussed in Chapter 1. The literature from Chapter 1 provided the background and overview on the current compressed air infrastructure in platinum mines. This chapter provides a step-by-step case study-based methodology on how the objectives were achieved. Figure 8 below provides an overview on the steps that need to be followed to implement the method.

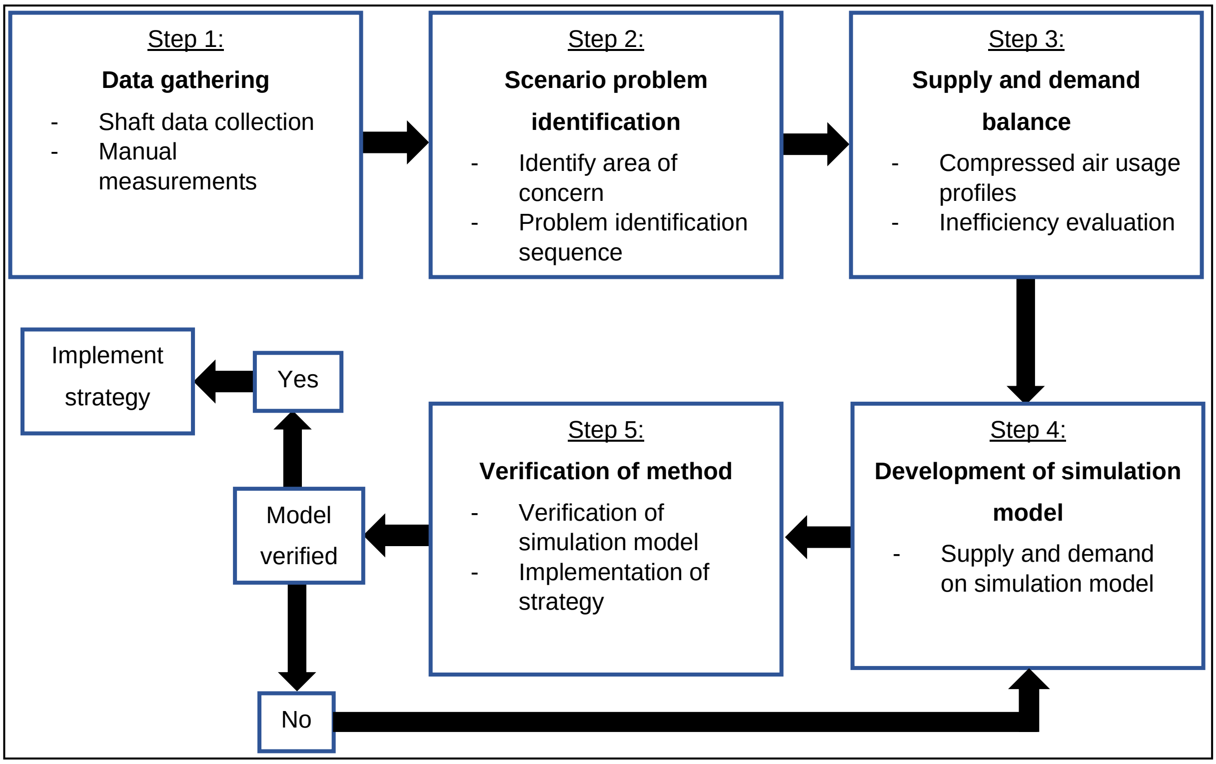

Figure 8: Simplified layout of method

From Figure 8, the first step of the method is to gather the required data and take the necessary measurements from the area of interest. The second step is to identify the problem area and identify the problem that needs to be solved. Step 3 is to analyse the data and develop a supply and demand balance where an inefficiency evaluation is also done. Step 4 is to develop the simulation model of the shaft. The fifth step is to verify the simulation model with actual data. If the simulation cannot be verified and provided accurate results, step four needs to be checked and repeated to ensure that the issues are not as a result of faults in the development step. After the verification of the simulation in Step 5, the model can be used to simulate an actual case study.

From the literature in Chapter 1 and the layout of the method in Figure 8, the sections below focus on each individual step within the method as described in Figure 8.

2.2 Compressed air network evaluation

2.2.1 Step 1: Data gathering

1. To ensure that the correct data are collected and used for the method, a few steps can be followed: Compressed air data gathering (SCADA)
2. Shaft layout data
3. Manual compressed air data collection

Shaft data collection

The first part of the data collection step is to gather the available data regarding the compressed air network. The data needed for the method is the operational data, compressed air flow data, and compressed air pressure data. The layout for the specific area of interest is also a key aspect when information regarding the problem is gathered. The focus is to collect data that can be used to analyse the shaft compressed air consumption. The layout is used to understand how the different operations integrate with the network.

The entire compressed air system can be monitored from the SCADA system. Most of the data needed for the analysis is available on the SCADA system. The layout data from the shaft need to be acquired from the drafting personnel on the shaft if they are not available from the SCADA system. The typical data collected from the SCADA system are consumption and supply data for the compressed air network.

The SCADA system from which the operational monitoring is controlled can also be used to adjust certain aspects of the systems within the mine. The data recorded and stored on the SCADA system are received from various instruments installed on the compressed air system. This measured data is the primary source of data for billing and continuous measurements at the shaft, meaning that these instruments are well maintained and regularly tested to ensure their accuracy. The compressed air system can be monitored and the specific flow and pressure measurements for various working areas can be observed. The compressed air supply can also be controlled to supply the specific demand.

The compressed air pressure supplied to the shaft is predetermined with a set point. This set point is the approved pressure that is supplied to the shaft during each shift. Higher set points lead to higher consumption in the shaft. Table 1 in Section 1.3.3 provides the different set points at which the underground equipment operates.

The compressed air flow into the shaft is demand driven. The higher the demand for compressed air underground, the higher the flow rate. The flow rates typically differ from shift to shift due to the variation in demand and equipment used.

The compressed air network can be managed from the SCADA system and all major areas of consumption within the mine can be monitored. However, some areas in the mine are not equipped with the necessary instruments to provide the SCADA with the required data.

To ensure that the data that are not readily available from the SCADA system are collected, it is done manually. The second part of the data collection section focuses on how this manual data collection process is done.

Manual measurements

The identification of areas where compressed air should be measured is crucial to ensure that the process can be repeated, and to ensure that the data collected are accurate. The different production areas where measurements are taken should be identified and the measurement points must be as close as possible to the same location on each operational level. These measurements should also be taken at the same time of day when done manually, to ensure the precision of the results. The manual measurements can be taken by similar equipment as the WIKA CPG1200 for the pressures and the FLEXIM FLUXUS G601 that was used for the measurements in this dissertation.

The operational levels on a platinum mine are designed in such a way that navigation and travelling within the mine is fairly easy. Each level has a station, which is the landing area where you arrive on the level from the shaft cage. The level is then divided into two half-levels – East and West or North and South – where the different active areas are located. These active areas are called X/C's.

Figure 9 below provides an overview of where pressure and flow are measured to determine current compressed air network pressure and consumption. The red dots indicate the different measuring points for pressure and the blue dots indicate flow rate measurement locations.

The flow rate measurements are taken at the start of the level, right after the split of the level to the east or west side, depending on which side is measured, and also at the entrance of each active X/C. The pressure measurements are taken on shaft surface and at the end of each X/C. The development end (furthest point from the station[1]) pressure is also measured.

[1] The station is the landing area where you enter the specific level from the shaft cage.

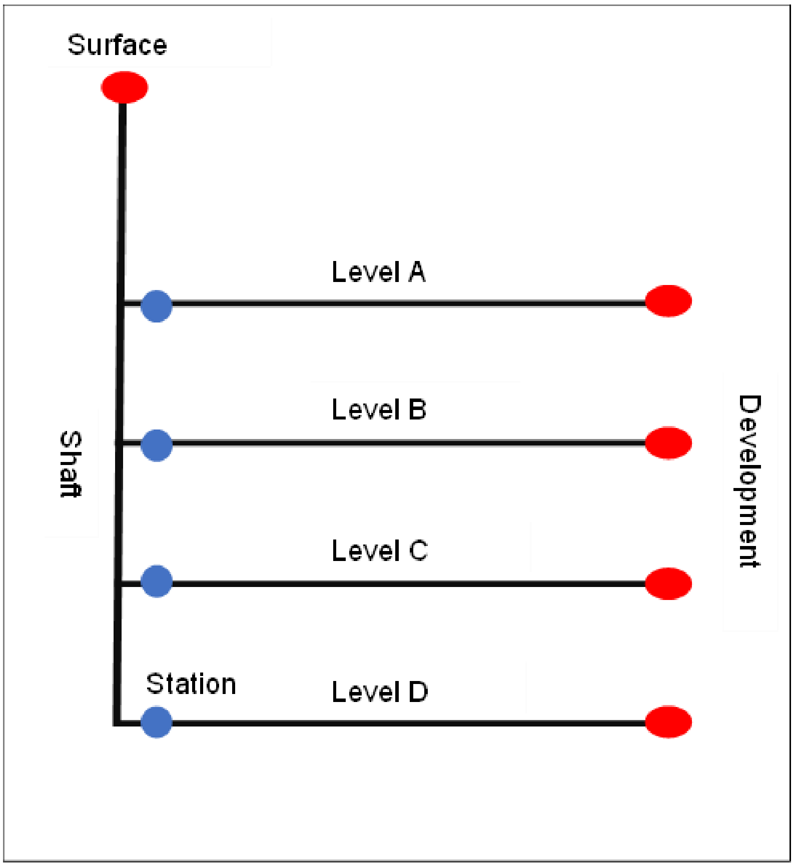

Figure 9: Shaft front view measuring points

Figure 10 and Figure 11 provide a close-up view of a specific level in a shaft. These views show at which locations on each level and X/C's the different pressure and flow measurements are taken.

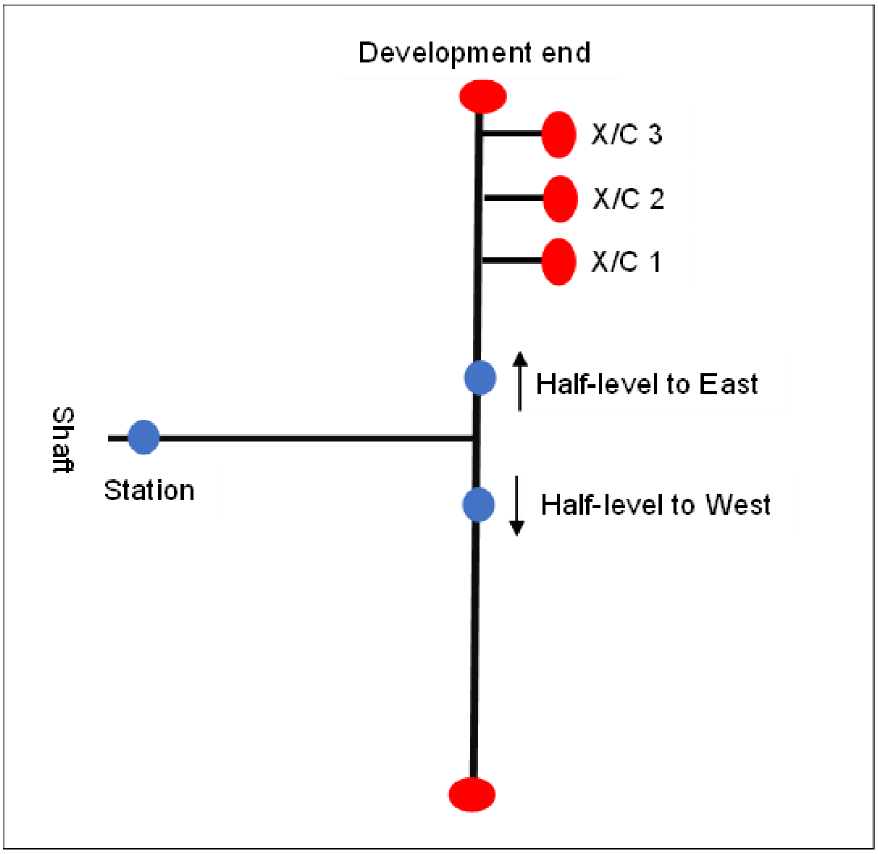

Figure 10: Level top view measurement points

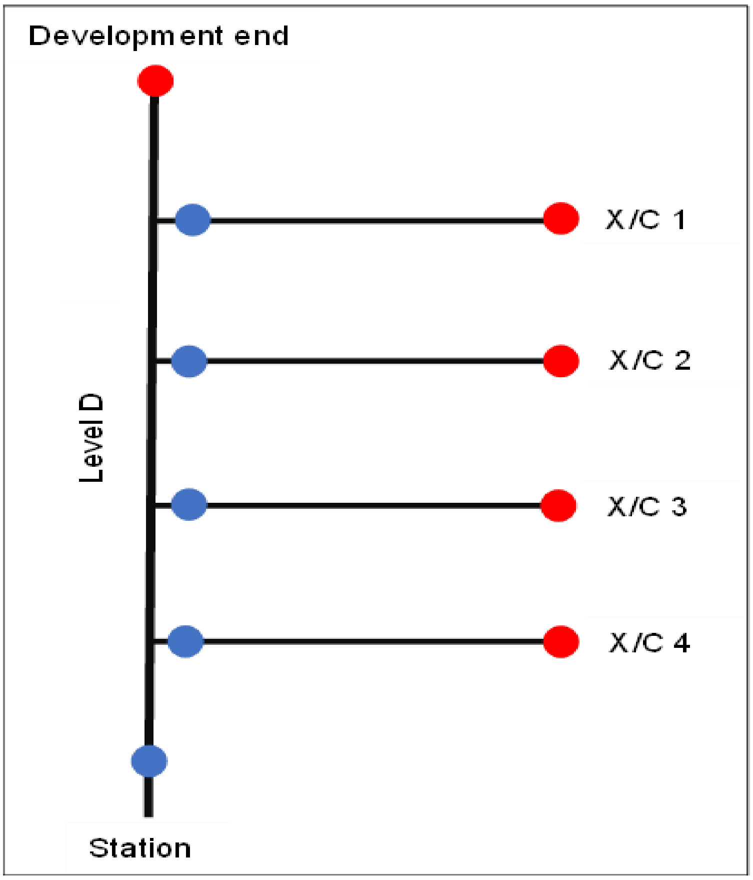

Figure 11: Level X/C top view

The measurements taken provide the pressure supplied and what pressures are at development areas. The flow rate measurements indicate the level's consumption. The X/C's flows indicate the amount of air that is lost due to leaks in the working areas.

Analysis of the measurements show which levels are high consuming and which have larger pressure drops. These levels are prioritised when considering inefficiencies. It is important to remember that the development end distances on each level differ and should be analysed accordingly. These distances depend on the mining boundaries and how far the mine has developed to date.

The measurements at the different locations are done in the cleaning shift (21:00 – 04:00). The cleaning shift, as mentioned in Section 1.3.3, is the time of day when compressed air demand is at its lowest when work is performed underground, and a baseline flow rate and pressure values can be measured. This baseline flow can typically vary between 40 000 m³/h and 80 000 m³/h, depending on the specific shaft. This difference can be due to inefficiencies in the shafts, or the size of the shaft itself. The only equipment consuming compressed air in the cleaning shift should be refuge chambers, loading boxes and rock loaders. None of the above-mentioned equipment is high consumers of compressed air. They do, however, require a specific pressure set point to be operated at as mentioned in Section 1.3.3.

2.2.2 Step 2: Scenario problem identification

The identification of the problem is primarily done by analysing the need for the study as discussed in Section 1.7. The need for this study specified that a compressed air simulation model needs to be developed to determine whether the current compressed air supply and infrastructure will be sufficient to supply future demand.

The problem identification can be done by following the short checklist below. The checklist is a self-evaluation guideline to ensure that the necessary steps for the problem identification was followed:

1. Obtain data and layout of the specific shaft.
2. Analyse the data and identify shortcomings.
3. Identify specific area of interest where issues are experienced.
4. Observe what the compressed air shortcoming in the specific area is.
5. Focus on a specific problem within the predetermined area.
6. Determine the scope of the problem.
7. Provide the specific scenario problem for the area.

After the problem identification has been completed, the method approach is formulated. The first step after the problem identification is to investigate the specific area of interest as identified in Section 2.2.2. The section below focuses on the supply and demand balance from the data gathered for the specific area.

2.3 Compressed air usage analysis method

2.3.1 Step 3: Supply and demand balance

Compressed air usage profiles

The compressed air provided to the shaft is supplied at specific pressure set point profile throughout the working day. This set points, as mentioned in Section 1.3.4, are predetermined and supply the required pressures to ensure that the underground pneumatic equipment can function. The profile below is following the same trend as the profile shown in Figure 4. This means that the specific set points for the different periods of the day are supplied to ensure that the pneumatic equipment function properly. Figure 12 below provides a typical weekday compressed air pressure profile for a platinum mine.

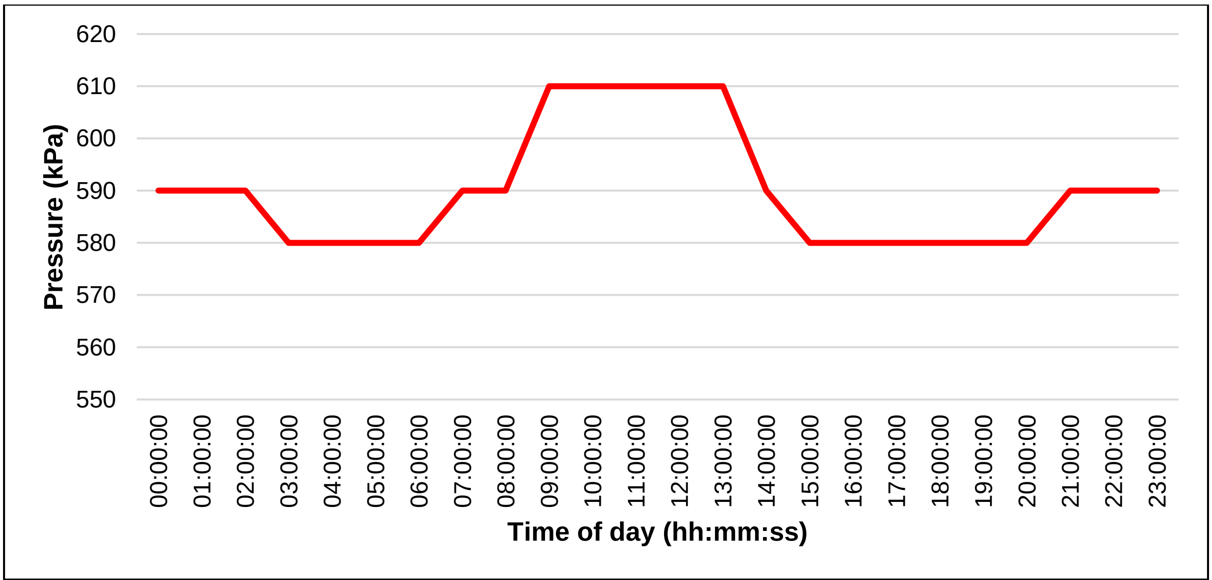

Figure 12: Typical shaft compressed air set point profile

The demand analysis of a shaft is done by investigating the compressed air flow and pressure profiles. Figure 13 below provides a typical weekday compressed air flow profile for a platinum mine.

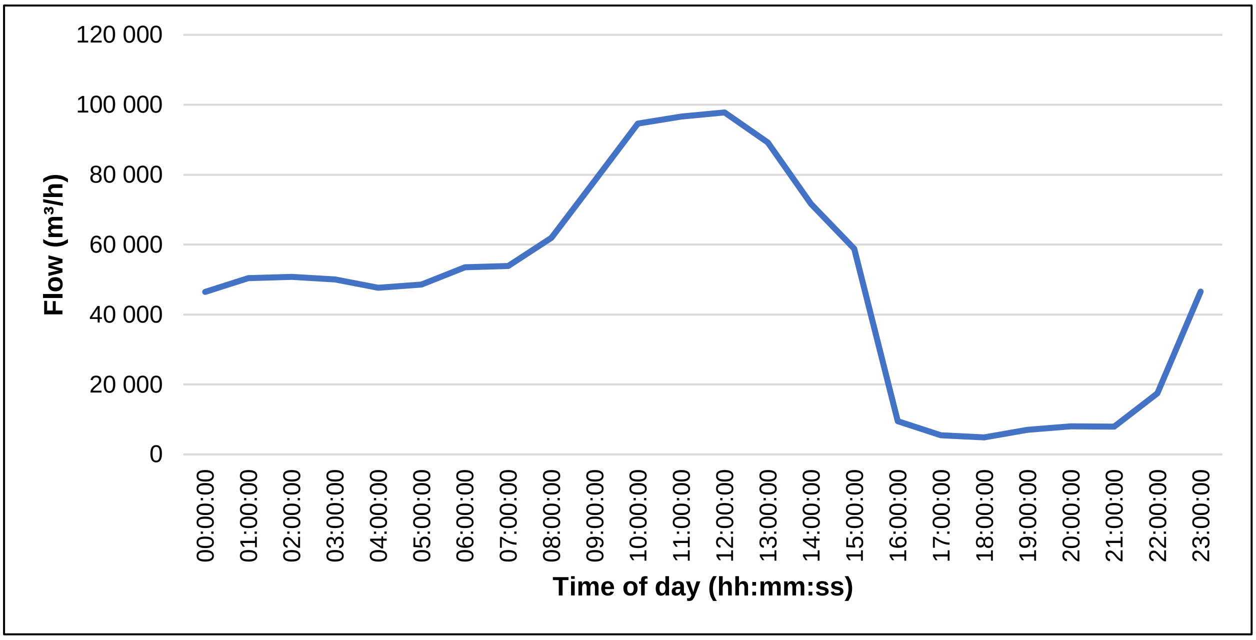

Figure 13: Typical shaft compressed air flow profile

The reason for analysing the pressure and flow profiles is to determine the compressed air supply and demand balance for the compressed air system. The supply (pressure) and the demand (flow) are the two main aspects to focus on when it comes to compressed air network efficiency. If either the supply or demand is out of balance, the flow and pressure profile will highlight this. The inefficiency evaluation is done after the analysis of the compressed air network balance has been done.

Inefficiency evaluation

The pressure and flow profiles above and the measurement data described in Section 2.3.1 are used to determine how effective the compressed air is used on a shaft. A manual shaft level compressed air audit needs to be done to determine which levels consume the most compressed air. Therefore, the equipment used for the level audit is a compressed air flow meter and a pressure meter. This equipment is used to measure the compressed air flow at the station of the level and at each X/C entrance, where the pressure meter is used to measure pressure in each X/C and at the development end.

The reason for the measurement in the X/C's is to determine which X/C consumes the most compressed air. The focus is to identify higher consuming areas and to address these inefficiencies. The pressure at the development end is measured to determine the pressure drop over the entire length of the half level. Figure 14 below provides an overview of a typical X/C demand flow profile.

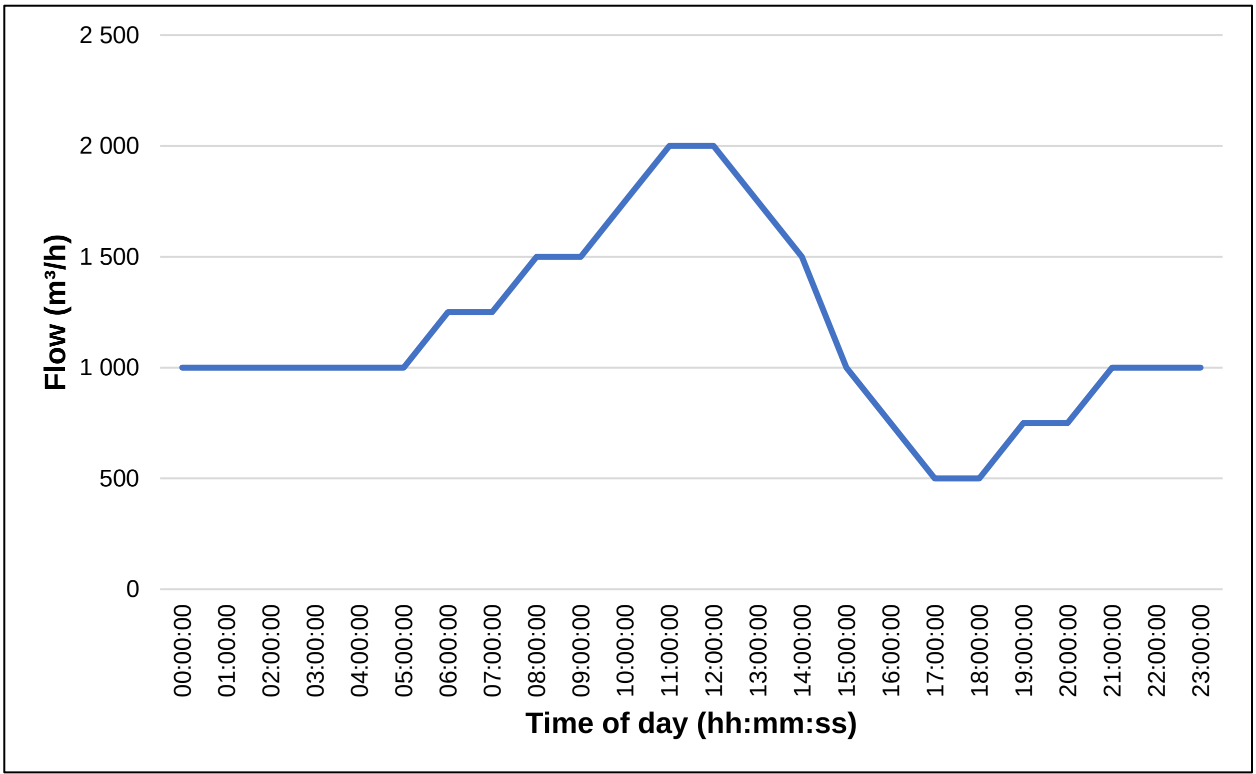

Figure 14: Typical X/C flow profile

The X/C profiles can differ from one to the other because of the amount of work that is being done in each X/C and the compressed air wastage in the working areas. One of the main factors to note is the identification of open-ends and compressed air pipe leaks. These factors can reduce compressed air pressure in working areas. Higher numbers of leaks and open ends in the level lower delivery pressure in working areas. Pipe leaks do not only reduce delivery pressure, but also have a major financial impact on operational costs, as mentioned in Section 1.3.5.

To ensure that the model development is done as accurately as possible, in conjunction with the estimated profiles and manual measurements taken, a leak audit needs to be done. The leak audit consists of a per level audit where the locations of all open ends, leaks and areas of misuse are identified, noted, and communicated to be repaired. These locations are updated on the layout as received from the mine. It is important to understand that leaks can have a negative impact on the efficiency of the network. The size of the leaks is noted by how loud the noise level is that comes from the leak in the pipe.

The key to an audit of this kind is to ensure that the measurements taken are accurate and all results collected are noted. The flow and pressure measurements, leak locations, shaft layout, and supplied compressed air set points are all used to calibrate the simulation model.

The influence that these inefficiencies have on the compressed air network is immense. The amount of compressed air that is lost needs to be added to the simulation and updated once the leaks have been repaired. The simulation model that was developed for this dissertation is discussed in the next section.

2.4 Simulation model development

2.4.1 Step 4: Development of simulation model

The purpose of the simulation is to enable the user to predict compressed air pressure or flow rate at a certain point in the compressed air network of the mine. The second benefit of the simulation is the ability of the user to determine delivery pressures in working areas at the specific set points. This means that a prediction can be made to determine at what distance into the level the required pressures will be available. The above-mentioned benefits and purpose need to be accompanied by an objective for the simulation. The objectives of the simulation are based on the need for the study as mentioned in Section 1.7. The simulation software that was chosen for the simulation model is Process Toolbox, as described in Section 1.5.

The three objectives of the simulation in this study are:

1. to investigate the effect of compressed air inefficiencies on the network pressure;
2. to investigate the effect of compressed air delivery pressure changes in working areas; and
3. to simulate whether the current compressed air infrastructure will be sufficient for future development in a specific area in the mine and how far development can still be done.

The simulation is based on actual layouts. The actual underground compressed air demand and supply measurement data (as mentioned in Section 2.1) are used in the simulation to improve the accuracy of the model.

The simulation consists of a supply side and a demand side. The supply side focuses on the actual compressed air supplied to the mine. The demand side focuses on the compressed air consumption in the working areas. Both aspects are discussed below.

Supply side

As mentioned in Section 1.5, PTB was the simulation software of choice. The supply side of the compressed air network simulation is done by making use of the compressor component. This component needs to be set up individually. This means that the maximum power rating, maximum output pressure, maximum flow, and the compressor load fraction is set up. The compressed air set points supplied to the shaft need to be integrated with the compressor component.

The compressor component can simulate realistic outcomes and, if correctly calibrated, can provide accurate results. Figure 15 and Figure 16 below provide the component properties of the compressor component.

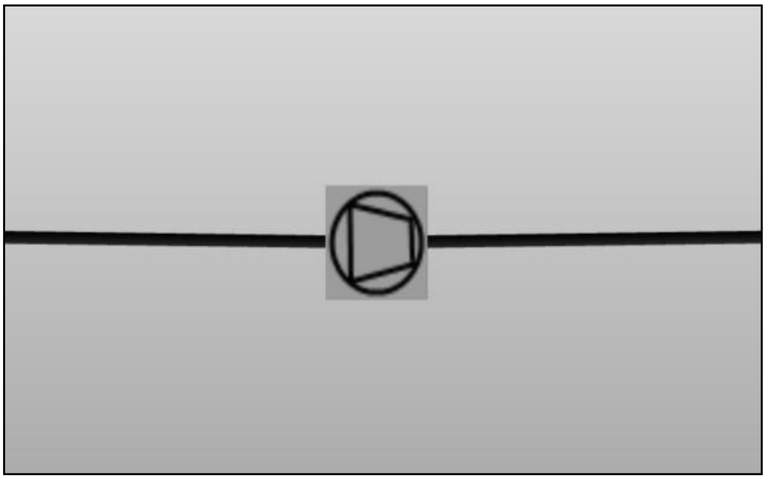

Figure 15: Compressor component in PTB

The compressor component consists of properties that specify what the operational data of the compressor are and how these inputs affect the working conditions of the compressor.

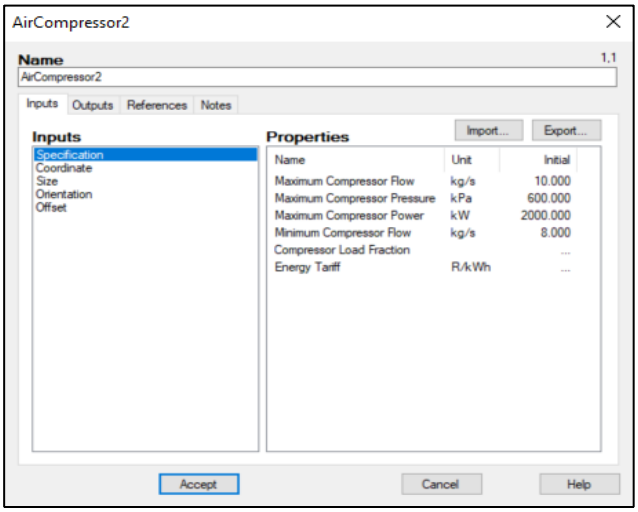

Figure 16: Compressor component specifications

The compressor supply needs to be balanced to match the desired demand. The specifications as seen in Figure 16 are used to calibrate the compressor component to be able to simulate based on actual compressor specifications. The maximum compressor flow, compressor pressure, compressor power, and minimum compressor flow values need to be calculated and verified to ensure that the values resemble the actual values for each compressor component used in the simulation. These values need to be set up for each individual compressor in the simulation, as not all the compressors have the same specifications. The demand side components for the simulation is discussed below.

Demand side

The demand side of the simulation has a few components that are essential to the simulation. The three main components to build the simulation model are the air pressure boundary, air pipes, and air nodes. All the components are set at standard conditions regarding the different property inputs of the component. These property inputs have been calculated and predetermined and do not need to be altered when making use of the PTB software.

The air pressure boundary acts as a starting point and end point condition for the limits of the simulation. The air pressure boundary component can be seen below in Figure 17.

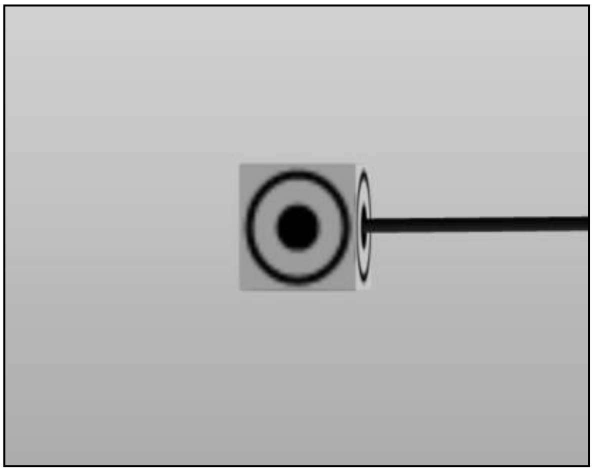

Figure 17: Air pressure boundary on PTB

The specifications for the air pressure boundary need to be set as the standard ambient conditions of the area. Details such as the atmospheric pressure, ambient temperature, relative humidity, and reference pressure are all important properties of the air pressure boundary. The air pressure boundary component details can be seen in Figure 18.

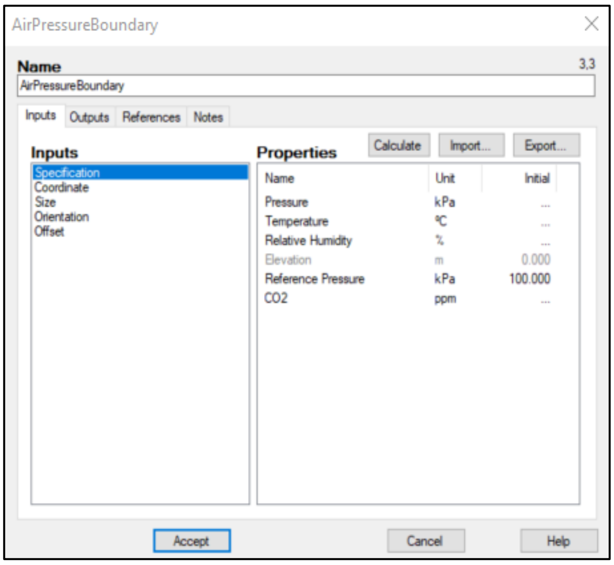

Figure 18: Air pressure boundary specifications

The other key element for building the compressed air network simulation is the compressed air pipes. Figure 19 and Figure 20 below provide an overview of the compressed air pipe component.

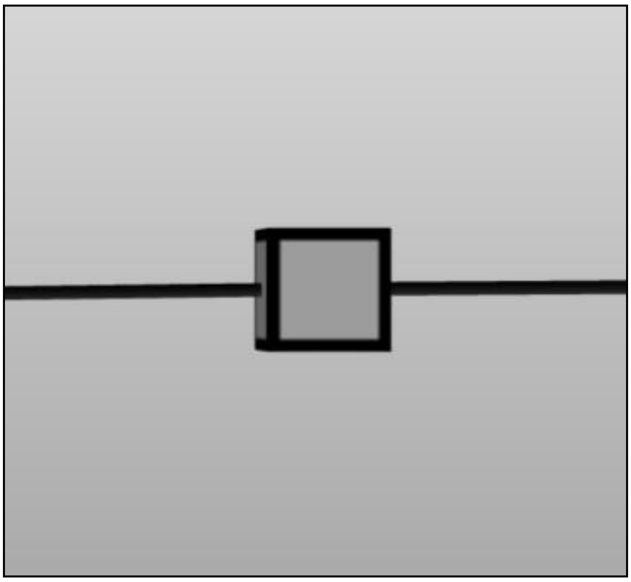

Figure 19: Compressed air pipe on PTB

The air pipe component is the essence of the simulation as this is the component that is used to build the piping configuration in the simulation. The flow, inlet pressure, outlet pressure, and inlet temperature are the main properties of the component. The flow input is the flow rate that the specific pipe needs to accommodate. The inlet pressure and outlet pressure are inserted to ensure that a pressure drop can take place over the length of the pipe. If there is no pressure difference, no flow will take place in the pipe. The inlet temperature is the average inlet temperature of the compressed air when flowing into the pipe.

The pipe component can also be adjusted to resemble a valve. The valve fraction and valve type are inserted for the pipe to have valve characteristics. The pipe diameter, pipe length, and surface roughness are also added to the properties of the pipe component.

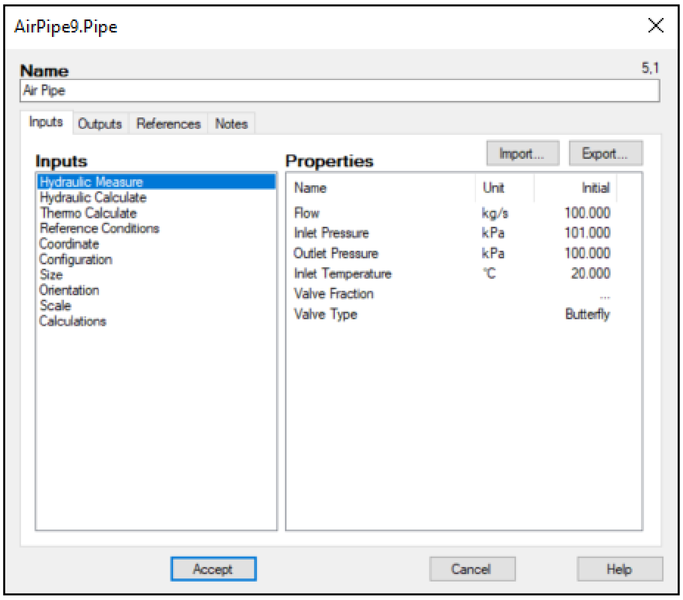

Figure 20: Compressed air pipe specifications

The compressed air nodes as seen in Figure 21 accompany the compressed air pipes in the building of the simulation. The nodes act as the binding tool between the different components in the simulation structure. Figure 21 and Figure 22 below provide an overview of the compressed air node layout and specifications as it is found in PTB.

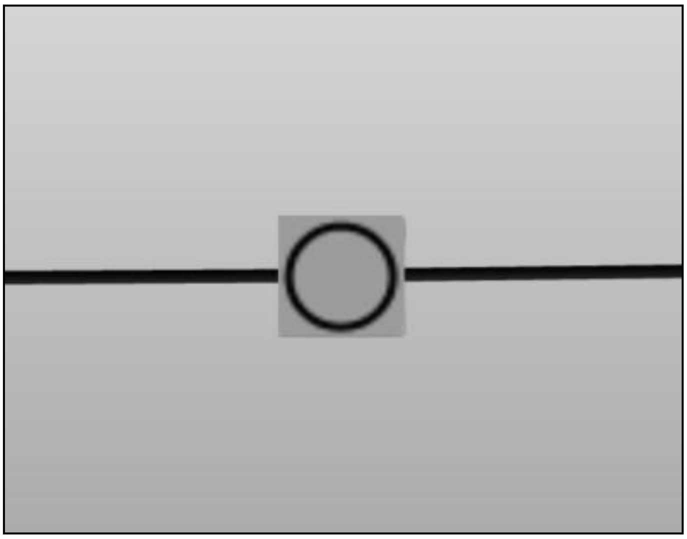

Figure 21: Compressed air node on PTB

The properties for the compressed air nodes are quite complex to set up, but is automatically set up for general compressed air applications. If changes need to be made to the current setup, they need to be done manually. The main areas where changes are typically made to the air node component are the pressure and ambient temperature.

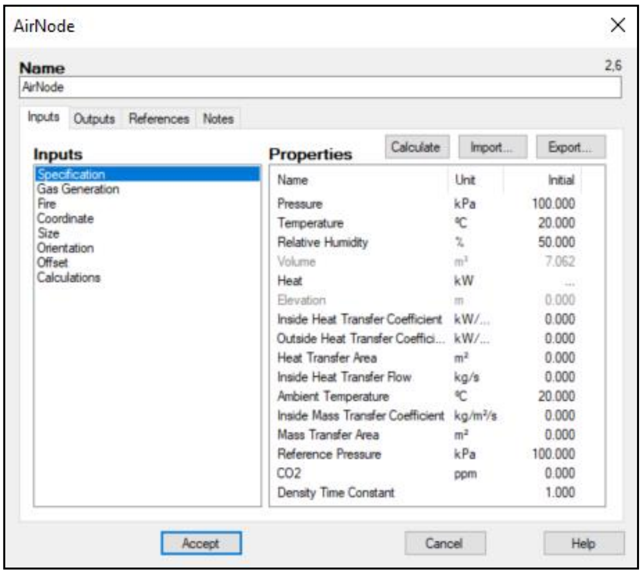

Figure 22: Compressed air node specifications

The different components all need to be calibrated and set up correctly to ensure the accuracy of the simulation. All the values used as inputs for the node component are standard values used from PTB. The purpose of the components overview above is to provide background on what the basic elements of a simulation on PTB entails. In depth details regarding the components of the simulation model cannot be supplied due to confidentiality agreements with the mine and the developers of PTB. Specific layouts for the case study is provided in Chapter 3.

The simulation needs to be built and compared to actual results. The accuracy of the simulation can only be determined once the simulation is verified. The verification of the simulation is discussed in the next section.

2.4.2 Step 5: Verification of simulation model

The verification stage of the study focuses on the evaluation of the need and whether the method developed is sufficient in providing an accurate solution strategy. This procedure considers the information provided in Chapter 1 and Chapter 2 and verifies the current data that was collected to the simulation that was developed.

Comparing actual measured data with simulated data is the method by which the model is verified. The development of the simulation is done by using the layout and actual measurements from Mine A. The simulation is then built and the comparison between the actual data and the simulation is completed. The baseline results and measurements as mentioned in Section 2.2.1 and Section 2.3.1 are used for the comparison.

The actual data in Section 2.2.1 and Section 2.3.1 are compared to the simulation model by making use of one of the following techniques [35]. The different techniques described below are proven and trusted methods to determine the margin of error when considering the comparison of data:

- Mean residual difference (MRD)
- Mean absolute error (MAE)
- Coefficient of determination

The above-mentioned techniques are discussed below.

Mean Residual Difference (MRD) [35]

The mean residual difference takes the average for both the simulation and the actual data point into consideration. The percentage error of the simulation can be determined by calculating the difference between the average simulated and average actual data points. The mean residual difference can be determined by making use of Equation 1 below.

Equation 1: Mean Residual Difference method (adapted from [35])

$$MRD = \left| \frac{1}{N} \sum_{n=1}^{N} (A_n - S_n) \right|$$

$$Err\% = \left| \frac{1}{N} \sum_{n=1}^{N} \left(\frac{A_n - S_n}{A_n} \right) \right| x\ 100$$

where:

MRD	=	Mean residual difference	*[-]*
$Err\%$	=	Relative error percentage	*[%]*
N	=	Number of data points	*[-]*
n	=	Data point	*[-]*
A	=	Actual measured data points	*[-]*
S	=	Simulated data points	*[-]*

The only disadvantage when making use of only the MRD is the fact that the positive and negative data points cancel each other out. This leads to an inaccurate model verification.

Mean Absolute Error (MAE) [35]

The MAE method follows the same concept as the MRD method. The main difference between the two is that the MAE calculates an error for each individual point. The average of each individual error is then used to calculate the relative error percentage. The MAE method calculation can be seen in Equation 2 below.

Equation 2: Mean Absolute Error method (adapted from [35])

$$MAE = \frac{1}{N} \sum_{n=1}^{N} |(A_n - S_n)|$$

$$Err\% = \left| \frac{1}{N} \sum_{n=1}^{N} \left(\frac{A_n - S_n}{A_n} \right) \right| x\ 100$$

where:

MAE	=	Mean absolute error	*[-]*

$Err\%$	=	Relative error percentage	*[%]*
N	=	Number of data points	*[-]*
n	=	Data point	*[-]*
A	=	Actual measured data points	*[-]*
S	=	Simulated data points	*[-]*

Coefficient of determination [35]

The coefficient of determination is a measurement of how accurately the data points can follow a linear relationship. The coefficient ranges between -1 and 1. A perfect positive linear relationship is achieved when the coefficient is 1, and a perfect negative linear relationship is achieved when the value is -1. A value of 0 indicates that there is no linear correlation in the data. The coefficient of determination can be calculated by making use of Equation 3**.**

Equation 3: Coefficient of determination method (adapted from [35])

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

where:

r^2	=	Coefficient of determination	*[-]*
N	=	Number of data points	*[-]*
n	=	Data point	*[-]*
A	=	Actual measured data points	*[-]*
S	=	Simulated data points	*[-]*

For this study, the mean absolute error (MAE) method was used. The reason for this is the fact that the number of measured points for the study was each compared to the results of the simulation as the study did not make use of that many data points. For a model to be considered accurate, an MAE percentage of less than 5% should be developed [62].

Simulation verification

When considering the above mentioned, the simulation is verified against actual data and an error is calculated to determine how accurate the simulation is. This will verify whether the simulation will be able to yield accurate readings when real data is considered and real-life scenarios are tested. Figure 23 below provides the pressures for a certain production level on Mine A. The pressures are for a 24-hour period from measured and simulated results.

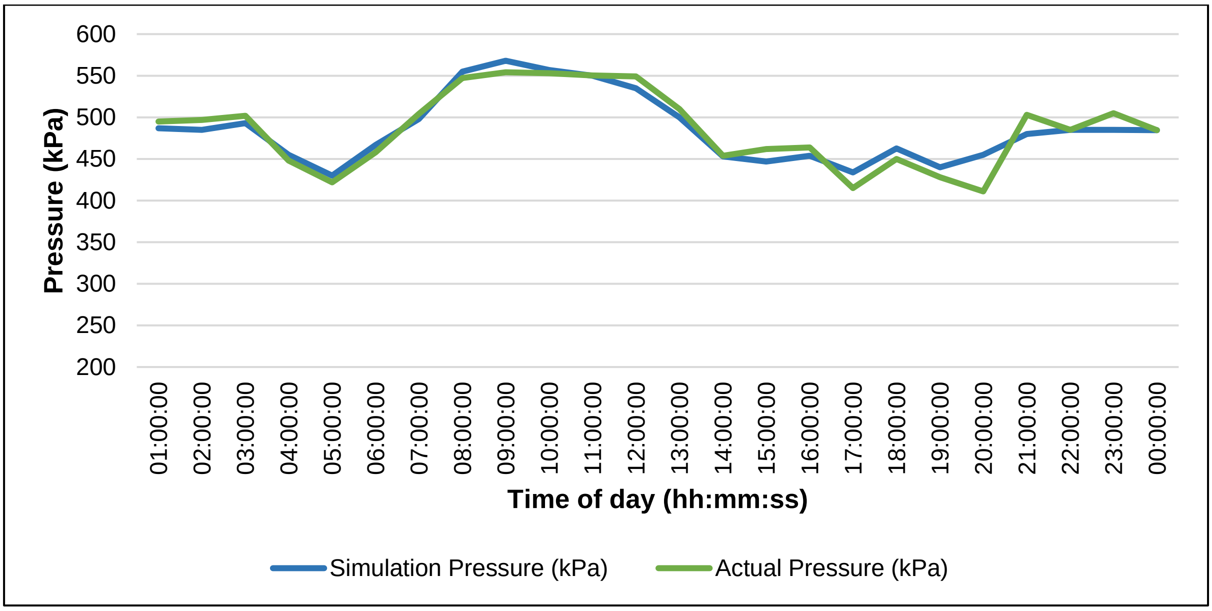

Figure 23: Mine A actual pressures compared to simulated pressures

Figure 24 below provides the flow rates for the same production as used in Figure 23. The flow rates are for a 24-hour period from measured and simulated results.

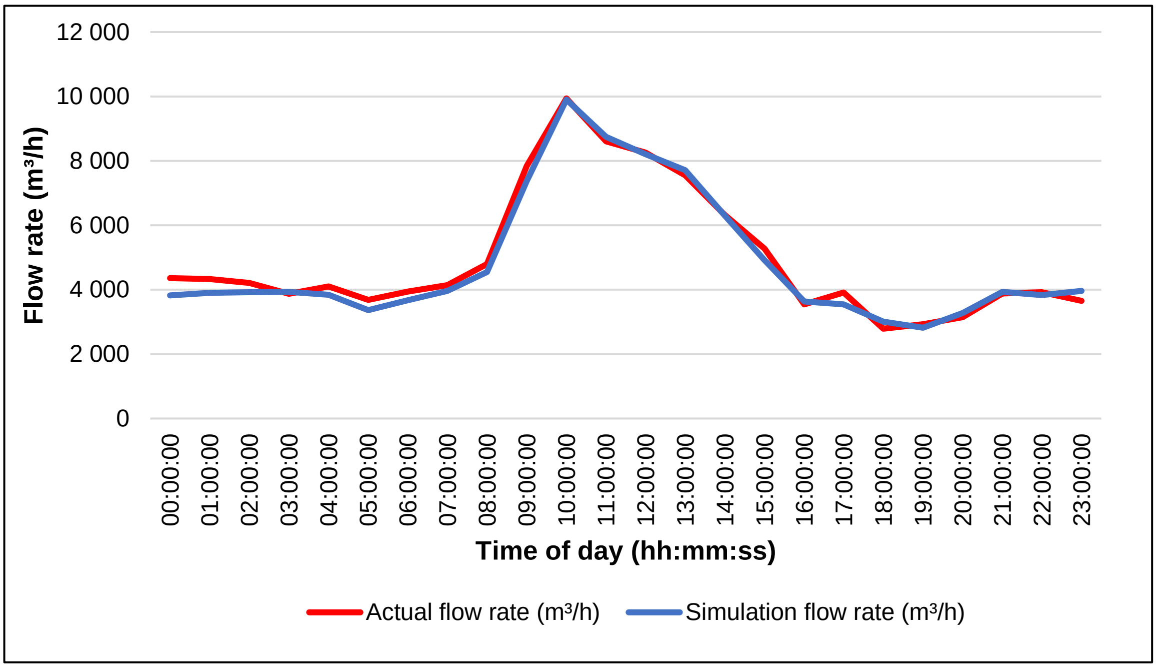

Figure 24: Mine A actual flow rates compared to simulated flow rates

The simulated data are very close to the actual measured data. Table A - 1 in Appendix A provides the data used for the graph as shown in Figure 23.

The calculated MAE percentage for the simulation pressure was 2.37%, and 4.94% for the simulation flow. This means that the simulation can be deemed accurate, as the error percentage was less than 5% [62]. It is therefore not necessary to make use of a secondary method besides the simulation model, as this will fall outside the scope of the dissertation. The accuracy achieved above is acceptable and therefore verifies that the simulation can be used for the solution.

2.5 Conclusion

Chapter 2 is the essence of the dissertation. The method from which the solution was developed has been formulated in this chapter.

The method focuses on the five steps as described in Section 2.1. These five steps each provided the necessary details per section to be able to successfully develop a simulation model as described in Chapter 1.

Chapter 2 takes all necessary aspects into consideration when the method is described. The availability of data, the problem identification, supply and demand, and the simulation itself are all aspects that have been focused on in the chapter.

The objective of the method was to develop a simulation that considers inefficiencies, investigates the effect of compressed air set point changes, and predicts whether the current network infrastructure will be sufficient for the demand in different working areas. The simulation model can be used to predict how much development can still be done with the current network specifications. It is important to note that the measurements taken to develop the simulation model was done manually. This means that the number of manual measurements used for the simulation model is very limited.

The simulation considers the current supply and demand of the specific case study and determines how much development can still be done on the specific level. The number of X/C’s that can still be developed are the benchmark from which the analysis is done. The development of a level can only be done if the received delivery pressure is above 400 kPa.

The result of Chapter 2 is a method that yielded a working simulation with an error percentage of less than 5%. This means that the simulation model had been verified and could be used for the case study that is investigated in Chapter 3.

CHAPTER 3: RESULTS AND MODEL DISCUSSION

3.1 Introduction

The method described in Chapter 2 was implemented on a case study at Mine A. The development of the simulation and the way in which the simulation was used to provide case study results are discussed. The aim of the study, as described in Section 1.7, was to develop a compressed air simulation model that is able to determine whether the current compressed air supply and compressed air network infrastructure will be sufficient for future development, regarding distance developed and demand, with current pressure requirements for equipment.

The five-step method that was developed in Chapter 2 was used to analyse the case study in Chapter 3. The chapter focuses on a case study on Mine A, as mentioned in Chapter 2. The case study was used to test different scenarios and input pressures to determine whether the current infrastructure can support the demand in the working areas.

The results from Chapter 3 will determine whether the implementation of the methodology was a success. By making use of a validation procedure, the method could be tested. If the above-mentioned is successful, the simulation can be used in industry.

3.2 Compressed air network evaluation implementation

3.2.1 Step 1: Data gathering

Shaft data collection

The data for the strategy was collected at a conventional shaft platinum mine in the Bushveld Igneous Complex (BIC). The mine used for the study is one of the mines in the BIC with the largest compressed air infrastructure when compared to the other mines in the region. Due to confidentiality agreement no further details with regards to the specific mine can be provided. The benefit of using this specific mine is the scale on which the study could be done. If the study could provide accurate results on one of the largest compressed air infrastructures in the BIC, and specifically 26 Level West at the specific mine, the study would most probably succeed on a smaller scale.

The specific level (26 Level West) that was chosen, was selected because it is the one of largest active production half-levels on the UG2 section when considering distance from station to development end on Mine A. A layout of the Western half-levels' development ends of the UG2 section for can be seen below. This illustrates the development distance of 26 Level West compared to the other levels. The layout below is based on the exact layout received from the drafting department at Mine A.

The reason to select one of the largest active production levels is the size of the compressed air network on that specific half-level when compared to the other levels. This means that if the simulation model can yield accurate results on one of the larger half-levels, it will provide accurate results on the smaller levels as well. The development end layouts can be seen below in Figure 25.

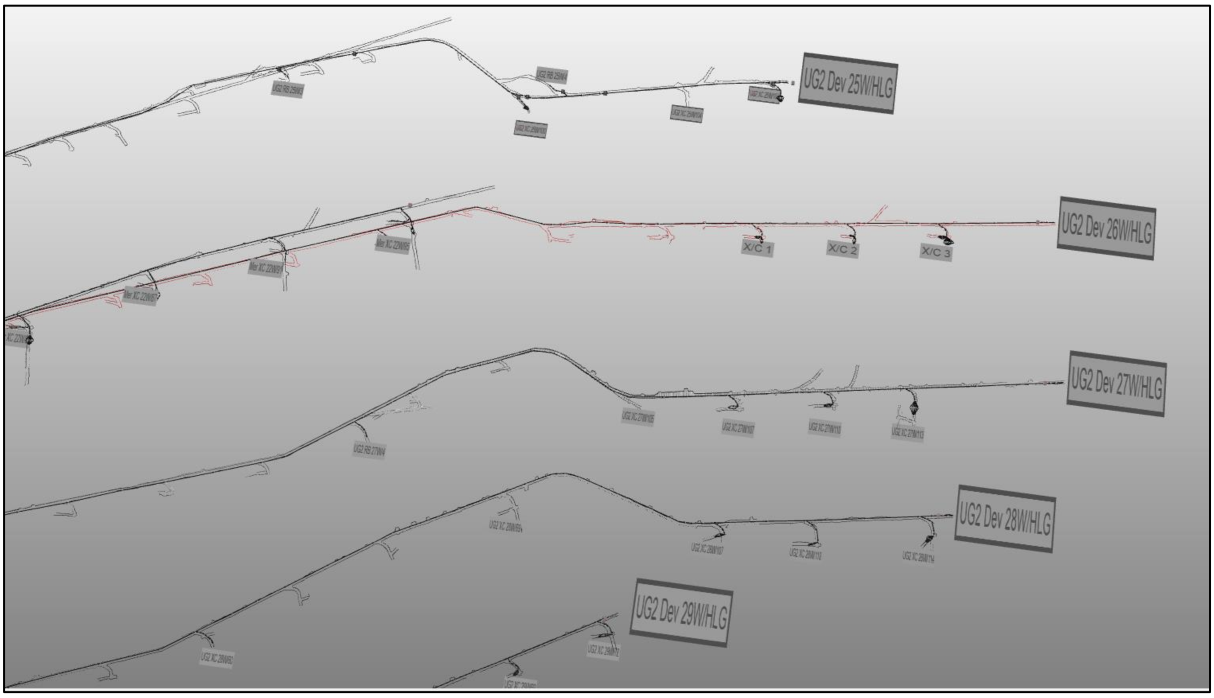

Figure 25: UG2 Levels development distance comparison

The compressed air data, shaft layout data, and manual compressed air measurements for the specific mine mentioned in Section 2.2.1 were collected. These measurements were taken from the SCADA system at the mine together with data from underground audits.

The layout used for the simulation was acquired from the drafting department at Mine A. The layout that was received was supplemented and verified by inspecting the different working areas when the audits on the shaft were performed. The entire shaft was audited, meaning, that the flow and pressure for all the level stations, active X/C's, and development ends were measured. All major leaks and noticeable inefficiencies were also noted and considered. A standard leak size flow rate was used to determine the flow rate from small, medium, large, and extra-large leaks. When considering these leak sizes, a benchmark was calculated to determine the flow rate per leak size. The operating conditions and pressures on the different levels of the mine is very similar, meaning the same size leak size will have the same flow rate and can therefore be used as standard to determine how leaks affect the compressed air network. The manual measurements section below provides an overview of the specific level that was used as the case study.

Manual measurements

The manual measurements for Case study A (26 Level West at Mine A) were taken by measuring flow and pressure on the different locations, as defined in Section 2.2.1.

The manual measurements were taken during the cleaning shift (Section 1.3.3). The benefit of taking the measurements during this shift is the fact that the demand for compressed is at the minimum and a baseline could be determined for the specific working area. It is important to note that a maximum baseline is not specified as the supply pressure from surface controls the maximum pressure supplied to the network and it is therefore not considered in the measurements.

Even though the blasting shift is the lowest consuming shift when considering compressed air it could not be considered for the baseline as no work is performed in the working areas during that time.

The baseline flow and pressure measured at the different measuring points for Case study A, as mentioned in Section 2.2.1, can be seen in Table 4 below.

Table 4: Case study A measured data

Location	Flow	Pressure	Pressure drop
Surface	57 000 m³/h	600 kPa	0 kPa
26 Level West - Station	3 800 m³/h	540 kPa	60 kPa
26 Level West – Active X/C 1	450 m³/h	530 kPa	70 kPa
26 Level West – Active X/C 2	1 250 m³/h	510 kPa	90 kPa
Development end	N/A	480 kPa	120 kPa

When considering the compressed air flow measured on surface, the average flow in a cleaning shift was approximately 57 000 m³/h. The total surface flow is the sum of all the level flows on the shaft and the amount of air consumed in the shaft barrel. This means that the flow for 26 Level West is only a small percentage of the total flow on the shaft. From the measurements taken on 26 Level West, the results show that the flow at the start of the level is at 3 800 m³/h in cleaning shift.

When considering the data in Table 4, the measured flow rates for the level and X/C's, the sum of the active X/C's flow rates do not equate to the total level flow rate. This is a typical indication that there is a loss of compressed air in the level other than the active working areas in X/C 1 and X/C 2. The typical inefficiencies which cause the higher flow rate are leaks in the system and possible loss of compressed air into old working areas.

The X/C's that were measured are the last and only two active X/C's on 26 Level West. Figure 26 below provides an overview on where the measurements were taken on 26 Level West in the station area.

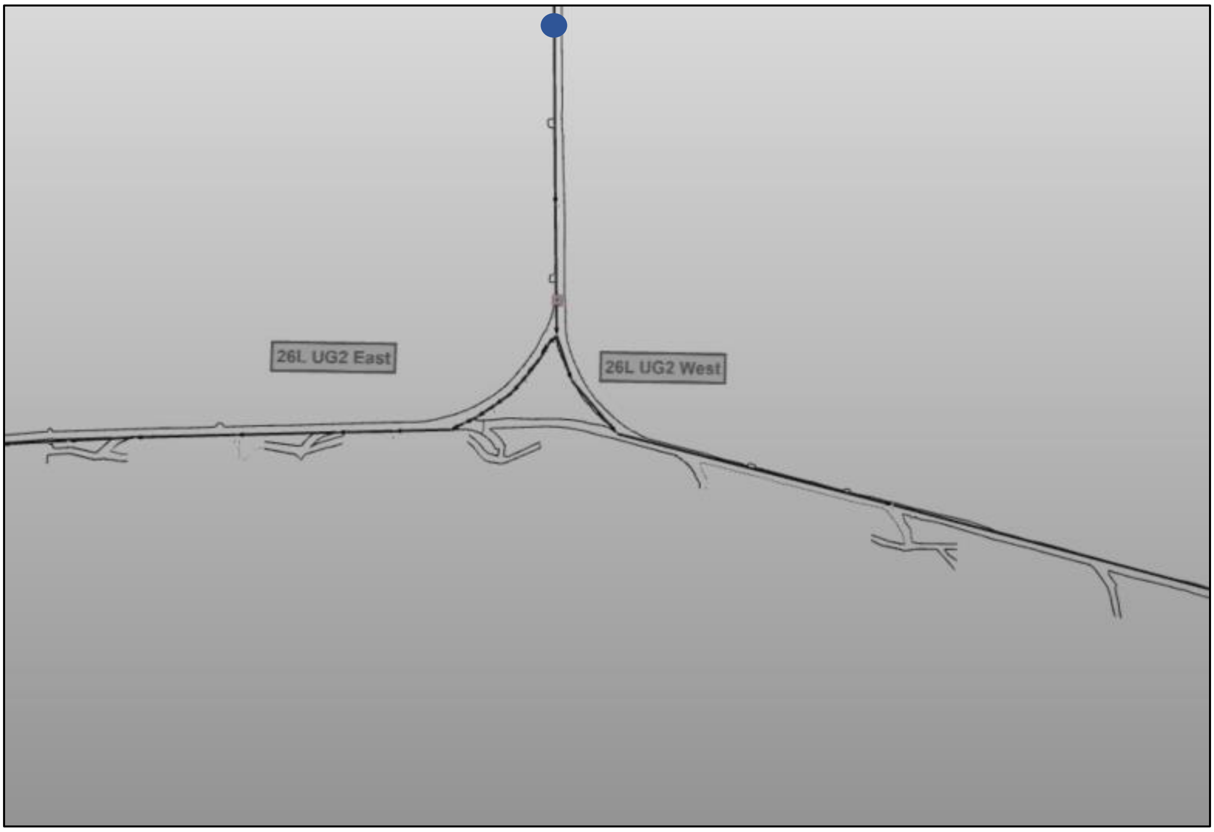

Figure 26: 26 Level West station overview

Figure 27 provides the development end and active X/C areas for the manual measurements taken.

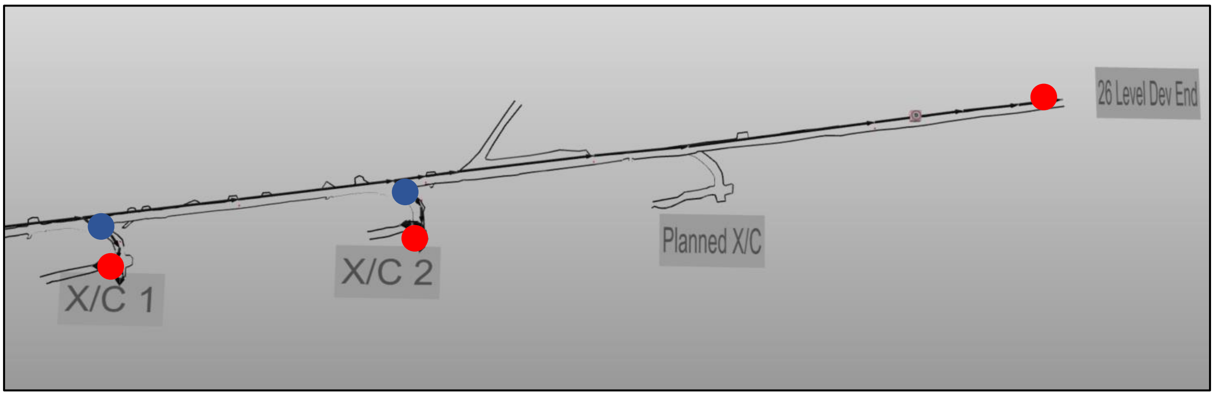

Figure 27: 26 Level West development end

For the study, these X/C's are referred to as X/C 1 and X/C 2. The planned X/C as seen in Figure 26 was still in development at the point when the manual measurements were taken. The flow and pressure measurements shown in Table 4 were taken during the cleaning shift, as described in Section 2.2.1.

The flow and pressure measurements from the above-mentioned X/C's differ quite significantly. There may be a few possible reasons for the variation in the flow and pressure measurements in the different X/C's. The flow rate in the X/C's is demand driven. This means that, of the two X/C's, X/C 2 has a higher demand than X/C 1. The reason for this demand does not necessarily mean that work was performed in the area when the measurements were taken. The high flow measurement could have been caused by inefficiencies within the network in the working areas. Open pipe ends and pipe leaks are large contributors to high flow in the system.

The difference in pressure can also be allocated to inefficiencies in the system. The higher flow in X/C 2 has a large effect on the pressure delivered to the development end. The delivery pressure in the various areas is important as this has a direct impact on the performance of pneumatic equipment used in the working areas.

3.2.2 <u>Step 2:</u> Scenario problem identification

The problem identification was done by taking the need for the study and identifying the specific issues from the data that were gathered. The problem identification was done by following the 7-step checklist as described in Section 2.2.2.

The 7-step checklist that was followed and the outcomes can be seen below:

1. Shaft data and layout obtained.
2. Shaft data and manual measurement data analysed, and specific shortcomings identified.
3. Specific area of interest identified as the development end of specific level.
4. Flow rate and pressure measurements were the main areas of interest in the identified areas.
5. Specific problem is to determine whether the current layout can support future development.
6. The specific scope of the problem is to make use of a simulation to determine a solution.
7. Specific scenario problem identified, and solution method developed in Chapter 2.

The above-mentioned steps were completed to collect the necessary data and develop the simulation model as described in the need. The supply and demand balance following the steps that have been completed are discussed in Section 3.3.1 below.

3.3 Compressed air usage analysis method implementation

3.3.1 Step 3: Supply and demand balance

Compressed air usage profiles

The compressed air supply to the shaft, as mentioned in Section 2.3.1, is based on a specific pressure set point. Even though the set point guides the pressure supplied and received, there can be various factors influencing the actual pressure that is supplied to the underground working areas, such as inefficiencies and high demand pneumatic equipment. There are no upper and lower limits on the pressure profile as this profile is a depiction of how the set points at the shaft are controlled and how much compressed air is used. The pressure received on the shaft section of Mine A can be seen below in Figure 28.

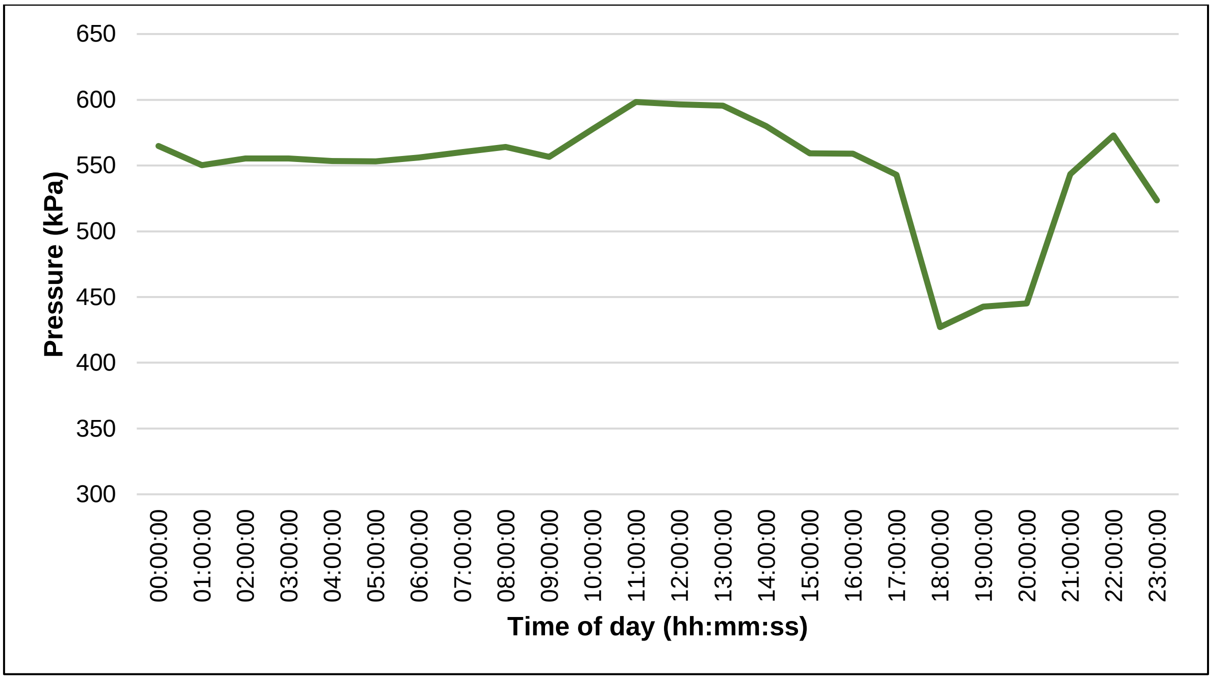

Figure 28: Case study A shaft surface pressure profile

The specific pressure that is supplied to the shaft does not necessarily reach the working areas. The typical pressure received on the station on 26 Level West for Case study A can be seen below in Figure 29.

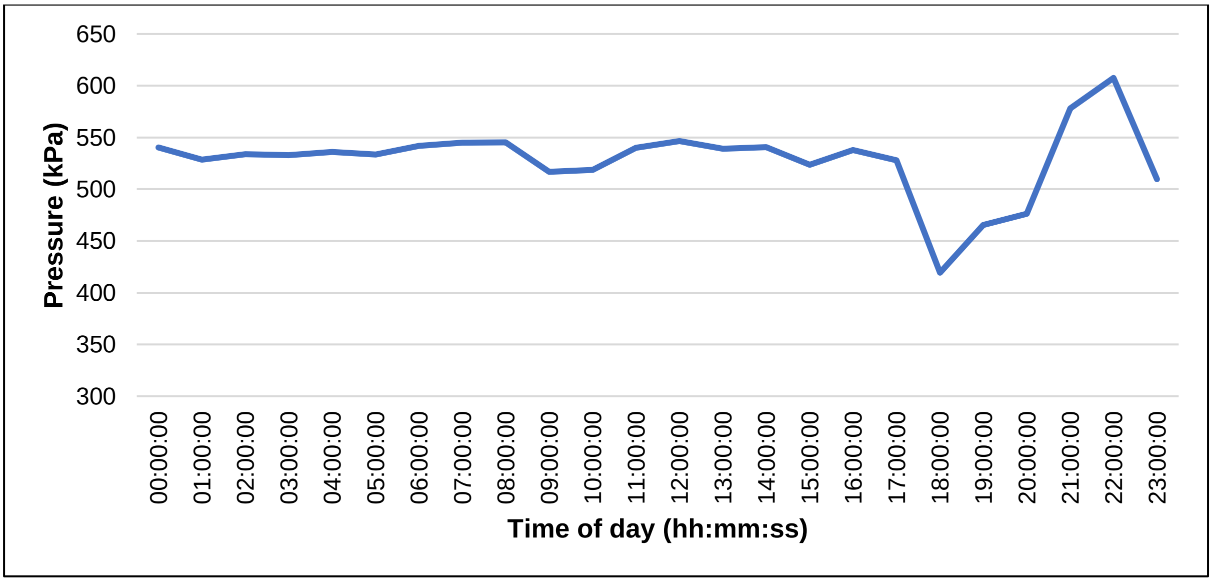

Figure 29: 26 Level West station pressure profile

The compressed air demand side of the balance is dependent on the usage of compressed air in the mine at a certain point in time. As mentioned in Section 2.3.1, the compressed air flow rate is an indication of how much compressed air is consumed underground. A typical weekday flow profile for mine A in Case study A can be seen in Figure 30.

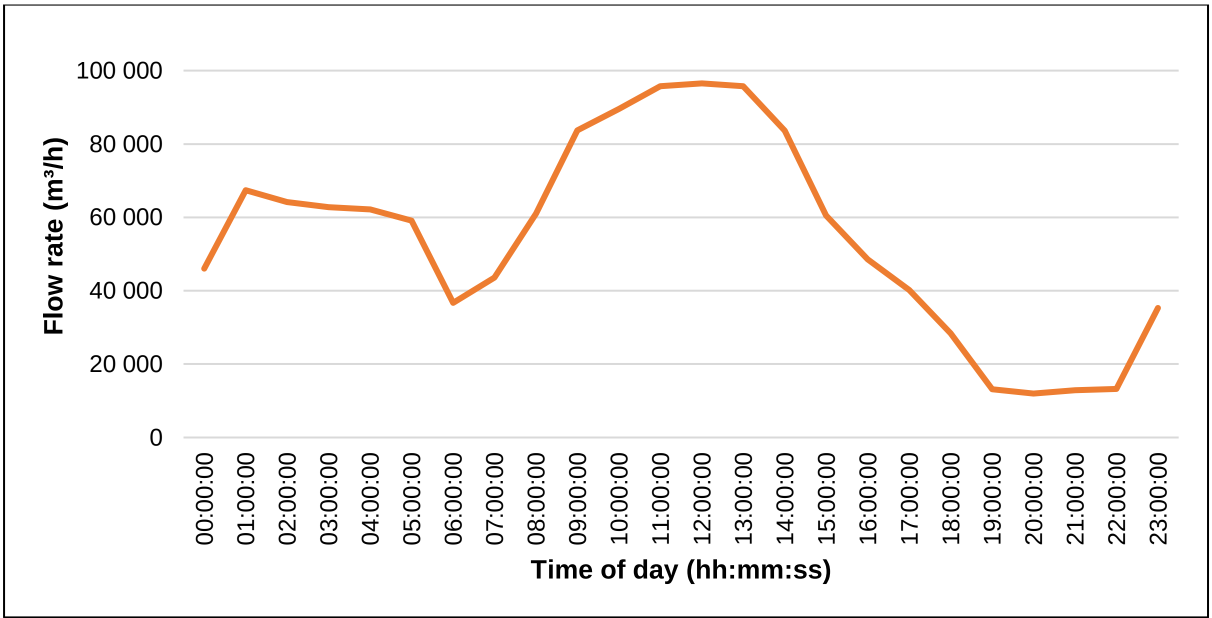

Figure 30: Mine A surface flow profile

The flow profile in Figure 30 shows how the demand varies during the day. The peak demand is during the drilling shift (06:00 – 14:00) and the lowest demand during the blasting shift (16:00 – 21:00); however, the blasting shift cannot be considered as there should not be any personnel in the mining working areas at that time. The increase in flow can be seen from 06:00 when the drilling shift starts and reaches a peak at 12:00.

Mine A typically closes the level valves during a blasting shift as there is no compressed air needed in the working areas during that time. This means that the flow that is displayed during the blasting shift is due to leakages in the shaft compressed air pipes or level valves that are not functioning properly.

The leaks in the system supports the fact that the pressure profile from 26 Level West in Figure 29 is lower than that measured on surface, as seen in Figure 28. The loss of compressed air from the pipes going underground affects both the flow and pressure profiles.

The flow profile for 26 Level West, as seen in Figure 31, shows a similar profile to what is seen in Figure 30, with the peak in the midday, but the overall flow rate is lower. It is also clear that 26 Level West has a malfunctioning level valve that cannot be closed during the blasting shift, resulting in a flow into the level during that time.

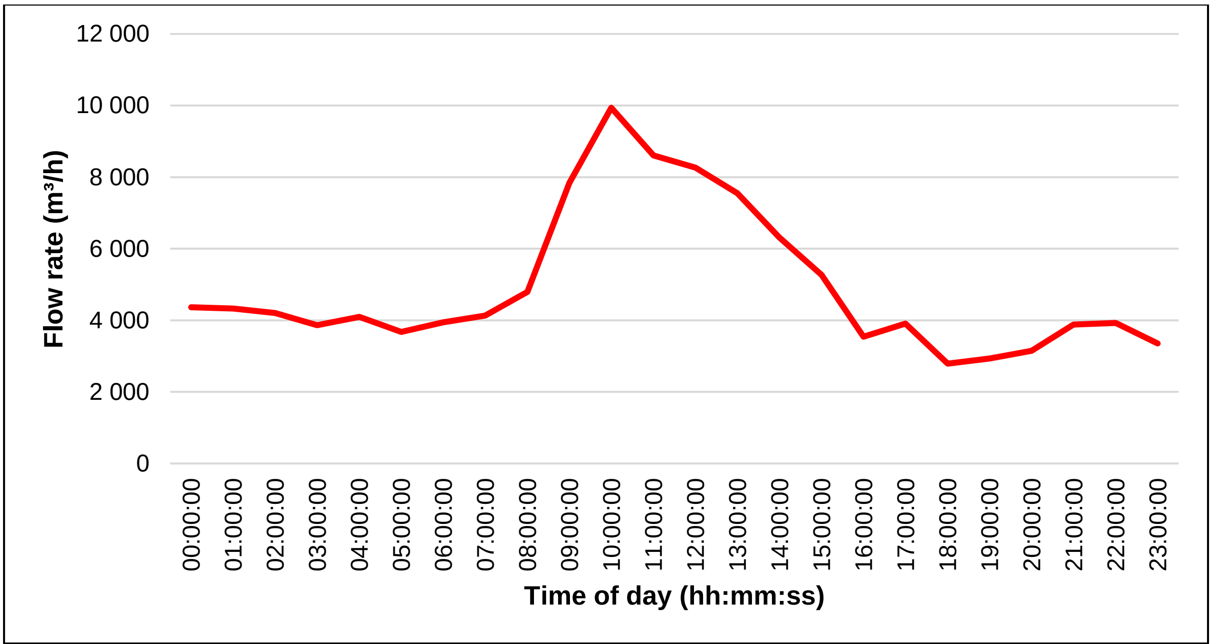

Figure 31: 26 Level West flow profile for Case study A

It is important to understand that leaks and open ends in the system play a large role when considering the delivery pressure and flow rate in the different working areas. The number of leaks on a specific level affect the efficiency of the compressed air distribution in the level. This means that the active X/C's on the level need to be analysed to determine what area in the level consumes the most compressed air. The older inactive X/C's should be blanked off to ensure that there is no wastage in that specific area. The reality is that higher flow rates closer to the station results in lower pressures further into the level.

Inefficiency evaluation

The X/C flows and pressures were measured for Case study A on 26 Level West. The baseline flow during the cleaning shift was determined as shown in Table 4. These measurements were taken manually.

The measured flow rates were scaled with the level flow profile to provide an approximate profile for the X/C baseline. The active X/C flow profiles for 26 Level West can be seen below in Figure 32.

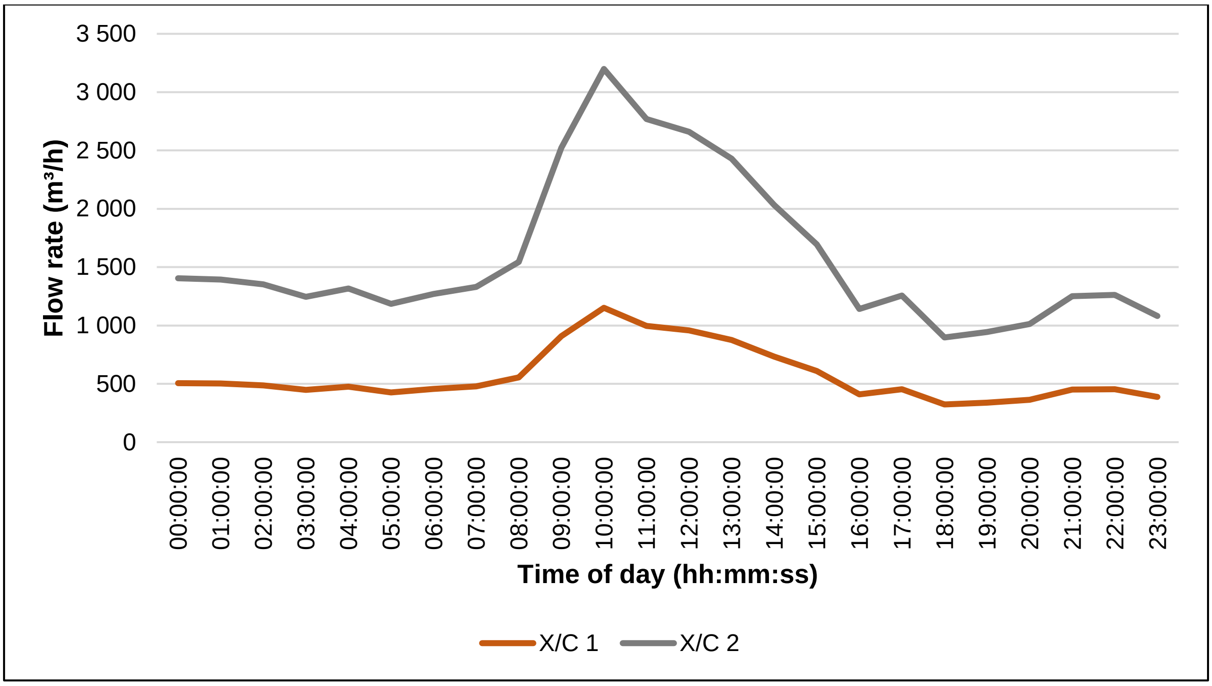

Figure 32: Active X/C flow profiles on 26 Level West

The comparison of the flow from X/C 1 and X/C 2 shows that there is a significant difference in the compressed air consumption in the specific working areas. The flow in X/C 2 is much higher than that of X/C 1. This flow rate difference also affects the pressure received after the X/C. When considering Table 4, the difference in the measured pressure from X/C 1 to X/C 2 is 20 kPa and from X/C 2 to development end is 30 kPa.

The high flow rate in the X/C's can be caused by leaks and open ends in the working areas. The station flow rate is a combination of consumption and leaks within the X/C's and in the main haulage. The audit done for Case study A on 26 Level West included a leak audit. The results for the leak audit can be seen in Table 5.

Table 5: Case study A leak audit

Number	Leak location	Leak size
1	RJ 140, Box 55	Small
2	RJ 210, Box 70	Medium
3	RJ 254	Medium
4	RJ 262	Small
5	RJ 266	Small
6	RJ 296, Box 91	Large
7	RJ 308, Box 93	Large
8	RJ 326	Medium
9	RJ 324	Medium
10	RJ 362, Box 101	Medium

From Table 5 above, the noticeable leaks in the main haulage on 26 Level West were identified. The leak audit in Table 5 only provides the leaks noted in the main haulage as the leaks in the working areas could be identified and quantified by the wastage flow into the X/C when the manual measurements were taken.

As mentioned in Section 3.2.1, these manual measurements were taken in the cleaning shift. This means that no high consuming pneumatic equipment was active in this shift. Therefore, the flow measurements taken while doing the compressed air audit is a direct representation of the total wastage flow caused by leaks and open ends in the working areas.

3.4 Simulation model implementation

3.4.1 Step 4: Development of simulation model

With the available data and compressed air audit that was performed for Case study A, a simulation model was developed to satisfy three main objectives for the simulation, as mentioned in Section 2.4.1. The simulation model was developed and calibrated to ensure that the results obtained were accurate. The simulation was verified in Section 2.4.2 and provided accurate results.

The simulation model components as shown in Section 2.4.1 were used to develop the model. All the components used were calibrated to ensure that the inputs used, and outputs obtained would be able to match the actual process data for the compressed air network of Mine A. The inputs and outputs for the simulation can be seen in Table 6 below.

Table 6: Simulation model inputs and outputs

Inputs	Outputs
Compressed air set points	Network pressures
Compressed air flow rates	Network flow rates
Pipe leak locations (wastages)	
Shaft specific layout	

Supply side

The simulation supply side of compressed air is set point controlled. The supply of compressed air is regulated by the compressor components in the simulation, as mentioned in Section 2.4.1.

Mine A has six compressors that are being used to supply compressed air, namely CENTAC 1, CENTAC 2, CENTAC 3, VK25, VK50 and VK100. At the time when the simulation was developed, the mine only made use of three compressors in a normal workday. The flow and pressure measurements for a typical workday for the three active compressors (VK25, VK50 and VK100) can be seen in Appendix B as it was used in the simulation. It is important to note that the different sizes of the compressors have not been provided. The reason for this is the fact that the dissertation focuses on the compressed air supply and not the rated power of the compressors. The importance only lies in what is supplied to the mine and not what the power demand for the compressors are.

Demand side

The compressed air demand side of the simulation model is composed of three main components, as mentioned in Section 2.4.1, namely compressed air pressure boundary, compressed air pipes, and compressed air nodes. Figure 33 below provides an overview of 26 Level West layout in the active areas for Mine A.

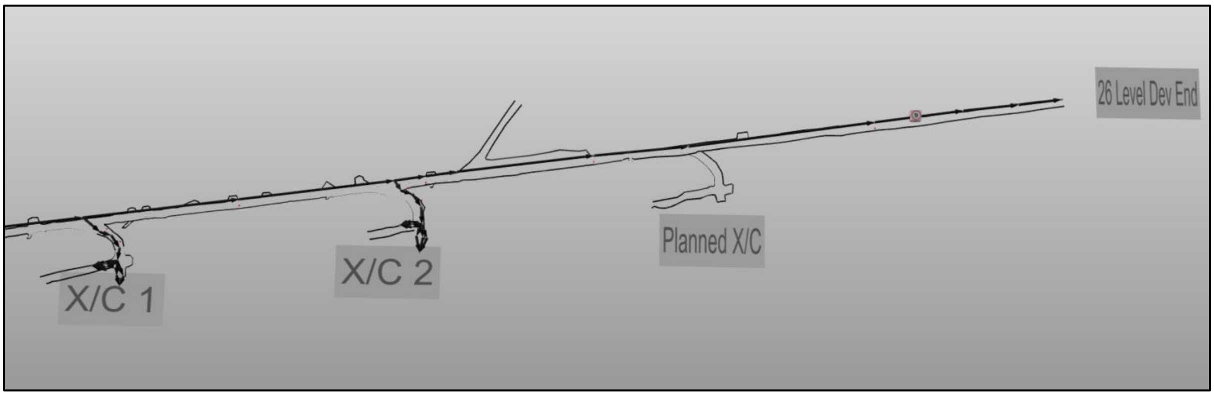

Figure 33: Active demand area for Case study A

The different components were calibrated and specified to ensure that the components were set-up to ensure the accuracy of the simulation. The demand side of the simulation was set-up to use actual measured data, as mentioned in Section 3.2.1. The station, X/C 1 and X/C 2 simulation inputs and outputs can be seen in Appendix C.

3.4.2 Step 5: Validation of method

The development of the simulation model was done to support the need for the study as stated in Section 1.7. The model takes the current compressed air network of Mine A into consideration and all supporting aspects regarding the layout and demand, as mentioned in Section 3.4.1. The balance between the current supply and demand on the compressed air network are key factors to determine whether the infrastructure will support future development.

The distance developed into the specific level plays a large role in the compressed air supply and demand. For the simulation, the distance developed was connected to the number of active X/C's and X/C's that can still be added on the specific level. These X/C's can only be developed if they can be supplied with the required compressed air pressure to ensure operation of pneumatic equipment.

As mentioned in Section 1.3.4, the minimum required delivery pressure is 400 kPa on the development end. The threshold of 400 kPa is used as the deciding factor to determine whether further development is possible. If the pressure on the development end in the cleaning shift were measured below 400 kPa in the simulation, the current supply will not be sufficient for future development on that specific level.

The simulation model was verified in Section 2.4.2. The validation of the model was done on 26 Level West for Case study A. This level is an active production level that currently has two active X/C's, as mentioned in Section 3.3.1. The manual measurements for the simulation were taken when two X/C's were active but no further development was done at that point.

However, in the meantime, a third X/C has been developed on 26 Level West. The flow and pressure measurements for the new active X/C were taken. The addition of the third X/C can be seen below in Figure 34. The validation of the simulation could be done by simulating the new X/C, which could then be checked by confirming the actual values that were manually measured.

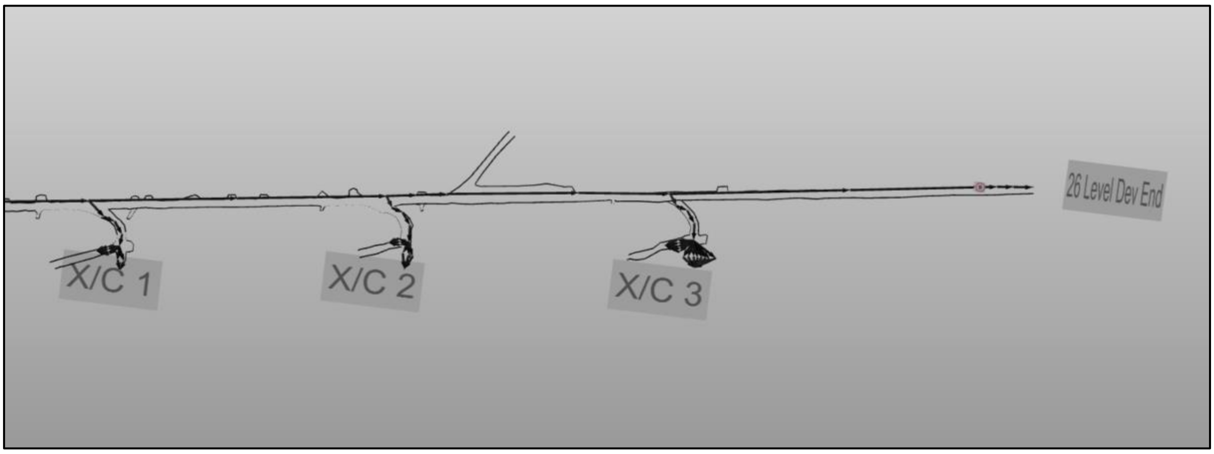

Figure 34: New layout of 26 Level West development end

The measurements taken for X/C 3 showed that the cleaning shift flow at 21:00 was 1 750 m^3/h and pressure was 482 kPa. The development end pressure was measured as 470 kPa. The flow profile for each of the X/C's on the level can be see below in Figure 35.

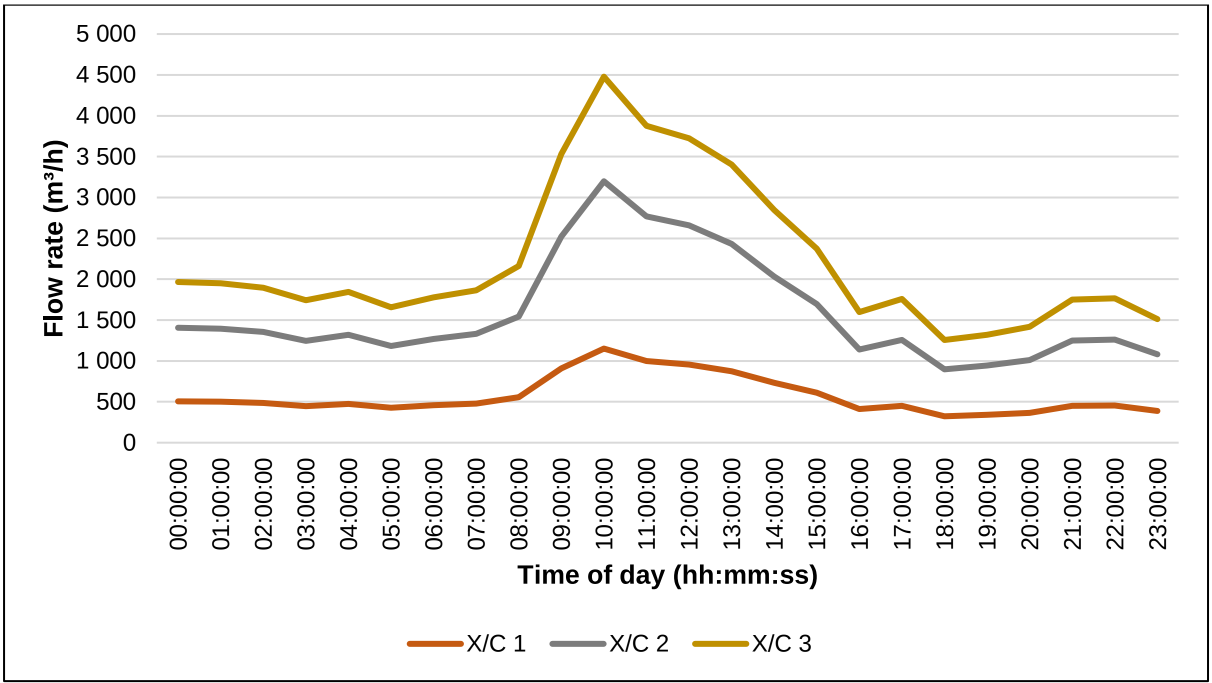

Figure 35: X/C flow profile with X/C 3 developed

The current planning for this specific level is to continue with future development. The simulation model was tested with different scenarios to determine whether the planned future development would be possible. The different scenarios for the simulation model on Case study A can be seen below in Table 7.

Table 7: Scenario set-up for Case study A

Scenario	Set-up
1	Layout with 3 active X/C's. (current)
2	Layout with 4 active X/C's. (1 additional X/C)
3	Layout with 5 active X/C's. (2 additional X/Cs)

The added X/C's were given an estimated baseline flow rate which was the same as the highest flow between the current active X/C's. The reason for this was to be conservative and ensure that a high flow could be accommodated. The results for the different scenarios of the simulation model and the development on 26 Level West can be seen in Appendix D. Figure 36 below provides an overview of the actual measured pressures and the simulation pressures for the development end on 26 Level West. The profile is for Scenario 1 from Table 7.

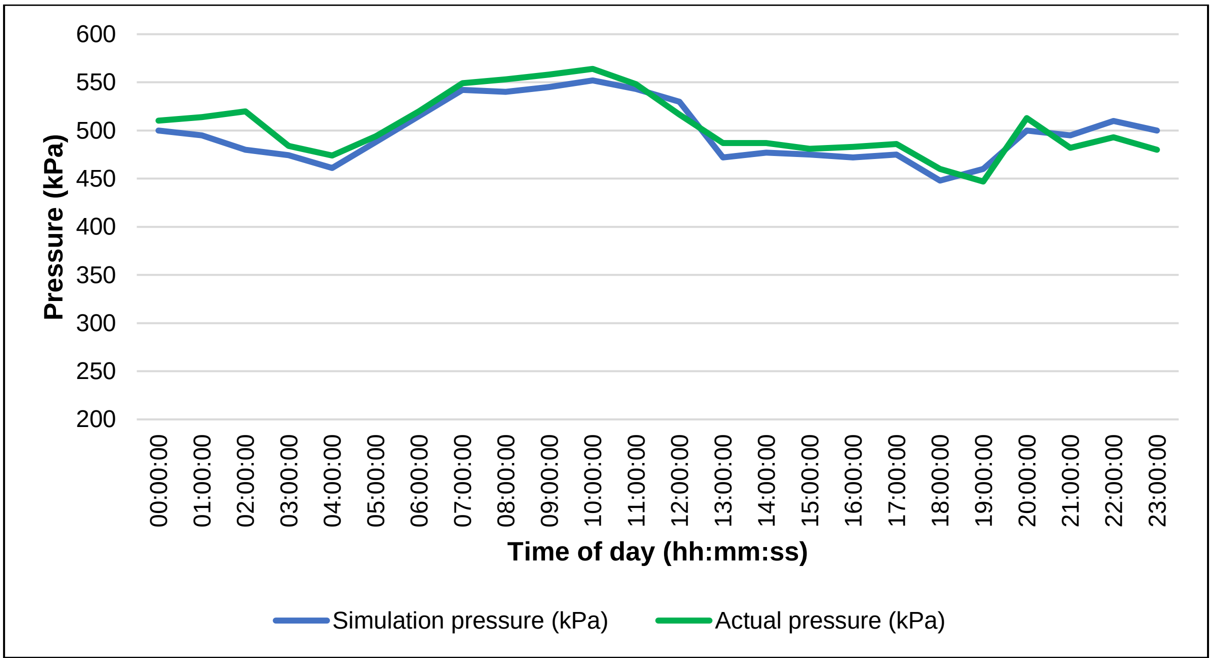

Figure 36: Scenario 1 and actual pressures comparison

Scenario 1 was used to validate the simulation model. The validation was done by making use of the manual measurements taken after the development of X/C 3 and comparing it to the results obtained in the simulation. The simulated pressure value at 21:00 was 500 kPa and the measurement taken was 482 kPa, therefore yielding an MAE of 2.60%. This result indicated that the simulation had been validated and could yield accurate results for the two remaining scenarios that were tested. As mentioned in Section 2.4.2, an MAE percentage of less than 5% is a good indication that the simulation is accurate.

After the validation of the simulation, Scenarios 2 and 3 were simulated. The results obtained showed that the added X/C's and increased demand would have a significant impact on the pressure supplied on development end of 26 Level West.

The pressure profiles for the development end for the three different scenarios can be seen below in Figure 37.

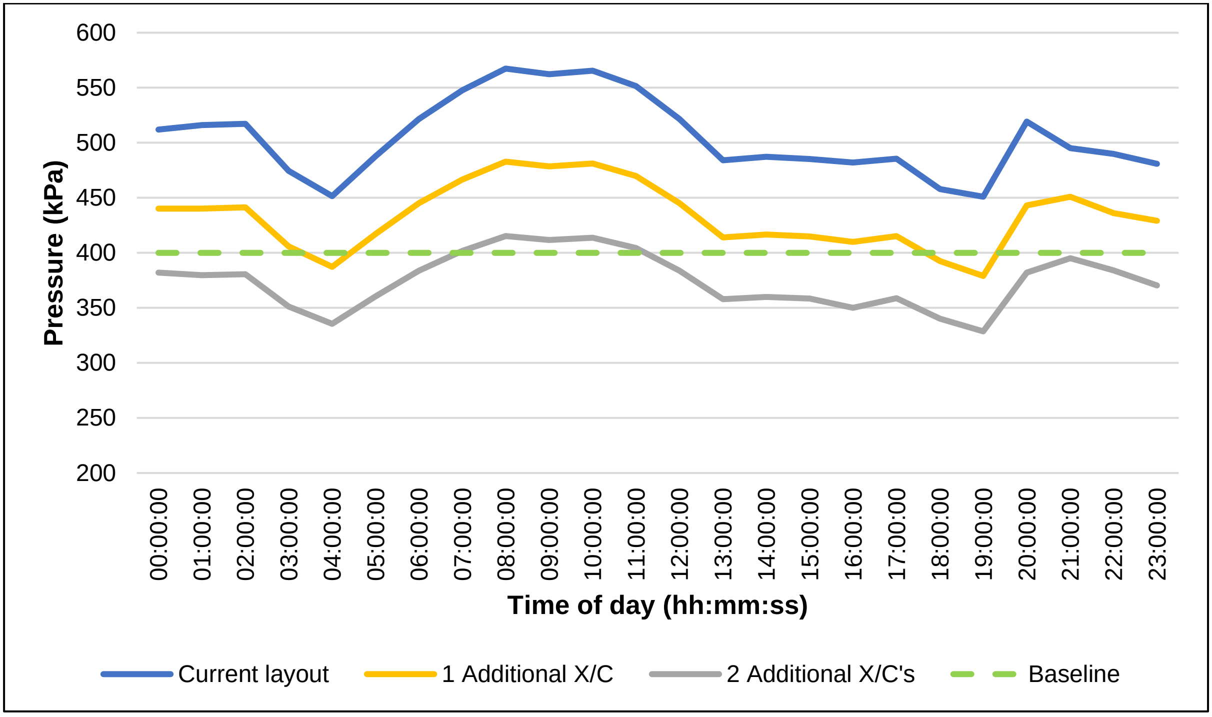

Figure 37: Development end scenario pressure profiles

The results show that the development on 26 Level West will only be able to support a third active X/C on the level. If a fourth and fifth X/C were to be added with the current supply of compressed air, the delivery pressure would not be sufficient to operate the necessary pneumatic equipment.

Figure 38 below shows how the layout of 26 Level West changed when the two additional X/C's were added.

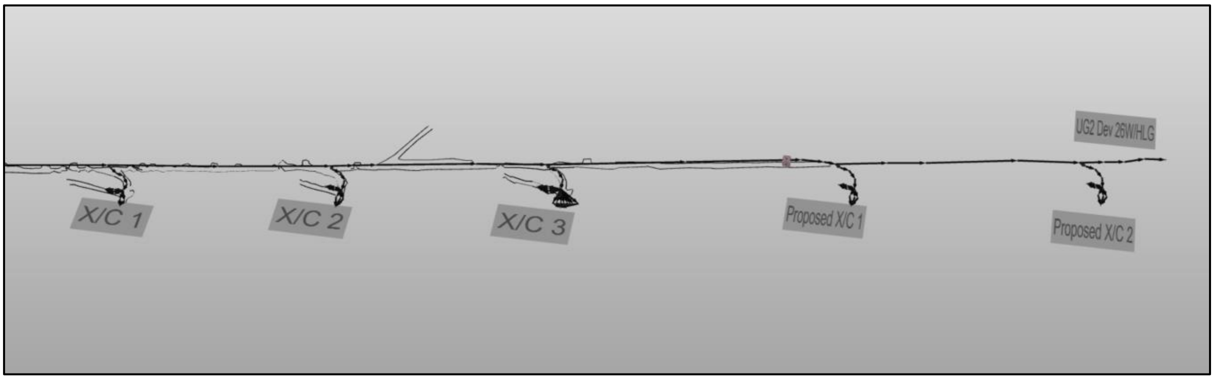

Figure 38: Scenario changes to 26 Level West for Case study A

Implementation of strategy

The possibility of developing the fourth and fifth X/C, and further than that in the future, means that changes must be made to the current compressed air network. The reason for the low delivery pressure can be due to network inefficiencies or excessive consumption in the working areas that need to be addressed in the level. The compressed air consumption on the higher levels of Mine A can also be responsible for the lack of pressure on 26 Level West.

When considering the changes that need to be made, one solution would be to increase the supply pressure to the shaft. The downside to this increase in pressure is the increase in operational cost involved. Should the pressure be increased, the leaks in the system will also be supplied with a higher pressure so that a higher wastage will be experienced. The easiest and most cost-effective way to increase the delivery pressure is to reduce the wastage in the working areas.

Three different scenarios were investigated and can be seen below in Table 8. A flow reduction change was made to reduce the wastage flow in each X/C's on 26 Level West. The delivery pressure on 26 Level West development end for the different scenarios can be seen in Appendix E.

Table 8: Future changes and scenarios for Case study A

Scenario	Flow rate change (m^3/h)
1	5 % wastage reduction per X/C
2	10 % wastage reduction per X/C
3	15 % wastage reduction per X/C

As can be seen in Table 9, the delivery pressure for each scenario on the development end for 26 Level West will only be above the threshold if more than a 15% reduction on wastage per X/C is achieved. It is important to keep in mind that these wastages need to be updated on the simulation as the network of the mine changes.

Table 9: Wastage reduction scenarios for Case study A

Wastage reduction scenarios			
Time (hh:mm:ss)	**5% wastage reduction**	**10% wastage reduction**	**15% wastage reduction**
00:00:00	393	404	416
01:00:00	391	403	415
02:00:00	392	404	416
03:00:00	361	372	383
04:00:00	345	355	366
05:00:00	371	382	394
06:00:00	395	407	420
07:00:00	414	426	440
08:00:00	428	441	455

09:00:00	424	437	451
10:00:00	426	439	453
11:00:00	417	429	443
12:00:00	395	407	420
13:00:00	368	379	391
14:00:00	371	382	393
15:00:00	369	380	391
16:00:00	338	348	358
17:00:00	369	380	392
18:00:00	350	360	371
19:00:00	338	348	358
20:00:00	393	405	418
21:00:00	385	396	409
22:00:00	395	407	420
23:00:00	381	393	405

If the changes are not made to the simulation model, the results yielded will not be accurate and cannot be used to validate scenarios that are tested. It is suggested that the simulation model be updated when the monthly planning and progress are discussed.

3.5 Conclusion

Chapter 3 provided the implementation and results of the strategy for the case study methodology discussed in Chapter 2. The chapter followed the step-by-step method as described in Section 2.2 to achieve the needed objective stated in Chapter 1.

The development of the simulation model was described, where the collection of manual measurements, supply and demand balance, and the inefficiency evaluation supported the necessary requirements to develop an accurate model.

The simulation model was developed, and the main objectives as stated in Section 2.4.1 were satisfied. The first objective was the investigation of the effect of compressed air inefficiencies on the compressed air network. This was achieved by investigating the inefficiencies and completing leak audits to identify how compressed air is wasted.

The simulation model, as described by the second objective, was developed, verified, and validated. The model was verified and provided an MAE percentage of less than 5%. The verified model and actual data were then used to validate whether the future development will be possible on 26 Level West for Case study A. The validation of the model yielded an MAE percentage of 2.60%, which suggests that the simulation model is accurate.

The third objective was satisfied from the results in Section 3.4.2 that a decrease in wastage of more than 15% is needed on 26 Level West to continue the successful development of the level.

Section 3.3.1 shows that an increase in delivery pressure set points is an option, but would not be cost effective. This means that, although set-point changes increase pressure to the working areas, it is not always the best solution.

The results from the simulation model showed that, at the current set points of compressed air at the shaft, the development of an additional X/C to the current three will not be possible. If an additional X/C is added, the delivery pressure to the development end will not be sufficient for the pneumatic equipment to operate. It is important to note that the simulation had been validated on only one case study. The reason for this is the poor condition of infrastructure on the level used for the case study. If the model was able to yield accurate results on a level that has major inefficiencies like 26 Level West, the model will also be able to predict accurate results for a level that has better efficiency. If a level with a better efficiency is selected the results will be more accurate as the wastage of compressed air will not influence the simulation as heavily as in the Case study for 26 Level West.

The implementation of the strategy provided that the wastage in the different X/C's could be a possible reason for the decreased delivery pressure when the additional X/C's were added on the simulation model.

A series of three wastage reduction scenarios were then simulated to determine whether a reduction in wastage can influence the outcome. The results from the three scenarios showed that the additional X/C's could be added if the wastage in each of the active X/C's on 26 Level West were reduced by at least 15% when considering the flow rate of each added X/C.

CHAPTER 4: CONCLUSION AND RECOMMENDATIONS

4.1 Introduction

Chapter 4 provides the conclusion of the study and emphasises the main aspects that were discussed. The key points for each chapter are discussed to illustrate how the objectives for the study have been accomplished.

4.2 Study summary

The importance of focusing on environmental, social and governance factors in industry is becoming more apparent and companies are experiencing more pressure from investors regarding ESG than ever before. The key aspect of ESG is a measure of a company's non-financial performance. The current forecast on ESG investments is expected to increase by approximately 100% from 2024 to 2034. The mining industry in South Africa is under immense pressure to ensure sustainable growth, with ESG adding to that.

The impact that the mining industry has on the South African economy is significant. South Africa is currently the largest producer of platinum group metals in the world, with almost 80% of the global supply. The sale of PGMs have been on the increase since 2017. The increase in sales has a direct influence on production and the growing demand adds pressure on mining companies to supply the market.

The operating costs to supply PGMs are high, and the process is energy intensive. Most of the electrical energy consumed on a deep-level platinum mine can be allocated to the compressed air system.

Compressed air systems in platinum mines are complicated networks that ensure the supply of sufficient pressure to the pneumatic equipment used. The equipment that is used all play a significant role in the development and operation of the mine. Equipment such as rock drills, rock loaders, pneumatic actuators, and loading boxes are used in platinum mines. The above-mentioned apparatus all require a minimum compressed air delivery pressure of 400 kPa to operate.

Should the correct pressure not reach the development areas where the equipment is used, the development and production of the mine is influenced. It has been noted that there is a need for a method to determine whether the current compressed air infrastructure and supply will be sufficient for future development and demand. A need was identified to develop a simulation model. The PTB simulation software was chosen as the desired program to be used for the study. The following objectives were formulated for the study:

1. Identify what the inefficiencies are in the compressed air system and address the influence they have on the network.
2. Develop a simulation model that can accurately predict how changes in a certain area will influence the network.
3. Simulate how much future development can be done in a specific area if general conditions are adjusted for the simulation model.

To reach the set objectives, a methodology needed to be developed. Chapter 2 provided an overview of a step-by-step process that needed to be followed to develop the simulation model. The five main steps for the method were data gathering, problem identification, supply and demand balance, development of the simulation model, and verification of the simulation model. The simulation model was verified. The calculated MAE percentage for the simulation model was less than 5%.

Chapter 3 was used to discuss the results obtained from the method. For this study, 26 Level West on Mine A was selected. The results in the chapter made use of gathered data and simulated data. A supply and demand balance was done after which the data from the balance could be used for the simulation model. The simulation model was validated and provided the results.

A 400 kPa minimum required pressure during a cleaning shift was chosen as the reference pressure to ensure that all the required pneumatic equipment would be able to operate as the simulation model tested three different scenarios. The first scenario simulated 26 Level West as the current developed and validated layout with three active X/C’s and the second scenario added one additional X/C, making it four in total on the level. The last scenario added two additional X/C to have a total of five active X/C's on the level.

With the current layout and supply of compressed air to Mine A and to 26 Level West, the level will only be able to develop one additional X/C (Scenario 2) along with the current three active X/C's on the level. The reason for this is the loss of compressed air pressure from the station area to the development end. The amount of compressed air wastage in the different X/C's need to be addressed to ensure further development with the current supply of compressed air to the shaft.

To be able to determine how much the wastage should be reduced in order to develop the five X/C's as in Scenario 3 mentioned above, a different strategy needed to be followed by reducing the wastage flow in each of the five X/C's on the model by 5%, then 10% and lastly by 15%. It is suggested that a minimum reduction in wastage of 15% per X/C is needed to ensure the development of a fifth X/C on the level.

Using the simulation model, the three main objectives for the study were addressed and met. The compressed air inefficiencies were investigated by identifying how they influence the network and how much should be reduced to ensure future development. The delivery pressure to the working area can be affected by several influences on the network. The main influences on delivery pressure are demand and inefficiencies. Lastly, the current compressed air supply will be sufficient for future development, only if the wastages and inefficiencies are addressed. If the reduction in wastage is not possible, the compressed air supply pressure to the shaft will need to be increased. Should the pressure set point be increased, an increase in operational costs can be expected.

The simulation model that was used needs to be updated as the mine changes and develops. If this is not done, the results obtained from the model will not be accurate and the possibility to test different scenarios will become impossible.

Should the simulation model be used appropriately, it will be able to continuously predict how much development can still be done at the current rate of supply and demand. The way in which the simulation model assists with development and planning in the mine, makes it a key tool that can be used to motivate sustainable mining operations. This sustainable mining operations can contribute to the environmental part of ESG.

4.3 Recommendations for future work

The successful development of a simulation model to determine whether the current supply network will be sufficient for future demand has been completed. The future development on Mine A will only be possible if wastages and inefficiencies are reduced.

It is suggested that the simulation model be used to address delivery pressure issues and inefficiency issues on the other levels of the mine and not only on 26 Level West. By doing this, the possibility to operate the compressed air network at a lower operating cost and more energy efficient is imminent.

The more cost effective the mine can operate, the better the chances are of increasing the sustainability of the entire operation. If the strategy is successful, it can be implemented at other mining operations.

A potential future study can take into consideration what the flow rates and wastages in the stoping areas are and address the reduction thereof. The results can be used for compressed air usage prediction per stoping area, the study applied in this dissertation could be more in depth and provide a better understanding of how each stoping area affects the compressed air supply to the development end. Another suggestion would be to install permanent instrumentation to provide continuous results of the measurements in the various areas of focus. Should there be a constant availability of data, the simulation model can be updated more frequently and better long-term decisions regarding compressed air supply and demand can be made.

By making use of more than one case study in future studies a more comprehensive result can be achieved and an overall better idea can be achieved on how the different levels influence the mine on an energy consumption basis. When considering more than one case study the number of measured points will also provide a more in depth view on how the simulation model is influence by changes in the infrastructure.

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APPENDIX A: SIMULATION VERIFICATION

The simulated results were very close to the actual measured data, which means that the results given in Table A - 1 are accurate.

Table A - 1: Verified simulation pressures

Time	Actual Pressure (kPa)	Simulation Pressure (kPa)
00:00:00	485	485
01:00:00	495	501
02:00:00	497	501
03:00:00	502	503
04:00:00	448	451
05:00:00	422	424
06:00:00	458	468
07:00:00	504	508
08:00:00	547	556
09:00:00	554	563
10:00:00	553	557
11:00:00	550	560
12:00:00	549	544
13:00:00	510	508
14:00:00	454	463
15:00:00	462	467
16:00:00	464	464
17:00:00	415	412
18:00:00	450	463

19:00:00	428	429
20:00:00	411	412
21:00:00	503	506
22:00:00	485	491
23:00:00	505	509

APPENDIX B: SIMULATION SUPPLY

As discussed in Section 3.4.1, the typical compressor pressure and flow measurements used for the simulation can be seen below in Table B - 1, Table B - 2 and Table B - 3, for the VK100, VK50 and VK25, respectively.

Table B - 1: VK100 Pressure and flow data

VK100		
Time (hh:mm:ss)	**Pressure (kPa)**	**Flow rate (m³/h)**
00:00:00	497	68 666
01:00:00	561	67 042
02:00:00	556	78 296
03:00:00	519	89 058
04:00:00	476	97 180
05:00:00	497	96 194
06:00:00	534	92 401
07:00:00	567	88 522
08:00:00	560	88 480
09:00:00	559	88 017
10:00:00	557	87 991
11:00:00	554	88 222
12:00:00	596	83 257
13:00:00	488	93 698
14:00:00	502	93 436
15:00:00	505	92 889
16:00:00	576	73 678

17:00:00	620	58 304
18:00:00	558	63 074
19:00:00	504	73 684
20:00:00	586	63 343
21:00:00	590	61 515
22:00:00	576	62 679
23:00:00	553	64 635

Table B - 2: VK50 Pressure and flow data

VK50		
Time (hh:mm:ss)	**Pressure (kPa)**	**Flow rate (m^3/h)**
00:00:00	497	33 535
01:00:00	561	31 182
02:00:00	556	31 005
03:00:00	519	9 970
04:00:00	475	666
05:00:00	497	0
06:00:00	534	0
07:00:00	566	28 204
08:00:00	560	42 505
09:00:00	559	47 868
10:00:00	557	47 845
11:00:00	553	47 957
12:00:00	596	45 386

13:00:00	488	3 711
14:00:00	502	0
15:00:00	505	0
16:00:00	576	0
17:00:00	620	0
18:00:00	558	0
19:00:00	504	8 170
20:00:00	586	28 091
21:00:00	590	29 687
22:00:00	576	30 223
23:00:00	553	31 117

Table B - 3: VK25 Pressure and flow data

VK25		
Time (hh:mm:ss)	**Pressure (kPa)**	**Flow rate (m^3/h)**
00:00:00	496	0
01:00:00	560	0
02:00:00	555	0
03:00:00	519	0
04:00:00	474	0
05:00:00	496	3 608
06:00:00	533	14 450
07:00:00	565	1 478
08:00:00	559	0

09:00:00	558	0
10:00:00	556	0
11:00:00	552	3 352
12:00:00	595	13 002
13:00:00	487	15 415
14:00:00	501	19 490
15:00:00	504	20 762
16:00:00	576	4 961
17:00:00	620	314
18:00:00	558	0
19:00:00	504	0
20:00:00	586	0
21:00:00	590	0
22:00:00	576	0
23:00:00	552	0

APPENDIX C: SIMULATION DEMAND

As mentioned in Section 3.4.1, the demand side for 26 Level West was developed and calibrated with actual results. The actual inputs for the areas as mentioned in Section 3.4.1 can be seen in Table C - 1 below.

Table C - 1: Case study A flow inputs

Time (hh:mm:ss)	Station	X/C 1	X/C 2
00:00:00	8 135	495	1 387
01:00:00	7 950	494	1 384
02:00:00	7 963	495	1 386
03:00:00	7 218	449	1 259
04:00:00	6 831	426	1 193
05:00:00	7 456	464	1 300
06:00:00	8 034	499	1 399
07:00:00	8 481	527	1 475
08:00:00	8 804	547	1 531
09:00:00	8 704	540	1 513
10:00:00	8 746	543	1 521
11:00:00	8 502	528	1 479
12:00:00	7 984	496	1 390
13:00:00	7 342	457	1 280
14:00:00	7 401	460	1 290
15:00:00	7 365	458	1 284
16:00:00	6 626	413	1 157
17:00:00	7 394	460	1 290

18:00:00	6 931	432	1 211
19:00:00	6 643	414	1 160
20:00:00	7 978	496	1 389
21:00:00	7 775	483	1 354
22:00:00	8 032	499	1 399
23:00:00	7 694	478	1 340

APPENDIX D: SIMULATION VALIDATION

The pressure measurements for the three different scenarios as mentioned in Section 3.4.2 can be seen below in Table D - 1.

Table D - 1: Pressure readings for different simulation scenarios

Pressure (kPa)			
Time (hh:mm:ss)	**Scenario 1**	**Scenario 2**	**Scenario 3**
00:00:00	512	440	382
01:00:00	516	440	380
02:00:00	517	441	381
03:00:00	474	406	351
04:00:00	452	387	335
05:00:00	488	417	360
06:00:00	522	445	384
07:00:00	548	467	402
08:00:00	567	483	415
09:00:00	562	479	412
10:00:00	565	481	414
11:00:00	552	470	404
12:00:00	522	445	384
13:00:00	484	414	358
14:00:00	487	417	360
15:00:00	485	415	359
16:00:00	482	410	350
17:00:00	485	415	359

18:00:00	458	393	340
19:00:00	451	379	329
20:00:00	519	443	382
21:00:00	495	451	395
22:00:00	490	436	384
23:00:00	481	429	370